Expression of Interest (EOI) of the INFN community
Questionnaire

Please indicate the name of the contact person for this submission:
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Please indicate all institutions collectively involved in this submission of interest:
INFN, the following Units of the Institute:

Sezione di Bari
Sezione di Bologna
Sezione di Catania
Sezione di Ferrara
Sezione di Genova
Laboratori Nazionali di Frascati
Laboratori Nazionali del Sud
Sezione di Padova
Sezione di Roma 1
Sezione di Roma 2
Sezione di Torino
Sezione di Trieste

The participating scientists are either employed by INFN or associated to INFN and employed by the following Universities: University of Bari Aldo Moro, Polytechnic University of Bari, University of Bologna, University of Catania, University of Eastern Piedmont Amedeo Avogadro, University of Ferrara, University of Genova, University of Padova, University of Roma La Sapienza, University of Roma Tor Vergata, University of Torino, Polytechnic University of Torino, University of Trieste.

Please indicate the items of interest for potential equipment cooperation:
Our potential equipment cooperation covers 4 areas:

- **i. PID in the forward region**
- **ii. VERTEXING**
- **iii. STREAMING READ-OUT**
- **iv. SOFTWARE TOOLS & COMPUTING**.

INFN contributions to **EIC physics** from **experimentalists** and **theorists** are discussed in the Appendix 2 and Appendix 3, respectively.

In all the areas, **INFN groups will collaborate with other Institutions sharing the same scientific goals.** Part of the potential collaborators have already been identified:

- i. **PID in the forward region:** Collaboration concerning the R&D, also for synergic aspects, and the constructions is presently foreseen with Banaras Hindu University, Duke University, Georgia State University, Stonybrook University.
- ii. **VERTEXING:** Most of the groups interested in vertex detector activities within the EIC community have recently joined the EIC Silicon Consortium, namely: LBNL, University of Birmingham, Rutheford-Appleton Laboratories, BNL Instrumentation Division, CCNU (Wuhan) and JLAB and ORNL. The Consortium and other groups that might join at a later stage are the INFN natural collaborators in R&D and in construction efforts.
- iii. **STREAMING READ-OUT:** INFN physicists will work in close contact with the colleagues of the EIC R&D Streaming Readout Consortium: BNL, JLAB, CUA, MIT, Stony Brook.
- **iv. SOFTWARE TOOLS & COMPUTING:** The software activity of the INFN groups will continue in the context of the EICUG Software Working Group.

Concerning the **time-lines of INFN potential equipment cooperation,** we foresee (Table 1 and answers to the questions related to "labor contribution" and "timing constraints"):

- a **preparatory phase** with R&D activities in **years 2021-2024** and
- a **construction phase in years 2025-2029.**

Details about the potential equipment cooperation, according to the present assessment level, are provided in the following for each item separately.

i. **PID in the forward region**

In the context of the relevant requirements of hadron identification and electron/pion separation at EIC, we anticipate **contribution to the PID system in the forward region**, where a wide momentum range (from a few GeV/c up to about 50 GeV/c) has to be covered.
We recall here the **main options**, where currently there is a large involvement of the INFN Groups, **and their status**. The high momentum domain imposes the use of a RICH with gaseous radiator, while a complementary approach is requested to cover the lower momenta range.

- The dRICH (dual RICH) including two radiators, namely a C-F gas and aerogel, can cover both needs. Monte Carlo studies with a standalone code have been performed indicating π,K,p identification from 3 GeV/c to 60 GeV/c as well as electron-pion separation from a few hundred MeV/c up to about 12 GeV/c. A dRICH prototype has been designed to be validated with a test beam exercise. An array of mirrors focalizes the light onto a limited instrumented area outside acceptance with reduced constraints on material budget and radiation tolerance. This facilitates complementary studies dedicated to fully validate the possibility to use SiPMs as photon sensors, able to operate in magnetic field, to detect single photons and to tolerate foreseen radiation levels. Preliminary studies in test beam with cooled SiPMs support the approach. A characterizing aspect of the studies is the coupling of the SiPMs with dedicated front-end ASIC and electronics system. The dRICH option is explored also under the eRD14 consortium.
- An alternative is a windowless gaseous RICH, where the gas radiator also provides the atmosphere of the gaseous MPGD-based sensors. In this case, the use of a single radiator species makes possible the design of a central optics, limiting the effect of the spherical aberration. A prototype with quintuple GEM readout was built and validated in a test beam exercise. R&D studies aiming at improving the MPGD-based photon sensors presently in use at COMPASS are ongoing, in particular concerning the miniaturization of the readout cells. This gaseous RICH requires to be complemented by a device for lower momenta making use of aerogel or TOF measurements. Moreover, R&D devoted to coupling MPGD photon sensors with innovative photoconverters based on hydrogenated nano diamond powder has been started with promising initial indications. All these studies are progressing within the activities of the eRD6 consortium.

We plan, during the years 2025-2029, **substantial engagement in the design and construction of the device/devices for PID in the forward region.** This contribution will be performed in the context of the concept that will be selected by the collaboration. In the next four years (2021-2024), we plan to **continue and enlarge the present R&D activity** in order to contribute to the definition of the concept of the forward PID system and, as first step, to the preparation of a corresponding Technical Design Report. The foreseen R&D activities are listed. Some items can be beneficial also to PID devices considered for the barrel and backward regions.

Current list of R&D activities:

- Development of **Monte Carlo and software analysis algorithms**; this activity includes:
  - Progressively importing the standalone existing Monte Carlo code in the global EIC frame
  - Further dRICH studies, also drive by prototype results
  - Development of a simulation code for the gaseous RICH with central optics design
  - Simulation of the pressurized RICH performance
- **Aerogel studies**
  - Within EIC, aerogel is of interest for PID systems in various kinematic domains.
  - characterizing samples from different potential suppliers, namely:
    - Novosibirsk
    - ASPEN
    - Chiba University, Japan (studies in collaboration with groups from the ALICE and LHCb experiments)
- **dRICH prototyping**
  - construction of a prototype
  - validation of the prototype in a test beam exercise
- **Sensor studies**
  - SiPMs

    The R&D program aims at characterizing in a test beam these sensors as single photon detectors. Three kind of tests are foreseen: non-irradiated units, after irradiation corresponding to 10^{11} neutron equivalent per cm^2, and applying a temperature annihilation protocol with high temperature cycles to part of the irradiated sensors. It is foreseen to test sensors from various manufacturers at a low temperature working point. These studies include the use of the front-end ALCOR ASIC developed for the experiment DarkSide. As a further step, ALCOR v2.0 ASIC specifically tailored to match the dRICH SiPM operational requirements will be designed.
  - MPGD-based photon detectors

    Test and characterization of the gaseous detectors read-out with VMM3 front-end chip; in fact, the read-out chip used so far (APV25) is no longer available and the identification of a new front-end chip is mandatory and urgent. The R&D dedicated to coupling MPGD photon sensors with photoconverters based on hydrogenated nano diamond powder will continue to establish the performance of the MPGDs when coated with the photoconverter, the preservation of the photoconverter quantum efficiency when used in gaseous detectors and the control of the nano diamond power characteristics in order to stably reproduce the best quantum efficiency figures.
  - LAPPDs

    Characterization of these devices as single photon detectors in particular concerning efficiency and performance versus rate.
- **Pressurized gaseous RICH**
  - The use of pressurized noble gases is considered as an ecofriendly alternative to the C-F gases, currently the reference option for high momentum RICHes. They can provide the same fine Cherenkov photon yields and chromaticity figures.
  - Conceptual design of a vessel compatible with the light material requirements;

- Use of the dRICH prototype to validate the pressurized gaseous RICH concept.

ii. **VERTEXING**

The detector concepts currently under study for experiments at the EIC include **a silicon vertex and tracking detector** as the innermost element covering the central rapidity region. Such a detector is needed to enable high-precision measurements that are key to the EIC science programme, in particular for the reconstruction of the primary vertex and secondary vertices from heavy-flavour decays: 3D fine space resolution is requested as well as tracking capability at the lowest accessible transverse momenta.

The main requirements in terms of integration, large acceptance, high granularity and low material budget are naturally met by the Monolithic Active Pixel Sensor (MAPS) technology, with sensor and electronics in the same silicon substrate. The needs for the vertex detector at the EIC correspond to develop a dedicated MAPS with associated powering, cooling, support structures, control and ancillary parts suited for integration in the central tracking system. This will include significant design, testing, prototyping and related R&D activities.

Recent interest and efforts to develop **a new-generation MAPS in 65 nm CMOS imaging technology** are emerging, in particular within the ALICE ITS3 project, whose sensor specifications and development timescale are largely compatible with those of the EIC. Such relevant synergies between the two projects will allow sharing of manpower, know-how and development costs.

The specific size and areas of the INFN potential cooperation in the construction activities for the vertex detector cannot be completely assessed at this stage. Based on the available resources and expertise in the INFN groups currently involved in EIC and in a projection of the future manpower availability, there are anticipated interests in connection with the following items:

- development of hardware and software tools for the basic functional module test;
- production/assembly of the basic modules and/or staves;
- design and development of the cooling system;
- design and development of the mechanical support structure;
- series qualification tests for chips, modules and other detector assembly components;
- production and analysis of detector performance simulations.

This item list could be confirmed at a later stage according to the development and growing of the interest within the INFN groups currently involved in the ALICE ITS3 project.

Leveraging the activities started within the ALICE ITS3 project, **the INFN contribution to the R&D for the EIC vertex detector** will include developments in the following hardware-oriented areas:

- techniques and tools for thinning, bending and interconnection of wafer-scale MAPS sensors based on 65 nm CMOS process;
- pixel-chip sensor test and characterization procedures;
- solutions for cooling, mechanical support structure and assembly procedure.

In particular, the INFN groups plan to explore the mechanical and etching processes currently available for **thinning** 12” wafers in **65 nm CMOS technoloy**, validate and optimize them for the application to 20-40 µm thin large area sensors, develop the necessary tools and procedures to handle the devices. The expertise gained for the construction of the ITS3 prototypes will be exploited by scaling and adapting the silicon **bending tools and technologies** (single-point tape-automated bonding, spTAB, and wire-bonding) to the dimensions and curvature needed for the EIC tracker. They also plan to contribute by developing and characterizing test systems and sensor prototypes with both **lab and in-beam tests**, including comparative tests of the sensor performance between flat and bent configurations.

Similarly, the development of solutions for the **cooling and mechanical support structure** of the ITS3 project can be faced for R&D of the EIC vertex detector. Carbon foam parts will be the baseline for both the mechanical and cooling systems, with the use of additional sheets in carbon fibre, if needed. Studies on the proposed cooling option will be carried out using Computational Fluid Dynamics (CFD) of forced air flow supported by tests of prototypes. The vibrational response and the position stability of the large curved sensor area, subjected to the gas flow, will be assessed by Finite Element Model and Dynamic Response Analysis, and again validated by tests.

The R&D towards engineering will also address several issues required for the final **detector assembly**: bending procedures, metrology approach, suitable alignment references.

Besides the R&D activity connected to hardware items, the INFN groups are also interested to contribute to **detector and physics performance studies based on Monte Carlo simulations of the EIC central tracking system**. The current involvement in the Tracking Working Group for the Yellow Report will be continued and enforced along the following main lines:

- contribution to the optimization of the baseline tracking system performance and to realistic implementation of material budget, services etc.;
- study of the expected physics performance with the EIC silicon vertex detector, in particular in the sector of the open heavy-flavour down to low transverse momenta.

This activity will be based on the currently ongoing implementation of the central tracking system in the Fun4All full simulation and will eventually benefit of Monte Carlo samples centrally produced in the EIC software and simulation community.

iii. STREAMING READ-OUT

Full CPU software-based triggers are substituting standard DAQ systems, where a first data reduction is achieved by using dedicated boards, filtering is applied by selection algorithms implemented on FPGAs while at maximum only the second level of the trigger is implemented by a CPU farm. A **triggerless approach** removes the hardware trigger, performs the full on-line data reconstruction and provides precise selections of final states of interest for further high-level physics analysis (a similar effort is currently faced at LHC in preparation for the high luminosity upgrade). In the resulting **streaming read-out data acquisition scheme**, each front-end channel over a threshold is transferred, together with appropriate time-stamp, disregarding the status of the other channels. A powerful station of CPUs, connected by a fast network link to the front-end electronics, receives all data samples, reorganizes the information ordering hits by time, includes calibration constants, and, at the end, applies algorithms to find specific correlations between reconstructed hits (software trigger), keeping and storing only filtered events. The software trigger implementation is by a high-level programming language, which is easily reprogrammable to accommodate any new requirements. It may also be scaled to match different experimental conditions and planned upgrades simply by adding more CPUs computing and data transfer resources.

The INFN groups will **contribute to building-up a triggerless scheme for EIC** data acquisition with particular interest in those detectors that are essential in the event selection. Planning includes working on the **on-line implementation of the calibration parameters**, providing a more precise reconstruction of the kinematical quantities, the **implementation of**

sophisticated reconstruction algorithms for a better resolution of close-by tracks and the **improvement in EM/hadron discrimination** for a more efficient background rejection.

A **realistic implementation** with the specific detector readout is necessary **to demonstrate the expected performance of a triggerless DAQ.** The combination of suitable front-end electronics, network facilities and CPU algorithms require to identify or develop the best option for each element, to assembly and to test the whole scheme and to compare results with more traditional approaches in order to validate the scheme.

Consequently, the **foreseen R&D activities** concern the system characterization in terms of performances/limitations by:

- construction of one or more prototypal systems to test different options, including the full-chain systems: front-end, interface boards to the data transport network, on-line data analysis and selection software;
- definition and measurement of laboratory and test-beam bench-marks and identification of the physics observables to be used for the validation;
- streaming read-out tests on existing detectors, which are expected to have performances similar to the EIC detectors:
  - @JLab-Hall D: prototypes of homogeneous electromagnetic calorimeter (PbWO4 and heavy-glass scintillators)
  - @JLab-Hall B: components of the CLAS12 detector (Forward Tagger Calorimeter, Forward Tagger Hodoscope, Forward ECAL, Forward TOF, Drift Chambers).

An example of the **on-going R&D activities** is related to the application of a streaming read-out system to the data acquisition of the Forward Tagger detector in Hall-B at JLAB in 2020. The performed steps include the identification of π^0 electro-production on lead and deuteron targets as the physics channel of interest, the test of clustering algorithms on on-line events reconstruction, the check of yield consistency between streaming and standard DAQ systems and the identification of single channel threshold as the critical issues, resulting in the need of high standards in the data transfer solution.

In this context, the main activities of the INFN groups will concern:

- the contribution to the design of the streaming read-out system, acquiring increasing competence during the R&D phase;
- establishing contacts with the Italian industries (e.g. CAEN) which may be involved in the construction of the hardware.

iv. SOFTWARE TOOLS & COMPUTING

INFN interest in contributing to the software needs of the EIC arises from several aspects:

- The active presence since an early stage of an expanding software working group (with active participation of INFN members) makes possible the construction of a common analysis framework for the whole EIC community;
- Being EIC a new project, the software tools needed for the analysis will be user-centered designed;
- New technologies under study like deep machine learning or the use of quantum computing are considered also for software tools and computing at EIC: an important impact in our field is expected.

Today the **activities of the Italian groups** are mainly focused on detectors. We plan, in the next five years, to **contribute to some of the common projects in the EICUG Software Working Group**; more specifically:

- Workflows, particularly to have the EIC software on federated resources, in the short term, and in the integration of HPCs including accelerated hardware as a longer term;
- Monte Carlo Event Generators, in the integration of TMD effects in modern, multi-purpose MCEG;
- Detector Simulations, both including the C++ description of sub-detectors in the specific interest of INFN and the full simulation of their response for performance optimization.
- Reconstruction tools, with main interest, to the sub-detectors with planned INFN contribution in connection with the streaming read-out approach;
- Data Model, where INFN physicists are already actively participating: define common input and output formats for the common software packages to facilitate the easy exchange between software components.

Contributions to **other common projects will be considered in the future**, namely:

- Discoverable Software
- Data Analysis and Preservation
- Explore User-Centered Design.

Here, a few considerations on the computational resources, concerning the INFN participation in the EIC. INFN has been deeply involved in the creation of the WLCG and host since 2003 a Tier-1 at CNAF as well as many Tier-2 both at CNAF and at other INFN computing centers. INFN is also strongly supporting the non-LHC experiments (among the most recent examples: Belle2, Dune, Virgo/Ligo). Moreover, improved computational resources are becoming available as reported in APPENDIX 1: CNAF is going to migrate in a novel data center with increased power capacity and INFN is member in an European Consortium for the pre-exascale computer Leonardo, to be hosted in CINECA, Bologna. The Italian groups in the EIC are using and will use the INFN computing infrastructure for simulations and, later, data analysis. In conclusion, the INFN support for the EIC-dedicated computing effort is expected in line with that for similar cases.

Please indicate what the level of potential contributions are for each item of interest:

The potential contribution is presented in Table 1.

The INFN in-kind contribution is related to the level of engagement by the INFN researchers, which results from a bottom-up process. The current labor assumption is provided answering the question concerning “labor”. With this level of engagement,

- the **global in-kind contribution** from INFN can be of the order of **7-8 M USD over the five years dedicated to construction**, namely the years 2025-2029;
- the **in-kind support for the R&D over the years 2022-2024** can be in total of the order of **1 M USD**.

The corresponding rough estimate of **labor cost** is 12M USD during the five years of constructions and 2 M USD during the four year of R&D activity. At least 1M USD for **travelling expenses** is expected over the whole nine-year period. Even if it is premature to define the details of the cost profile, this level of potential contribution is regarded as compatible with the current projection over the next 10 years of the INFN investment in Nuclear Physics research.

The resource sharing among the four areas of potential equipment cooperation will be defined later. About COMPUTING, the increased needs related to data crunching, which are expected in a time scale beyond the ten-year horizon, are not included in the present assessment.

Please indicate what, if any, assumptions you made as coming from the EIC Project or the labs for your items of interest:

The model for our equipment cooperation is collaborative and the collaboration effort will be detailed in the agreements with the future partners. This model makes it difficult to formulate a complete answer. Therefore, we list here the needs that, in any case, will require support from the Project and the labs, even if the list may not be exhaustive. They are:

A. <u>Generic support</u>

- Office space;
- Laboratory space;
- Access to internet;
- Access to guest houses or equivalent accommodations;

B. <u>Concerning PID, VERTEXING, STREAMING READ-OUT</u>

- Engineering contributions to the project in **matter of safety**, to guarantee being compliant with the local regulation;
- Engineering contribution to assist our engineers in the **design of the detector mechanics and the design of the power and cooling supply** in order to guarantee the overall compatibility with the other components of the experimental setup;
- Engineering and Technical contribution during the **installation phase** to assist our personnel in order to avoid too heavy travelling costs;
- Training of our personnel to qualify them as authorized users of specialized facilities according to specific requirements;
- Access to **technical facilities**;
- **Administrative support**
  - in procedure to grant the **access to the laboratory**;
  - in **purchasing** items that have to be delivered directly at the laboratory;
  - in **import procedures** of devices built in Italy.

Please indicate the labor contribution for the EIC experimental equipment activities:

The time commitment of members of the INFN group in the EIC efforts, described in this EoI and **summarized in Table 1,** is anticipated to be as follows:

- **Years 2021-2023**, **40 researchers** (approximately 50% INFN or Universities staff; 50% PhD students and postdocs) for a **total FTE of 10**;
- **Year 2024**, **50 researchers** (approximately 50% INFN or Universities staff; 50% PhD students and postdocs) for a total **FTE of 20**;
- **Years 2025-2029**, **80-100 researchers** (approximately 50% INFN or Universities staff; 50% PhD students and postdocs) for a total **FTE of 45-55**; also, INFN **technical personnel** corresponding to a total **FTE of 10**.

Please indicate if there are timing constraints to your submission:

The time constraints both in labor availability and financial resources already included answering to the questions related to “items of interest for potential equipment cooperation”, “potential contributions” and “labor” are presented **in Table 1**. In short form, R&D activities, requiring less investment and labor resources are foreseen till 2024. A substantial increase of financial and manpower resources are expected during the construction period 2025-2029.

Please indicate any other information you feel will be helpful:

Synergies with other experimental programmes

The INFN groups presenting this EoI are presently involved in the experimental programmes at JLab and in the ALICE and COMPASS experiments at CERN. This effort will continue in the next years in parallel with the R&D and construction activities for EIC, providing unique synergy opportunities. In fact, EIC and the other activities are all dedicated to hadron physics, therefore sharing the same cultural background, while detector technologies and data analysis methods are also common. The natural consequences are an optimal usage of the available know-how in physics and detectors, including the technical and technological competence of the dedicated personnel in the INFN units, allowing sharing of manpower, know-how and costs. Moreover, very complete training possibilities for the young newcomers are made possible: they can be exposed at the same time to preparatory activities for the future experiments at EIC and the challenges of running experiments.

Expertise and previous experience

PID: Wide experience and expertise concerning PID devices is available within the INFN groups signing the EoI, thanks to the participation in a number of projects: **COMPASS RICH, ALICE High Momentum RICH (HMPID), CLAS12 RICH, mRICH R&D, HERMES dual radiator RICH, ALICE Time-of-Flight (TOF) detector**. They have designed, coordinated and largely realized the COMPASS RICH, a wide acceptance gaseous RICH making use as photon sensors of MAPMTs, MWPCs and MPGDs equipped with CsI photocathodes. They have contributed to the development and construction of the ALICE High Momentum RICH (HMPID), a proximity focusing RICH with liquid C_6F_{14} radiator and MWPCs with CsI photocathode. They have led the design and construction of the aerogel RICH for CLAS12, a large area device with a hybrid optics with direct and reflected light configurations, and, in the context of eRD14, have contributed to the development of the mRICH. They have contributed to the HERMES dual radiator RICH, using aerogel and C_4F_{10} gas. They have been responsible of the development, realization and operation of the JLab-HallA liquid freon proximity focusing RICH. They led the effort for the development and construction of the ALICE TOF detector, based on the MRPC technology and providing PID capabilities in the intermediate momentum range. They have specific expertise in the field of SiPM devices and in the development of front-end electronics.

VERTEXING: Some of the INFN groups have consolidated expertise in development, construction and operation of silicon detectors. Such expertise is based on previous experience with the CERN silicon pixel trackers for fixed target experiments in the years 1990-2000 (WA97/NA57 heavy-ion experiments at the CERN SPS), followed by more recent and ongoing contributions to the ALICE silicon pixel detector (LHC Run1 and Run2 phases) and the upgrade of the ALICE inner tracking system (LHC Run3).

STREAMING READOUT: Some of the INFN members are working on triggerless DAQ test systems at JLab. The triggerless DAQ activity for the Electron Ion Collider (EIC), in collaboration with the Massachusetts Institute of Technology (MIT), is also funded by the Italian Ministry of Foreign Affairs (MAECI) as Projects of great Relevance within Italy/US Scientific and Technological Cooperation under grant n. MAE0065689 - PGR00799.

SOFTWARE TOOLS and COMPUTING: Members of the INFN groups involved in the EIC have or had coordination responsibilities in the Software and Computing Groups as well as in data analysis of COMPASS, ALICE and experiments at JLab. More specifically, there is wide expertise on the software and analysis side, in particular based on the experience in development of tracking, vertexing and PID reconstruction software, as well as physics analysis software. In these groups, there are also active software developers and project managers of Git and CVMFS repositories, VOMS and data (real and MC) production as well as experts in computing resource management.

Available infrastructure
The INFN activities in all the Units are supported by the **local available facilities: mechanical workshops, electronics laboratories, clean rooms.**
Other **specific infrastructures** facilitating R&D and constructions are available:
PID

- A laboratory equipped for photon detector R&D and constructions in Trieste, where the photon detectors for COMPASS RICH have been developed and built.
- An advanced electronics laboratory in Torino, where the ASIC for SiPM readout is being designed and prototyped.
- A workshop for large size detector constructions at Laboratori Nazionali di Frascati.
- A laboratory for sensor, radiator and mirror characterization in Ferrara, where the CLAS12 RICH components have been validated.
- For SiPM annealing studies climate chambers and dedicated laboratories for silicon devices in Ferrara and Bologna.

VERTEXING

- Adequate infrastructures are available in the INFN Units contributing to the upgrade of the ALICE vertex, namely Bari, Bologna, Catania, Laboratori Nazionali di Frascati, Padova, Torino and Trieste, including:
- cleanrooms for solid state detectors, equipped with chip test setups and devices for qualification tests, vision probes for optical measurements and digital microscopes;
- pull/bond-tester and ultrasound micro-bonder machines;
- metrology labs, equipped with coordinate measuring machines and portable measuring arms suitable for components with complex geometries;
- mechanical workshops, equipped with a Computerized Numerical Control (CNC) 5-axis machining centre and a CNC 7-axis turning centre suitable to manufacturing of complex precision components and prototypes for research projects.

SOFTWARE TOOLS and COMPUTING

- INFN-CNAF in Bologna, ReCaS data centers in Bari and Catania, WLCG Tier-2 sites and additional local farms in Bari, Catania, Padova, Roma, Torino and Trieste (details are provided in Appendix 1).

CERN support
We would like to underline the relevance and the support to our activity that will come from having the EIC experimental activity as a **CERN "recognized experiment"**. CERN is the European "national" laboratory, a unique point of accumulation of scientific and technological know-how facilitating both the R&D and the construction activities. The possibilities offered to recognized experiments include easy access to CERN scientific information and to CERN sites, possibility to organize meetings at CERN, access to test beams, access to technological laboratories, workshops and other services.

TABLE 1 – Labor and investment for R&D and construction in period 2021-2029.

Years	Labor, scientists	Labor, technical personnel	In-kind investment R&D	In-kind investment constructions	Travelling	Manpower	Investment, TOTAL
	(FTE)	(FTE)	(USD)	(USD)	(USD)	(USD)	(USD)
2021	10		minimal		minimal	0.4 M	0.4 M
2022-2023	10		1 M		0.3 M	1.6 M	2.9 M
2024	20						
2025-2029	50	10		7-8 M	0.7 M	12 M	19.7 - 20.7 M
Investment 2021-2029, TOTAL			**1 M**	**7-8 M**	**1 M**	**14 M**	**23-24 M**

Three appendices are included:

- ***APPENDIX 1 - About INFN** : a short-form introduction to the Italian National Institute of Nuclear Physics;*
- ***APPENDIX 2 - INFN groups and Physics at the EIC** : The main areas of interests of the INFN groups in the EIC Physics programme are underlined;*
- ***APPENDIX 3 - The INFN theoretical contribution to the EIC physics programme** : the EIC-related activities of the INFN theorists are reported.*

APPENDEX – about INFN

This Appendix is intended to provide a quick introduction to the Italian National Institute for Nuclear Physics.

INFN (Istituto Nazionale di Fisica Nucleare, *National Institute of Nuclear Physics*) is the Italian research Institute, supervised by the Ministry of Education, Universities and Research, with the mission to perform fundamental research in the field of the fundamental constituents of matter and of the interactions regulating their behaviour. The Institute has complete autonomy concerning scientific goals within the designated mission, regulation, internal organisation and financial management.

INFN origin

It was a Fermi's intuition the need of a national institution dedicated to nuclear physics. Conditions to make it possible have been established only after the second world war: groups from the Universities of Rome, Padua, Milan and Turin founded INFN on 8th August 1951 to uphold and develop the scientific tradition established during the 1930s by Enrico Fermi and his school, with their theoretical and experimental work in nuclear physics.

In the latter half of the 1950s, INFN designed and built the first Italian accelerator, the electron synchrotron developed in Frascati, where the first national laboratory was established. Other key steps of the initial period are the constitution of a computing centre, build in 1955 in Pisa and the strong Italian support to the foundation of CERN, recognized by designating Edoardo Amaldi as first CERN Director General.

INFN human resources

INFN fulfils its mandate thanks to a community counting more than 5000 scientists, physicists and engineers, 1000 of them employed by INFN, the others from Universities and other research institutes, who are associated to the Institute activities. Among them, about 1000 PhD students and post docs are included. The research personnel are assisted by about 650 units of technical personnel and 300 units of administrative staff.

INFN financial resources

The main source of funding is from the Department of Education, Universities and Research and it amounts to approximately 300 M€ (2019) per year. It covers the salaries of the staff, including post-doc positions, the operation costs of the INFN sites and the INFN research infrastructures and the costs of research equipment and consumables. A further financial source, of the order of 50 M€ per year, is obtained from European and regional funds, as well as from specific national programmes.

Organization

INFN is well present in the territory, with twenty Units (Sezioni), six Associated Groups, four National Laboratories (Laboratori Nazionali di Frascati - LNF, Laboratori Nazionali del Gran Sasso - LNGS, Laboratory Nazionali di Legnaro - LNL, Laboratori Nazionali del Sud - LNS), three

National Centers (CNAF, now the main INFN computing centre, Galileo Galilei Institute – GGI for theoretical physics, Trento Institute for Fundamental Physics and Applications - TIFPA) and the European Gravitational Observatory (EGO) consortium (INFN, Italy; CNRS, France; NIKHEF, the Netherland). The headquarters of the Institute are located downtown Rome, in a historical building of the XVI century, Palazzo Lante. A map of the location of the INFN sites is presented in Fig. 1.

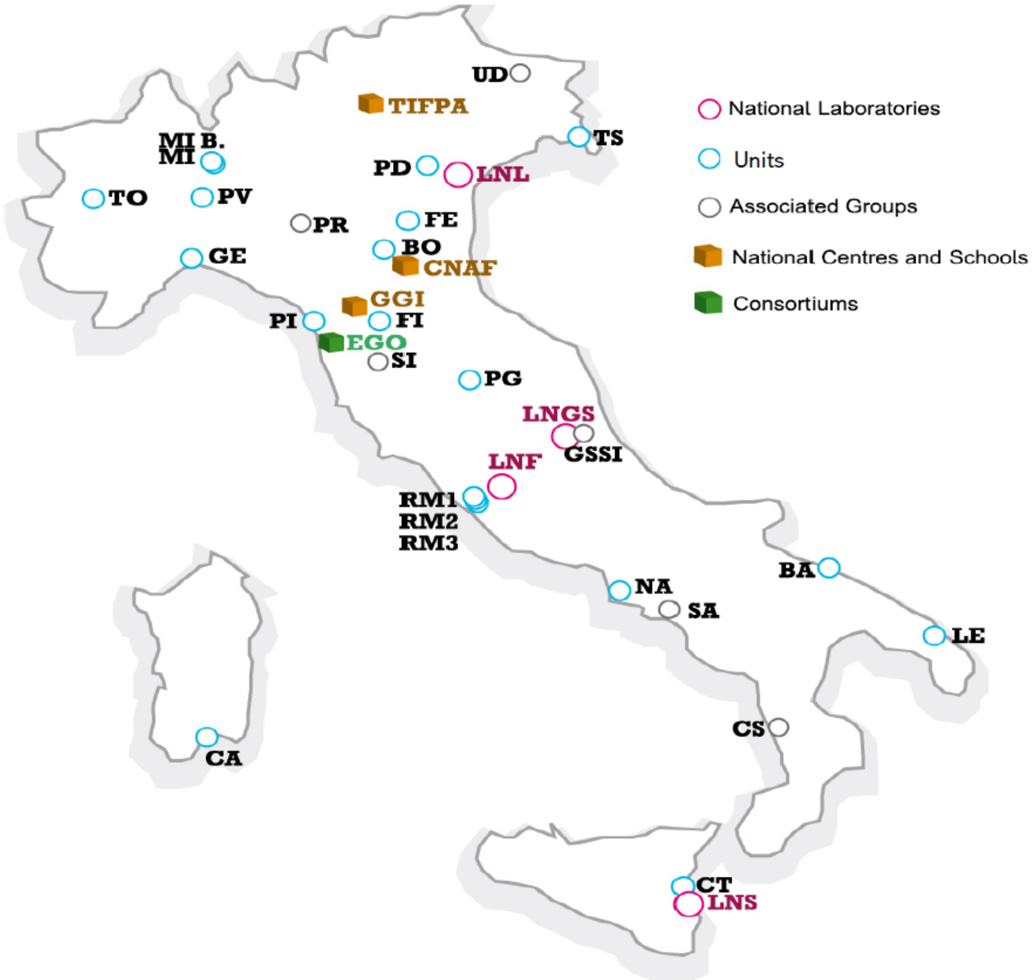

Figure 1. Map of INFN sites

In Fig.2, we show the complete organogram of the INFN, comprehensive of scientific and managerial bodies. The Governing Council is the Institute's decision-making body. It consists of the President of INFN and the Executive Board, the directors of the laboratories and divisions, the representatives from the Ministry of Education, Universities and Research (MIUR), the Ministry for Economic Development, and representatives from the staff of INFN. Council decisions are implemented, as appropriate, by the President, the Executive Board or the laboratory/units directors for those regarding local activities and by the General Director, in charge of the administrative activities, who is assisted by the administrative headquarters office. There are also advisory bodies, which assist the governance of INFN in taking scientific, managerial and financial decisions. Of upmost relevance are the five parallel National Scientific Committees, dealing with Subnuclear, Astroparticle, Nuclear, Theoretical Physics and Technological activity. Their members, one per each Division or National Laboratory, are elected by the researchers resulting in a strong bottom-up vocation of these bodies, that play a major role in shaping the Institute choices in matter of research. These committees are in charge of evaluating new proposal of experiments and monitoring the progress of the already approved research programmes as well as of budget sharing proposals within the global budget, which is assigned by the Governing Board to each of the five scientific areas.

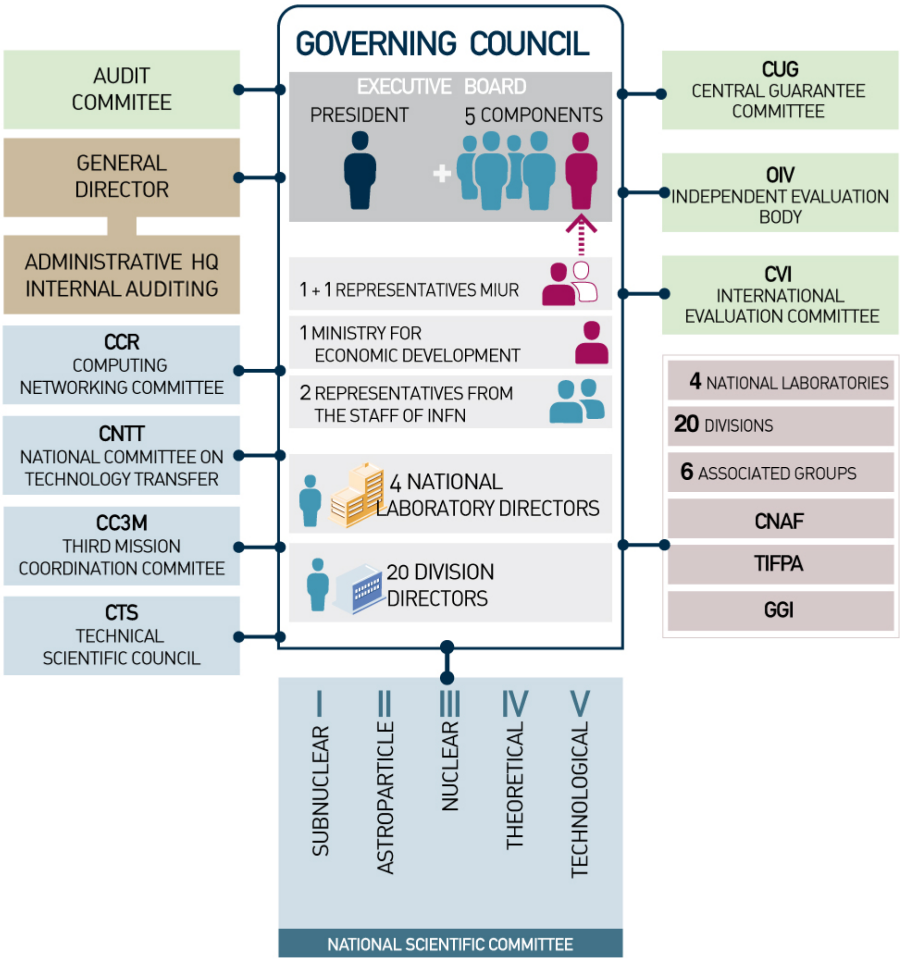

Figure 2. The organogram of INFN

Scientific activity.

INFN scientific activity is illustrated in the following in short form and, therefore, only by examples, without aiming at an exhaustive description. The INFN research classification related to the five National Scientific Committees is adopted.

The **National Scientific Committee for Subnuclear Physics** coordinates INFN activities in Particle Physics at Accelerators. The main research areas are the particle physics at the energy frontier, flavour physics, charged lepton physics and the proton structure. Experiments with internationally recognized high impact on the field and research and development for high profile future projects are supported. The Committee gives strong and very visible contributions to a broad set of international experiments: ATLAS and CMS accompanied by the experiment TOTEM and LHCf for the physics in the very forward region, Flavour Physics including LHCb and BES III, Charged Lepton Physics including the participation in BELLEII, Proton Structure including the COMPASS experiment at CERN and detector R&D for the experiments at Future Accelerators.

The **National Scientific Committee for Astroparticle Physics** is devoted to experiments which explore the fundamental properties of matter constituents and their interactions through the study of neutrino properties (ICARUS, T2K, JUNO, Gerda, Cuore), the search for fundamental constituents of dark matter and dark energy (XENON1T, DarkSide), the direct detection of gravitational waves (Advanced Virgo at EGO), the study of the spectrum and composition of the cosmic background radiation (FERMI, ASM-02, MAGIC, CTA), precision measurements related to General Relativity and Quantum Mechanics.

The **National Scientific Committee for Nuclear Science** supports experiments running in national and international laboratories and spanning a wide energy interval from a few eV to a few TeV. In the lower energy domain, there are experiments concerned with the measurement of cross-sections of astrophysical interest; among them: LUNA, ERNA, Pandora, experiments at the n-TOF facility at CERN as well as experiments dedicated to the exploration of the periodic table looking for heavier and heavier elements, or nuclei far from stability. Experiments at the future facility SPES (Selective Production of Exotic Species) are in preparatory phase. High energy nuclear physics in the hadron physics sector is pursued with the participation to ALICE and to the experimental activity at the Jefferson Laboratory in Virginia (USA). This Committee also supports experiments dealing with symmetries and fundamental interactions, as those making use of low energy antiproton beam performed at CERN (ASACUSA, AEGIS) for the study of the possible difference in the gravitational interaction of matter and antimatter, and experiments for the measurement of the EDM of deuteron, the Zemach radius of proton, violations of the Pauli principle.

The **National Scientific Committee for Theoretical Physics** provides strong support to the theoretical physics programme in Italy. The theoretical research covers six different lines of scientific investigation: String and Field Theory, Particle Phenomenology, Hadronic and Nuclear Physics, Mathematical Methods, Astroparticle Physics and Cosmology and Statistical and Applied Field Theory. A large fraction of this theoretical research is in close relationship with experiments, as evidenced by the works in precision standard-model physics, physics beyond the standard model, flavour physics and neutrino physics, hadron physics, dark matter and cosmology.

The **National Scientific Committee for Technological Activity** coordinates advanced technological research for INFN experimental activities and promotes the development of instruments, methods and techniques for fundamental physics and their application beyond fundamental research. These activities contribute to strengthening links with universities and national research institutes and match requests coming from society. There are three main areas of activity: *i)* development of radiation detectors, electronics and software; *ii)* production and development of particle accelerators and new prototypes; *iii)* interdisciplinary applications. Technologies are widely used also outside physics research and have social and economic impacts (e.g. medical imaging, cancer therapy, protection of cultural and environmental heritage).

Research infrastructures.

Laboratori Nazionali di Frascati – LNF (Frascati)
The historical laboratory of the INFN, houses **DAFNE** (e^+e^- collider, world record of luminosity at low energy), **SPARC** for the production of light by a free electron laser, the **BTF** (beam test facility) delivering e^+, e^- beams with high intensity for testing and application purposes. Plasma acceleration is developed here, within the **EuPRAXIA** European project, with the aim to host the first European FEL using the plasma acceleration technique.

Laboratori Nazionali del Gran Sasso – LNGS (Assergi)
The world largest fully operating **underground laboratory**, easily accessible via a dedicated highway exit. Outstanding experiments studying **neutrinoless double beta decay**, **dark matter search** and reactions in stars and **Big Bang nucleosynthesis** have found their natural home here, thanks to the low background environment.

Laboratori Nazionali di Legnaro – LNL (Legnaro)
This laboratory is one of the two dedicated to nuclear physics and astrophysics. **Five accelerators** for different energies and nuclear species allow a continuous experimental activity by Italian and international groups. The **SPES project**, aimed at the production of **radioactive beams for fundamental and medical research**, is based here. The cyclotron, already installed and under test, will deliver the first beams for experiments in 2022.

Laboratori Nazionali del Sud – LNS (Catania)
The other laboratory of INFN dedicated to nuclear physics, astrophysics and applications. The core machine of the laboratories, the **superconducting cyclotron**, is undergoing a major upgrade, for higher intensity, in order to expand the scientific program to **exotic beam** physics and for the **NUMEN experiment**, designed to access the nuclear matrix elements entering the expression of the life time of the double beta decay. The CATANA facility to **treat ocular cancer** with proton beams is operational here.
The **KM3Net** experiment for the detection of neutrinos in the deep sea water, is built here, close to the installation site, in the sea.

The list of INFN infrastructures is enriched by **LABEC** (in Florence), a laboratory dedicated to nuclear techniques for cultural heritage studies making use of a **Tandetron** accelerator for both mass spectroscopy (**AMS**) and analysis with ion beams (**IBA**), **LASA** (in Milan) where **superconductivity** applied to particle accelerators is exploited, and **TIFPA** (in Trento), born to foster research in new fields, technologically strategic for industry applications as **space research**, **proton therapy** and **silicon sensor development**. Up-to-date **technologies for the observation of gravitational waves** are exploited at the **EGO Observatory**.

CNAF is the national centre of INFN dedicated to Research and Development on Information and Communication Technologies. Deeply involved in the development of Grid middleware and in the management of the Grid infrastructure since the early stages, it hosts the Italian Tier-1 site of the WLCG (Worldwide LHC Computing Grid). CNAF also represents a key computing facility for many astro-particle and neutrino-physics experiments, making it one of the most important centers for distributed computing in Italy with a total of about 30,000 CPU cores, 30 PB disk and 60 PB tape storage. Its migration in a new data center with a power capacity of 10MW is currently planned. Overall, **the INFN scientific computing infrastructure** includes more than 30 sites, ranging from CNAF and nine WLCG Tier-2s (three of them hosted in the large **ReCaS data centers** in the south of Italy), to about 20 smaller sites, including WLCG Tier-3s and not-LHC experiment farms. The total installed CPU power exceeds **80,000 CPU cores**, while the total storage net capacity is around **60 PB on disk** and **100 PB on tape**: the vast majority of resources (95%) are concentrated

in the 16 largest data centers. The connection bandwidth ranges from the 2x100 Gbps links for CNAF (to LHC Tier-1s and CERN) to the 20-40 Gbps available for most of the other sites. Very recently, in a European Consortium of Austria, Hungary, Slovakia, Slovenia and Italy (with Ministry of University and Research, CINECA, INFN and SISSA), INFN is participating in the construction of **Leonardo, a pre-exascale computer**, to be hosted at CINECA in Bologna.

A special mention deserves the **Gran Sasso Science Institute (GSSI)**. Founded by INFN as a PhD-dedicated international school, its high formation value has been recognized in 2016 by the Ministry of Education, Universities and Research, transforming the school in a regular PhD course with four different academic paths, keeping a privileged link with INFN, thanks also to the close presence of the LNGS.

APPENDIX - INFN groups and Physics at the EIC

The experimental physicist groups from the INFN Units or National Laboratories presenting the EoI have a long history and covered leading roles in the study of the spin content of the proton, in its multidimensional structure, in the study of hadronisation and in hadron spectroscopy. They have been and are driving many analyses focused on the measurements of the polarized structure functions and observables that show effects of TMD PDFs and GPDs, on the study of the nucleon structure in diffractive and small-x processes, on the searches for new bound states in the hadron spectra, and on the analysis of the outcome of ion-ion collisions.

In the next years, the strong engagement in their ongoing experimental research in COMPASS and ALICE at CERN and in Hall-A and Hall-B at Jefferson Laboratory will continue. Moreover, there are initiatives to either complete or revise the analysis of archived data from the HERMES and ZEUS experiments at HERA. All these activities constitute a very effective synergy in preparation for the EIC.

The physics interests and perspectives of the Italian groups participating to the EIC project will cover three main subjects, i.e.

- Colour charges in nuclear matter and hadronization
- Structure of the nucleon and of the nuclei
- Spectroscopy (and search for exotic states).

The present EIC accelerator design and detector concepts, optimized for broadening the physics reach, fulfil all the requirements posed by the physics items of our main interest. We are confident that this policy will be maintained and reinforced over the design and construction phases following the current timelines to guarantee the whole physics outcome in a timely schedule.

In the following, we outline our expectations and foreseen activities in preparation for the EIC realization.

Coloured charges in nuclear matter and Hadronisation

A large fraction of our community is highly interested and deeply involved in the study of non-perturbative QCD phenomena with heavy-ion collisions at ultra-relativistic energies. They are currently contributing to the characterisation of the hot QCD matter created in ion-ion collisions with the ALICE experiment at the LHC. They plan to contribute to the EIC Physics as well, with interest in these specific Physics topics:

- search for non-linear QCD phenomena at low-x and high gluon density;
- study of the interaction of fast coloured partons in nuclear matter;
- understanding the hadronisation of heavy-flavoured quarks.

The Italian groups have a long experience in detailed measurements of hadron production and in their modification in the environment created with nuclear collisions, particularly for what concerns measurements of the production of strange and heavy-flavoured hadrons. Italian groups presenting this EoI have covered leading positions in the coordination of Physics and Analysis Working Groups within the ALICE Collaboration and will continue their research in the coming years, in parallel to the construction of the EIC facility.

The ALICE experiment studies the formation and properties of the Quark-Gluon Plasma and, among the various topics related to hot QCD matter, it also aims at understanding the underlying mechanisms for particle production in hadronic collisions, which are ultimately connected to the phenomenology of hadronisation of coloured charges. One of the key evidence for the formation of the QGP in ultrarelativistic heavy-ion collisions is the manifestation of “jet quenching”, namely the suppression of high-p_T hadrons and jets, believed to be due to energy loss of coloured partons in the hot QCD medium [1]. The EIC would open the possibility to study with calibrated probes the interaction of light and heavy quarks in the cold nuclear matter with a large variety of ion beams. In addition to that, recent results at the LHC have shown a significant modification in the hadronisation of charm quarks in nuclear collisions [2] as compared to hadronisation in vacuum (i.e. from LEP results in e^+e^- collisions and in DIS experiments [3]). Similarly to what observed in the light-quark sector, the Λ_c^+/D^0 production ratio is measured to be significantly enhanced in ion-ion collisions, pointing towards either a new mechanism present in the production of baryons (i.e. quark coalescence) or to a strong modification of charm fragmentation. It must be noted that an enhancement in the baryon-to-meson ratios and most notably of the Λ_c^+/D^0 is already observed in pp and p-Pb collisions at the LHC [4] with respect to e^+e^- collisions. This observation might suggest that different mechanisms are at play because of the parton-rich environment in the initial stages of these collisions [5]-[6].

Studies of charm hadron production at the EIC will allow probing this in detail, studying hadronisation and how the cold nuclear environment can possibly modify this fundamental process or give rise to new features.

The physics-oriented activities of these groups, in the preparatory phase of the EIC, concern contributions to items in the sectors:

- studies with Monte Carlo Event generators for eA;
- reconstruction of charmed meson and baryons with full simulations;
- studies of the physics reach and implications in heavy-ion physics.

Structure of the nucleon

Present research activities of the groups interested in the study of the structure of the nucleon [7]-[14] are nicely matching the future research at the EIC. COMPASS centre-of-mass energy is very close to the lowest energies at the EIC. Therefore, results obtained at COMPASS can be directly used for estimating the size of the different effects; some of them can also be used for benchmarking the EIC. JLab, which is covering with high precision the valence region, can provide valuable insights on the impact of higher twist terms in the cross-section.

In the preparatory phase for physics at the EIC, these groups plan to contribute to a list of items:

- Optimization of the multidimensional binning for TMDs and GPDs analysis; when dealing with multiple kinematic dependencies, any binned analysis has an implicit integration inside the phase space bin, which folds together physics and instrumental effects. Any consequent phenomenological fit will inherit such unwanted effects.
- Implementation of spin dependent part of the cross section inside general purpose Monte Carlo Event Generators; this task is broader than the EIC scope since it will be beneficial for all running and planned experiments accessing the structure of the hadron and the hadronization of quarks and gluons, SIDIS, e^+e^- and Drell-Yan reactions.
- Detailed studies about the implications for TMDs and GPDs of the performance of the EIC detector with full simulation, accounting for machine background, and expected efficiencies and resolutions of the different detectors.
- Development of analysis tools and new extraction strategies: e.g. TMDs are complicated objects, which enter in the cross-section always as convolutions between two of them, both PDFs and FFs (SIDIS), FFs and FFs (e^+e^-) or PDFs and PDFs (Drell-Yan). The phenomenological analysis of the measured TMD dependent observables requires introducing a model to describe the transverse momentum dependence of the TMDs. In the preparation for the EIC, we will engage with the strong theoretical groups in Pavia and in Torino to discuss and implement new approaches aimed to reduce the model dependency of the phenomenological analysis.
- The radiative corrections alter the event kinematics, cause a migration of events between the bins and therefore introduce cross talks among the various terms of the SIDIS cross-section Fourier decomposition. A full knowledge of the hadron tensor (and its full 4D kinematic dependence) is necessary in order to get a proper correction. Such a description can only be achieved combining the information of various experiments into a common simulation framework.
- Investigation of the saturation effects and of the differentiation among models can be obtained combining the existing information from inclusive and diffractive electron-proton and electron-ion scattering. The scope can be enlarged from diffractive processes, with little or no breakup of the outgoing hadron, to the more general target fragmentation scenario and specifically to the forward proton and neutron production. Target fragmentation measurements represent an opportunity for the EIC and could extend the reach of the 3D nucleon structure studies, giving access to the nucleon multiparton structure and correlations. HERA data on forward proton/neutron production could possibly provide a testing ground.

Spectroscopy

INFN groups presenting this EoI have also a long-standing expertise in the study of Hadron Spectroscopy. A renewed interest in the field comes from many unexpected observations of exotic hadrons in the heavy quark sector including the proliferation of non-standard multi-quark mesons, the so-called XYZ states, the observation of charmed penta-quark P_c baryons and meson-gluon hybrids [15]-[18]. While these discoveries came from e^+e^- colliders and b-hadron decays at LHCb, it is now recognized that they can be studied in alternative processes such as photo- and electro-production [19]-[22].
Some of the Italian groups are involved in fixed target experiments using CLAS and CLAS12 spectrometers at the Jefferson Laboratory, that provide access to the light-quark spectrum,

including hybrid baryons and s-channel production of P_c. However, no access to XYZ states via t-channel exchange is possible with the 12 GeV electron beam.
The ability to study heavy quarkonia through photoproduction in ep collisions has been proved at HERA while the COMPASS collaboration has studied muon production of the J/ψ final state finding an indication of a new X(3872) state and also setting limits on Z_c photoproduction in the J/ψ π N final state.
A **luminosity** as high as 10^{34} cm^{-2} s^{-1} expected at EIC, coupled with a **detector with high acceptance for exclusive processes**, opens the possibility to access the most relevant topics in hadron spectroscopy.
The main physics interests in ep processes are:

- via coupling of the quarkonia to intermediate light mesons in the t-channel [23];
- production of XYZ in semi-inclusive J/ψ n π processes;
- search for P_c heavy pentaquarks with hidden charm in the s-channel production of J/ψ, where the signature is given by the deviations of the cross-section from that provided by the quark counting rule [24];
- search for $\mathrm{P_b}$ heavy pentaquarks with hidden bottom $\mathrm{P_b}$ in the s-channel production of Υ(nS) [25];
- J/ψ and Υ production via odderon (3 gluons) exchange [26];
- study of proton-resonance transition GPDs from hard exclusive electro-production of photons and mesons ($\pi, \rho, \phi, \omega, \cdots$) providing insight on the quark and gluon content of the excited states of the nucleon [27]-[28].

The access to eA processes allows studying the effect of medium propagation of exotic hadrons in cold matter and nuclear transparency. The relevant topics of interests are:

- X(3872) propagation in cold matter;
- nuclear modification of the X(3872) and other exotic hadrons.

Additional open heavy flavour deep processes of interest are:

- study of transition GPDs in $\Lambda_c D^0$ associate charm production;
- semi-inclusive eD^0 production to access sea charm PDF;
- semi-inclusive J/ψ production to access gluonic distribution.

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APPENDIX - The INFN theoretical contribution to the EIC physics programme

The INFN theoretical activities of interest for the EIC have their main focus on how hadron phenomenology emerges from the interactions generated by the symmetries of QCD, and from the breaking of these symmetries. The main goal is building accurate 3D maps of the internal dynamics of partons and of their mutual interactions in order to shed light on the composition of hadronic masses and spins in terms of elementary constituents, eventually achieving a microscopic understanding of the mechanisms of QCD confinement. Shaping these maps in momentum and coordinate space requires advanced non-perturbative tools: Transverse Momentum Dependent distributions (TMDs), Generalized Parton Distributions (GPDs), Double Distributions (DDs), Distribution Amplitudes (DAs), etc., and related form factors. These non-perturbative distributions are all important and complementary. For example, 3D maps in momentum space from TMDs and in coordinate space from GPDs are not related by a Fourier transform; TMDs and GPDs are different projections of the same *mother* Wigner function which contains the most complete tomographic information on hadrons, including insight into the partonic orbital momenta.

The INFN theoretical activities are organized under the INFN project NINPHA (National INitiative in Physics of HAdrons) which is structured in five units (Torino, Pavia, Genova, Perugia, Cagliari) with currently 15 staff members, 12 (post-doc) collaborators and 3 Ph.D. students. There are three main research lines.

NINPHA members are engaged in **theoretical and precision studies of the properties of the non-perturbative tools mentioned above**, such as proper factorization theorems (in relation to their counterpart in the standard collinear framework), universality, transformation under proper evolution equations, matching of TMD-based calculations to highly accurate perturbative calculations at larger energies, gauge-invariant definition of orbital angular momentum, properties of the energy-momentum tensor and the decomposition of hadron mass, etc..

There is also an intense **phenomenological activity on the extraction of TMDs and GPDs of quarks in the proton** from robust global fits including data sets provided by past/running fixed-target experiments (HERMES, COMPASS, JLab12) and colliders (TEVATRON, RHIC, LHC, SLAC, KEK). The outcomes, which are accurate at the top $\mathrm{N^3LL}$ level in the resummation of soft gluon radiation, are being used to estimate the impact of EIC pseudo-data on the uncertainty of various SIDIS (polarized) observables. In a similar fashion, progress is being made on a realistic description of TMDs and GPDs in light nuclei, which are necessary first of all to explore the medium modifications of partonic densities as well as the in-medium fragmentation, but also to extract information on the 3D structure of the neutron, and in turn to achieve a precise flavor separation of parton densities. All these studies will be especially valuable for the future EIC, particularly in view of the use of light-ion beams.

Finally, NINPHA members are also active in **exploratory studies and modeling of various quantities** in order to expose qualitative features of these quantities, make reasonable predictions for yet unmeasured observables, guide the choice of appropriate functional forms in fits of measured observables. These studies include: *a*) the basically unknown gluon (polarized) TMDs and new possible channels to address them at the EIC (through single and associated quarkonium production); *b*) a Light-Cone unifying picture of quark TMDs and GPDs to support a comprehensive experimental investigation of SIDIS observables on nucleon and light-nuclei targets; *c*) partonic dynamical correlations exposed through DDs; *d*) model wave functions of (exotic) mesons and baryons tuned to reproduce their excited spectrum; *e*) effective field theories (together with dispersion relations) to study the 3-body decays of such exotic hadrons, especially the CP-violating ones, in order to explore possible effects of new physics.

The NINPHA project encompasses theoretical explorations but all its members work in close contact with several experimental collaborations, in particular with the Italian experimental colleagues active at CERN and JLab, who are interested in the future Electron-Ion Collider and who are organized in the INFN project named EIC_NET. The goal is to provide an up-to-date theoretical background and a sophisticated framework such as to reduce as much as possible the model dependence of the phenomenological analysis needed to extract information on the hadronic structure. This Expression of Interest (EoI) literally expresses the interest of the whole Italian community involved in the EIC physics program, and it represents a unique opportunity of synergic technological, experimental, and theoretical effort.

All NINPHA members are also **members of the EIC Users Group (EICUG)**, and are actively contributing to the activities of the various Physics Working Groups in the context of the *Yellow Report* process promoted by the EICUG Steering Committee. Some NINPHA members have specific responsibilities inside the EICUG organization: F. Murgia (Cagliari), M. Radici (Pavia), and S. Scopetta (Perugia) are members of the Institutional Board; B. Pasquini (Pavia), former member of the Conference and Talk Committee, is one of the conveners of the Physics Exclusive Working Group, and is member of the IAC at the CFNS (Stony Brook); M.Radici (Pavia) is member of the EICUG Steering Committee and of the Committee for the EICUG Charter Review.

Researchers of all NINPHA units are at the forefront in their area of expertise. Here in the following, the research plans of each NINPHA unit are described in more detail.

- **Torino**. The Torino group has pioneered the extraction of (polarized) TMDs from SIDIS and e^+e^- processes. Their parametrization of the Sivers, transversity and Collins functions are being used to estimate the impact of EIC pseudo-data on SIDIS observables. As a further step in the effort to understand hadronic transverse momentum dependent phenomena, they will analyze SIDIS data by including maximal constraints from perturbative QCD up to the $\mathcal{O}(\alpha_S^2)$ order. Special attention will be devoted to the intermediate transverse momentum region, which represents the domain of transition between the perturbative regime (where the collinear framework works) and the non-perturbative regime (where the TMD framework is applicable). The focus will be first on unpolarized cross sections and multiplicities then will be extended to polarized TMDs like the Sivers, transversity and Collins functions. Universality-breaking effects due to process-dependent soft factors will be investigated in relation to hadronic collision processes, in collaboration with the NINPHA unit of Cagliari.

- **Pavia**. The Pavia group has a long standing experience in phenomenology, modeling, and exploratory studies of hadronic structure. After the release of the first extraction of the unpolarized quark TMD from a global fit with more than 8K data points (the outcome being also used to estimate the impact of EIC pseudo-data on the unpolarized SIDIS cross section), they will carry on the transition to precision physics by extending the top perturbative accuracy recently reached in the fitting framework "NangaParbat" to a global fitting strategy including (polarized) SIDIS data, in particular for the Sivers effect that represents the EIC "golden channel". They will also keep on benchmarking with the LHC EW Working Group codes, in order to deepen the exploration of the impact of nonperturbative effects on Standard Model parameters (such as the W mass). In parallel, the group will also extend the exploration to inclusive jet production and hadron-in-jet production in view of the predicted possibility of abundantly observe jets at the EIC. On one side, this class of observables will contribute to constrain the TMD fragmentation functions extracted from the global fit. On the other side, when polarization is switched on, it will improve the accuracy of transversity as a collinear parton density extracted from the Pavia's global fit of semi-inclusive di-hadron production data, leading to a more precise determination of the nucleon tensor charge, the so-called EIC "silver channel". The Pavia diquark spectator model for quark TMDs will be extended to include both T-even and T-odd gluon TMDs, focusing on the low-x phenomenology attainable at the EIC in order to explore the transition from the DGLAP to the BFKL evolution regime. The well established unifying framework for TMDs and GPDs within the Light-Cone picture of the 3-quark model Fock state of the nucleon will be reformulated in terms of model-independent relations with DAs input from lattice, opening the way to a comprehensive analysis of collinear PDFs, TMDs, and GPDs. Starting from the pioneering studies of the Wigner function (and its counterpart in full momentum space, the Generalized TMD - GTMD) and its relation to the orbital angular momentum of partons, new processes like the di-jet production in ultra-peripheral proton-nucleus collisions will be studied to access the Wigner function and the orbital angular momentum of gluons both at small and moderate x. Finally, the problem of renormalization of the energy-momentum tensor and its scheme dependence will be addressed: it has non-trivial consequences on the decomposition of the mass sum rule of the proton.
- **Genova**. The Genova unit has a long tradition in hadron spectroscopy. Tetraquarks, pentaquarks and hybrids have been (and will continue to be) studied in collaboration with experimental groups at JLab and LHCb. A fully relativistic description of the three-body bound system will be pursued in collaboration with the Perugia unit, in order to explore excited states of baryons and assess their true nature of exotics. Recently, small CP violations have been observed in heavy hadron decays in the charm sector. The group will apply the formalism for 3-body decay to develop a 3-body dispersive approach including final-state interactions effects, that would help improving the sensitivity to CP-violating phases in 3-body decays measurable at the EIC, like $D \rightarrow 3\pi$.
- **Perugia**. This unit has long standing experience in the realistic description of momentum distributions and spectral functions of (light) nuclear systems, which is a prerequisite to expose genuine novel effects due to quarks and gluons when embedded in the nuclear environment. Reliable description of light nuclei is also necessary when trying to extract information on the 3D structure of the neutron, which in turn allows to achieve a precise

flavor separation of the various parton densities. The Perugia group is actively pursuing a Poincarè covariant description of light nuclei in the Light-Front form of relativistic dynamics with a realistic description of the 3D nuclear structure both in momentum and coordinate space. This effort supports the current experimental investigations on the neutron TMDs and nuclear GPDs at JLab, and it will be especially valuable for the future EIC in view of the use of light-ion beams. As for hadron colliders, the group is also investigating multiparton dynamics to extract new information on the proton structure either from parton-parton correlations encoded in DDs, which can be isolated in double-parton scattering in proton-proton collisions, or from color fluctuations in diffractive proton-nucleus scattering. On a more fundamental level, the non-perturbative spin-momentum correlations inside hadrons will be described in the framework of both the Bethe-Salpeter and gap equations, with the aim of extending the existing Euclidean investigations directly to Minkowski space.

- **Cagliari**. Similarly to the Torino and Pavia units, with which it traditionally collaborates, the Cagliari unit has a well recognized experience in the phenomenology of TMDs, particularly regarding (polarized) hadronic collisions. The group members will focus on the computation of state-of-the-art predictions and estimates for unpolarized cross sections and azimuthal and spin asymmetries in the kinematical configurations of the EIC and of the (polarized) fixed-target experiment at the LHC. More in detail, they will address: *a*) the poorly known gluon TMDs through quarkonium production in SIDIS and hadronic collisions, taking advantage of the expertise of the Genova and Perugia units about quarkonium spectroscopy and polarized hadronic collisions, respectively; *b*) the puzzling transverse Λ polarization, observed in unpolarized hadronic collisions and e^+e^- annihilations, and interpretable in terms of polarizing TMD fragmentation functions; *c*) the azimuthal distribution of hadrons inside jets produced in all hard processes; *d*) the single and double spin asymmetries in D meson production in polarized proton-proton collisions of interest at RHIC and the forthcoming NICA experiment.