Letter of intent

Acronym and project title: PRODY, **P**recision **R**esearch on **O**rigins of **D**rell-**Y**an: understanding the fundamental particle interaction process ranging from pQCD to non-perturbative regime, from LHC-to-SPS-to-SIS

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1 Research objectives

Dilepton production in nuclear collisions serves as a powerful probe for investigating the properties of strong-interaction matter and the internal properties of hadrons across a broad range of collision energies. The kinematic variables of the lepton pair, in particular the Lorentz invariant mass, allows access to a variety of fundamental phenomena. For instance, the mass region around M_{ll} $\simeq$1.1-1.5 GeV is characterized by a dip in the vacuum electromagnetic spectral function. This dip is expected to be filled in the presence of chiral mixing, a mechanism associated with chiral symmetry restoration. In this regime, the degeneracy of hadrons and their SU(2)-parity partners is predicted — a hallmark of restored chiral symmetry — which can be probed directly via dilepton measurements. Consequently, dilepton production is a major focus of ongoing and future experiments — including HADES, CBM, DiCE/NA60+, ALICE/ALICE3, and LHCb U2 — spanning facilities from SIS18 to the LHC.

To extract the continuum (or thermal) radiation emitted from the hot and dense interaction zone, contribution from late hadron decays and initial state radiation has to be carefully identified and subtracted. For the latter, contributing processes vary substantially when going from the highest collision energies available down to energies relevant for studying the high net-baryon density region of the QCD phase diagram. An important question in this context is the dilepton production by prompt antiquark-quark annihilation. While the Drell-Yan process (DY) is well understood at highest energies where scattering process can be described perturbatively with a precision mainly determined by the knowledge of the parton distribution function, the break down of that factorisation ansatz towards lower beam energies is not well understood. The exploration of the "low-energy" region will thus be essential to identify the transition between the two regimes, push perturbation theory to its limits and gain further insights into the hadron structure.

Pre-equilibrium annihilation processes (DY-like processes) pose a significant challenge to dilepton spectra at lower collision energies, as a perturbative treatment of such contributions is currently lacking. At the lowest beam energies, such contributions have been modeled based on hadronic degrees of freedom, as exemplified in the one-boson change model incorporating radiation from the internal line. Also at large collision energies DY production can be a limiting factor. For collision systems that produce only a small four-volume like for instance in collisions of light nuclei or protons, thermal radiation is moderate. Recently, these types of collision came into the focus of strong-interaction matter research in the light of intriguing observations analogue to those in large collision systems. Consequently, the isolation of thermal radiation hinges on the meticulous quantification of DY, or DY-like contributions.

Moreover, at higher energies and in the large dilepton mass region, the cross section and angular distributions of the DY process become susceptible to transverse momentum-dependent parton distribution functions. Despite the strong experimental and theoretical mastery of DY processes — particularly in the gauge boson mass region — the limits of applicability remain uncertain. Furthermore, the precision of perturbative calculations is not well established, even when incorporating resummation and parton showers in collinear factorization (which is the most advanced theoretical approach). To go beyond these limits, a concerted effort is required from both theory and experiment.

We will combine our expertise to address key theoretical and experimental challenges in the study of dilepton production.
On the **theory side**, we aim to: (i) **push perturbation theory to its limits** and identify the transition between perturbative and non-perturbative regimes; (ii) **understand the nature of non-perturbative DY-like processes** using dedicated non-perturbative methods; (iii) **compute differential observables** such as M_{ll}, p_{T} and polarization observables of DY and DY-like pairs across a wide energy range — from the LHC down to SPS and SIS energies.
On the **experimental side**, we will: (iv) **develop advanced analysis techniques** to isolate thermal radiation from non-equilibrium dilepton sources, apply these techniques to existing datasets from **HADES**, **ALICE**, and **LHCb**, and conduct feasibility studies for upcoming experiments at **CBM** and **DiCE/NA60+**.
A particular emphasis will be placed on photon polarization observables, which offer additional sensitivity to the production mechanisms. All studies will be performed for both proton-proton (pp) and proton-nucleus (pA) collisions.

The study of DY and DY-like processes is also intimately connected to a deeper question in QCD: the charm quark content of the proton, particularly in the valence quark region corresponding to Bjorken-x>0.1. This region remains largely unexplored with respect to charm contributions. A non-perturbative charm production contribution, known as intrinsic charm, was predicted in the early 1980s. While recent experimental results have hinted at its presence, conclusive evidence remains elusive. Low-energy nuclear collisions, particularly through the study of open charm hadrons ($\mathrm{D}/\bar{\mathrm{D}}$) and charmonium states such as J/ψ, provide an optimal testing ground for intrinsic charm. These signatures are expected to be especially sensitive near mid-rapidity, where model predictions suggest enhanced visibility of non-perturbative effects. Forthcoming high-statistics measurements at CBM and DiCE/NA60+, with detailed coverage in rapidity and p_{T}, could provide crucial tests of the importance of intrinsic charm.

2 Connection to Transnational Access infrastructures (TAs) and / or Virtual Access projects (VAs)

The **PRODY** project is strongly connected to planned and ongoing programs at the major TA facilities and infrastructures that host complementary experimental programs relevant to the physics proposed here: GSI/FAIR (CBM, HADES), CERN (DiCE/NA60+ (SPS), LHCb, ALICE (LHC), INFN and ECT* workshops related to the project.

3 Estimated budget request

The estimated budget covers 4 PhD students (matched by 50% from other funds), working group meetings at the participating institutions and the organization of the annual workshops at ECT*. The total cost for a funding period of 4 years amounts to 230k Euro (including 25% overhead).

4 Participating and partner institutions

Participating institutions: [1]Münster University, Germany (DY theory, ALICE, CBM); [2]Goethe University Frankfurt, Germany (ALICE, CBM, HADES); [3]INFN, Sezione di Torino, Turin, Italy (DiCE/NA60+); [4]CEA, France (theory DY); [5]Sezione INFN, Cagliari, Italy, Italy (DiCE/NA60+, theory DY/DY-like); [6]Gießen University, Germany (phenomenology pp); [7]Technical University of Darmstadt, Germany (CBM, HADES); [8]GSI, Germany (CBM, HADES); [9]CNRS, France (HADES, LHCb); [10]IFJ PAN, Poland (ALICE, phenomenology pp, pA, theory DY-like); [11]Jagiellonian Universiy Krakow, Poland (CBM, HADES, DY theory); [12]University of Florence, Italy (theory pp, pA).
Partner institutions: ALICE, CBM, DiCE/NA60+, HADES and LHCb collaboration institutions.