Jefferson Labs secondary beams for nuclear physics

Stefano Grazzi

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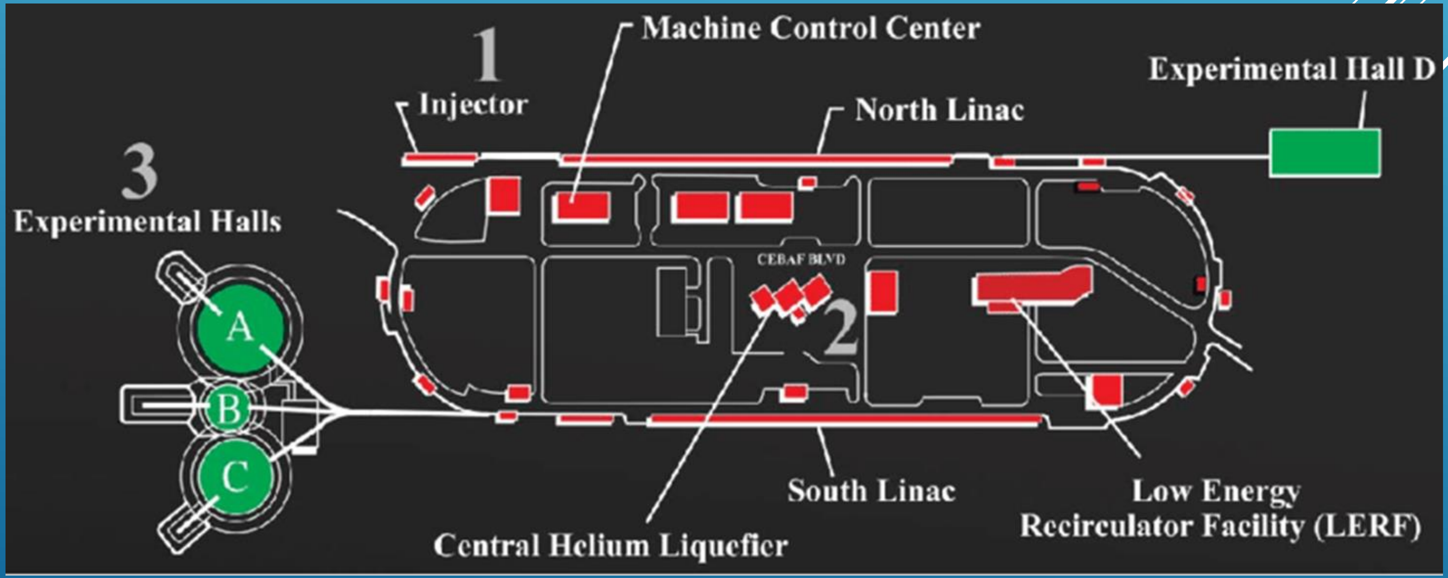
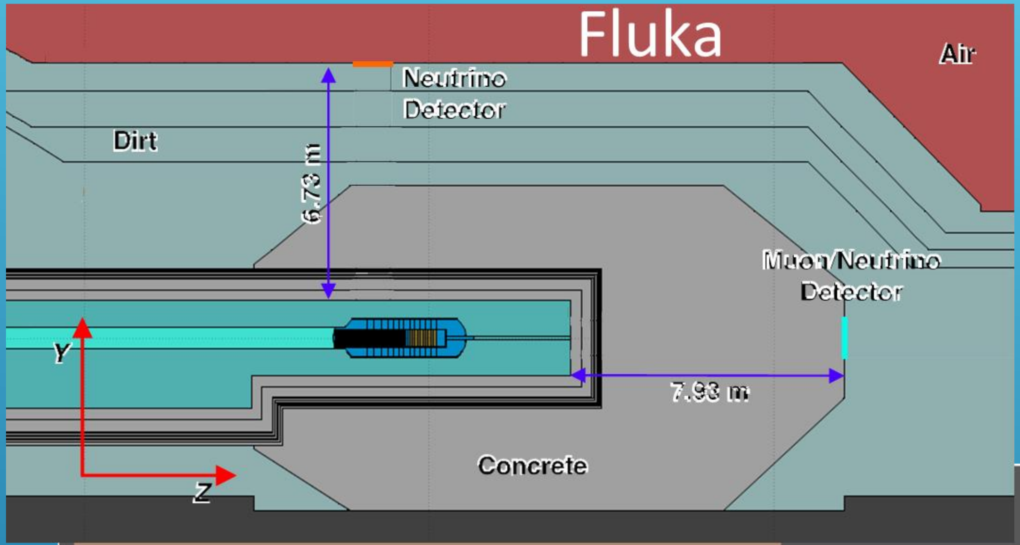
JEFFERSON LAB ACCELERATOR FACILITY

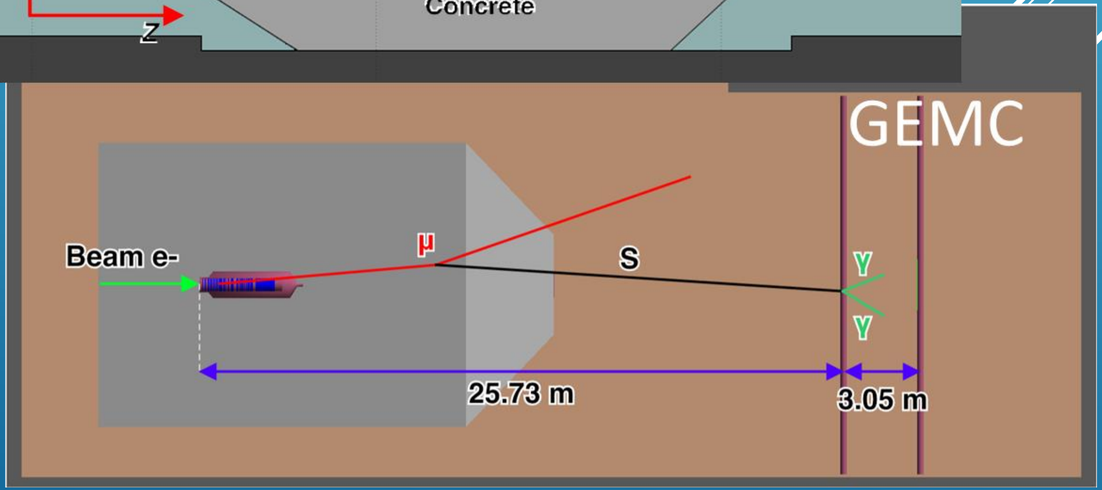
- The Jefferson Lab (JLab) is a US Department of Energy laboratory in Newport News, Virginia.
- CEBAF is a continuous wave electron accelerator
- Four experimental halls receive a e-beam with energy up to 11-12 GeV
- Current of 75 uA --> 10^{22} EOT/year
- Physics program includes: the study of the hadron spectrum, nucleon structure, nuclear interaction, and BSM searches.
- Future upgrade to 22 GeV



SIMULATION FRAMEWORK

- Two Monte Carlo simulations tool to describe interaction of beam with Hall's Beam Dump and subsequent transportation of the secondary particles:
  - FLUKA and GEANT4 toolkits.
- FLUKA used to simulate secondary muons and neutrinos beam
- GEANT4, via the GEMC interface, is used to simulate a hypothetic Light Dark Matter (LDM) source generated by secondary muon beam.
- A combination of two tool is used converted FLUKA information in the LUND format (particle ID, vertex and momentum), and fed to GEMC.



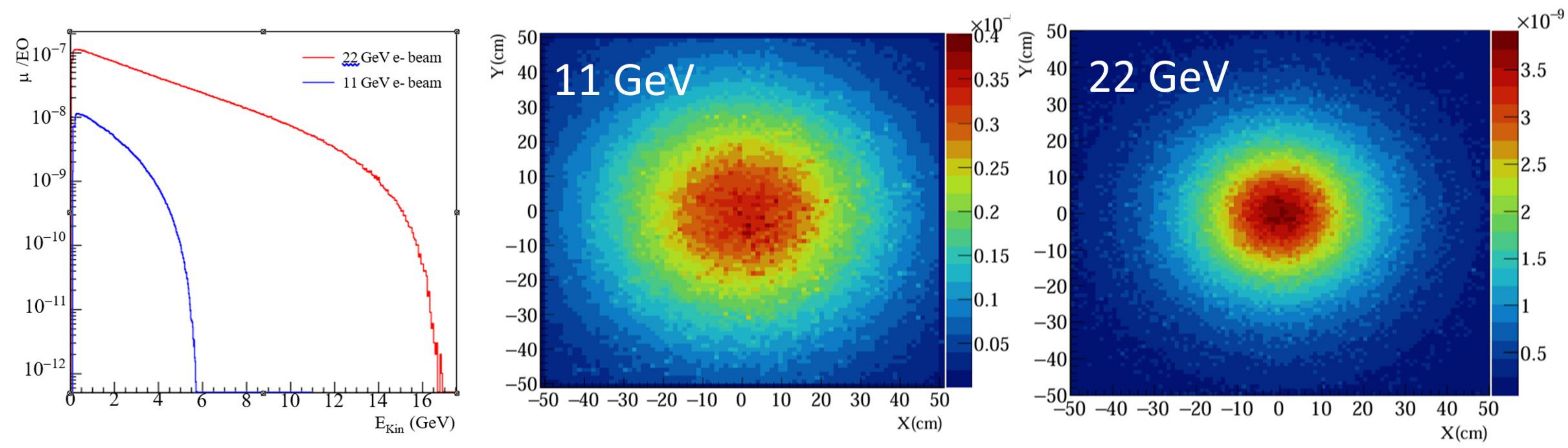


SECONDARY MUON BEAM

- A high-intensity multi-GeV electron beam hitting a thick target produced μ via two classes of processes:
  - Decay by Photo-production of π's and K's
  - Direct $\mu^+\mu^-$ pair production.
- Simulation of muon prodution are done for both 11 GeV and 22 GeV e-Beam, the spectrum produce is Bremsstrahlung-like
- 22 GeV case covers an extended energy range (up to ~16 GeV) with an almost ×8 yield. The spatial distribution results in being more forward-peaked.

Table 1. Summary of JLab secondary muon beam features.

Beam Energy	Flux /EOT		σ_x (cm)	σ_y (cm)
	100×100 cm^2	25×25 cm^2		
11 GeV	9.8×10^{-7}	1.5×10^{-7}	24.6	25.1
22 GeV	7.6×10^{-6}	1.9×10^{-6}	20.9	20.9



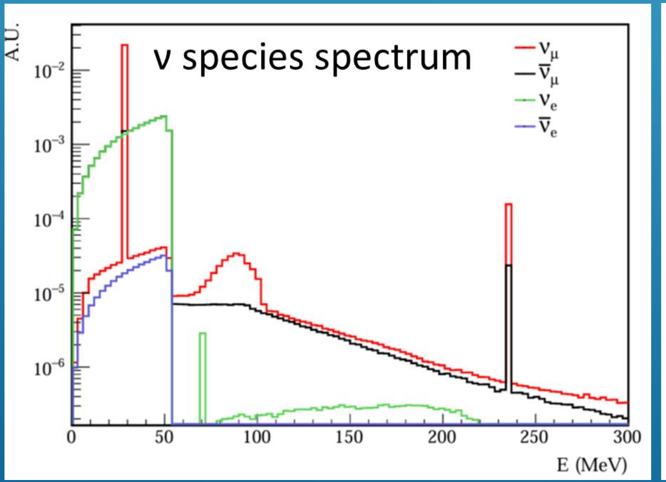
SECONDARY NEUTRINO BEAM

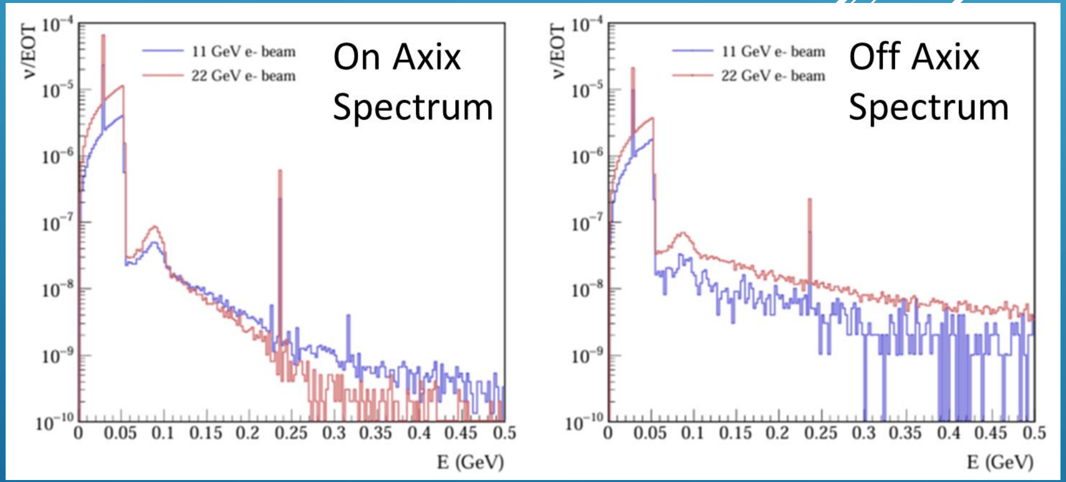
- High-energy p or e- hit a target, generate $\pi^{\pm}$ and $K\pm$ that decay in flight (DIF) or decay at rest (DAR) into neutrinos. 4 (anti)neutrino (left) species are produced; in nuclear reactor source only electron:
  - $\pi^{+} \longrightarrow \mu^{+} + \nu_{\mu}$ $E_{\nu} \sim 29.8$ MeV, almost monochromatic;
  - $\mu^{+} \longrightarrow \bar{\nu}_{\mu} + \nu_{e} + e^{+}$ E_{ν} in the range 0–52.8 MeV;
  - $K+ \longrightarrow \mu^{+} + \nu_{\mu}$ $E_{\nu} \sim 236$ MeV, almost monochromatic.

Table 2. Summary of JLab secondary neutrino beam features. Yields are obtained integrating the neutrino flux in the energy range 0–500 MeV.

Beam Energy	Off-Axis Flux [ν/EOT/m^2]	On-Axis Flux [ν/EOT/m^2]
11 GeV	6.7×10^{-5}	2.9×10^{-5}
22 GeV	1.9×10^{-4}	6.3×10^{-5}

- DAR neutrinos can be used to studying coherent elastic neutrino-nucleus scattering (CEvNS).
  - Recently observed process and candidate for the study of non-standard (BSM) neutrino interactions.





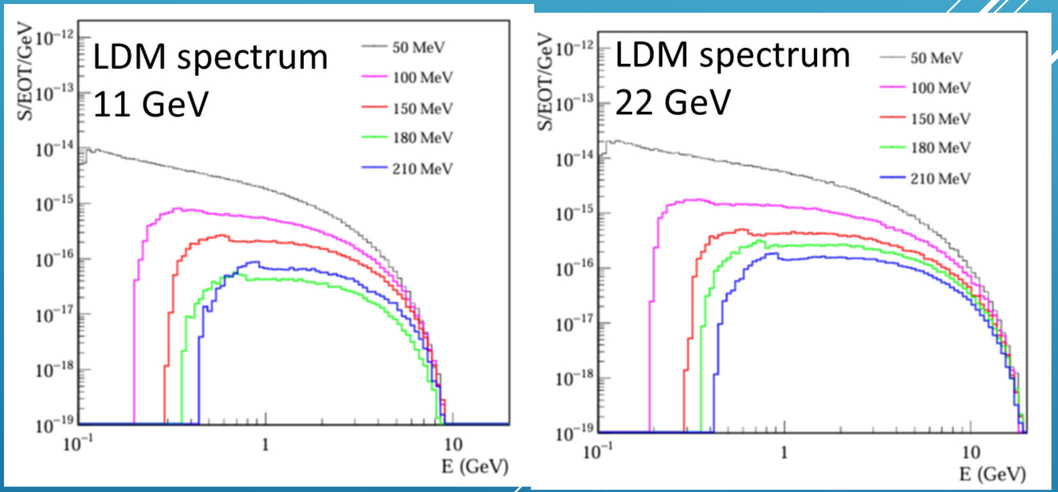
SECONDARY DARK MATTER BEAM

- Particle nature of dark matter remains one of the biggest endeavors in fundamental science.
- Big effort in search of weakly interacting massive particle candidates (WIMPs).

Table 3. Summary of JLab scalar dark matter beam features.

Beam Energy (GeV)	m_S = 50 MeV		m_S = 180 MeV	
	S/EOT	σ (m)	S/EOT	σ (m)
11	5.27×10^{-15}	1.556	1.32×10^{-16}	0.488
22	1.90×10^{-14}	1.22	1.44×10^{-15}	0.304

- The lack of experimental evidences has motivated the interest toward sub-GeV LDM
  - Minimal model to explain the $(g-2)_\mu$ anomaly -> new *leptophilic* scalar dark matter state (*dark scalar* or *S*) couples only to muons.
  - Secondary muons beam may radiate a *S* particle.
- If $m_S < 2m_\mu$ -> *S* decay into two photons
  - decay width, $\Gamma_{\gamma\gamma}$, which depends on the μ–*S* coupling constant, g_μ, and the ratio of muon to *S* masses, m_μ/m_S
  - Simulations were performed assuming $g_\mu = 3.87\ 10^{-4}$ and m_S in the range 25 MeV–210 MeV.



$$\Gamma_{\gamma\gamma} = \frac{\alpha^2 m_S^3}{128\pi^3} \left| \frac{g_\mu}{m_\mu} \frac{4m_\mu^2}{m_S^2} \left[1 + \left(1 - \frac{4m_\mu^2}{m_S^2} \right) \arcsin^2 \left(\frac{4m_\mu^2}{m_S^2} \right)^{-1/2} \right] \right|^2$$

CONCLUSION

- The existing high-intensity electron beam facilities may provide low-cost, opportunistic, high-intensity secondary particle beams that will broaden their scientific programs.
- Detail the characteristics of muon, neutrino, and hypothetical light dark matter beams obtained
- CEBAF energy upgrade extend the energy range up to 16 GeV and the muon flux by almost an order of magnitude for the secondary muon beam
- For the secondary neutrino beam, the DAR yield is expected to double, and, for the dark matter beam, the dark scalar particle yield would increase by up to an order of magnitude.