EMMI Workshop:
Science at the luminosity frontier:
Jefferson Lab at 22 GeV

December 9-13, 2024 • LNF, Frascati, Italy

TOPICS
- Charmed and light hadron spectroscopy
- Structure of hadrons
- QCD in Nuclei
- Opportunities fo BSM opportunities

ABSTRACT

This workshop will focus on the continuing development of the scientific case for a 22 GeV upgrade to CEBAF made possible by recent novel advances in accelerator technology. CEBAF's envisioned capabilities, at the highest luminosities, will enable exciting opportunities that give scientists the full suite of tools necessary to comprehensively understand how QCD builds hadronic matter in the valence region. Through this workshop, JLab and its user community will continue to build the science case with descriptions and concrete projections for experiments that would become possible with an upgrade. While the JLab 12 GeV program is running, it is already time to plan the future developments for the facility.

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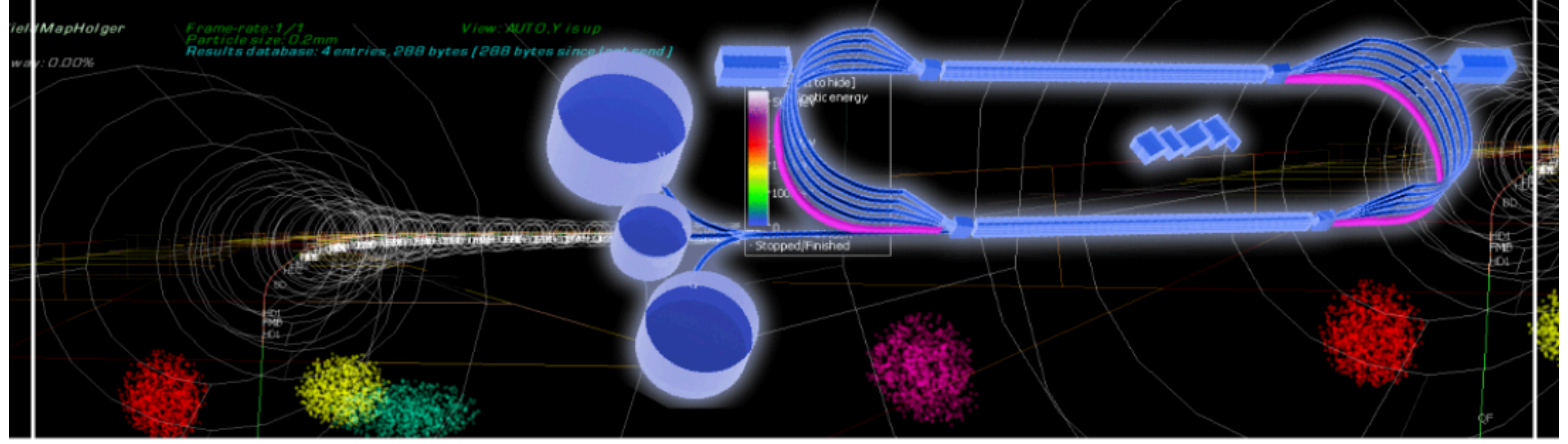

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Science at the Luminosity Frontier: Jefferson Lab at 22 GeV

9–13 Dec 2024
INFN, Laboratori Nazionali di Frascati
Europe/Rome timezone

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	Pseudoscalar Mesons and Emergent Mass *Auditorium B. Touschek, INFN, Laboratori Nazionali di Frascati*	*Khepani Raya* 14:30 - 14:50
15:00	**Probe QCD Confinement via pi^0, eta and eta'** *Auditorium B. Touschek, INFN, Laboratori Nazionali di Frascati*	*Karol Kampf* 14:55 - 15:15
	Overview of Sub-GeV Physics in the Dark sector (theory side) *Auditorium B. Touschek, INFN, Laboratori Nazionali di Frascati*	*Luc DARME* 15:20 - 15:40
	Experimental overview of Sub-GeV Physics in the Dark sector *Auditorium B. Touschek, INFN, Laboratori Nazionali di Frascati*	*Mariangela Bondi* 15:45 - 16:05
16:00	**The BDX experiment** *Auditorium B. Touschek, INFN, Laboratori Nazionali di Frascati*	*Marco Spreafico* 16:10 - 16:25
	Coffee break *Auditorium B. Touschek, INFN, Laboratori Nazionali di Frascati*	16:25 - 16:45
	AI for BSM physics searches *Auditorium B. Touschek, INFN, Laboratori Nazionali di Frascati*	*Patrick Moran* 16:45 - 17:00
17:00	**Probing light dark particles with η and η' decays** *Auditorium B. Touschek, INFN, Laboratori Nazionali di Frascati*	*Sergi Gonzalez-Solis* 17:05 - 17:20

18:00		
QCD Confinement, Fundamental Symmetries and BSM *Aula Salvini, INFN-LNF* 17:30 - 18:30	**Nuclear Dynamics** *Aula Seminari, INFN-LNF* 17:30 - 18:30	**Spatial Structure, Mechanical Properties and Emergent Hadron Mass** *Auditorium B. Touschek, INFN, Laboratori Nazionali di Frascati* 17:30 - 18:30

Summary of
QCD confinement, fundamental symmetries and BSM
session

M.Battaglieri (INFN),
L.Gan (NCU)

INFN clas Jefferson Lab e- JLab12

Emergent mass in QCD

- Precision SM physics: mass in QCD

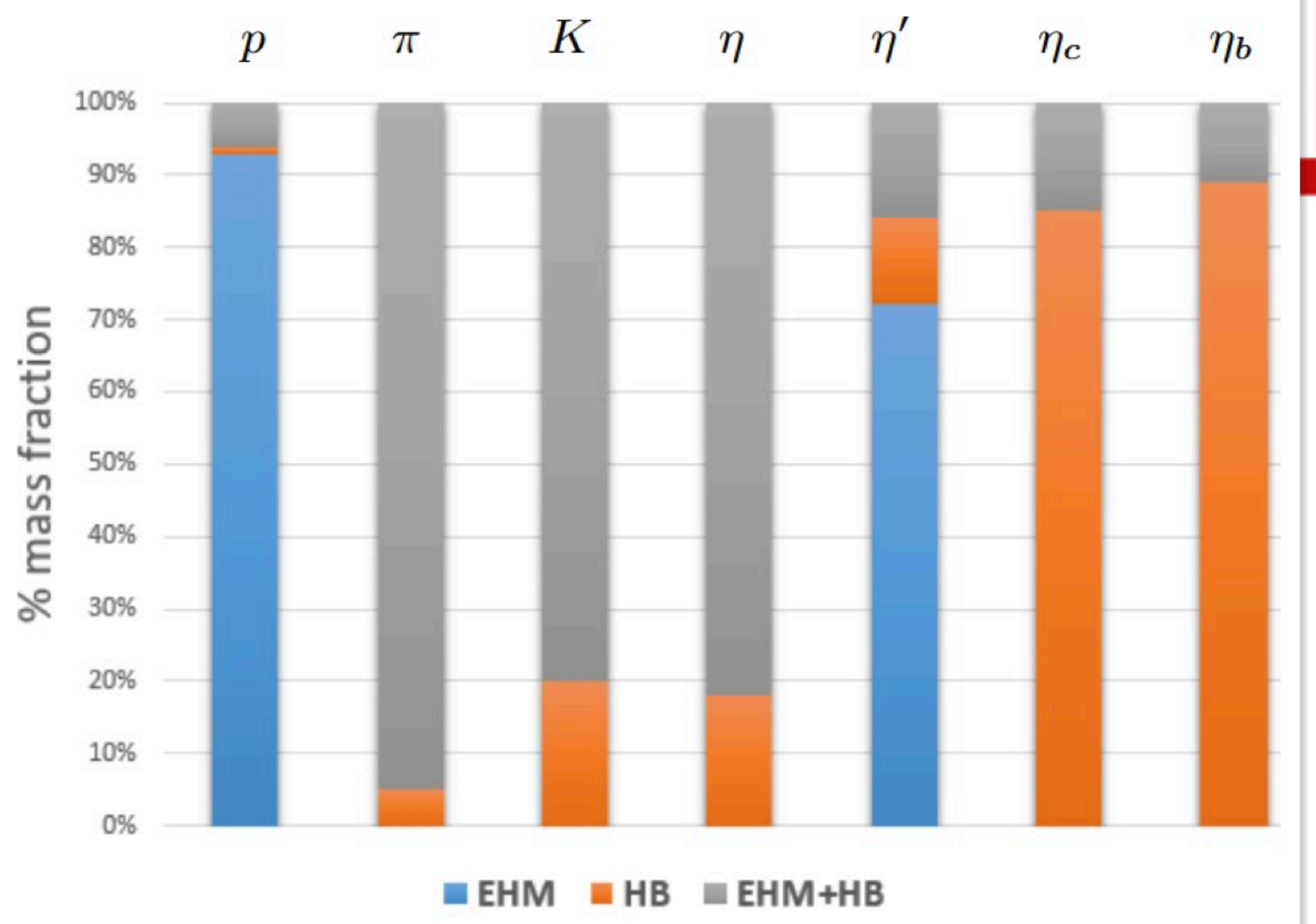
Pseudoscalar Mesons and Emergent Mass

Khépani Raya Montaño

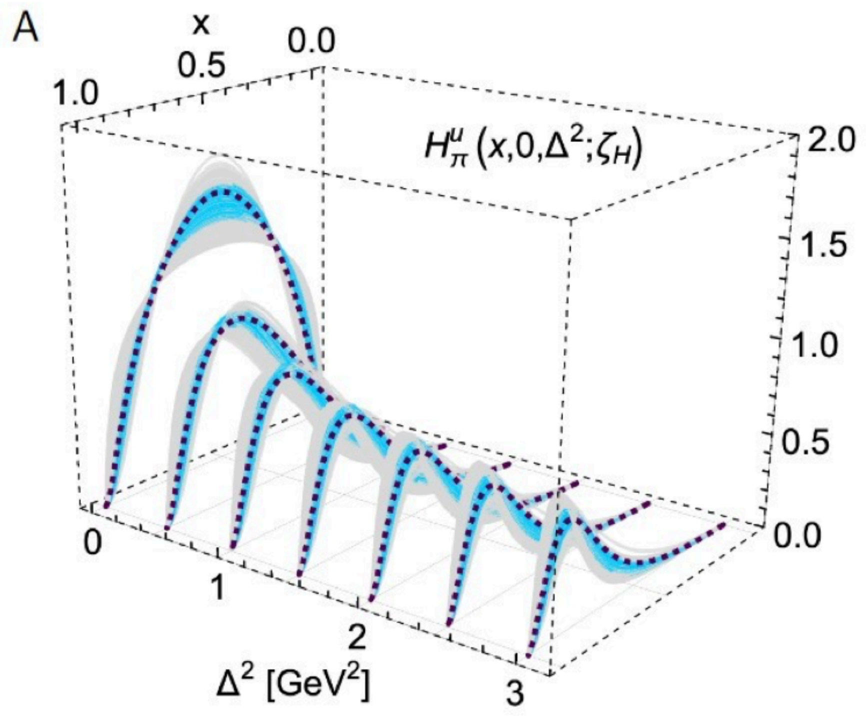
- **QCD** is characterized by two **emergent** phenomena: confinement and dynamical generation of mass (DGM).

- The examination of ***all*** pseudoscalars is crucial in elucidating the role of the **mass generation** mechanisms on the structural **properties**.
  - An so the **emergent** features of the strong interactions. (confinement, mass generation)
- Light **pseudoscalars** hold a special role due to their link with **symmetries and anomalies** in the Standard Model.
- **Modern facilities** are set to scrutinize their properties at **unprecedented** depth.

Accardi:2023chb Arrington:2021biu Chen:2020ijn



- The **emergent phenomena** in **QCD** produces unique outcomes:
  - The degrees-of-freedom are not directly accessible, we get to observe hadrons (**confinement**).
  - Through their own mechanisms, **dynamical mass generation** is present in both **matter** and **gauge** sectors of QCD; the later yielding a running **coupling** that saturates at infrared momenta.
- **Pseudoscalar** mesons are an ideal platform to inquire on these facets of **QCD**:
  - Their mere **existence and properties** are connected with the **mass generation** in the Standard Model and, potentially, **confinement**.
  - Modern facilities are **capable** to address the properties of **NG bosons** and it's connection with QCD's emergent phenomena.
- Theory has evolved to the point where **all sorts of** parton **distributions** of pseudoscalar mesons are **within reach**.
  - TFFs are valuable as they encode symmetries, their breaking, scaling violations, and the transition between soft and hard scales.



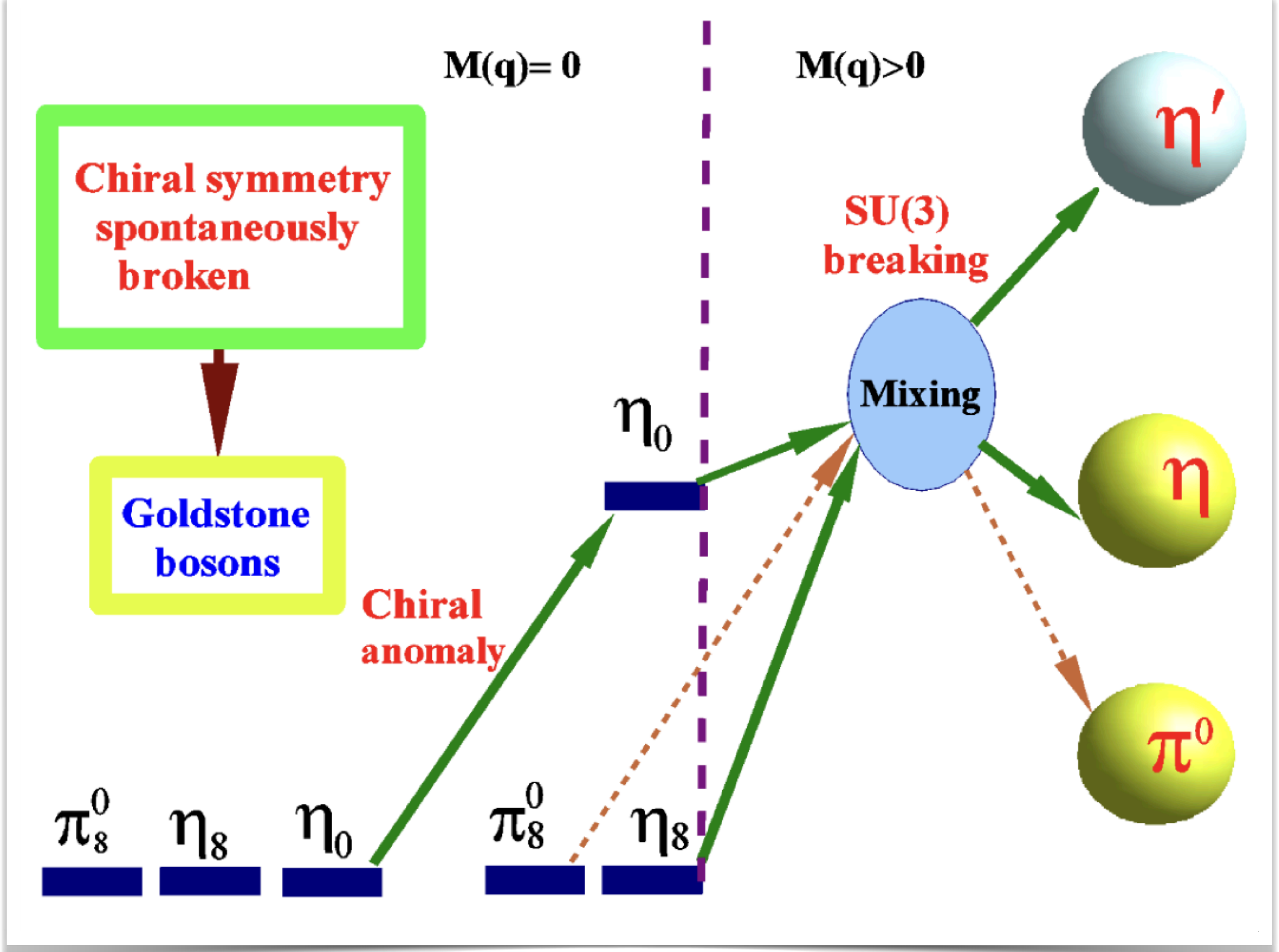
Emergent mass in QCD

- Precision SM physics: confinement

Probe QCD Confinement via π^0, η and η'

Karol Kampf
Charles University, Prague

QCD at low energies



Decays of π^0

neutral pion: the lightest hadron
rich experimental activity: Hades, KLOE-2, A2), JLab, NA62, ...
accessible also at lattice

EFT

- separated degrees of freedom (simplification)
- building the most general Lagrangian
- ordering principle (powercounting)

example: ChPT

- neutral sector of low energy QCD: the important theoretical challenge of understanding EFT
- BSM: tantalizing theoretical connection with a different BSM sector!
- In this talk focused mainly on $\pi^0 \to \gamma\gamma$ decay.
- summary: more theoretical understanding needed, and maybe more calculations needed

Precision test of SM (and beyond)

○ Precision SM and BSM physics

Probing light dark particles with η/η' decays

Sergi Gonzàlez-Solís (sergig@icc.ub.edu)

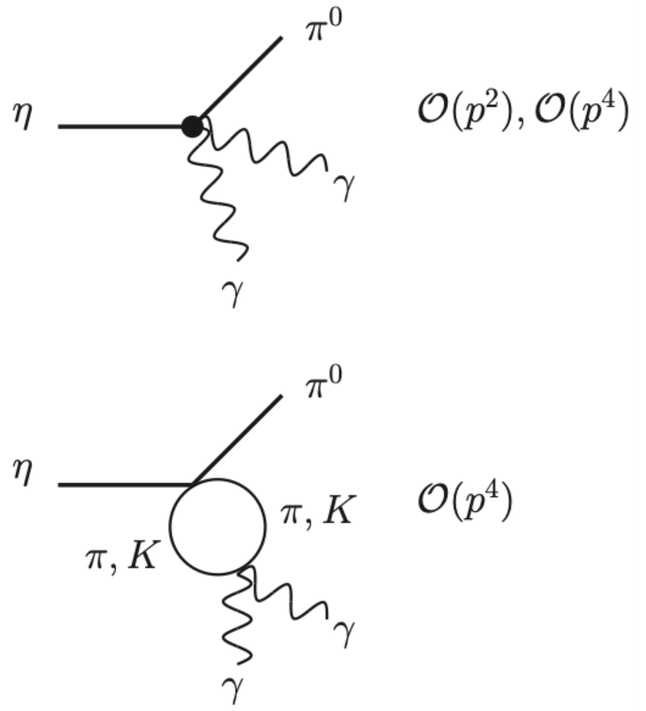
η/η' laboratory for dark sectors

- The η is a pNGB, $m_\eta \simeq 548$ MeV and $\Gamma_\eta = 1.31$ keV
- The η': not a pNGB due to $U(1)_A$ anomaly, $m_{\eta'} \simeq 958$ MeV, $\Gamma_{\eta'} = 196$ keV
- Eigenstates of the C, P, CP and G operators: $I^G J^{PC} = 0^+0^{-+}$
- Flavor **conserving** decays $\Rightarrow$ laboratory for symmetry tests
- All their EM and strong decays are **suppressed** at LO $\sim \mathcal{O}(\alpha_{em}^2)$ or $\mathcal{O}((m_u - m_d)^2$
- Window to **BSM** physics through rare decays:

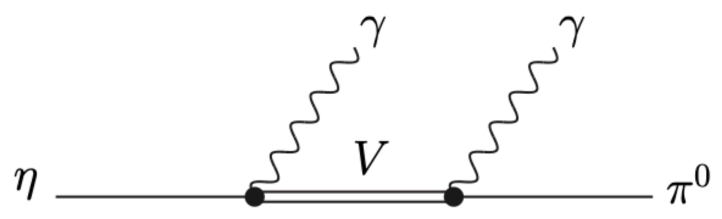
$\eta \to \pi^0\gamma\gamma$ decay: Theoretical motivation

- **SM motivation**:

Reference	$\Gamma(\eta \to \pi^0\gamma\gamma)$ [eV]
$\mathcal{O}(p^2)$, $\mathcal{O}(p^4)$ tree-level χPT	0
$\pi + K$ loops at $\mathcal{O}(p^4)$	1.87×10^{-3}
Experimental value (pdg)	0.34(3)

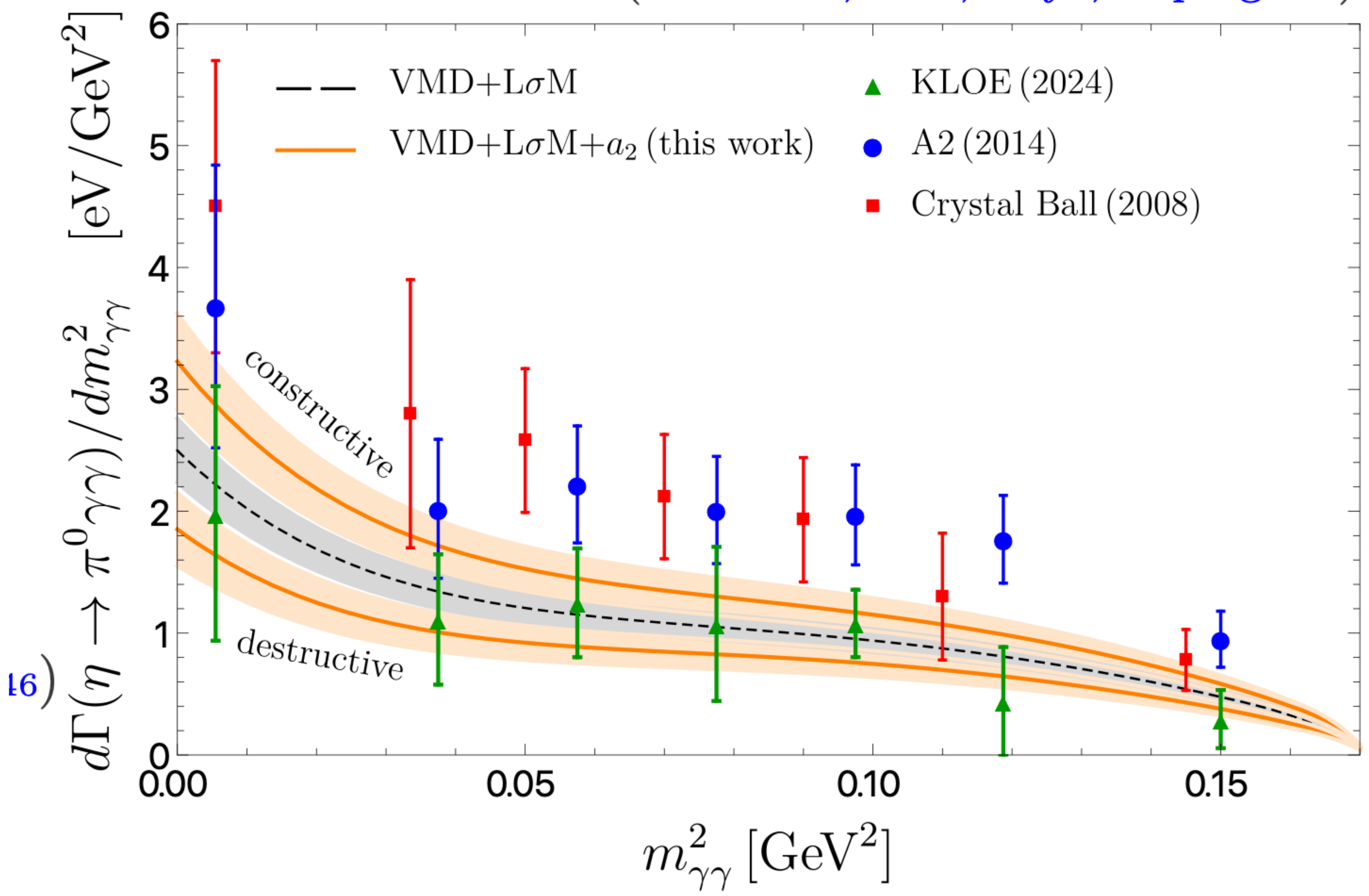


  - 1^{st} sizable contribution comes at $\mathcal{O}(p^6)$, but LEC's are not well known
  - To **test ChPT** and a wide range of chiral models, *e. g.* VMD and LσM



- **BSM motivation**: search for a B boson via $\eta \to B\gamma \to \pi^0\gamma\gamma$

(Escribano, SGS, Royo, in progress)



- Exploring **dark sectors** is an important and growing element of BSM physics
- A wealth of exciting ongoing/future **experiments** to search for dark sector particle signatures exist/planned
- η/η' mesons are an interesting place to look for dark particles because probe coupling to light quarks and gluons
- BSM searches in parallel with SM η/η' decay studies

BSM and DS searches

- BSM physics

Overview of sub-GeV Physics in the Dark sector (theory side)

Luc Darmé

IP2I – UCBL

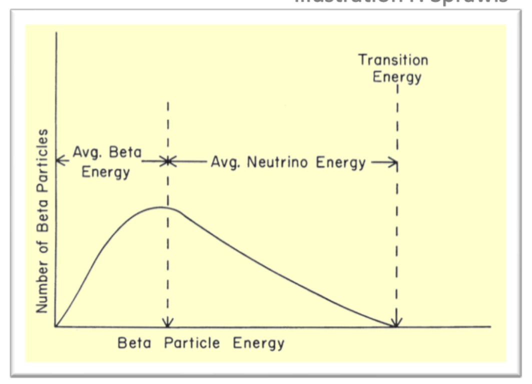
Back in time: neutrinos as a dark sector

- In the thirties, the study of beta nuclei decays led to a puzzling situation
  - → Energy conservation appeared broken …

$^{1}_{0}n \longrightarrow {}^{1}_{1}p^{+} + e^{-} + \bar{\nu}_e \quad \rightarrow \quad {}^{60}_{27}Co \longrightarrow {}^{60}_{28}Ni + e^{-} + \bar{\nu}_e$

Only this part « known »!

Illustration P. Sprawls



FIPs: Feebly Interacting Particles

- FIPs = the particle interacting the most with the SM = "new neutral particle which interacts with the SM via suppressed new interactions"

Summary: portal interactions

- FIPs are neutral particle, must be coupled to a neutral "current" in the SM

	SM operator		FIPs / dark sector
Scalar portal	$\|H\|^2 \quad (d=2)\,,$	$\longrightarrow$	Dark Higgs
Vector portal	$F_{\mu\nu} \quad (d=2)\,,$	$\longleftrightarrow$	Dark photon
Neutrino portal	$LH \quad (d=5/2)$	$\longleftrightarrow$	HNL

Portal interactions – Vector portal

	SM operator		FIPs / dark sector
Vector portal	$F_{\mu\nu} \quad (d=2)\,,$	$\longleftrightarrow$ $F'^{\mu\nu}$	Dark Photon

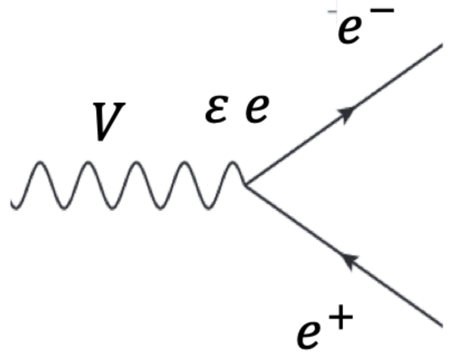
Mixes with the hypercharge / photon

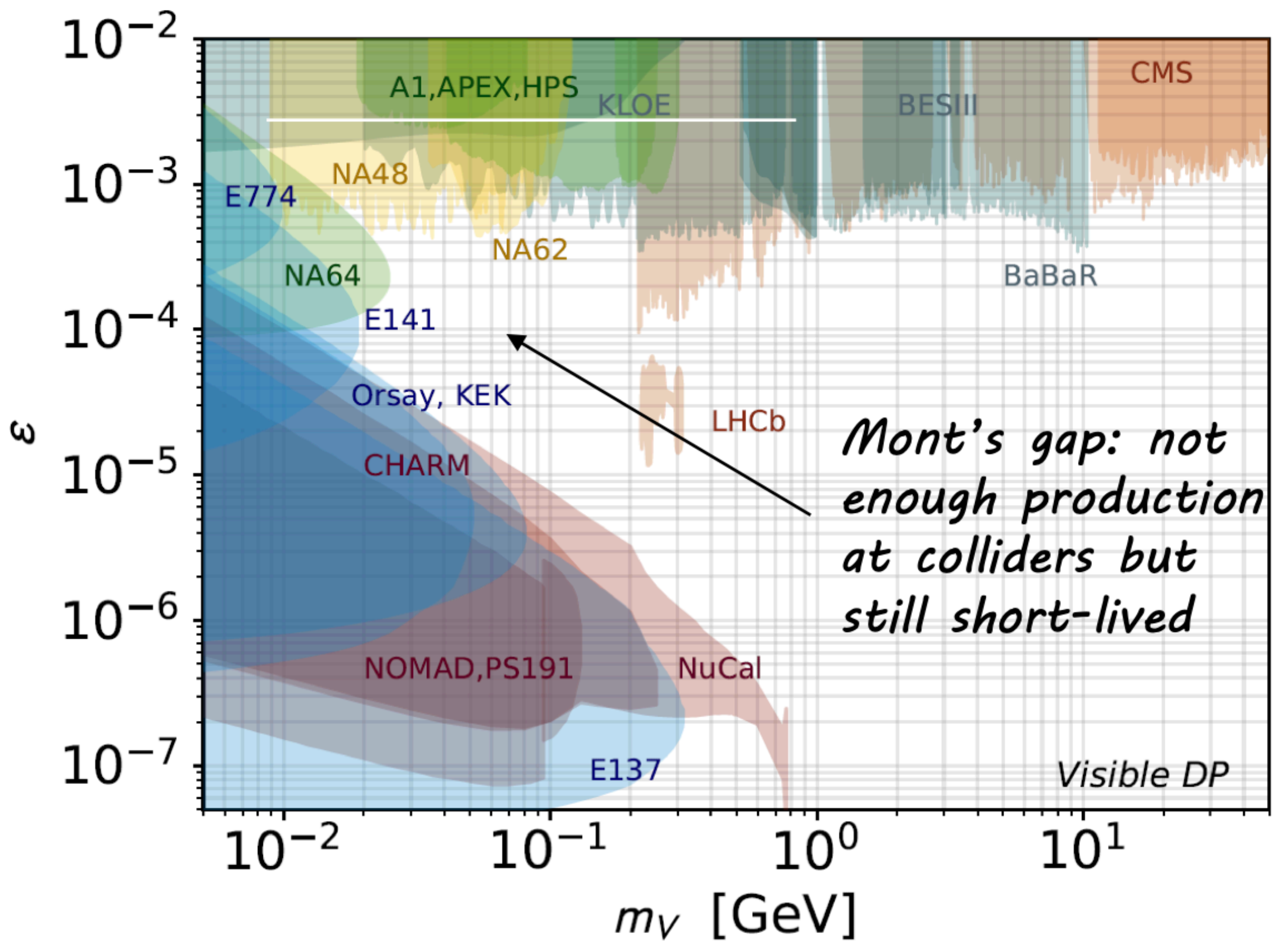
$O_{vector} \propto \varepsilon\, F_{\mu\nu}\, F'^{\mu\nu}$ ➡ Induces kinetic mixing between the photon and the dark photon

- After recovering proper kinetic terms, the dark photon inherits a fraction of the EM current

→ Easily produced from electrons/positrons experiments

→ Relatively fast decay rates





Mont's gap: not enough production at colliders but still short-lived

- Sub-GeV dark sectors are a generic class of extension of the Standard Model
- They arise quite typically from new UV theories designed to solve various flaws of the SM, and are often the smoking gun of a larger symmetry at work in the UV
- Their interaction with the SM can be classified, leading to a small number of « portals » to test experimentally
- For an e^+ or e^- various production channels are available, with larger rates possible in e^+ – based experiments.

Near future Dark Sector search: X17 mystery

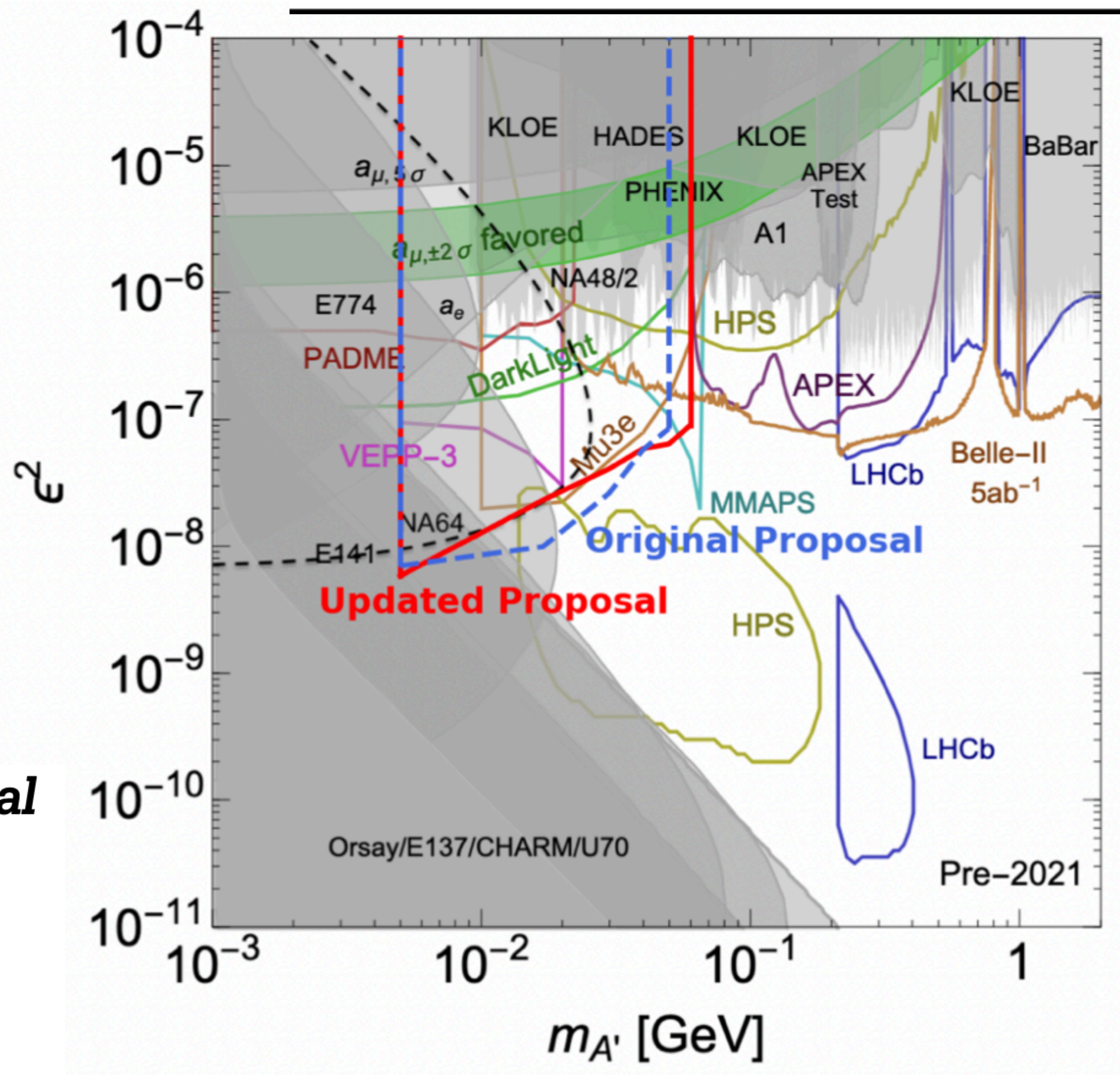
BSM and DS searches

- BSM physics

Experimental overview of Sub-GeV Physics in the Dark Sector

Mariangela Bondì

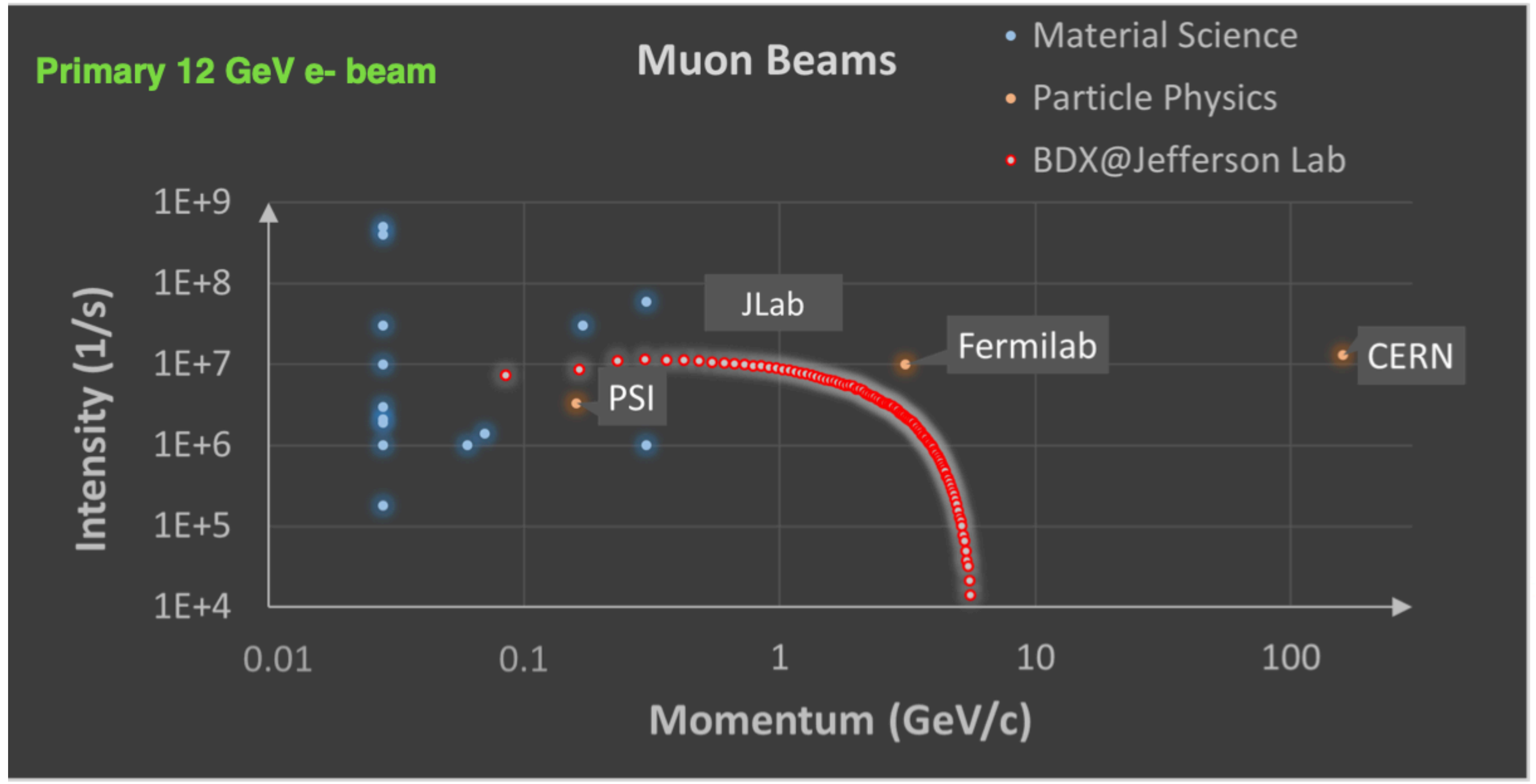
INFN - Sezione di Catania



- *JLAB already features a significant experimental program dedicated to Dark Sector*
  - *Exploiting CEBAF unique capabilities to produce and detect Dark Photons*
    - *Current experiment: APEX, HPS, BDX-MINI*
    - *Experiments running in near future: X17, BDX*

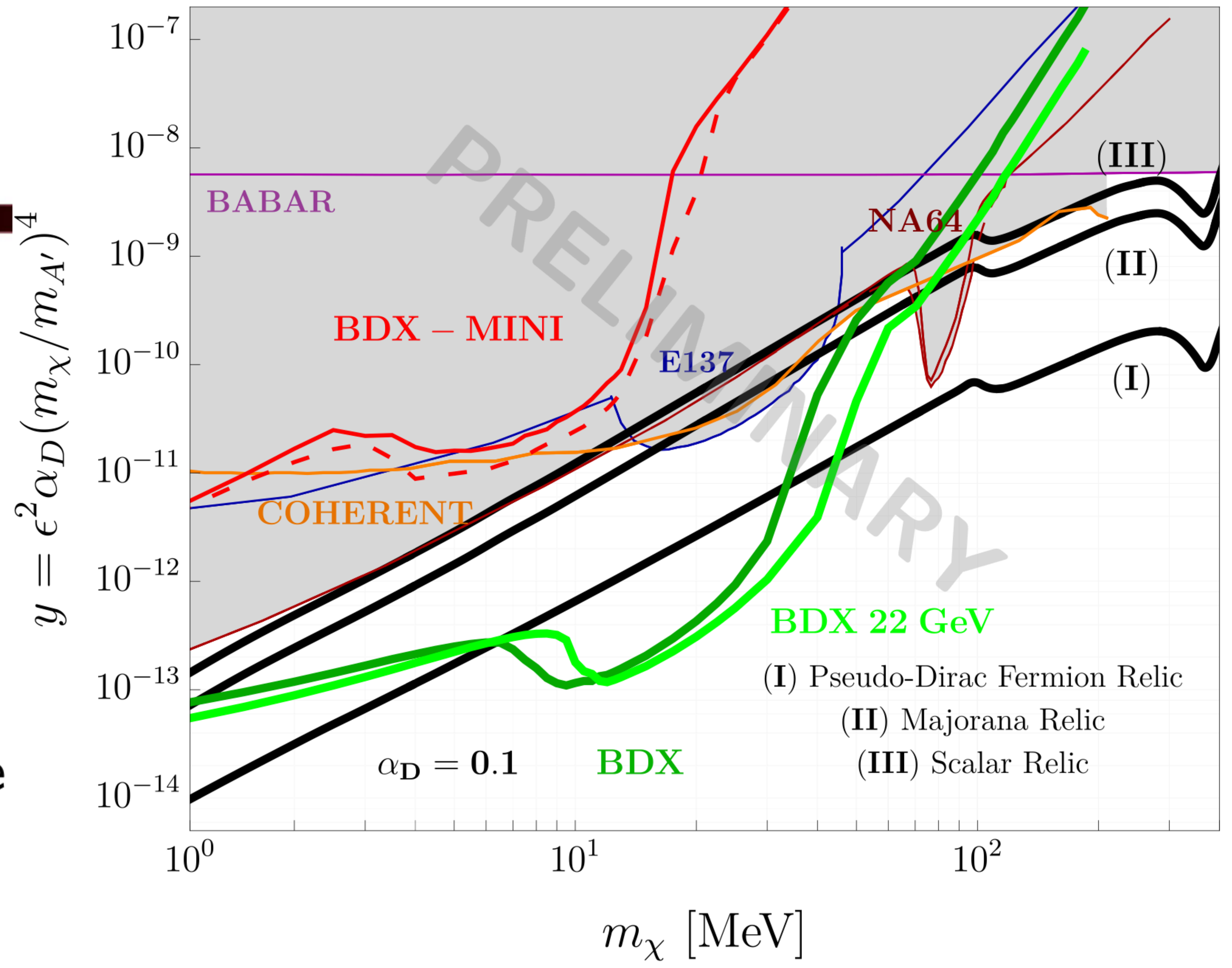
- ***Future upgrade of the facility offer even more opportunities***
  - ***Secondary beam @ 11 GeV***
  - ***Secondary beam @ 22 GeV***
  - ***Positron Beam***

- The flux increases with the energy of primary beam:
  - Muon flux (11 GeV e- beam): 9E-7 μ/EOT
    - Rate ~ 3E8 μ/s
  - Muon flux (22 GeV e- beam): 5E-6 μ/EOT
    - Rate ~2E9 μ/s
  - Muon flux profile σx and σy ~ 20 cm



BSM and DS searches

- BSM physics



The BDX experiment

Marco Spreafico

BDX

- Experimental setup
- Physics reach

BDX-MINI

- Experimental setup
- Results

BDX@22 GeV

- Background@22 GeV
- Physical reach @ 22 GeV

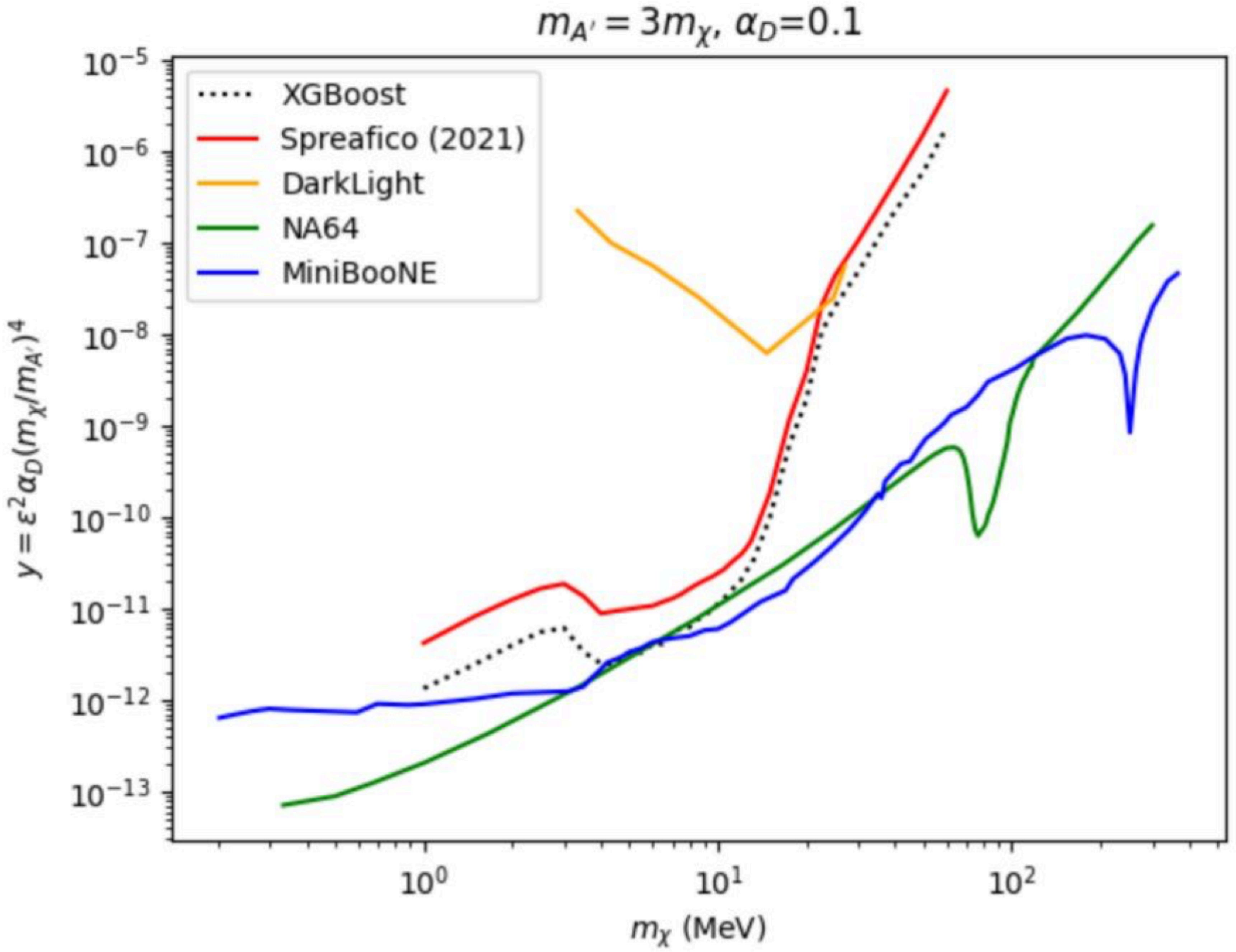
- Dark matter in the MeV-to-GeV range is largely unexplored
- **BDX**: search for Dark Sector particles in the MeV-GeV mass range
  - Technique viable to probe different DM candidates
  - JLab provides unique opportunities to probe different models
- **BDX-MINI**: pilot version of BDX
  - First modern beam dump experiment searching for Light Dark Matter
  - Detector optimized for LDM searches
  - Analysis aimed to LDM detection
  - Evaluated exclusion limit → competitive to flagship experiments
- **BDX@22 GeV**: extend BDX results but more difficult run conditions
- Beam dump experiment at e beam dump highly sensitive to Light Dark Matter in the MeV-GeV range

  → BDX-MINI remarkable results demonstrate that BDX is a mature, ready-to-run experiment

AI for BSM Physics Searches

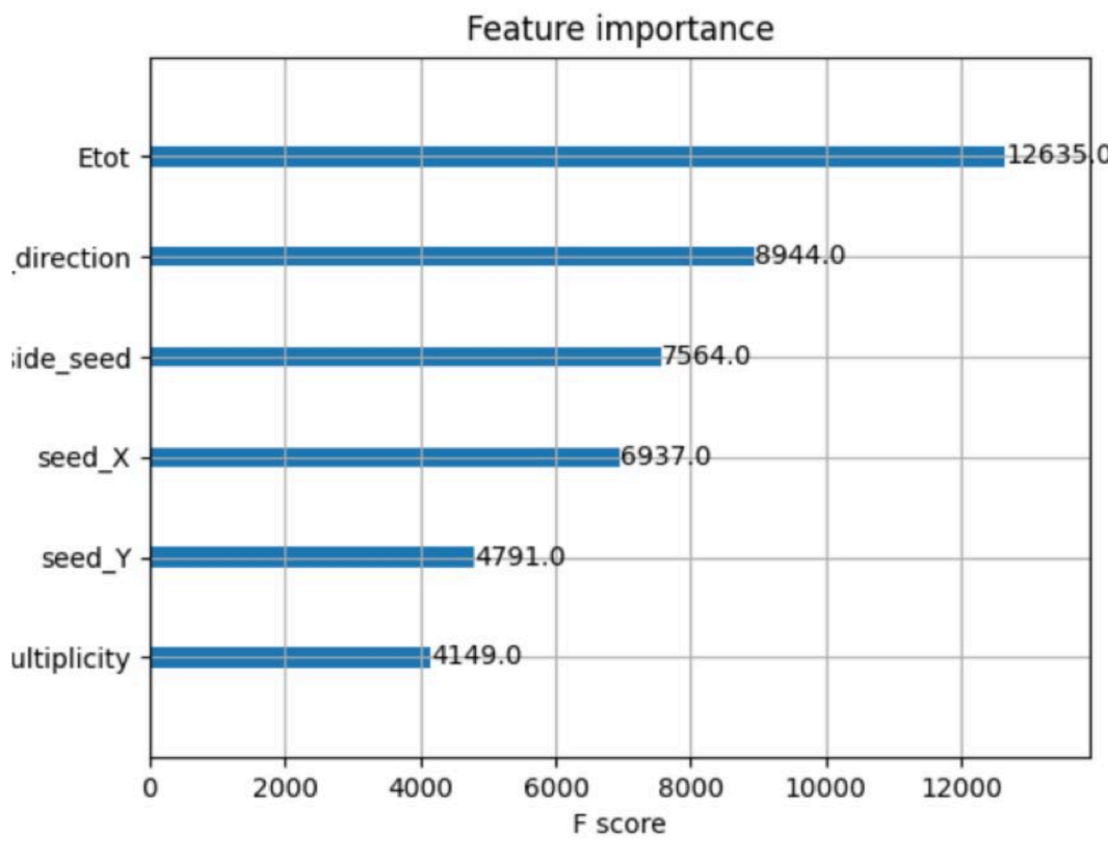
Patrick Moran, The College of William & Mary

1. Dark Matter Detection
2. Anomaly Detection using Generative Models
3. Precision Measurements using Deep Learning

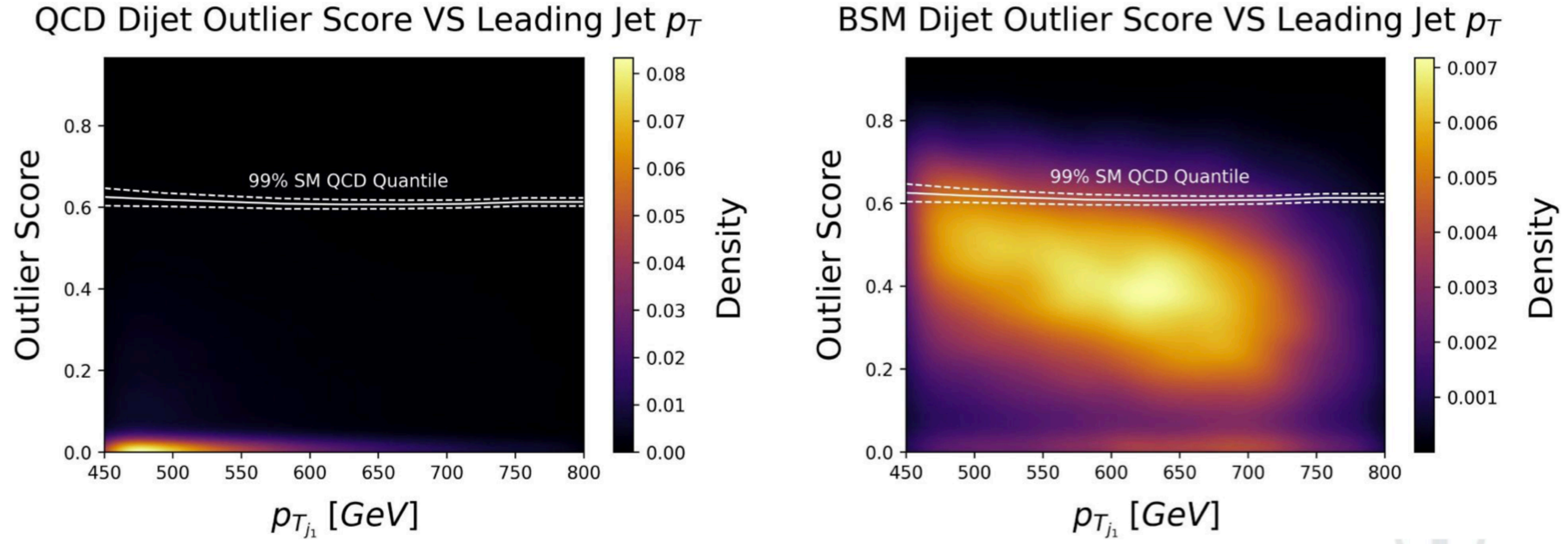


Input Features

1. Total energy
2. Shower direction
3. Energy outside the seed (i.e. outside the highest energy crystal)
4. x-y position of the seed
5. Multiplicity (number of crystals above the threshold)



Anomaly Detection: BSM Dijet Separation at LHC



Quantile	True Positive Rate	True Negative Rate
68%	**68.48 ± 0.22 %**	**93.05 ± 0.06 %**
95%	**95.27 ± 0.10 %**	**43.07 ± 0.22 %**
99%	**99.04 ± 0.05 %**	**12.74 ± 0.15 %**
Fiducial cuts (99%)	**98.92 ± 0.05 %**	**2.35 ± 0.06 %**

Summary

- QCD fundamental symmetries can be studied thanks to precision measurements at high-luminosity CEBAF
- Progress in theory and comparison to precise measurements are the key to test the SM
- The transition to 22 GeV will enhance the physics reach widening the kinematics range
- Worldwide effort to explore new theoretical-motivated BSM scenarios using existing facilities
- The luminosity frontier at medium energy is complementary to the high energy searches
- BSM physics opportunities at 22 GeV will extend the Dark Sector searches already part of the current JLab program
- Hi-lumi + energy upgrade = high intensity secondary beams (mu, nu, LDM) at JLab
- New tools (AI-based) will enhance the sensitivity to anomaly detection in a largely unbiased and unsupervised approach (already tested on current data sets)

CEBAF at 22 GeV

- **PRECISION** for SM tests
- **EXTENDED** phase space for BSM physics