Frontiers in Neutrino, Cosmology and Astroparticle Physics

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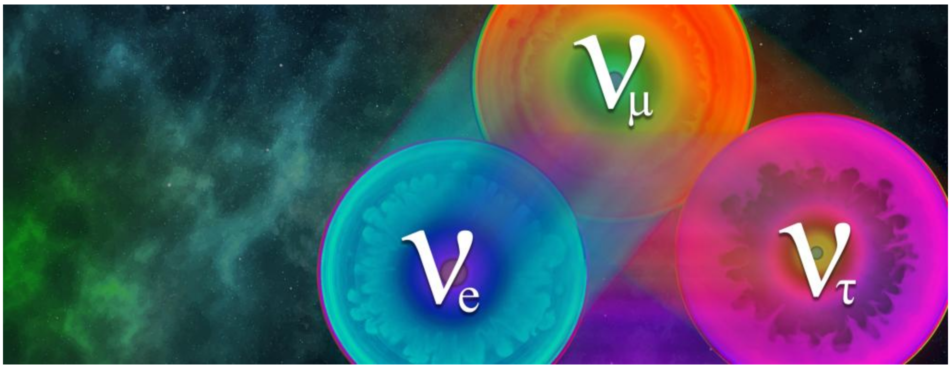

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Neutrino Texture Definitions and Phenomenology. Two case studies: S4-Motivated and Vanishing whole Trace.

Author: Elsayed Lashin[1]

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We draw attention to the role the unphysical phases play in the definition of a neutrino texture, and apply this to two textures: one defined by a vanishing whole trace, and one defined by one-equality and one-antiequality.

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Modular Symmetry, Extra Dimensions, and the Origin of Flavor

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This talk introduces a modular-symmetric approach to flavor, motivated by the geometry of extra dimensions. I focus on the modular A4 framework with three moduli, assigned separately to the lepton and quark sectors. At their fixed points, each modulus exhibits a residual symmetry that shapes the corresponding mass and mixing patterns.

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Transformers for particle colliders analyses

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The Transformer network, originally introduced for online language translation, has recently achieved remarkable success, particularly with the emergence of the GPT family. In this talk, I will explore how Transformer architectures can be adapted for analyses in particle colliders. At the core of Transformer models lies the attention mechanism. I will review various types of attention mechanisms, including self-attention, cross-attention, and sparse attention. Finally, I will discuss how different AI interpretability techniques can be applied to gain insight into the model decision-making process, effectively transforming machine learning from a "black box" into a more transparent "white box" system.

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Probing anomalous quartic gauge coupling via $WW\gamma$ using Machine Learning Algorithms

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We probe the anomalous quartic gauge coupling via $WW\gamma$ using Machine Learning transformer algorithms in SMEFT, and improve constraints on the effective field theory parameters.

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The 3+1 formalism in teleparallel theories of gravity

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We present recent advancements in the 3+1 formalism within two reformulations of general relativity: the teleparallel equivalent, and the symmetric teleparallel equivalents of general relativity. Both theories are based on the torsion and nonmetricity of a flat linear connection, respectively, and their Lagrangians are expressed in terms of the torsion scalar T and nonmetricity scalar Q. These scalars differ from the Ricci scalar R of general relativity by boundary terms. The bulk equations of motion in these theories are equivalent to those of Einstein's gravity; however, equations of motion that present a different gauge evolution for the lapse and shift can be obtained from integration by parts of the boundary term in the 3+1 Lagrangian or the Hamiltonian. We investigate the impact of these choices in Hamilton's equations, hyperbolicity properties, and their consequences in a numerical relativity framework.

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Dyonic-Taub-NUT-AdS: Thermodynamics and Phase-Transitions

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Taub-NUT spaces are one of the less understood spaces in General Relativity. Here we introduce consistent thermodynamics for these spaces, i.e., thermal quantities satisfy the first law, Gibbs-Duhem and Smarr's relations. Furthermore, we uncover the rich phase structures of these spacetimes for different horizon geometries, which could be spherical, flat, or hyperbolic. We work in extended thermodynamics to study the phase structure of the three horizon cases, in the mixed ensemble. These investigations revealed a different phase structure for the flat and hyperbolic cases in comparison with dyonic solutions with vanishing NUT charge and spherical horizon! In the latter case, a continuous phase transition occurs at high temperatures and pressures, i.e., above the critical point, but in the former cases, it occurs at low temperatures and pressures, i.e., below the critical point! Generically, the spherical case, with nonvanishing NUT charge, is characterized by two critical points with continuous phase transition between them.

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Explaining MiniBooNe and CDF II anomalies using scalars and the Inverse seesaw mechanism

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For decades, the Standard Model has provided an excellent explanation for many phenomenological observations; however, several mysteries remain, such as neutrino oscillations and the origin of neutrino mass. Additionally, there are significant tensions with experimental data, including the 7σ deviation in the W-boson mass reported by the CDF II experiment and the excess of electron-like events observed by the MiniBooNE experiment, which deviates by 4.8σ from Standard Model predictions.We extend the Standard Model with additional scalars and fermions to address these issues. Specifically, we expand the fermion sector by adding singlet fermions and right-handed neutrinos to implement the inverse seesaw mechanism. For the scalar sector, we introduce a hypercharge $Y = 2$ triplet scalar, a hypercharge $Y = 1$ neutral singlet scalar, and a hypercharge $Y = 4$ doubly charged singlet scalar. This specific combination is proposed to satisfy the aforementioned anomalies: the CP-even and CP-odd components of the triplet scalar are utilized to fit the MiniBooNE data, while the remaining scalar particles are employed to satisfy the CDF II constraints.

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Exact solutions of Finslerian versions of Einstein's field equations

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Finsler gravity is a modern extension of Einstein's General Relativity, using Finsler geometry (which generalizes Riemannian geometry) to describe spacetime, allowing for direction-dependent physics, potentially explaining phenomena like dark energy or dark matter, and offering new perspectives on cosmology by studying non-Riemannian "Finsler spacetimes" that still recover Einstein's theory

in specific limits, exploring modified gravity theories. Special famous Finsler metrics are (α, β)-metrics. Certain (α, β)-metrics that appear naturally as a spacetime geometry that is compatible with Lorentz symmetry breaking. These metrics, such as generalized m-Kropina metrics (see, [3]), have the potential to be useful in modified gravity and cosmology. As part of my research, I investigate the geometric properties of the generalized m-Kropina metrics, such as the conditions under which they become Einstein-type metrics. As a result, we are able to determine the circumstances under which a generalized m-Kropina metric F becomes an exact solution to either "Chen and Shen's Finslerian non-vacuum field equation" or "Pfeifer and Wohlfarth's vacuum field equation" (see, [1], [2]). Examples of generalized m-Kropina metrics in dimension 4 are presented here. These metrics have significant applications in modified gravity and cosmology. The main results of this talk is contained in [4].

[1] B. Chen and Y. B. Shen, On a class of critical Riemann-Finsler metrics, Publ. Math. Debrecen 72/3-4 (2008) 451-468.
[2] C. Pfeifer and M. N. R. Wohlfarth, Finsler geometric extension of Einstein gravity, Phys. Rev. D 85, 064009, 2012.
[3] C. Pfeifer, S. Heefer and A. Fuster, Identifying Berwald Finsler Geometries, Differential Geom. Appl. 79, 101817 (2021).
[4] Ebtsam H. Taha, "On the generalized m-Kropina metrics", arXiv:2510.22466 [math.DG].

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From kinetic gases to an accelerated expanding universe - The Finsler Friedmann equation

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The dynamics and the gravitational field of kinetic gases are usually described by the Einstein-Vlasov/Boltzmann equations. The evolution of the gas on phase space is encoded in the 1-particle distribution function (1PDF), while the Einstein equations determine the gravitational field of the kinetic gas from an energy momentum tensor that is obtained by averaging the 1PDF over all physical gas particle velocities (or momenta). Thus, the dynamics of the kinetic gas are described on phase space, but its gravitational field is derived on spacetime through an averaging procedure, which does not take all available information of the gas into account. The immediate questions is, how does the full 1PDF of a kinetic gas gravitate?

In this talk, I will discuss that Finsler gravity naturally elevates the geometry of spacetime to the same phase space footing as kinetic gas matter. It couples the full 1PDF to gravity without loosing information through averaging. In homogeneous and isotropic symmetry, the Finsler gravity equation takes a similar form as the Friedmann equations. Remarkably we find that this Finsler Friedmann equation possesses solutions describing an accelerated expanding universe without the need of a cosmological constant or any other additional quantities.

The talk is based on the article
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Modified Hybrid Inflation, Reheating and Stabilization of the Electroweak Vacuum

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We propose a modification to the standard hybrid inflation model, that connects a successful hybrid inflation scenario to the standard model higgs sector, via the electroweak vacuum stability. The proposed model results in an effective inflation potential of a hilltop-type, with both the trans-Planckian and sub-Planckian inflation regimes are consistent with the recent Planck/BICEP combined results. Reheating via the inflation sector decays to right-handed neutrinos is considered. We show that the couplings of the SM Higgs to the inflation sector can guarantee the electroweak vacuum stability up to Planck scale. The so-called hybrid Higgs-inflaton model leads to a positive correction for the Higgs quartic coupling at a threshold scale, which is shown to have a very significant effect in stabilizing the electroweak vacuum. We find that even with O(1) neutrino Yukawa couplings, threshold corrections leave the SM vacuum stability intact.

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Probing the Cosmic Expansion: Dark Energy in the Era of Recent BAO Observations

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The nature of Dark Energy remains one of the most profound mysteries in modern cosmology, acting as the primary driver behind the late-time accelerated expansion of the universe. This talk explores the current landscape of dark energy research in light of the latest Baryon Acoustic Oscillation (BAO) observations from premier surveys such as the Dark Energy Spectroscopic Instrument (DESI). We will examine how these "standard rulers" provide high-precision measurements of the Hubble parameter $H(z)$ and the angular diameter distance $d_A(z)$, allowing us to map the expansion history of the cosmos with unprecedented accuracy.

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New Path Equations in Einstein Non-symmetric Geometry

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Adopting Bazanski approach, two new classes of path equations are derived in Einstein non-symmetric geometry. The first class is the path equations of a test particle moving in a gravitational field, while the second class represents path equations of charged particles. The path equations of charged particles give rise to Lorentz force. Moreover, these path equations may represent an interpretation of some interactions between torsion and electromagnetic potential even if the electromagnetic force vanishes. It is to be noted that the above two classes of paths are formulated in terms of Einstein non-symmetric connection. An explicit formula of such a connection, satisfying the Einstein metricity condition, is obtained by localizing the global formula given recently by Ivanov-Zlatanovi{\'c}.

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Extended Thermodynamics and Phase Structure of Charged Rotating Black Holes with Chern-Simons Coupling

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Higher-dimensional gravity is not just an extension of Einstein's theory, and the physics of higher-dimensional black holes is not only richer, but also different from that in 4-dimensions.
In this work, we investigate the extended thermodynamics of charged, rotating black holes with equal angular momenta in five-dimensional anti-de Sitter spacetime within the framework of Chern-Simons gravity. We establish a consistent thermodynamic description by rigorously demonstrating the verification of both the first law and the Smarr's relation. Our results affirm the robustness of the formalism in this setting and reveal unique features, such as a non-trivial dependence of the total energy and angular momenta on the electric charge. This dependence provides a concrete illustration of how higher-dimensional black hole physics can differ qualitatively from its four-dimensional counterpart.

1

Primordial gravitational waves in generalized Palatini gravity

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Extended Palatini gravity is the metric-affine gravity theory characterized by zero torsion, nonzero metricity and a quadratic of the antisymmetric Ricci curvature. It reduces dynamically to general relativity plus a geometric Proca field. In this work, we study imprints of the geometric Proca field on the gravitational waves. Our results show that the geometric Proca leaves significant signatures in the gravitational wave signal, and gravitational wave energy density could be large enough to be detectable by the next upgrade of the existing GW detectors. Our results, if confirmed observationally, will be an indication that the gravity could be non-Riemannian in nature.
https://doi.org/10.1016/j.dark.2023.101336

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Novel Source of Gravitational Waves from First-order Phase Transition from Right-handed Neutrino Production

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We discuss a new source of gravitational waves (GWs) from first-order phase transitions arising from particle production from the walls of bubble walls, which inevitably modifies the standard GW spectrum produced from bubble walls collisions hitherto known. The new characteristic feature of the GW spectral shape entails a change of slope in frequency, which could be detected at GW detectors like LISA or SKA at low frequencies. We show that this opens the numerous and intriguing possibilities to probe beyond the standard model scenarios, involving heavy particles which can be produced in such a manner, including heavy Right-handed neutrinos, involving high scales of seesaw and leptogenesis. We will also show the impact on the analysis in dark matter formation and axion physics.

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Stochastic Gravitational Wave Background and the Secrets of the Early Universe

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Gravitational waves offer a powerful probe of the early universe, providing insights into its dynamics and fundamental physics. This talk will explore the stochastic gravitational wave background (SGWB) and its potential origins, including signals detected in the NANOGrav 15-year dataset. I will discuss how hybrid inflation can generate topological defects, such as cosmic strings, and contribute to the SGWB, highlighting model-building approaches that link theory to observation. This talk aims to bridge theoretical insights with observational data.

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Machine Learning for Future Gravitational-Wave Observatories

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Future gravitational-wave observatories will operate in a regime of unprecedented sensitivity, long-duration signals, and complex environmental noise. In this talk, I will discuss recent developments in applying machine learning to gravitational-wave data analysis, with a focus on deep-learning models for signal detection, the separation and reconstruction of overlapping long-duration signals, and data-driven waveform generation. I will also highlight the role of machine learning in characterizing and mitigating seismic and environmental noise, particularly in the context of next-generation detectors such as the Einstein Telescope.

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From High-Energy Physics to Frontier Biophysics: AI-Driven Methods Across Scientific Domains

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Accurate background modeling and signal extraction are central challenges in modern neutrino, cosmology, and astroparticle physics experiments, which operate on large and complex datasets. In this talk, I present recent applications of artificial intelligence to background estimation in high-energy physics, with a focus on machine-learning–based methods developed within the CMS experiment. These approaches enable robust, data-driven modeling of complex backgrounds and enhance sensitivity to rare processes.

I further demonstrate how similar AI methodologies can be transferred to frontier problems in biophysics and drug discovery, where challenges such as high-dimensional data, limited labeled samples, and the need for physical interpretability closely parallel those encountered in astroparticle physics. In particular, I discuss AI-based techniques for computing induced molecular polarizability relevant to drug repurposing, as well as the use of graph neural networks for predicting drug–target activity.

This work illustrates how AI techniques developed for particle physics can be repurposed across scientific domains, highlighting artificial intelligence as a unifying framework for research at the frontiers of fundamental physics and biophysics.

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Search for new physics in CMS open data and future colliders

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Abstract: We examine the angular distribution of both low and high-mass dimuon pairs using the open data from CMS, and with simulated electron-positron collisions from the proposed International Linear Collider (ILC). This collider operates at a center-of-mass energy of 500 GeV and is designed with an integrated luminosity of 4 ab(^{-1}). Our main focus revolves around the cos(\theta_{\text{CS}}) variable, which is defined in the Collins-Soper frame. In the Standard Model, the production of dimuon pairs primarily occurs through the Drell-Yan process, which displays a notable forward-backward asymmetry. However, alternative scenarios extending beyond the Standard Model propose different shapes for the cos(\theta_{\text{CS}}) distribution. This angular distribution has substantial potential to distinguish among these various models, especially if we detect any excesses that exceed the predictions of the Standard Model.

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The upgrade of the CMS muon system for the High Luminosity LHC

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The current CMS muon system employs a combination of detector technologies, each optimized for specific regions. Drift Tubes (DT) and Resistive Plate Chambers (RPC) are deployed in the barrel,

while the endcap utilize cathode strip chambers (CSC) and RPC. To address the anticipated higher background rates in the endcap, new detector stations will be installed. These stations will utilize triple gas electron multiplier (GEM) and improved resistive plate chambers (iRPC) technologies, offering enhanced time and spatial resolution and improved rate capability. The GE1/1 station, based on GEM technology, was installed in the endcap region during LS2, covering the pseudorapidity range $1.55 < |\eta| < 2.18$. Two additional GEM stations, GE2/1 and ME0, are planned for future installation to further enhance muon reconstruction in the endcap and extend the muon system's coverage up to $|\eta|$ 2.8. This presentation will present an overview of the new triple-GEM (GE2/1, ME0) and iRPC (RE3/1, RE4/1) detector stations that will be installed before Long Shutdown 3.

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Exploring Z' and Right-Handed Neutrinos in the BLSM at the Large Hadron Collider use machine learning

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We study the collider phenomenology of the B-L extension of the Standard Model (BLSM), focusing on the production and decay of a heavy neutral gauge boson (\(Z' \)) at the Large Hadron Collider (LHC). In this framework, the \(Z' \) can decay into pairs of heavy right-handed neutrinos (\(\nu_R \)), which subsequently decay into charged leptons and \(W \) bosons. These processes give rise to three distinctive final states: (i) two leptons plus four jets (\(2\ell + 4j \)), (ii) four leptons plus missing transverse energy (\(4\ell + \text{MET} \)), and (iii) three leptons plus two jets and MET (\(3\ell + 2j + \text{MET} \)).
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To enhance signal sensitivity and suppress Standard Model backgrounds, we employ multivariate analysis techniques based on Boosted Decision Trees (BDTs), as well as selection optimizations using the \texttt{XGBOOST} framework. The classifiers are trained on kinematic observables sensitive to the masses of the \(Z' \) and \(\nu_R \). We demonstrate that all three final states offer significant discovery potential for both the \(Z' \) and heavy \(\nu_R \) at the High-Luminosity LHC. Our results highlight the testability of the BLSM at current and future collider experiments, and provide a promising avenue for probing the origin of neutrino masses and the baryon asymmetry of the Universe.

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Closing

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