INSTITUTE FOR PARTICLE PHYSICS PHENOMENOLOGY

NEWSLETTER
MARCH 2025

WELCOME TO THE IPPP!

As we welcome the longer days and renewed energy of spring, we are delighted to bring you the latest edition of the Institute for Particle Physics Phenomenology's biannual newsletter. This year is particularly special, as 2025 marks the 25th anniversary of the IPPP—a milestone that highlights a quarter-century of pioneering research, collaboration, and impact in the field of theoretical and phenomenological particle physics.

In this issue, we showcase some of the exciting work taking place within our community, from research highlights and recent publications to reports on workshops and major events. We also look ahead to upcoming conferences, including the celebration of our 25-year journey this autumn. Our partnerships continue to thrive, as seen in the recent visit to CERN by Durham University leadership, strengthening our ties with the global physics community.

We extend our heartfelt thanks to all who contributed to this edition and to everyone who continues to make the IPPP a vibrant hub of discovery and innovation. Whether you are a long-time colleague or new to our network, we hope this newsletter informs and inspires you.

Enjoy the read, and we look forward to celebrating this landmark year together!

ANNOUNCEMENTS

1. The IPPP is pleased to announce the following workshops:

- Dark Matter Beyond the Weak Scale III, which will take place April 7-10 at the University of Oxford. ***https://conference.ippp.dur.ac.uk/event/1458/***
- The SM@LHC Workshop will take place April 7-10 at the IPPP in Durham. ***https://conference.ippp.dur.ac.uk/event/1429/***
- New nu Physics: from Colliders to Cosmology, which will take place 9-11 April at the IPPP in Durham. ***https://conference.ippp.dur.ac.uk/event/1377/***
- PASCOS 2025, the 30th International Symposium on Particles, Strings and Cosmology, will take place on July 21-25, 2025 in Durham. ***https://conference.ippp.dur.ac.uk/event/1371/***
- Last but not least, the IPPP's 25th jubilee event is planned on September 24 and 25. ***https://conference.ippp.dur.ac.uk/event/1454/***

2. The Associateship, Durham IPPP Visiting Award, and Senior Experimental Fellowship programmes are continuing. We encourage applications for all three schemes and invite you to consult the following web pages for application deadlines:
IPPP Associateship: ***https://www.ippp.dur.ac.uk/ippp-associateships***
DIVA: ***https://www.ippp.dur.ac.uk/diva***
Senior Exp. Fellowship: ***https://www.ippp.dur.ac.uk/senior-experimental-fellowships***
Our next intake will be in September 2025.

3. We encourage organisers of workshops related to HEP theory to reach out for support. The IPPP can help organise workshops in the UK, administratively and financially.

DURHAM UNIVERSITY AT CERN

To mark 25 years of the IPPP, Durham University's Vice-Chancellor Karen O'Brien and Pro Vice-Chancellor (Research) Colin Bain were invited to visit CERN. They were accompanied by IPPP director Michael Spannowsky, deputy director Jeppe Rosenkrantz Andersen, and staff members Jessica Turner and Djuna Croon.

They had the opportunity to tour CERN's world-leading facilities, including:

- The Synchrocyclotron – CERN's very first particle accelerator
- The superconducting magnet assembly hall
- The data centre
- The ATLAS detector
- A section of the LHC tunnel at ALICE
- The central control room

During the visit, the group engaged in a round-table discussion where both the experimental and theory communities at CERN spoke highly of their collaboration with the IPPP.

We would like to thank CERN for their warm hospitality, and hope this visit strengthens our partnership and further supports the joint venture between STFC and Durham University in advancing the IPPP. May we have many more years of collaboration!

NEW POSTDOCS

ARTURO DI GIORGI

Joined the IPPP neutrino group last October after completing his PhD in Spain at the Autonomous University of Madrid and the Institute of Theoretical Physics (UAM/IFT). His research focuses on particle physics beyond the Standard Model, exploring topics such as extra dimensions, axions, heavy sterile neutrinos, and dark matter. At Durham, he will continue this path, with a special focus on how neutrino physics can constrain such new physics scenarios.

AJJATH ABDUL HAMEED

Completed her PhD at IMSc, Chennai, India, and then spent three years as a postdoc at LPTHE (CNRS), Paris, before joining IPPP. Her research focuses on precision theoretical calculations relevant to high-energy particle collider experiments.

Specifically, she works on techniques required in multi-loop, multi-leg calculations within perturbative gauge theories. Such precise theoretical predictions are crucial for refining our understanding of the Standard Model and identifying potential deviations that could hint at new physics. Her interests include higher-order corrections in QCD and Electroweak theory, infrared subtraction methods, and resummation techniques.

KAJAL SAMANTA

Completed his PhD at IIT Guwahati, India. Before joining IPPP, he was working as a postdoc at Fudan University, Shanghai, China and a visiting research fellow at UCLA, USA. He is working on theoretical high energy physics and Collider phenomenology at different colliders, namely at the LHC, BELLE, BABAR, COMPASS, HERMES, EIC, etc.

His research focuses on higher-order perturbative QCD computation and precision physics, Soft Collinear Effective Theory (SCET) and hadron physics. It includes the computation of the soft-virtual corrections, different resummation techniques, transverse momentum-dependent distribution functions, namely PDF and FF and their phenomenology to understand the hadron structure.

WORKSHOP REPORT "BEAUTIFUL AND CHARMING BARYON WORKSHOP"

In September 2024, the IPPP hosted 12 researchers from experiment and theory for an in-person topical workshop on the phenomenology of flavoured baryons, with further researchers listening in via Zoom. The topics covered were wide ranging and focused on four topics.

The main topic was progress in the predictions and measurements of the charged- and neutral-current decays of Lambda baryons. Members of the LHCb, CMS, and BESIII collaborations provided overviews of ongoing and upcoming measurement at their respective experiments, while lattice QCD researchers discussed their efforts in sharpening the theory predictions. Highlights were discussions of lepton-flavour universality probes and angular analyses, which have the potential to corroborate the ongoing anomalies in the decays of flavoured mesons.

Further topics of interest included measurements of baryon lifetimes and their respective theory predictions as well as the theoretical description of the baryon spectrum. The latter was highlighted to be a crucial input to ongoing LHCb measurements due to the entanglement of a large number of baryon states above the first threshold.

Finally, the workshop participants discussed how to better constrain the production cross sections for flavoured-baryon production at the LHC and other colliders. This edition of the workshop was organised by Yasmine Amhis (IJCLab, France), Thomas Blake (Warwick U) and Danny van Dyk (IPPP), following a similar workshop in early 2020 that was conducted purely virtually due to the coronavirus lockdown. The organisers hope that it will not take another four years for the next edition to materialise.

ANNUAL THEORY MEETING 2024

The 57th Annual Theory Meeting took place from 16–18 December 2024, hosted at Durham University by the Centre for Particle Theory, UKLFT, FPUK, and the IPPP. Over three days, leading experts gathered to present and discuss cutting-edge developments across a wide range of topics in theoretical physics. The meeting provided an opportunity for researchers to engage with the latest advances, exchange ideas, and explore new directions in the field.

The first day opened with a discussion on the future of the High Luminosity Large Hadron Collider by Sinead Farrington (Edinburgh), setting the stage for reflections on upcoming experimental challenges. Katy Clough (King's College London) followed with an exploration of numerical relativity and its role in fundamental physics. Later sessions ventured into formal aspects of theoretical physics, with Eric Perlmutter highlighting connections between random matrix theory and 2D conformal field theory, and Roberto Emparan presenting new insights into the microstates of black holes.

On the second day, the meeting broadened its scope to the intersection of nuclear and particle theory. David Ireland provided an overview of the UK's nuclear physics programme, followed by Felix Ringer, who outlined key areas where nuclear and particle theory can inform one another. Theoretical models of dark matter took centre stage with David Marsh's talk on axion phenomenology, while Christopher White presented the double copy theory and its implications for understanding gauge and gravity theories. The day concluded with discussions on quantum mechanics at colliders, with Herbi Dreiner assessing locality via Bell's inequality and entanglement, and Tilman Plehn reflecting on the growing role of machine learning in theoretical physics.

The final day turned to broader structural and strategic discussions within the community. Claudia de Rham examined gravity from an effective field theory perspective, offering insights into its role in cosmology and beyond. A session dedicated to the Particle Physics Advisory Panel (PPAP) provided an overview of its ongoing efforts in shaping UK research priorities, before the meeting concluded with a town hall discussion led by Grahame Blair and Karen Clifford from the STFC, who outlined the council's vision for future funding and projects.

Beyond the rich programme of talks, the Annual Theory Meeting once again served as an invaluable opportunity for researchers to reconnect, discuss their work in an informal setting, and foster new collaborations. As the field continues to evolve, the ATM remains a key moment in the UK's theoretical physics calendar, and we look forward to its next edition in 2025.

HIGGS MAXWELL MEETING 2025

On 19th of February, the Royal Society of Edinburgh hosted the annual Higgs-Maxwell Workshop, bringing together particle physicists from Durham, Edinburgh, Glasgow, and Lancaster to discuss machine learning and the future of particle physics, in celebration of the most recent Nobel Prize in physics.

The workshop began with a podium discussion on the future strategy for collider physics, with Aidan Robson (University of Glasgow) and Guy Wilkinson (University of Oxford) giving an overview of future linear and circular colliders, respectively. They explored the anticipated timelines and luminosity goals for electron-positron colliders and emphasised the potential of these future colliders to enhance precision measurements of the Higgs boson. The floor was then opened to attendees to quiz Aidan and Guy on the different technologies, with a focus on questions from early career researchers.

The podium session was followed by a talk from Miguel Crispim Romão (IPPP, Durham University) on "Machine Learning in Search for New Physics." He discussed the application of artificial intelligence and machine learning techniques in model-independent searches, anomaly detection methods, and the exploration of complex beyond the Standard Model parameter spaces. Romão also highlighted the use of machine learning in detecting exotic dark matter candidates, such as boson stars, through micro-lensing events.

After lunch, Giuseppe Callea (University of Glasgow) gave a talk on “Machine Learning Applications to Higgs Analyses in ATLAS”, in which Giuseppe showcased how the ATLAS collaboration at CERN employs advanced machine learning methods to improve particle reconstruction and data analysis, leading to significant background rejection and precise testing of the properties of the Higgs boson.

Gurtej Kanwar (University of Edinburgh) followed and discussed “Machine Learning for Lattice Gauge Theories”. The talk highlighted the challenges in lattice field theory simulations and introduced emerging ideas for applying machine learning methods to accelerate computations, such as normalising flow methods. Gurtej explained how harnessing such methods has the potential to allow for more efficient and accurate lattice QCD calculations.

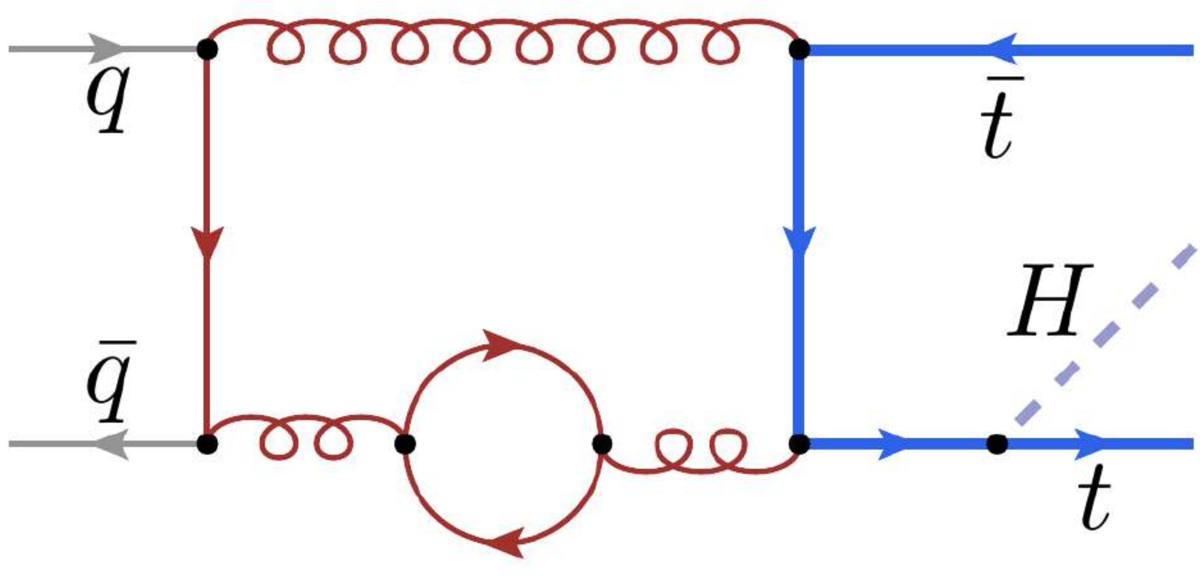
The workshop concluded with a talk from Christos Leonidopoulos (University of Edinburgh) on "ML/AI Applications in Experimental Particle Physics”. Christos explored the integral role of machine learning and artificial intelligence in advancing experimental techniques and enhancing data analysis within particle physics, particularly in handling complex datasets and improving real-time data processing during experiments.

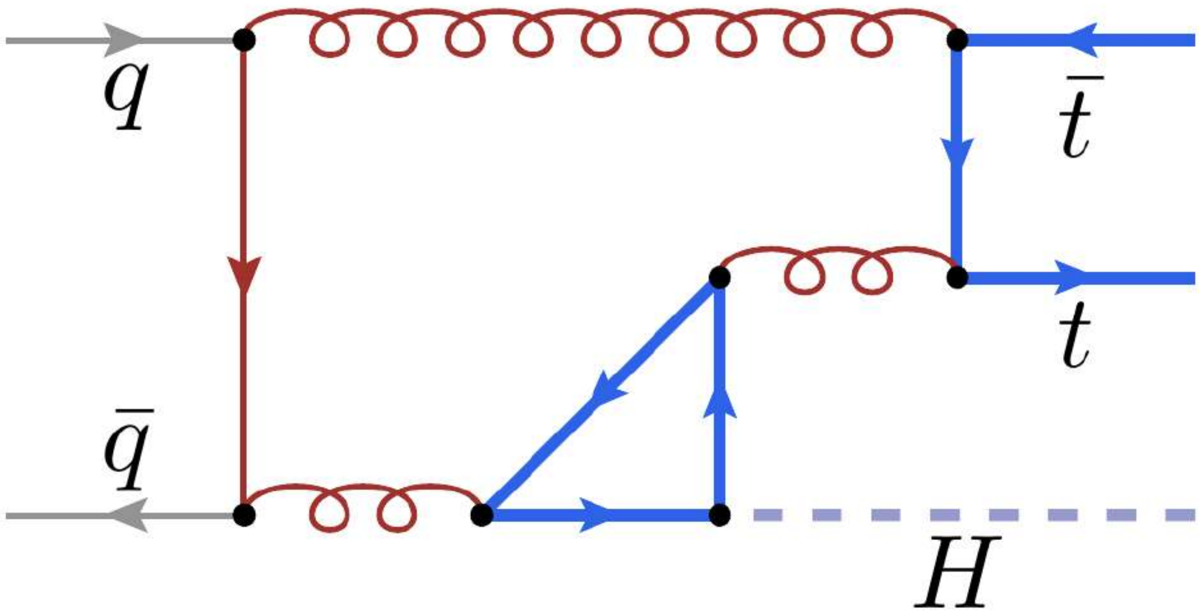
Overall, the Higgs-Maxwell Workshop 2025 provided a platform for fruitful discussions on current research and future directions in particle physics, fostering collaborations among physicists from various institutions.

CUTTING-EDGE SCATTERING AMPLITUDES FOR $t\bar{t}H$ PRODUCTION

Higgs boson production in association with a top-quark pair was observed for the first time in 2018 at the Large Hadron Collider (LHC). The process is particularly interesting because of its direct sensitivity to the top-quark Yukawa coupling, the largest of the Higgs couplings, and its potential to constrain CP-violation of the coupling.

Current projections indicate that the statistical uncertainty on the process will shrink to the order of 2- 3% at the high luminosity (HL) LHC, leaving a systematically dominated measurement. The dominant systematic uncertainties come from the modelling of the signal and background. With next-to-leading order QCD scale uncertainties at the level of 10- 15%, next-to-next-to-leading (NNLO) QCD corrections are critically needed to match the experimental precision in HL-LHC.



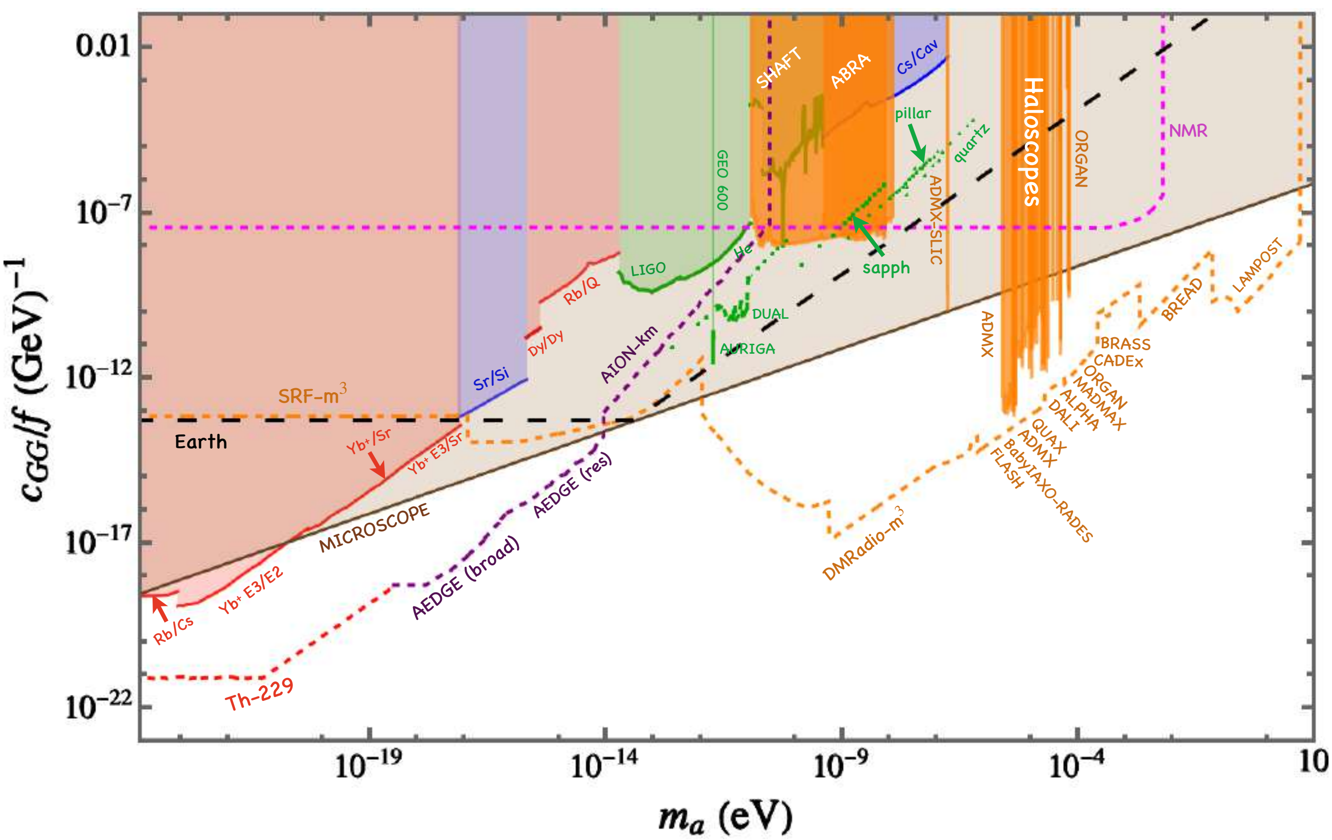


In arXiv:2402.03301, researchers at Aachen, Durham and Karlsruhe, including Anton Olsson who will start at the IPPP as a PDRA in December and our own Stephen Jones, presented numerical results for the two-loop virtual amplitude entering the NNLO corrections to $t\bar{t}H$ production containing loops of massless or massive quarks. The work serves as a proof of concept for a method relying on numerical reduction combined with the numerical computation of Feynman integrals to obtain amplitudes with high precision, even when the complexity of the calculation is such that obtaining a fully symbolic result is intractable.

In ongoing work, further refinements of the method are being used to obtain the remaining $t\bar{t}H$ amplitudes and build an interpolation framework for efficient distribution of amplitudes with high multiplicity final states.

DETECTING AXION-LIKE PARTICLES WITH QUANTUM SENSORS

Many experimental strategies aimed at discovering dark matter primarily target candidates with substantial masses, typically ranging from 10 to 1000 times that of a proton. However, challenges arise when considering dark matter that is considerably lighter. In direct detection experiments, if the mass of dark matter particles is below the GeV scale, the momentum they transfer is often insufficient to surpass the recoil threshold necessary for detection. Similarly, any potential annihilation signals from light dark matter with masses below the kilo-electronvolt (keV) scale would produce soft X-rays or an even softer spectrum This poses significant difficulties in distinguishing genuine dark matter signals in indirect detection from the pervasive background in the X-ray and optical spectrum.



Comparison of the sensitivity reach of different experiments searching for the effects of axion-like particle dark matter as a function of its interaction with gluons and its mass [1].

Very light dark matter has several attractive properties. Simulations have shown that dark matter with masses well below an eV can produce a broader core in dark matter haloes than heavy dark matter candidates, which agrees with observations. Very light dark matter also predicts fewer small scale structures than heavy dark matter. It could explain why we observe fewer dwarf galaxies than expected. These discrepancies might stem from limitations in the simulations, or intriguingly, they could also suggest that dark matter is composed of much lighter particles than previously thought.

Since established experimental search strategies are limited when it comes to very small dark matter masses, the emergence of extremely precise quantum sensors has revolutionised this field. Atomic clocks, Laser and atom interferometers as well as resonant cavity experiments have significantly improved their sensitivity in the last decade and can now probe a parameter space that was previously been far out of reach. Future breakthroughs such as a nuclear clock taking advantage of the ultra-narrow transition in Thorium-229 and a large scale atom interferometer will allow for unprecedented tests of effects from very light dark matter.

One of the leading candidates for very light particles are axion-like particles that appear in more fundamental theories than the Standard Model when global symmetries are spontaneously broken. Guillaume Rostagni, Sreemanti Chakraborti and Martin Bauer calculated the interaction strengths of axion-like particles at low energy scales where these experiments are performed. In a comprehensive paper, the linear and quadratic couplings of axion-like particles to nucleons, electrons and photons are calculated and used as an input to derive the sensitivity of current and future quantum sensors experiments [1]. The results can be used to compare the reach of different experiments and decide on the best approach to search for axion-like particles with any combination of couplings to Standard Model particles. The distinctions between axion-like particles as dark matter candidates and scenarios where they do not contribute to dark matter are thoroughly explored.

In addition, this research introduces innovative strategies for detecting axion-like dark matter, specifically by investigating the presence of fifth forces that emerge from the exchange of axion pairs [2]. Additionally, quadratic interactions facilitate the absorption of axion pairs in haloscopes and helioscopes, potentially greatly enhancing the sensitivity of these experiments. A key finding of this work is the nuanced behaviour of the axion field value, which can lead to localised regions where interactions with axion-like particles become non-perturbative, indicating a significant deviation from the vacuum field value [3].

References:

[1] https://arxiv.org/abs/2408.06412
[2] https://arxiv.org/abs/2307.09516 (Phys.Rev.Lett. 132 (2024) 10, 101802)
[3] https://arxiv.org/abs/2408.06408