



H2020 MSCA RISE 2020
GA 101003460



PROBES General Meeting

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INFN Torino



PROBES General Meeting
INFN sezione di Pisa, Nov. 27, 2025

- Introduction: the INFN group activities at JLAB
- PROBES deliverables: results achieved in the last 4 years
 - Deliverable 1.1 WP1 (feb25):
 - CLAS12/SBS detector commissioning
 - Deliverable 1.2 WP1 (feb25):
 - HPS/BDX commissioning
 - Deliverable 1.3 WP1 (feb25):
 - bulk magnets and streaming-readout
 - Deliverable 2.1 WP2 (feb25):
 - CLAS/SBS physics results
 - Deliverable 2.2 WP2 (feb26):
 - HPS/BDX physics results on light matter search
 - Deliverable 2.3 WP2 (feb26):
 - Physics results on neutron star Equation of State

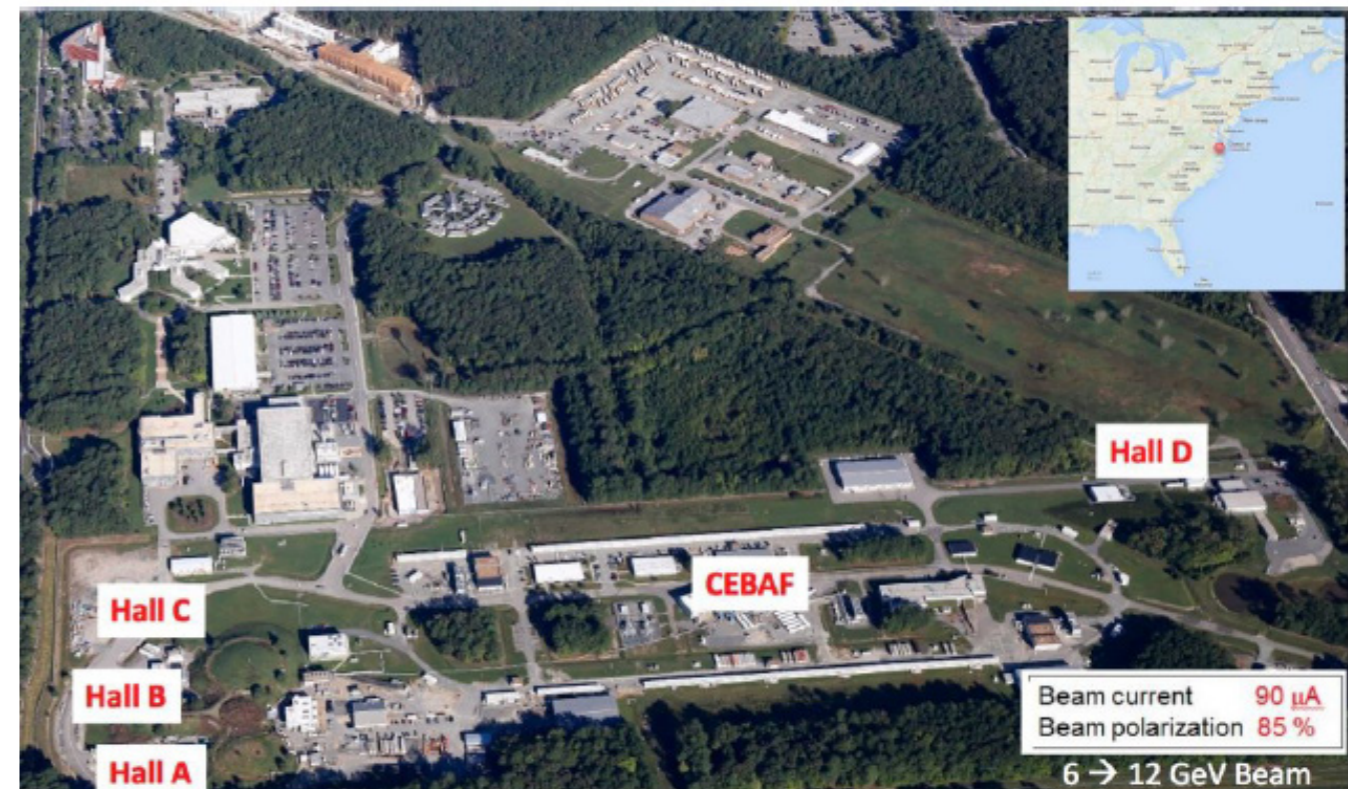
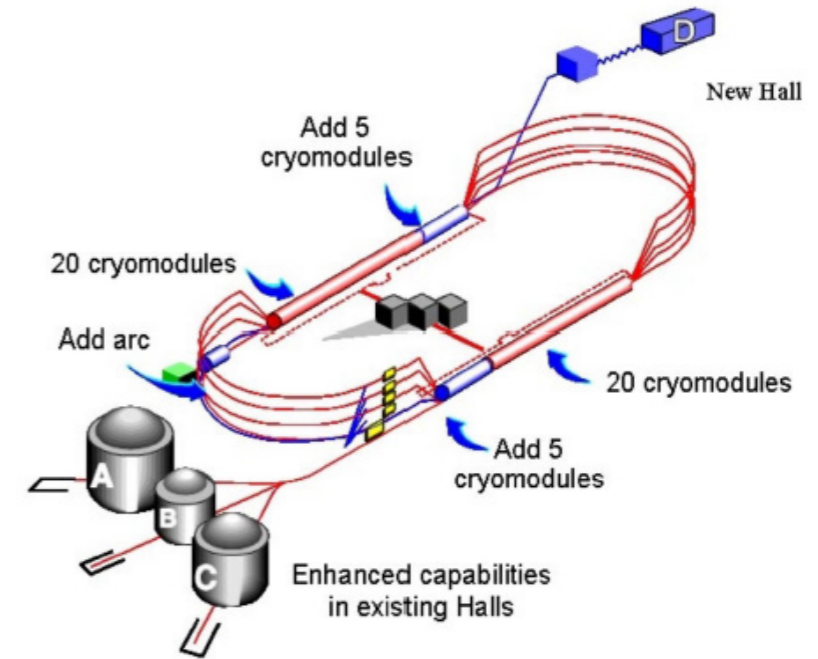


JLAB and the INFN commitment



Jefferson Lab: Advancing Frontiers in Hadron Physics

- **World-class electron beam:**
 - CEBAF delivers a precision 12 GeV continuous electron beam characterized by
 - High intensity
 - High polarization (>85%)
- **Unique Experimental Facilities:**
 - Home to four state-of-the-art experimental halls, enabling a broad range of investigations
- **Research focus:**
 - Probing the fundamental nature of confined quark and gluon states
 - Exploring hadronic structure and interactions in nuclei
 - Searching for new physics Beyond Standard Model
- **A facility at the Luminosity Frontier:** up to $10^{39} \text{ cm}^{-2}\text{s}^{-1}$
- **Upgrade from 6 to 12 GeV completed in 2018**



Experimental Halls at Jefferson Lab

Hall A

- Form factors
- PDF's
- Hypernuclear physics
- BSM physics

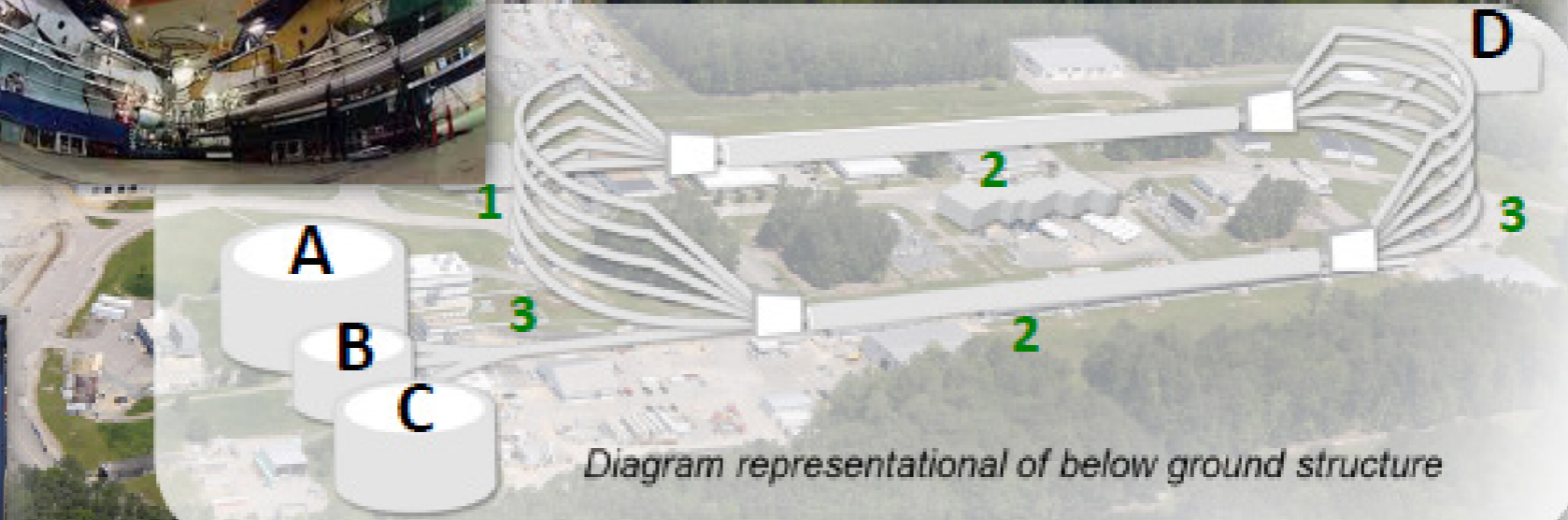


Hall D - GluEX

- Exploring the origin of confinement by studying exotic systems in photon-induced reactions



Newport News (VA) – In operation since 1991



1. INJECTOR
2. LINACS
3. RECIRCULATION ARCS

Hall B

- Studies of 3D nucleon structure
- Meson and baryon spectroscopy
- Nuclear effects investigations
- Dark photon searches



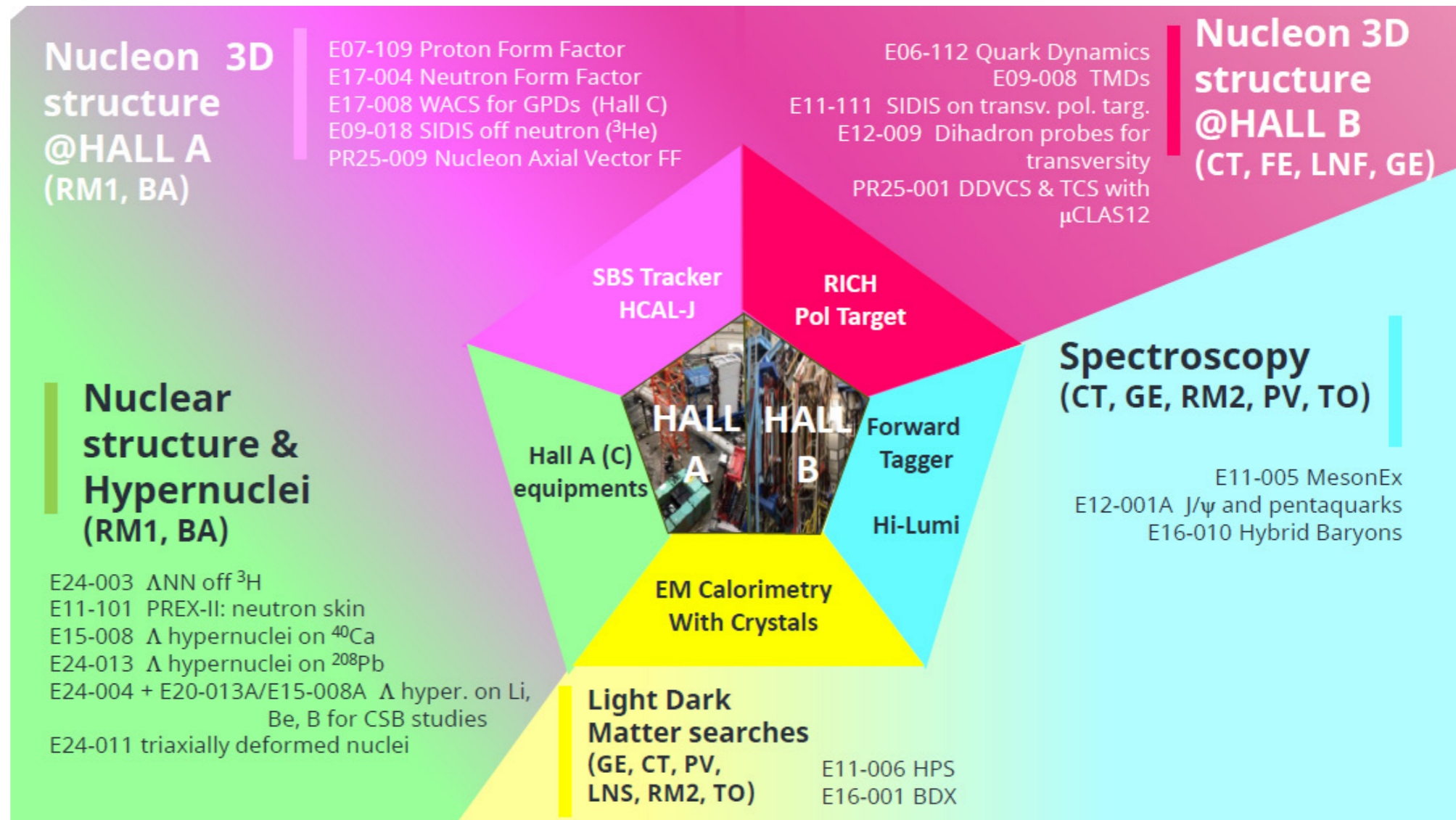
Hall C

- Precision studies of valence quark properties in nucleons and nuclei
- Hypernuclear physics



JLAB12: the Italian collaboration at JLAB

- The Italian group is present at JLAB since the very beginning of CEBAF operations
- Many leadership roles covered
 - More than 20% of approved experiments has Italian spokespersonship
 - activities on Hall A, B, C



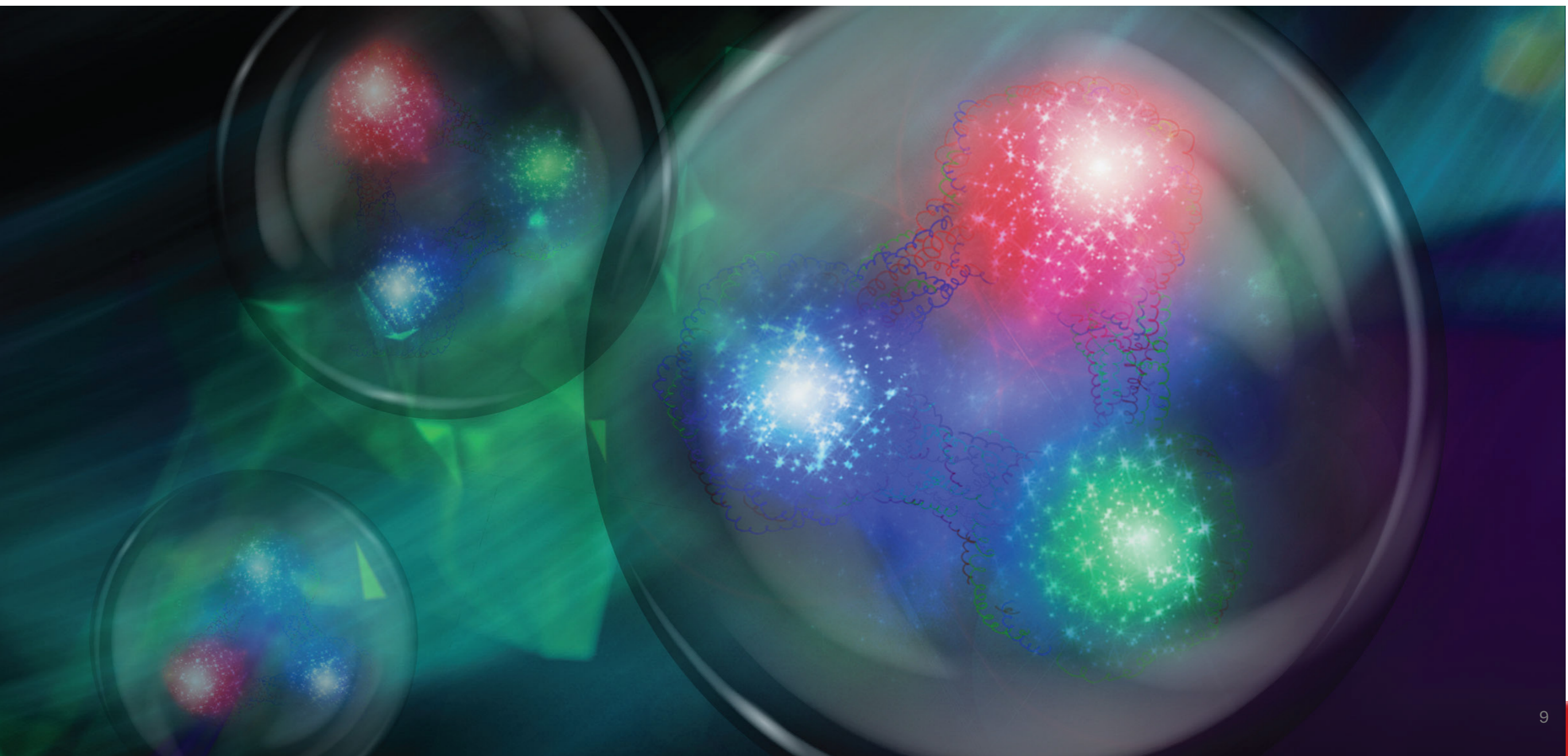
- 2026 group composition
 - Groups in several INFN units: BA, CT, FE, GE, LNS, LNF, PV, RM1, RM2, TO
 - 54 researchers, 24.1 FTE
 - 8 technologists, 2.85 FTE
 - 9 technicians + some “hidden” FTEs (PNRR synergic activities) + theory collaborators

PROBES/INFN (hadron physics) business

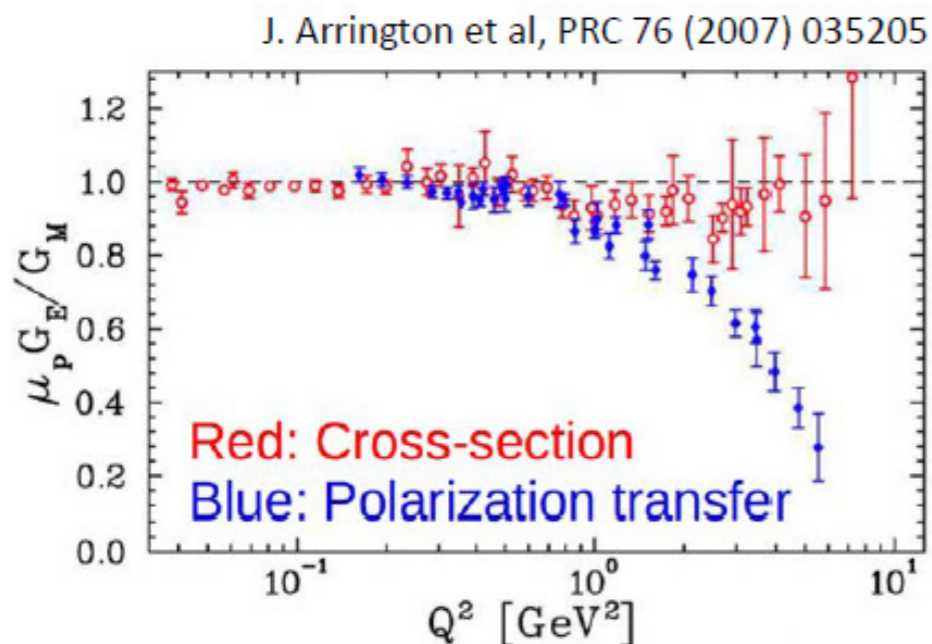
- 30 INFN users benefitting from support for secondments
- ~1570 secondment days in 4 years
- 5 critical cases (not completing 30 minimum days by feb. 26), as of end nov. 2025

unit	mani project(s)	2022	2023	2024	2025	2026	TOTAL	tot/unit		%
BA	SBS/AXFF	20	16	22	0		58	58	Bari	0.04
CT	CLAS12/BDX/HPS/SEC. BEAMS	30	54	16	30		130			
CT	CLAS12	15		16	24		55			
CT	SBS			19	17		36			
CT	BDX + SEC. BEAMS			63			63	269	Catania	0.17
FE	CLAS12	15		17	14		46			
FE	CLAS12	95	48		26		169			
FE	CLAS12	12	21	35	31		99			
FE	CLAS12			23	14		37			
FE	CLAS12				39		39	364	Ferrara	0.23
GE	CLAS12/BDX/HPS	61	72				133			
GE	CLAS12/BDX/HPS	12	32	39	30		113			
GE	CLAS12/BDX		30	62			92			
GE	BDX/ SEC. BEAMS		24				24			
GE	CLAS12			11	8		0			
GE					26		0	362	Genova	0.23
LNF	CLAS12	21	41		34		96			
LNF	CLAS12	33					33			
LNF	CLAS12	32					32			
LNF	CLAS12	23					23			
LNF/KEK					44		44	228	LNF	0.14
PV	CLAS12/BDX			15	22		37			
PV	CLAS12			11			0	37	Pavia	0.02
RM1	SBS				56		56			
RM1	SBS			24	31		55	111	Roma1	0.07
RM2	CLAS12/BDX		22	12			34			
RM2		15					0			
RM2	CLAS12			12	8		20	54	Roma2	0.03
TO	CLAS12/HPS/BDX		22	7	20		49			
TO/JPARC					43		43	92	Torino	0.06
								Gtotal		1575

Physics searches



- SBS/BB proposed a comprehensive program for Form Factors measurements at high momentum transfer ($Q^2 \sim 14 \text{ (GeV/c)}^2$) at the high luminosity frontier
 - Run from 2020 onwards
 - Measurements through cross sections and polarization transfer techniques



Two arms spectrometer: trade-off between acceptance and luminosity

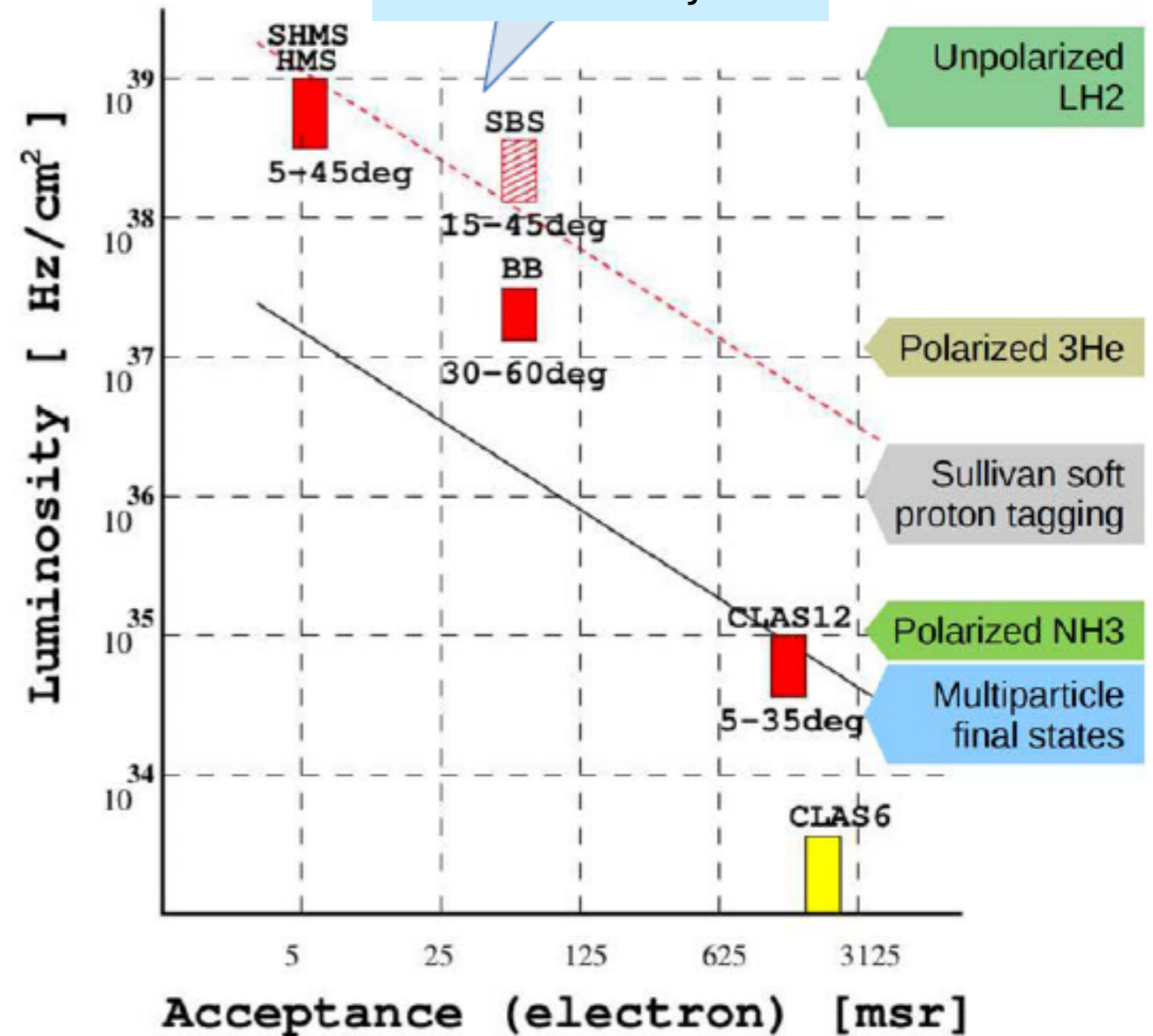
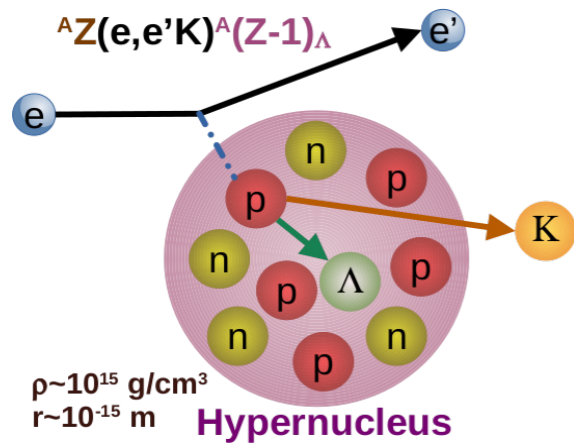
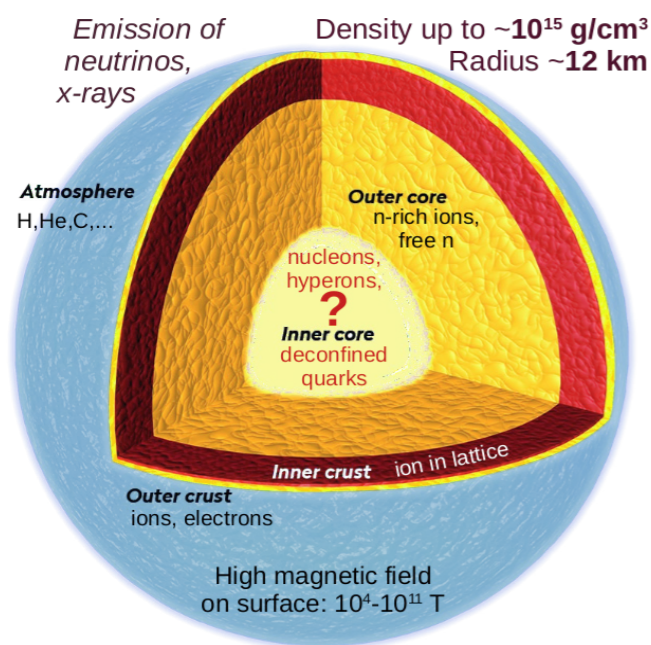


Figure of Merit $\propto L \cdot \Omega \cdot E^2 / Q^{16}$

Hypernuclear program: from nuclei with strangeness to neutron stars

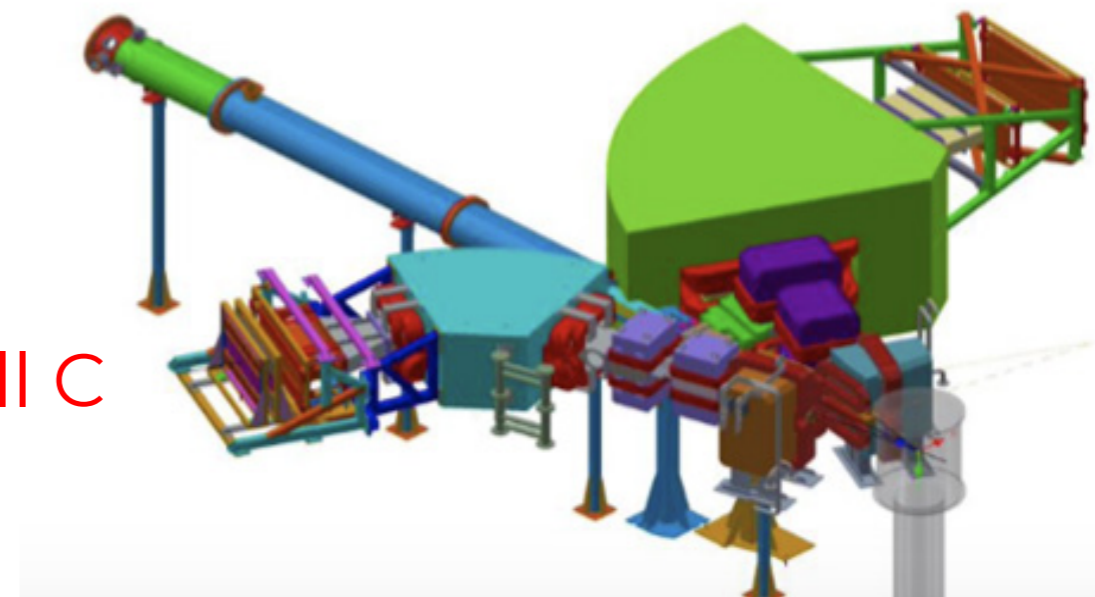


- Kaon electroproduction ($e, e'K^+$) exploited at JLAB since 2000, as an effective tool for hypernuclei production and investigation

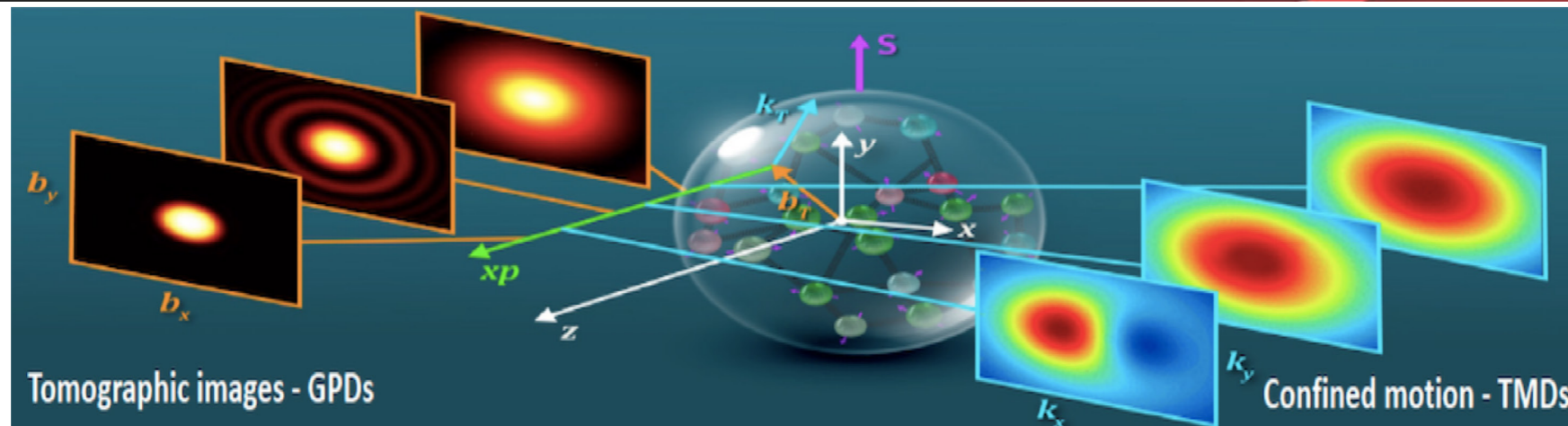


- Hypernuclear spectroscopy
- Study of repulsive ΛNN 3-body repulsive forces to solve the so-called hyperon puzzle (massive neutron stars radius)
- Investigation of charge symmetry-breaking effect in YN interaction
- Using Λ as a probe to infer triaxial nucleon deformation properties

- 5 experiments re-designed to run in Hall C
- Experimental equipment: **HES** + **HKS** magnetic spectrometers (to detect electrons + kaons)

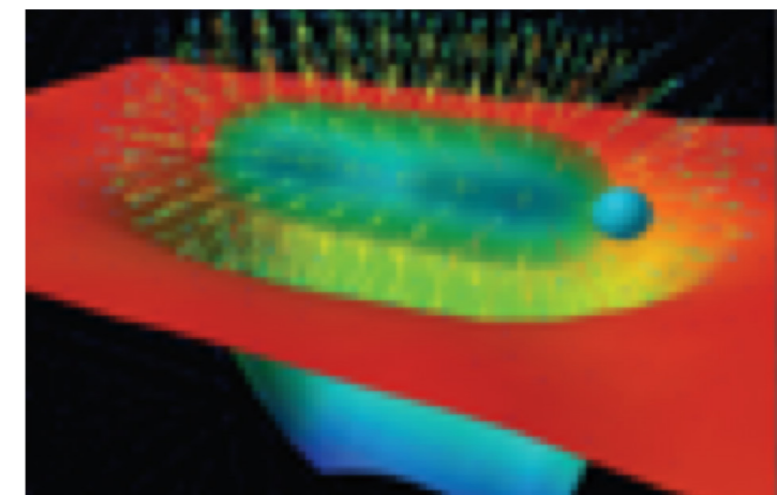
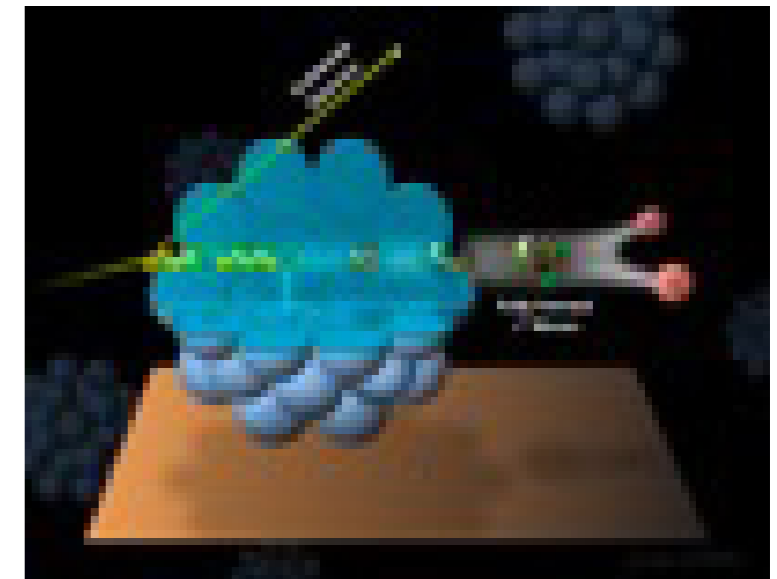


The CLAS12 physics program



- More than 45 approved experiments, with large coverage of nuclear physics fields – organized in 11 run groups to optimize accelerator usage & experimental configurations

- Nucleon and nuclear structure, spatial and momentum tomography, form factors, ...
- Cold nuclear matter, NN correlations, hadronization, color transparency, ...
- Exploring the origin of confinement: meson and baryon spectroscopy



Understanding the properties of the nucleon – where do we stand?

- Which is the origin of its mass, and where is it located?

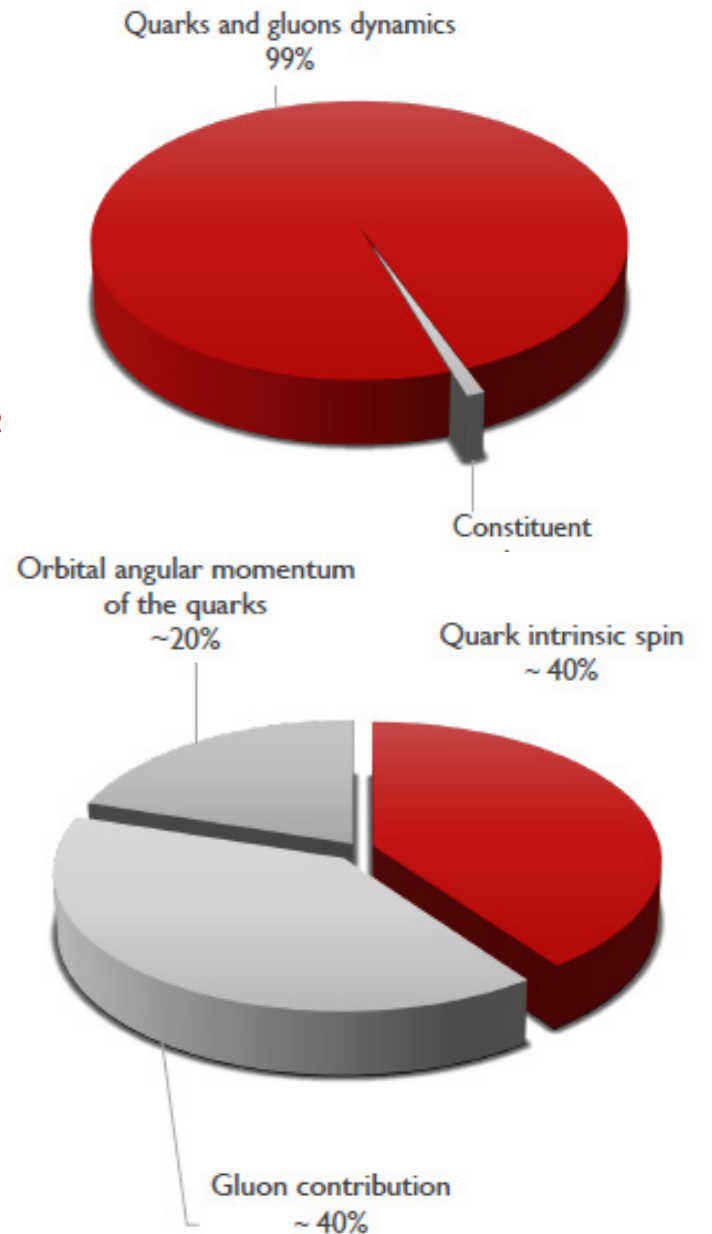
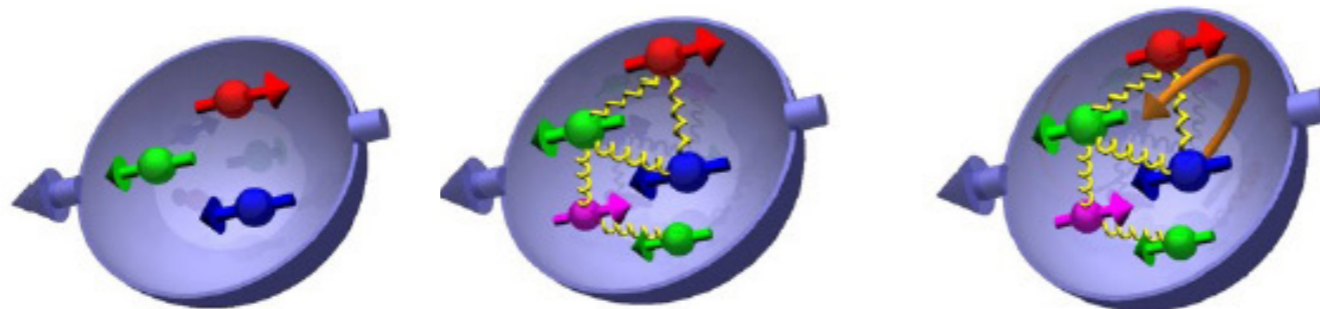
- Which is the origin of its spin?

- The spin comes from the interplay among parton intrinsic properties and their interactions

- dynamic feature

- the quark spin is not the dominant term! 25% from quarks/antiquarks (known since the 80's)
 - 35% from gluons
 - Sizeable contributions from spin-orbit effects
 - Large uncertainties

$$\frac{1}{2} = \frac{1}{2} \left(\Delta\Sigma(\mu) + \Delta G(\mu) + L_q(\mu) + L_g(\mu) \right)$$



- Can we measure the intensity of the strong force in a proton?

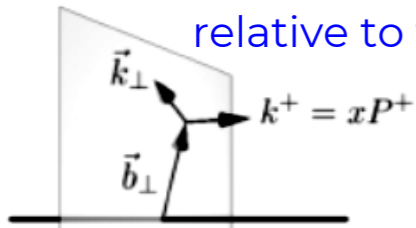
- Can we measure the nucleon mass radius?

- Can we measure the pressure and shear forces inside a proton?

Generalized Parton Distributions: encode information on the nucleon structure

Momentum Space

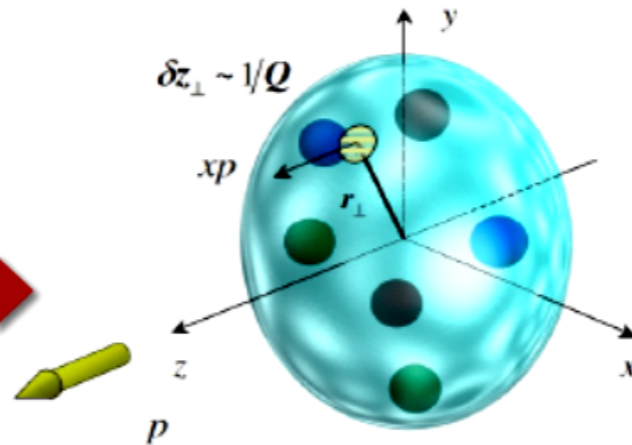
k_{\perp} : transverse momentum relative to the parton



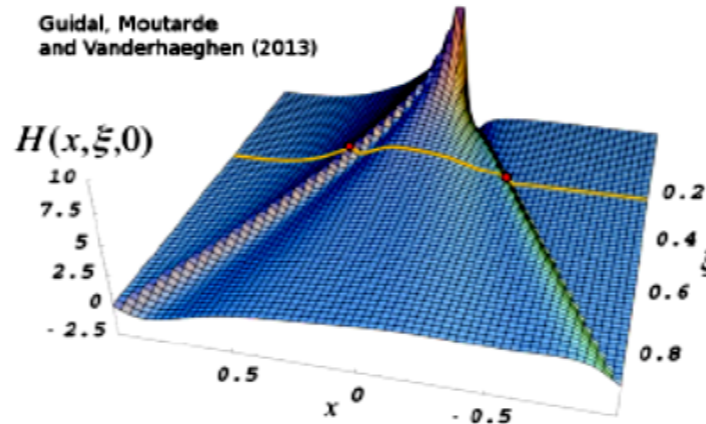
$$\int d^2 \vec{k}_{\perp}$$

Generalized Parton Distributions

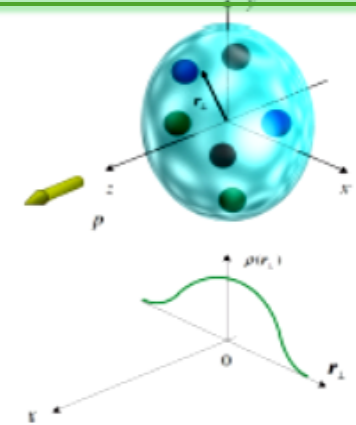
$$H, \tilde{H}, E, \tilde{E}(x, \xi, t)$$



Guidal, Moutarde and Vanderhaeghen (2013)

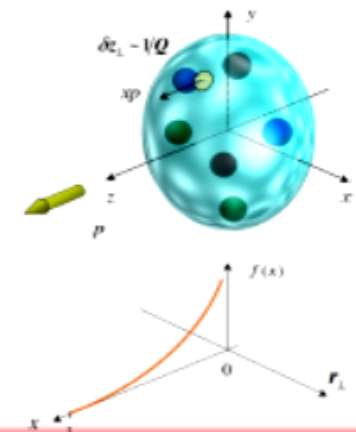


Electro-magnetic Form Factors (Elastic scattering)



Coordinate Space

$$\int d^2 \vec{b}_{\perp}$$



b_{\perp} : impact parameter position of the parton relative to the hadron

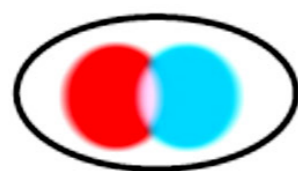
Parton Distribution Functions (DIS)

$$W(x, \xi, \vec{k}_{\perp}, \vec{k}_{\perp} \cdot \Delta_{\perp}, t)$$

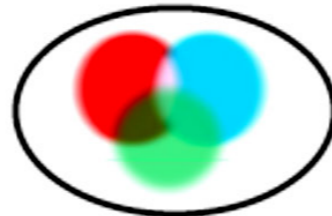
Generalized Transverse Momentum Distributions

- **Form Factors (FF)** describe the transverse position of partons
- **Parton Distribution Functions (PDF)** describe longitudinal momentum distributions
 - From exclusive scattering
- **Generalized Transverse Momentum Distributions (GTMD)** correlate transverse position and longitudinal momentum distributions
 - from semi-inclusive scattering

Hadrons beyond the Constituent Quark Model

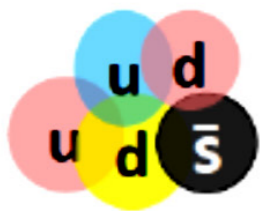


ordinary mesons

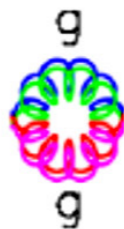


ordinary baryons

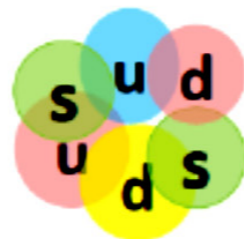
non- $q\bar{q}$ & non- qqq color-singlet combinations



pentaquarks



glueballs



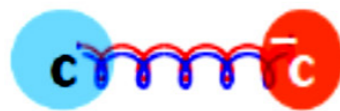
H-dibaryon



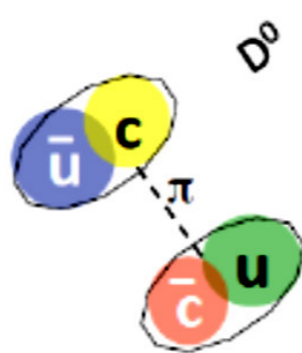
diquark-diantiquarks



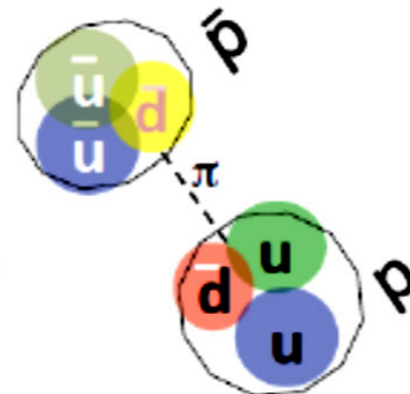
heptaquarks



hybrids



deusons



molecules

QCD intrinsically allows for the existence of hadrons formed by gluons only, or a mixture of quarks and gluons

- Their quantum numbers may be the same as for ordinary $q\bar{q}$ pairs... but they can also be forbidden combinations!

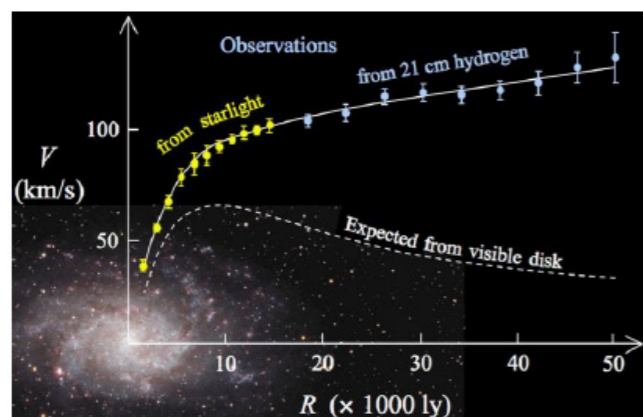
exotics



The existence of Dark Matter

- There is clear evidence for the existence of Dark Matter
 - Trend of galactic rotation curves
 - Gravitational lensing effect
 - Isotropy of cosmic microwave Background

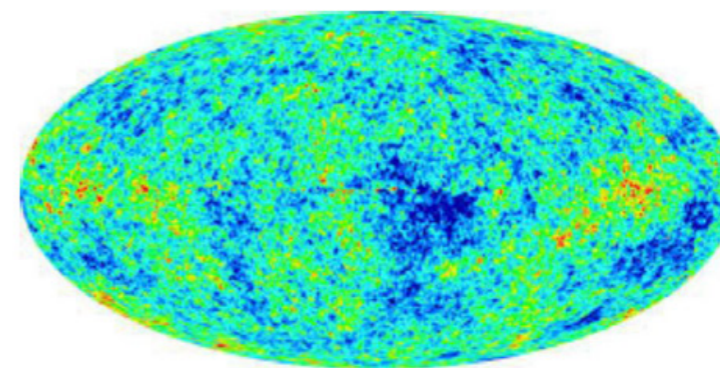
85% of the universe is composed by Dark Matter



Galactic Rotation Curves



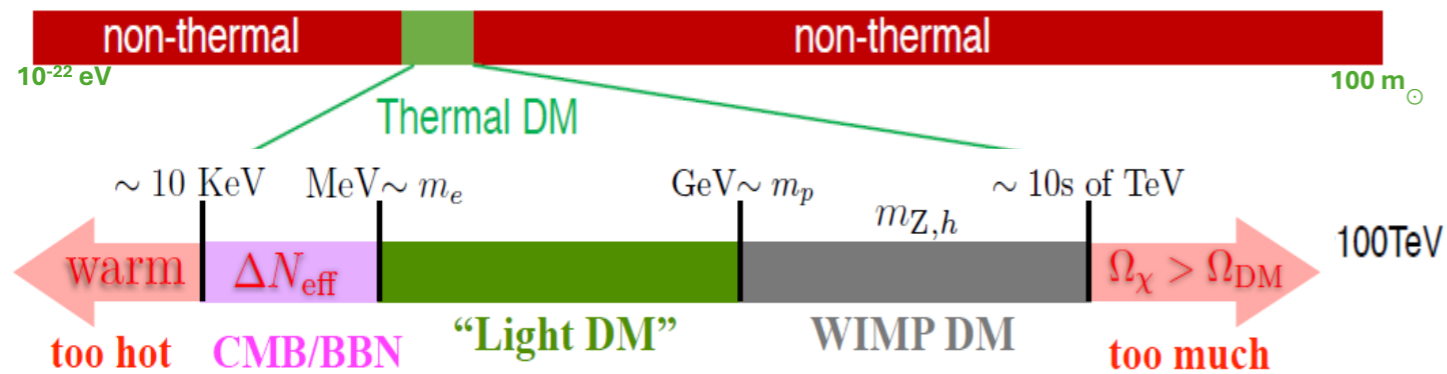
Gravitational Lensing



Cosmic Microwave Background

- ◀ The fundamental nature and origin is one of the key issues in particle physics
- ◀ The Standard Model cannot account for Dark Matter – new ideas and models are needed
- ◀ Mass scale problem: astrophysical evidences do not pose mass constraints
 - ◀ The range of DM mass spans ~ 90 orders of magnitude

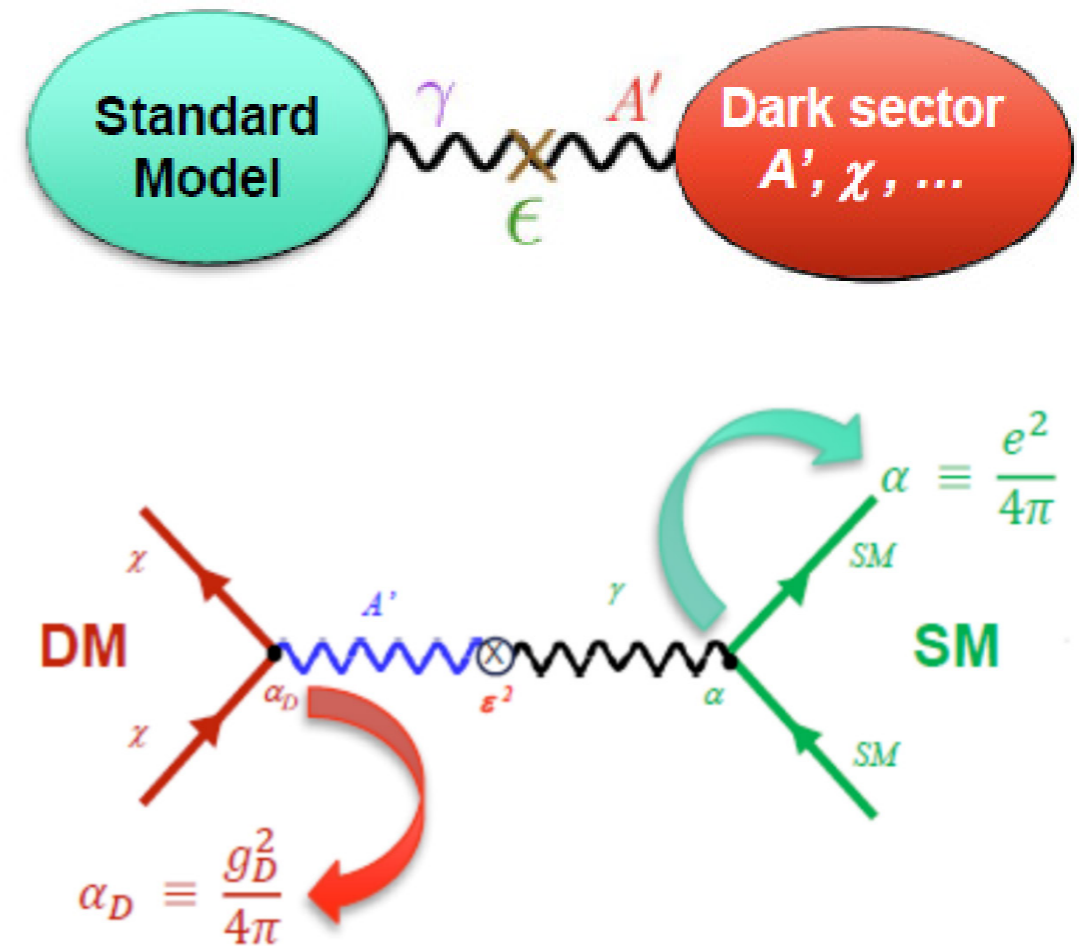
Light Dark Matter at accelerators: hidden sectors and mediators



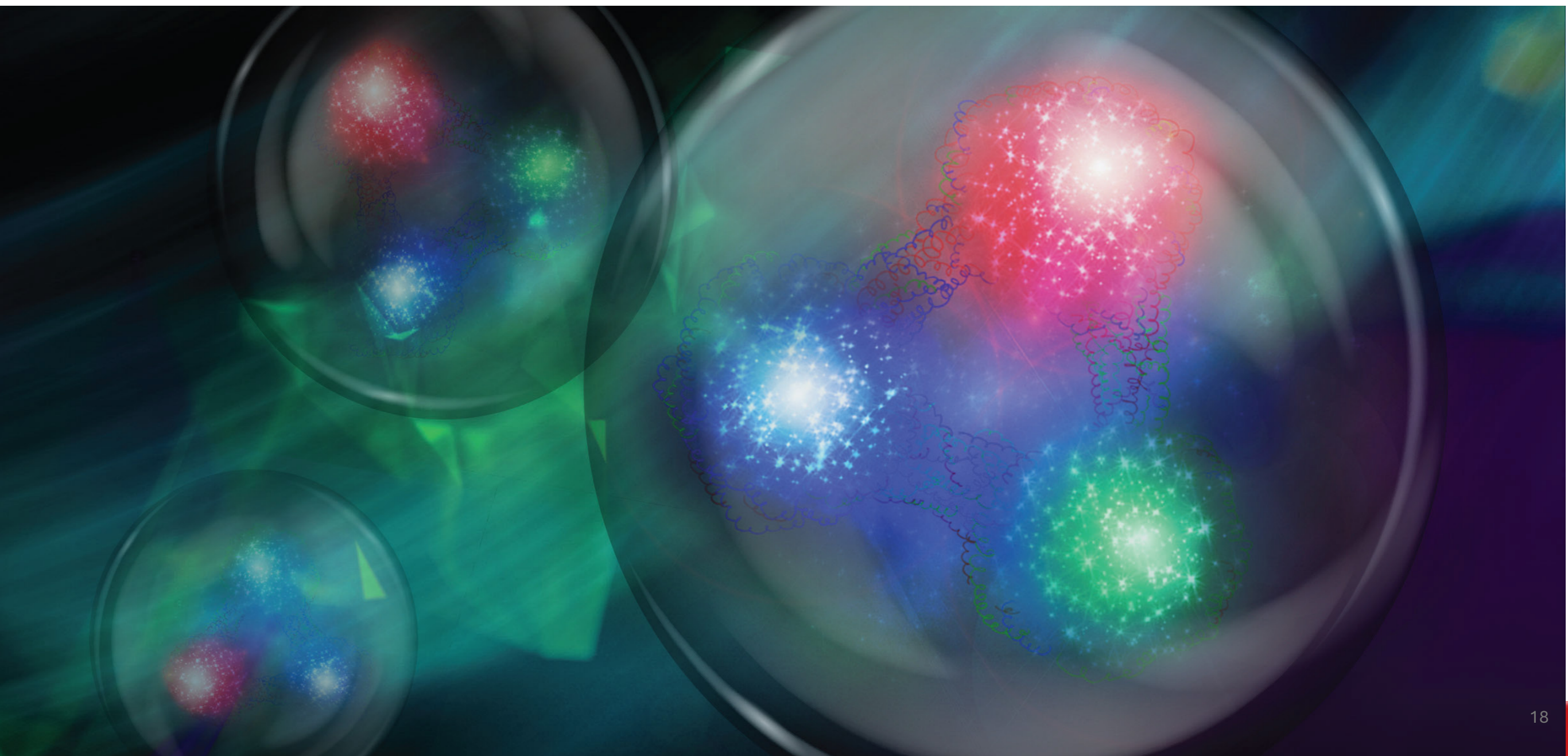
- WIMPs cannot be lighter than 2 GeV
- Light DM (MeV-GeV) thermal relics require light mediators to achieve the required annihilation cross section for freeze-out
 - Non-SM portal interaction required

- **Dark photon:** vector gauge boson of a new sector $U(1)_D$, secluded from SM and neutral under SM (B. Holdom, PLB166, 196 (1986))
 - Kinetic mixing of $U(1)_D$ with SM $U(1)_Y$ through the coupling constant ϵ
 - The $e\epsilon$ coupling to the fermions can be as small as to 10^{-7}
 - The phenomenology depends on the $m_\chi/m_{A'}$ ratio

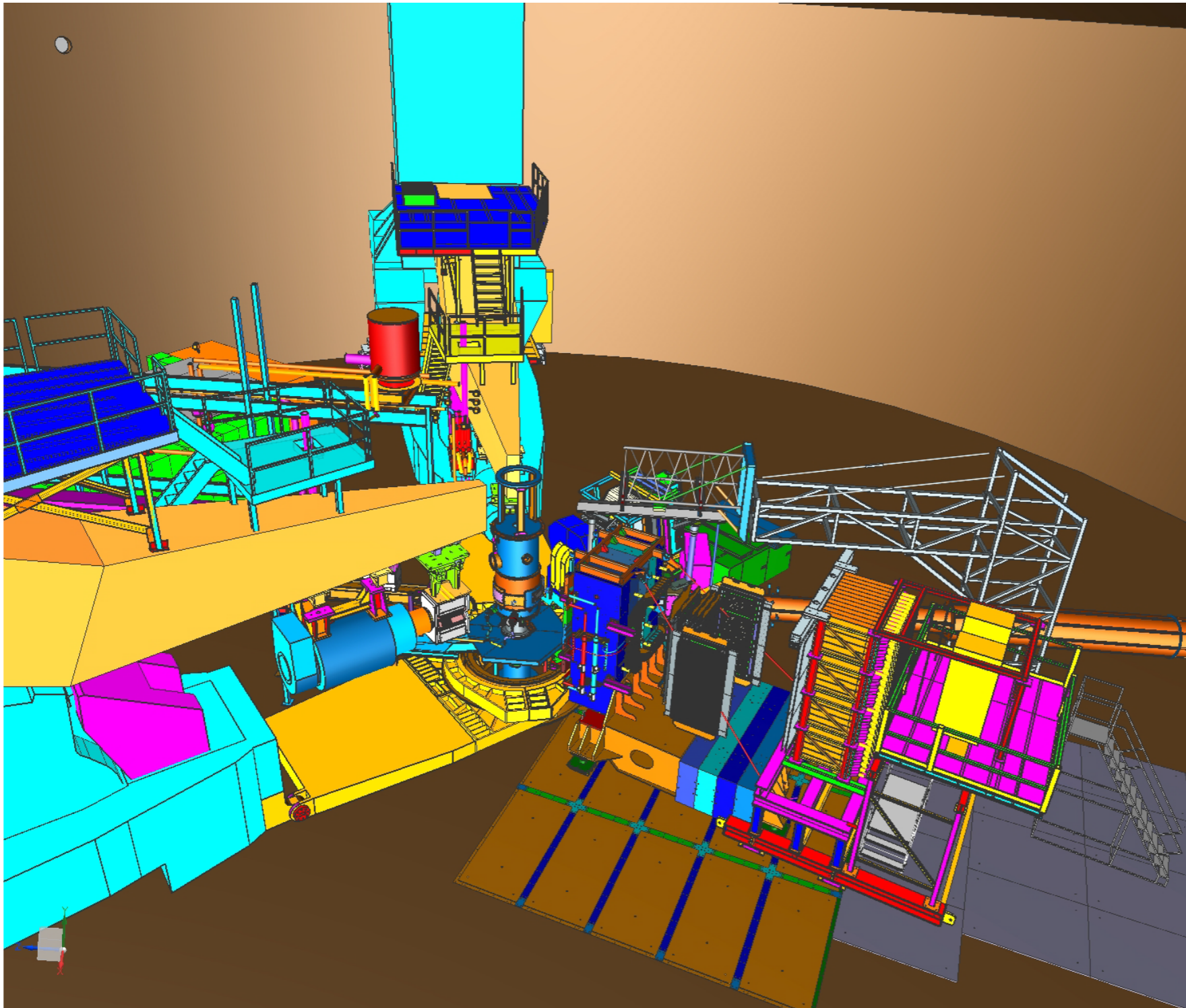
$$\langle\sigma v\rangle \propto \frac{\alpha_D \alpha m_\chi^2}{m_{A'}^4}$$



Detectors/experimental equipments at JLAB



Hall A: SBS

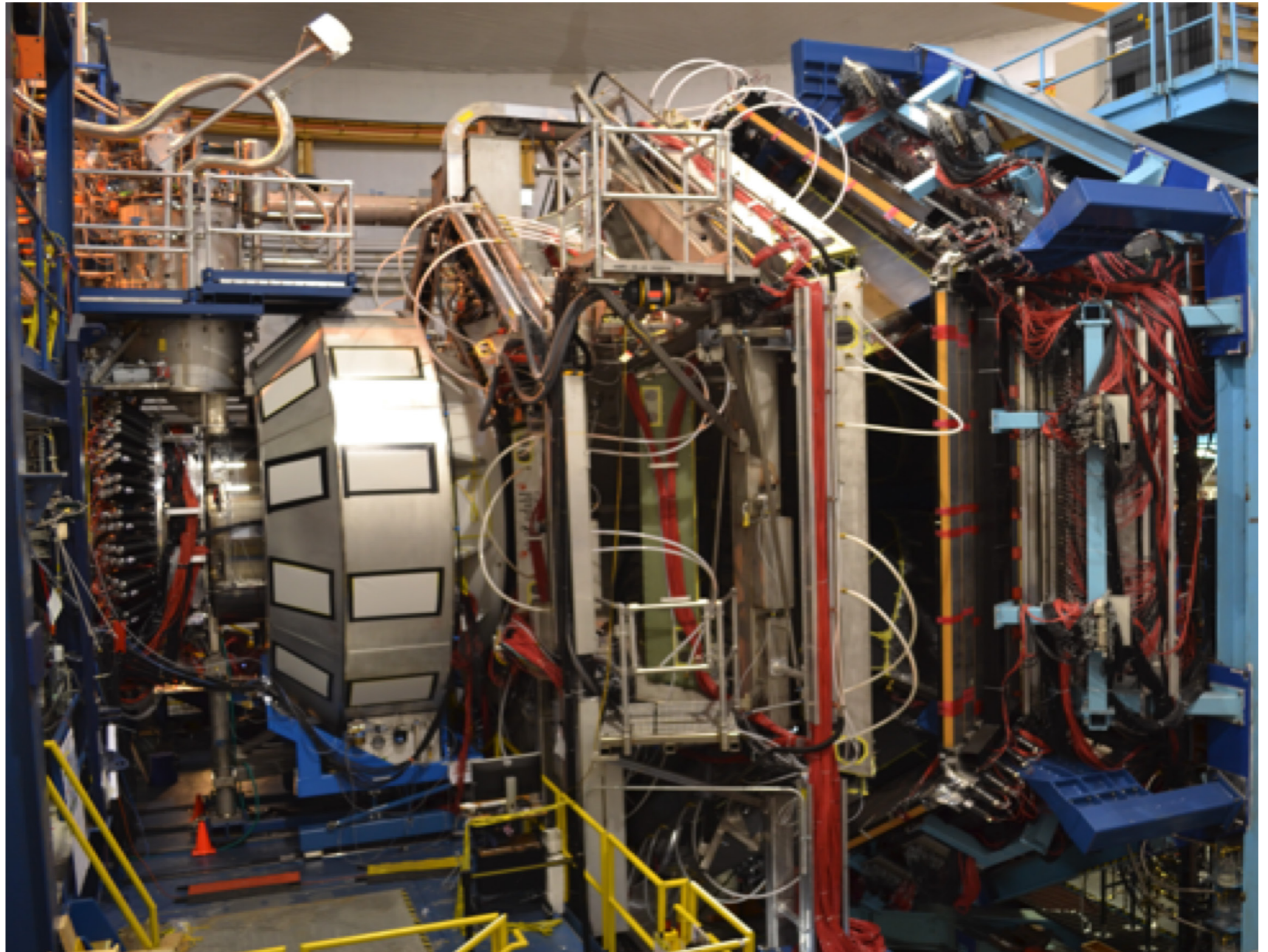


Two arms
spectrometer

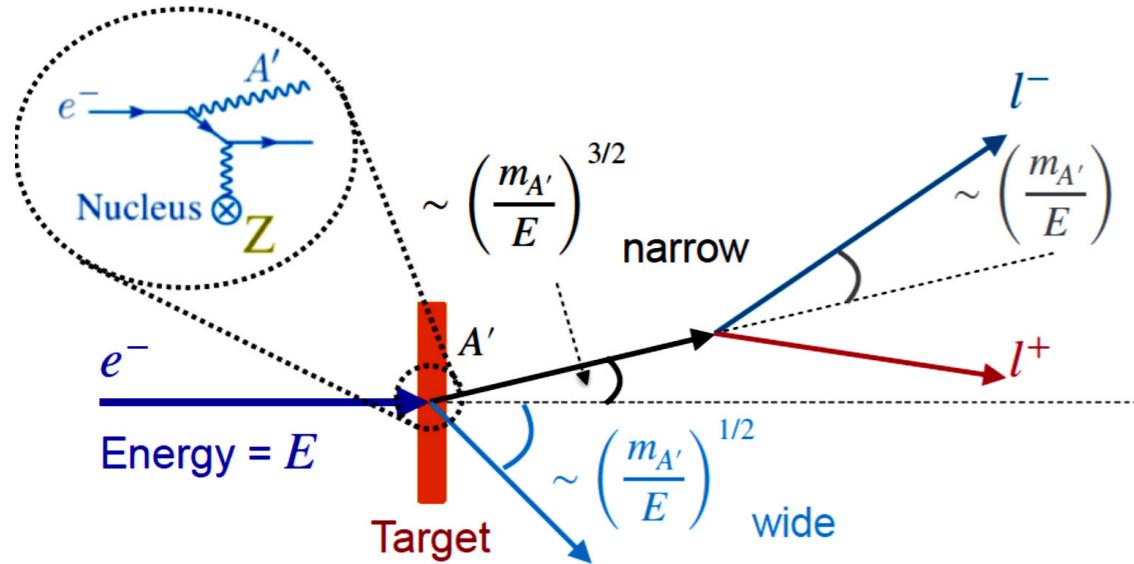
Various
configurations
possible

Hall B: the CLAS12 apparatus

- Construction completed in 2017
- In production since 2018
- Targets:
 - Cryogenic: LH₂, LD₂, LHe, LAr
 - D₂, ⁴He
 - ¹²C to ²⁰⁸Pb
 - Polarized: NH₃, ND₃, ⁶LiH, ⁷LiD, ³He-gas

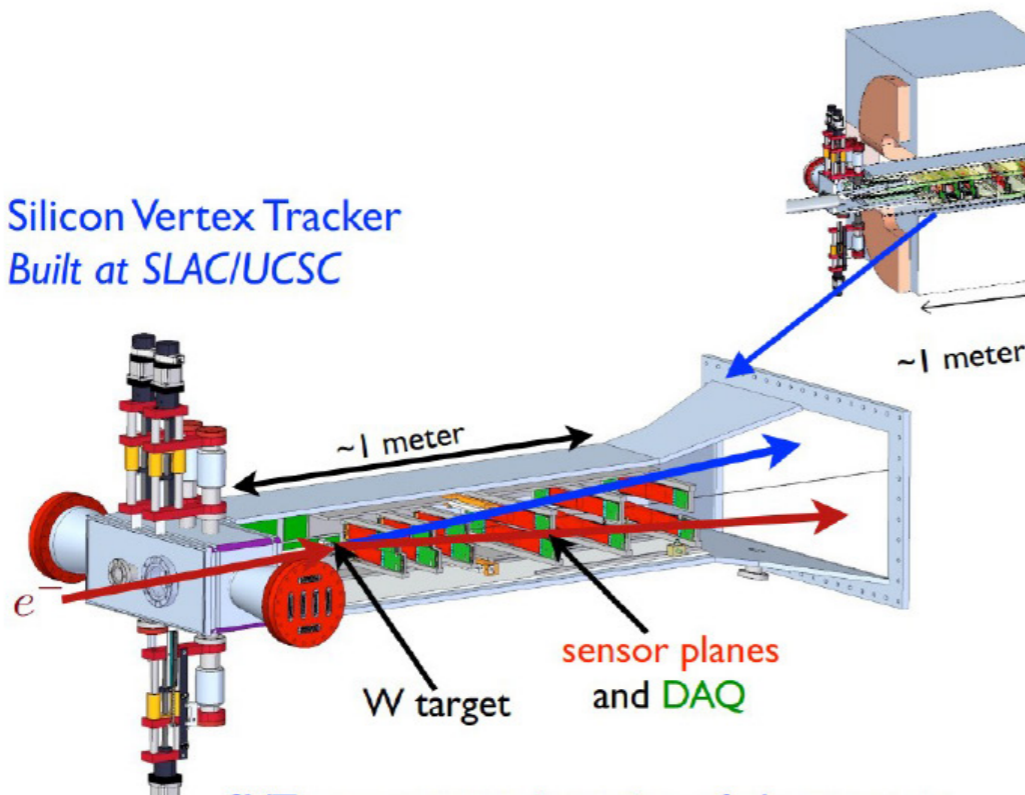


Hall B: the Heavy Photon Search (HPS) Experiment

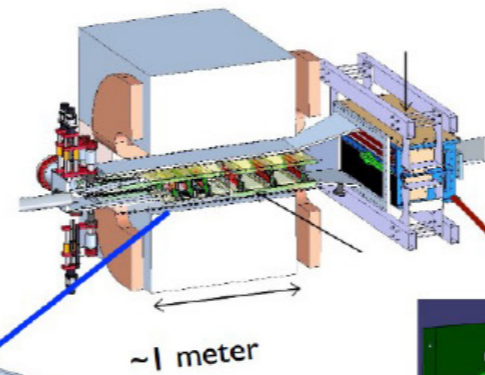


- Dark photons produced via brehmsstrahlung on a thin target
 - Very good forward acceptance needed
 - Precise tracking
- Electromagnetic calorimeter (Ecal): provides e^+e^- trigger with precision timing
- Silicon vertex detector (SVT) measures trajectories of e^+e^- and reconstruct mass and vertex position
- Dipole magnet spreads e^+e^- pairs and allows momentum measurements

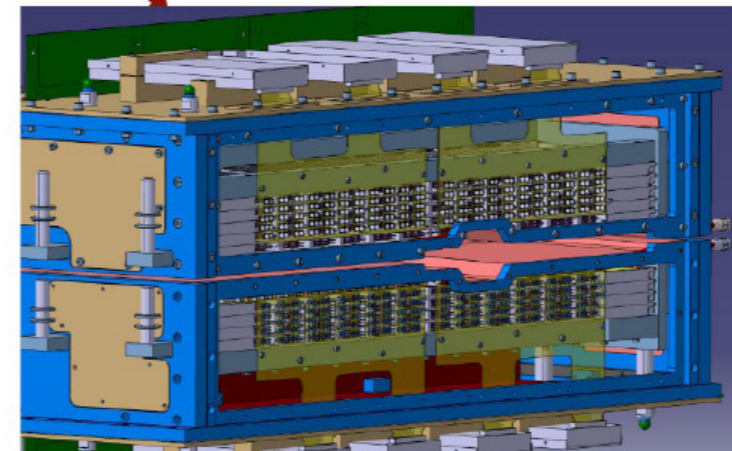
Silicon Vertex Tracker
Built at SLAC/UCSC



SVT measures trajectories of electrons to reconstruct e^+e^- mass and vertex position.



PbWO₄ ECal
Built by JLab/Orsay/INFN



ECal identifies e^+e^- pairs with precision timing to reject single e^- backgrounds.

• Search of light dark matter downstream the Hall-A beam dump

- Major labs are currently running beam-dump experiments to uncover Light Dark Matter signals
- BDX could be one of the first to provide breaking data

• Light DM production

- High intensity e^- beam impinging on a thick target: χ particles produced together with SM particles

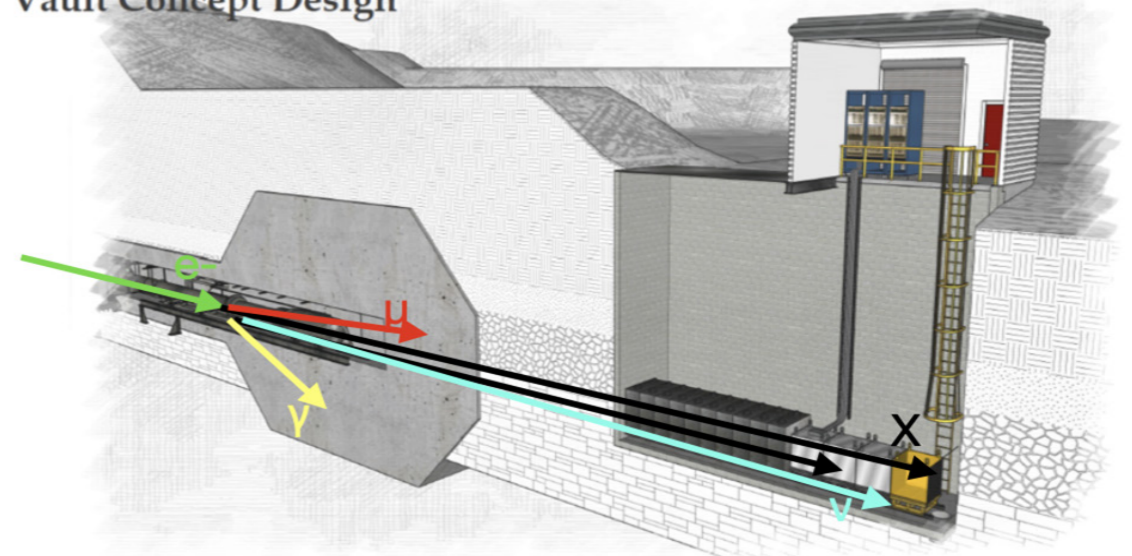
• Light DM detection

- χ scatter in the detector against electrons or nucleons releasing a visible signal

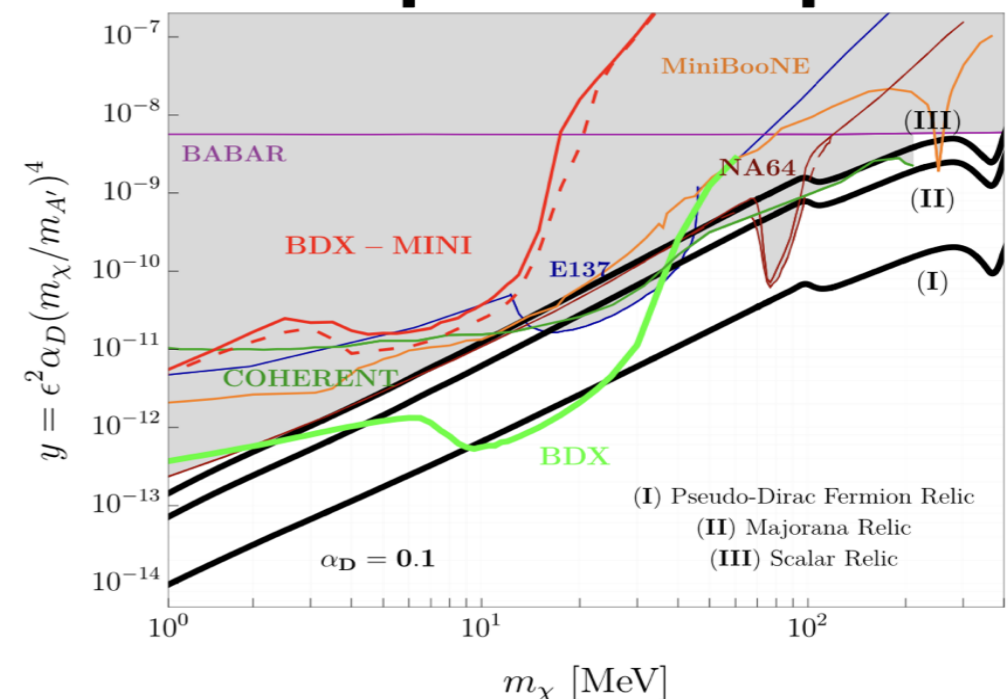
• Experimental set-up

- High intensity ($\sim 65 \mu\text{A}$) 11 GeV e^- beam impinging on Hall A beam dump
- Passive shielding layer before the detector to reduce SM beam-related background
- BDX detector:
 - Homogeneous EM calorimeter of BGO and PbWO_4 crystals
 - Veto system: two layers of plastic scintillator counters

Beam Dump Experiment (BDX)
Vault Concept Design



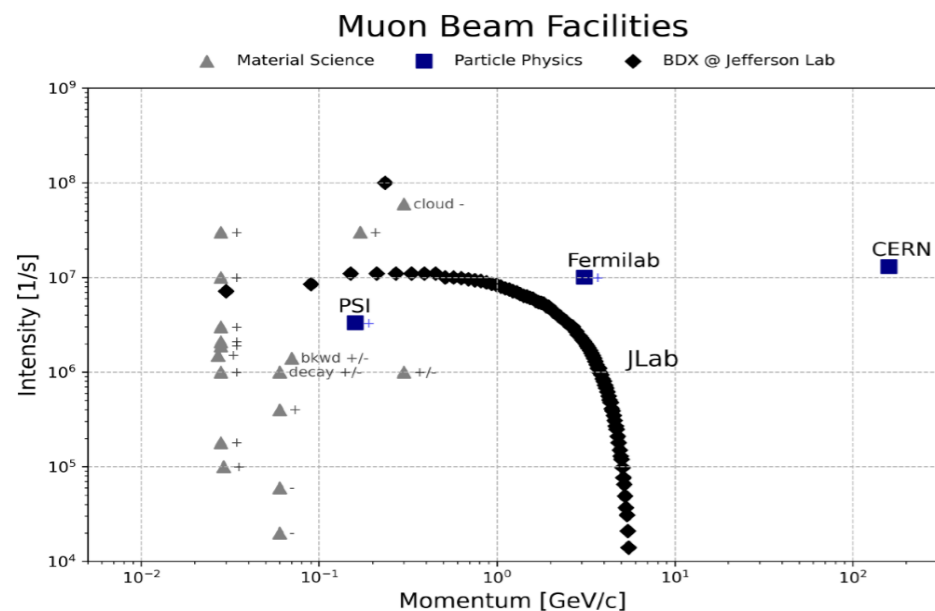
LDM parameter space



In red BDX Demonstrator result . M. Battaglieri et al, PRD 106 (2022), 7,072011

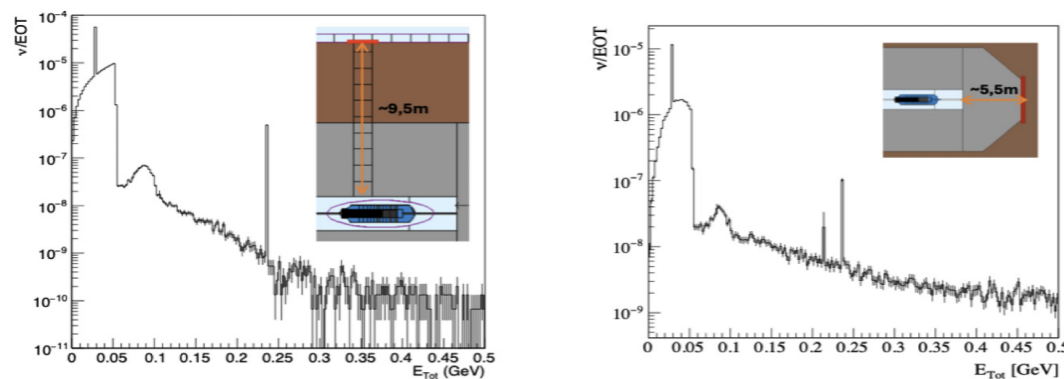
Secondary beams at JLAB

- New initiatives under study to exploit the intense secondary beams produced by the interaction of the CEBAF electron beam on the dump
 - Muons, neutrinos, neutrons... and possibly unknown stuff!
 - Feasibility estimations undergoing
 - Strong interest among a broad community: “BDX and beyond” kickup workshop in September 2025 @JLAB



- **Expected muon flux:**

- Energy spectrum of typical bremsstrahlung shape
- Flux evaluated at 6 m beyond the dump: $\sim 8 \times 10^8 \mu/s$



- **Expected neutrino flux:**

- Off-axis: $\sim 6 \times 10^{-5} \nu/EOT$
- On-axis: $\sim 3 \times 10^{-5} \nu/EOT$

Conclusions and Outlook

- Jefferson Lab in enabling groundbreaking non-perturbative QCD studies through high luminosity and advanced instrumentation
- Broad plans being prepared for the next and far future!
 - Next-generation experiments to advance understanding of nucleon structure, dark sectors, and strangeness dynamics in QCD
 - Strategic upgrades, including the 22 GeV energy boost, to expand exploration into new regimes of hadronic physics
 - New experiments with intense positron beams

