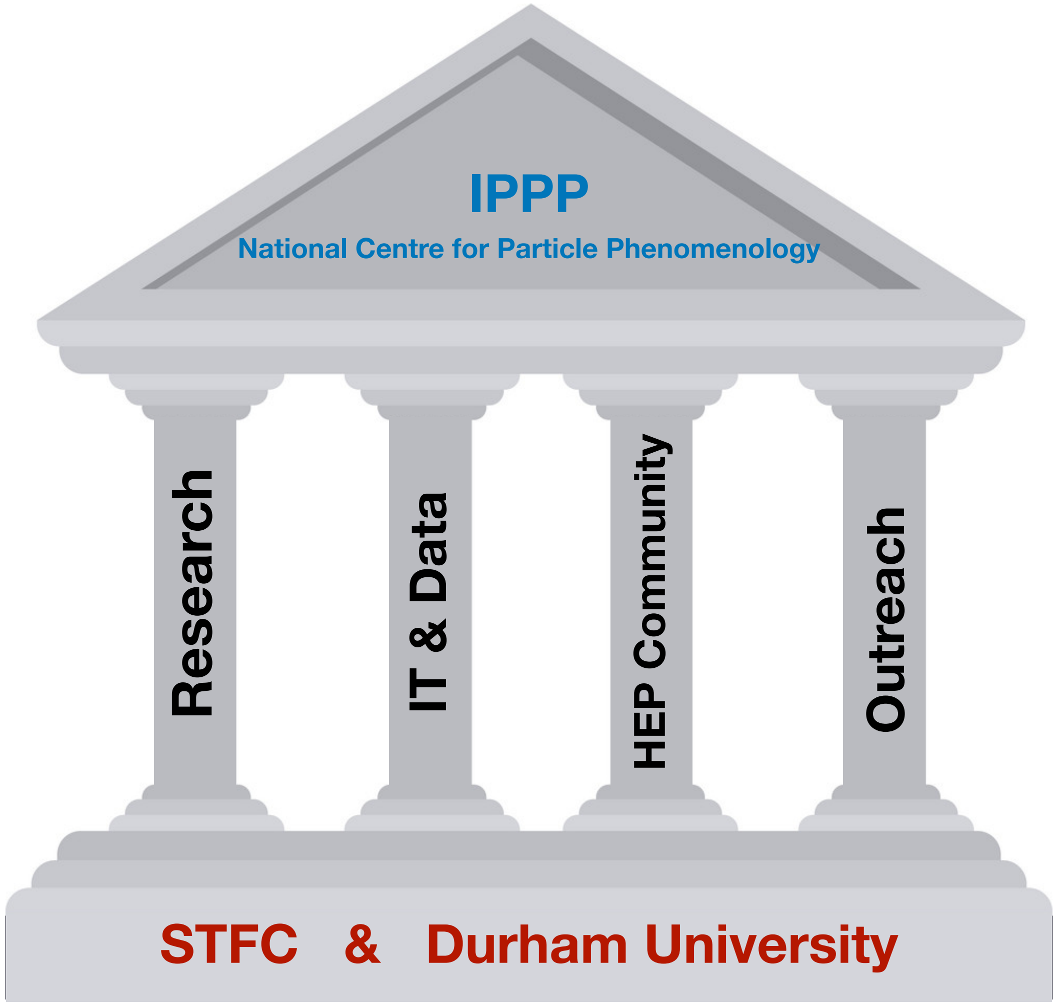
Institute for Particle Physics Phenomenology (IPPP)

— UK’s national centre for particle phenomnology —

Michael Spannowsky
IPPP Durham

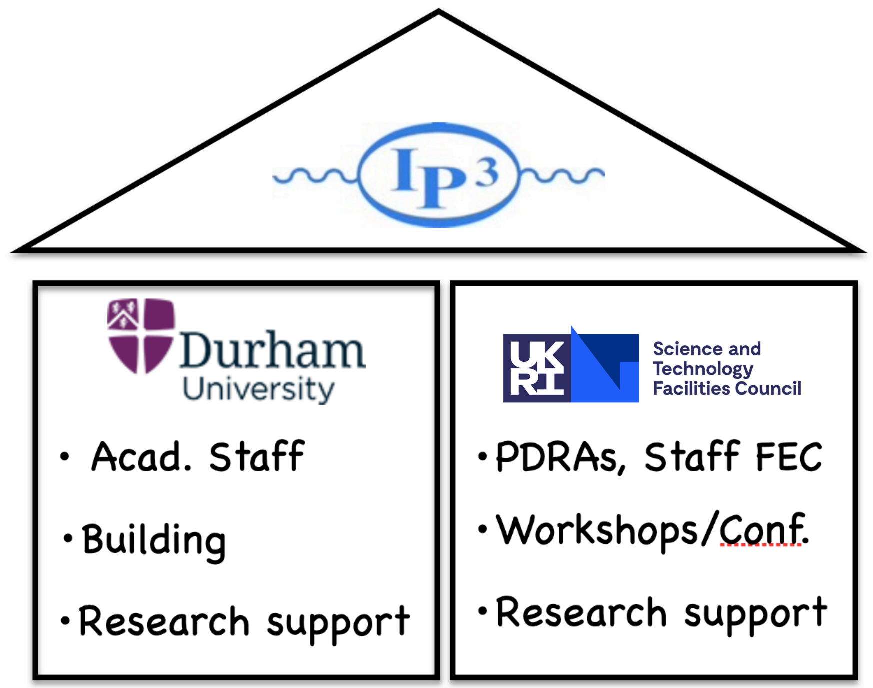
Historical overview

- IPPP was founded in 2000 as a consequence of a PPAC call
- Rutherford Lab Theory group replaced by the Durham University hosted Particle Physics group
- IPPP takes on responsibilities of a national centre
- Grew from a handful of members to over 90 (in 2016). Currently, 70-80 group members



Structural overview

The Institute for Particle Physics Phenomenology (IPPP) in Durham is UK's National Centre for Particle Phenomenology



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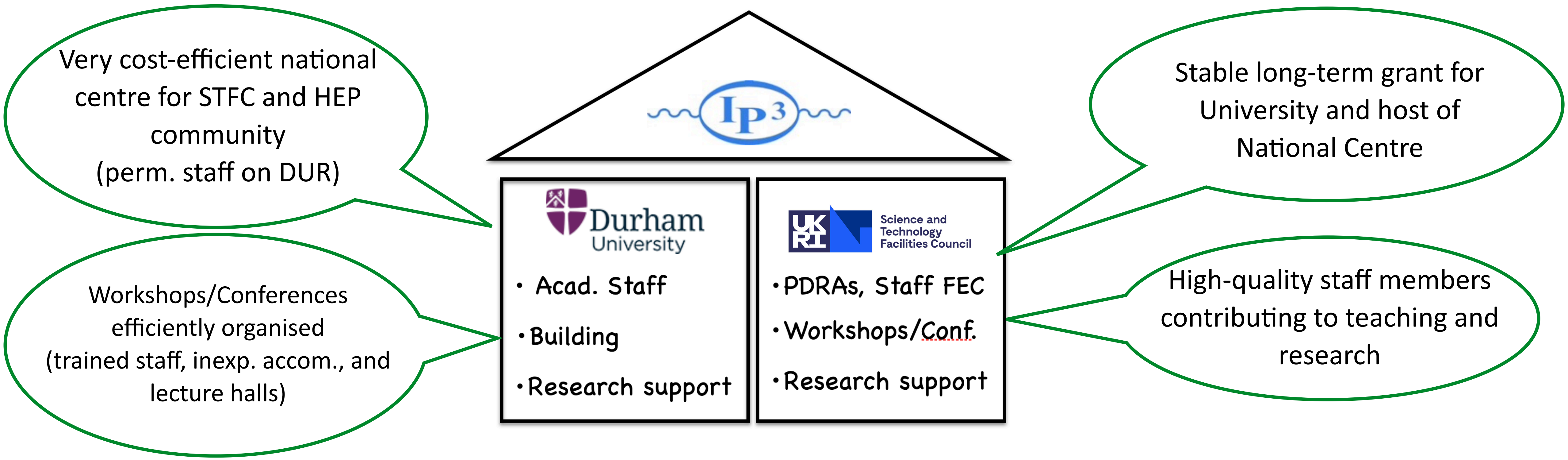


Perm. staff needs to deliver on University objectives (teaching, admin., research)

- 40 (R) / 40 (T) / 20 (C)
- Staff academics, i.e. free in research etc

Perm. staff has obligation to deliver on all objectives of national centre

- workshops/conf/schools
- Engage with (Sen)Assoc/DIVA
- Support all STFC-funded research

Structure of IPPP

Steering Committee

Computing Advisory Board

University Research Institute Committee

HEPData

J. Byers and G. Watt

- Data management plan of most HEP experiments
- Data conservation for posterity
- Collaboration with INSPIRE, NNDC etc

Computing

A. Boucher, P. Clark and P. O'Connor

- Tier-2 PhenoGRID, WLCG
- Heterogenious Computing
- Com, Support, HEPForge
- IT Security

19 Research Groups across **10 research areas**

Precision Phenomenology	**Glover, Jones, Maitre**
Event Generator Development	**Krauss, Richardson**
Electroweak Physics	**Pecjak, Schoenherr**
Flavour Physics	**Schacht, van Dyk**
Collider Phenomenology	**Spannowsky**
Low-energy Phenomenology	**Bauer**
Astroparticle physics	**Chadha-Day, Croon**
Neutrino Physics	**Soler-Martinez, Turner**
Non-perturbative Physics	**Khoze**
Physics Beyond the Standard Model	**Abel, Alonso**

Outreach

L. Coghill and F. Sergio

- School initiatives
- Science Fairs and Open Days
- Social Media Engagement
- EDI seminars and meetings

IT/Data Management

- Development and maintenance of HEPData
- Provision and maintenance of high-performance and grid computing infrastructure
- IT safety, reliability and complex operations (CPU/GPU/Grid/web development)

HEP Community support

- Organisation of workshops, conferences and schools
- Awarding of and engagement with Diva Fellowships, Associateships and Senior Experimental Fellowships
- Provision of guidance and strategic outlook

Research

- Conduct world-leading research in particle physics phenomenology
- Support particle physics experimental collaborations
- Support and collaborate with UK-based researcher and research groups

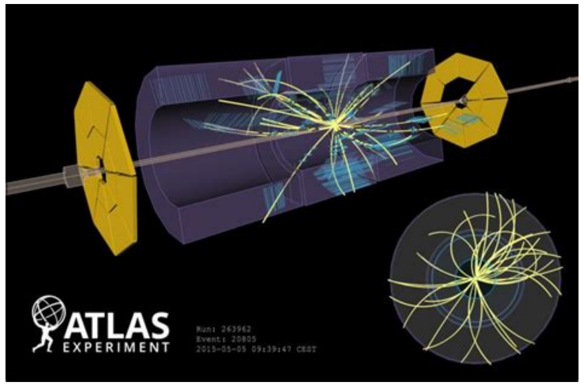
Outreach

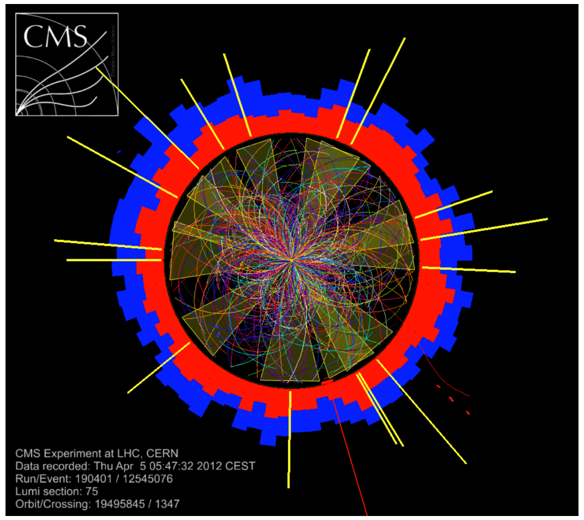
- Organise and initiate outreach activities (Master Class, Science Fairs, Saturday Morning Physics, Royal Society events etc.)
- Provide a platform for UK-based HEP groups to help improving and coordinating their outreach activities (workshops, tech support)

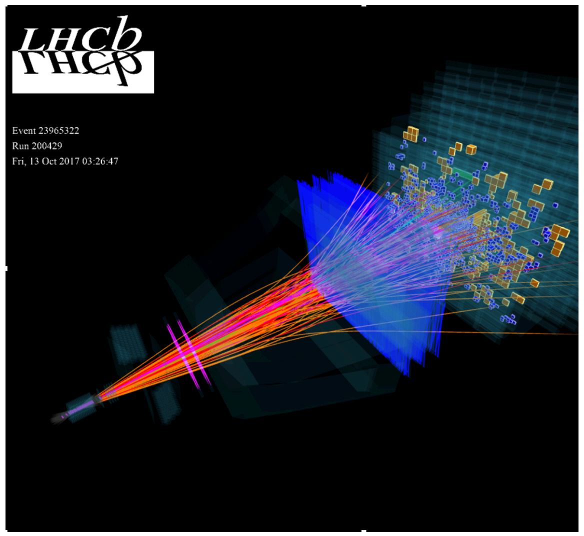
Objective of IPPP is to deliver on those four pillars

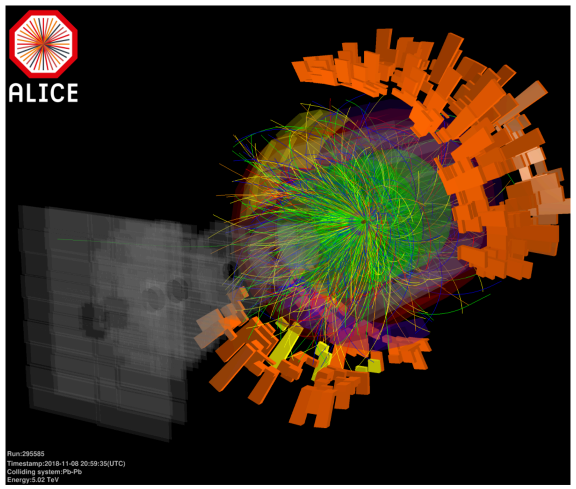
What is HEPData ?

- Unique *open-access* repository for scattering **data** from more than 9000 experimental **HEP** (“hep-ex”) papers.
- Publication-related data complementary to event-level data provided through recent CERN Open Data portal.
- Traditional focus on unfolded measurements, but in recent years also include material for *recasting* LHC **searches**.
- Based in **I**nstitute for **P**article **P**hysics **P**henomenology (**IPPP**) at Durham University (UK), going back to 1970s.
- Funded by UK **S**cience & **T**echnology **F**acilities **C**ouncil (**STFC**), with current grant until 09/2026.

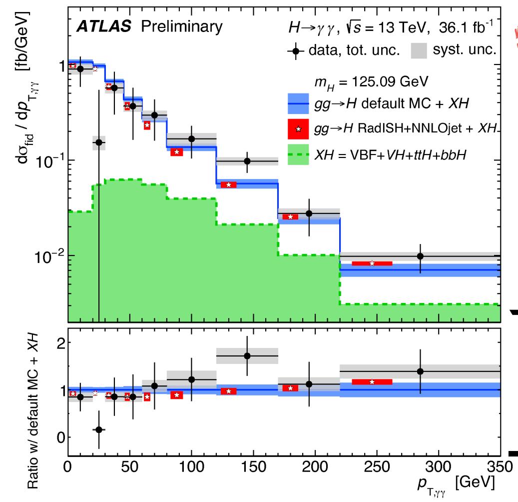


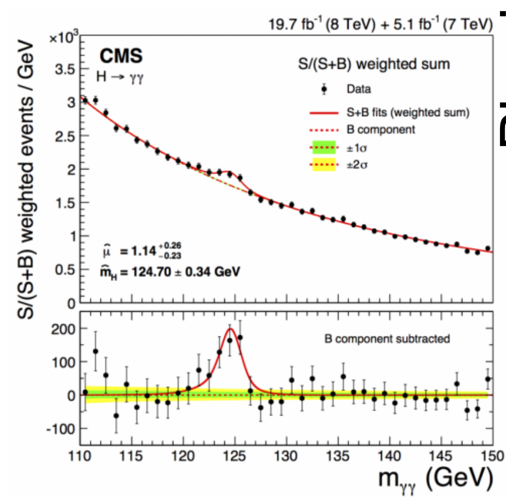






Reconstruction of final states by experiments





Physics relevant information, pictures to numbers

HEP Data

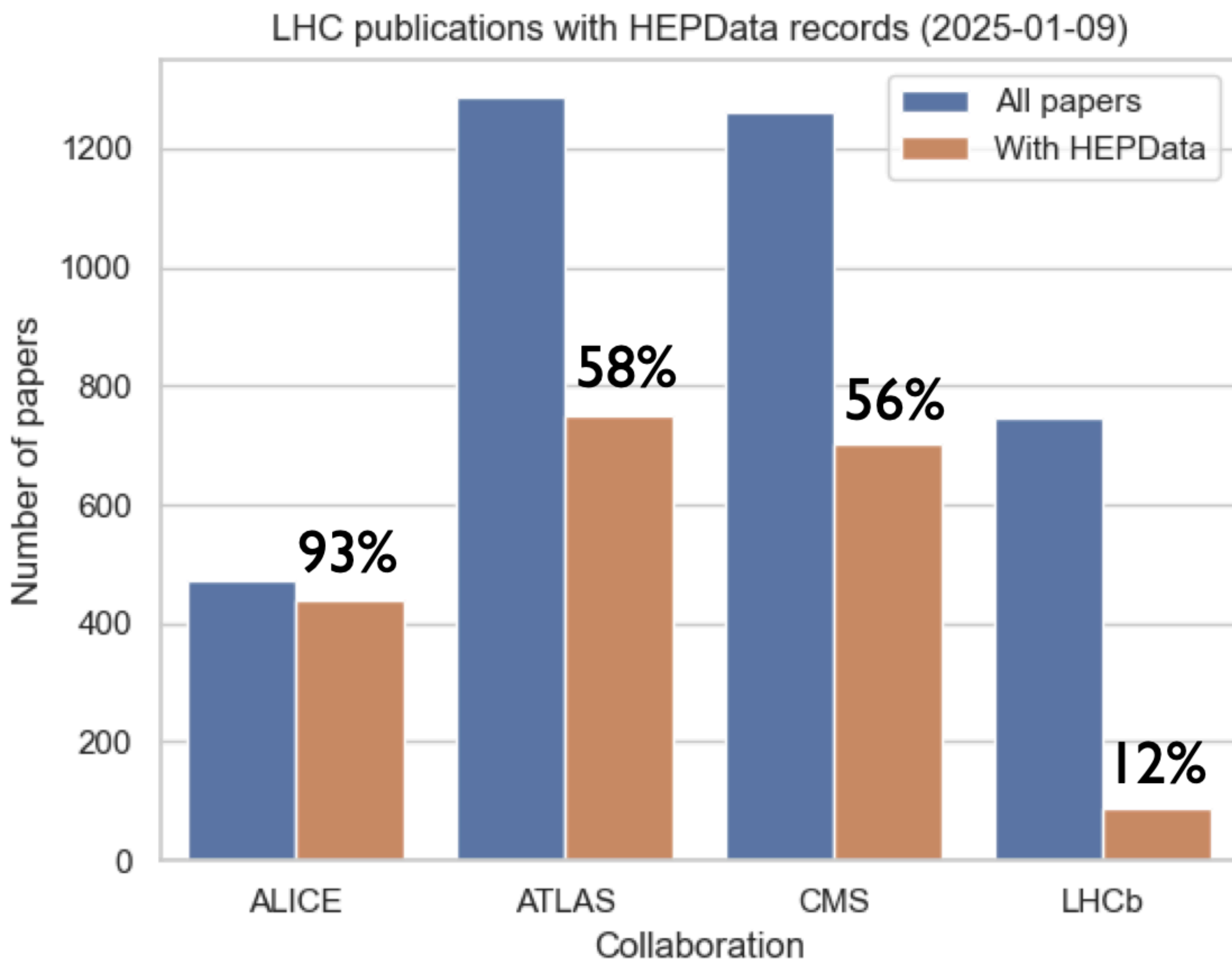
Validation

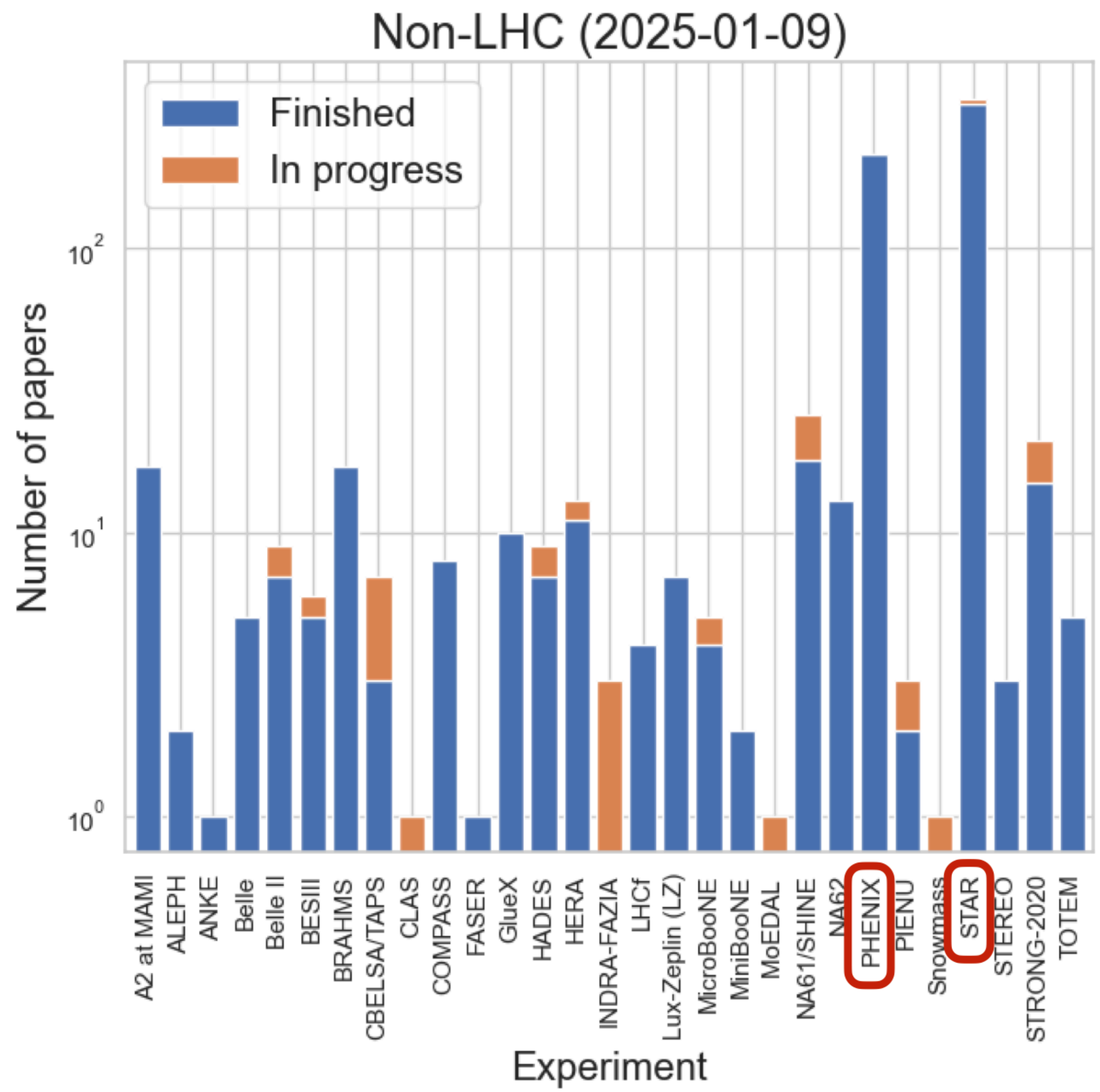
Data preservation

Interpretation

Education

Coverage of experiments





HEPData framework is open for everybody

Outreach at IPPP

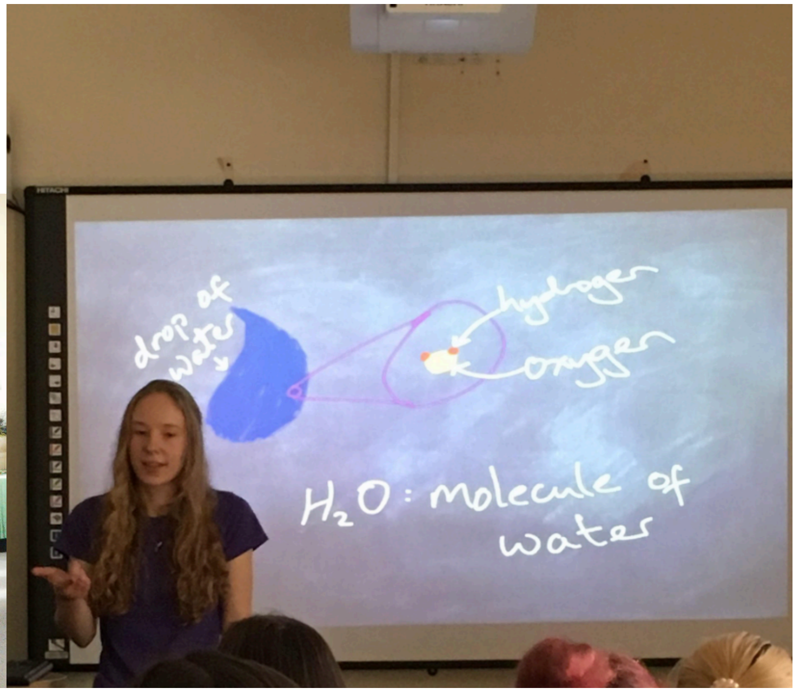
- Science Fairs
- Science Festivals
- School engegement
- Master Class
- Social Media

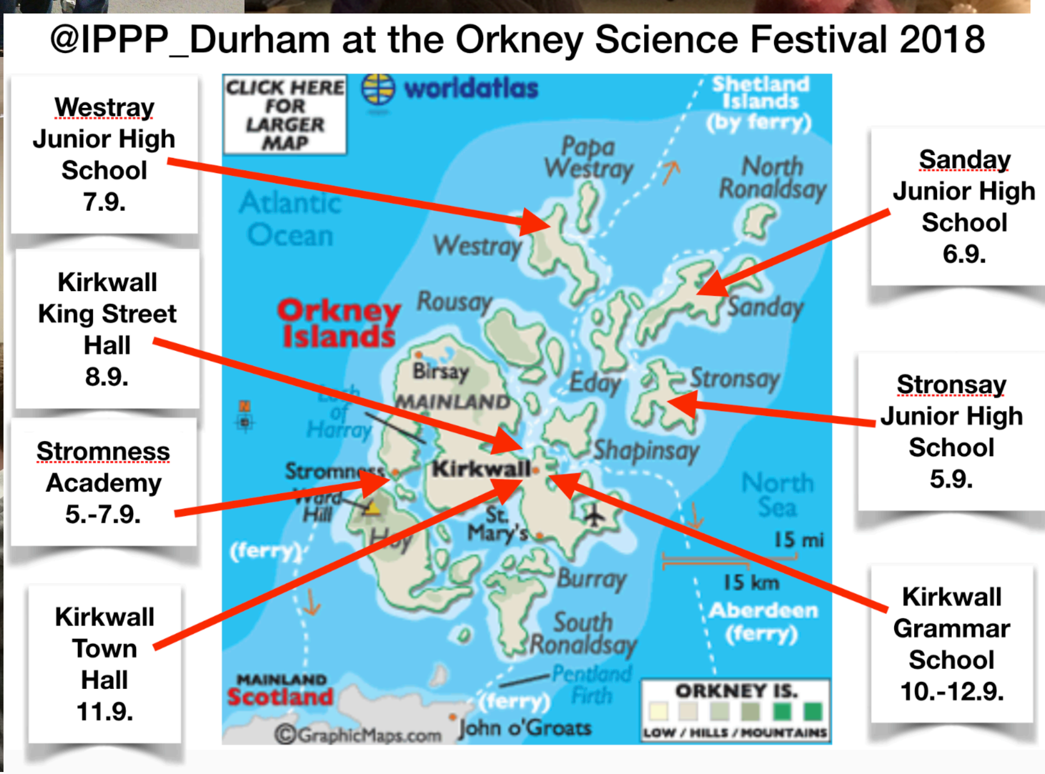
youtube: @ipppdurham9492

X: @IPPP_Durham

Francesco Sergio

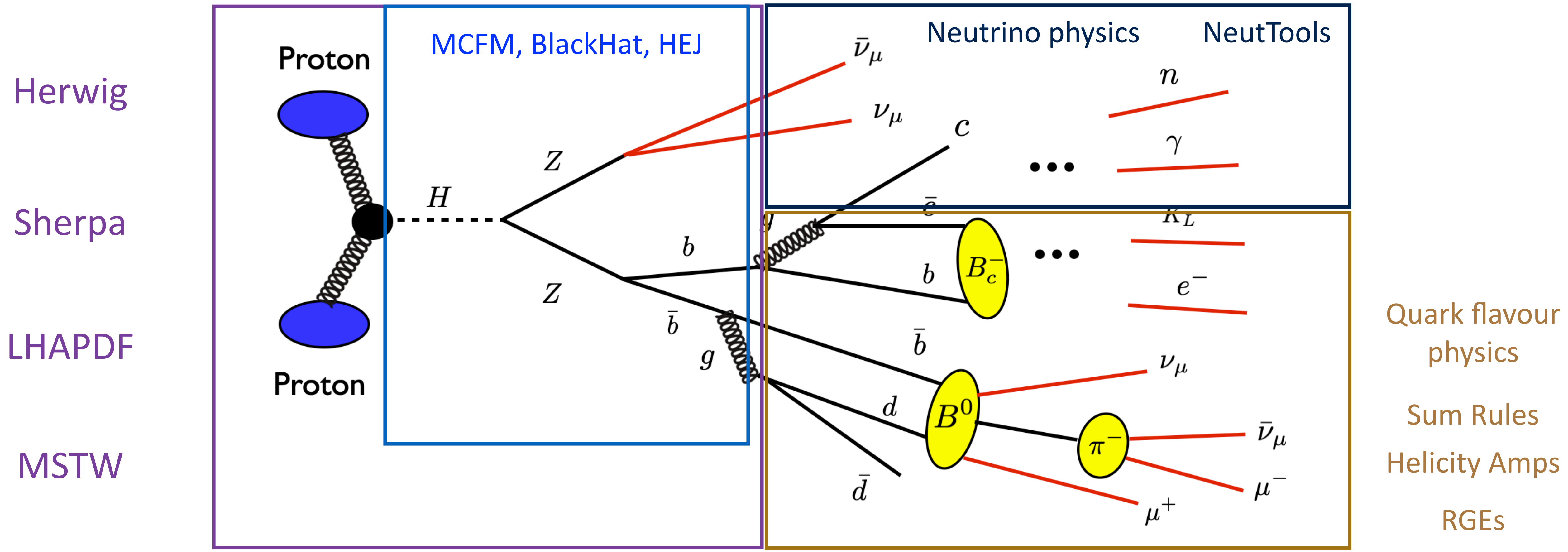
Lorraine Coghill





Research

Core research delivers full end-to-end support for the HEP community in agreement with STFC's funding priorities



- Informs and guides large international experimental collaborations:

  ATLAS, CMS, ALICE, LHCb, DUNE, NA62, Belle II and future experiments

- End-to-end coverage of HEP processes

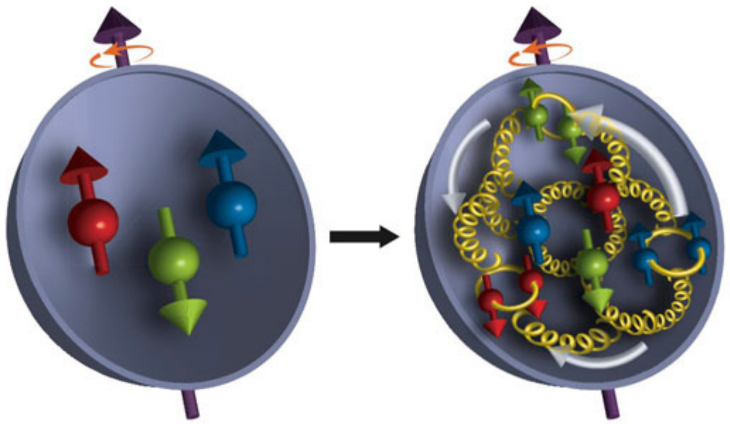
- Service-centred research is labour-intensive and requires strategic long-term commitment

Understanding the structure of the proton

Frank Krauss Stephen Jones

- **Generalised Parton Distribution (GPD)** encode information about longitudinal momentum and transverse spatial position
  - ➡ 'tomographic image' of proton in position space
  - ➡ reduce to ordinary PDFs in forward limit
  - ➡ Accessed in exclusive processes, like **deeply virtual compton scattering (DVCS)** and **exclusive meson production**

- **Transverse Momentum Distribution (TMD)** of partons, giving insight into the momentum-space structure, beyond collinear approximation
  - ➡ reduce to PDFs when integrated over transverse momentum
  - ➡ Accessed in **semi-inclusive DIS (SIDIS)** and **Drell-Yan**



EIC (Electron-Ion Collider) will provide **high-luminosity, high-energy electron-nucleon collisions** with **polarisation**, enabling precise measurements of observables sensitive to TMDs (Silvers, Boer-Mulders) and GPDs (DVCS, meson production)

➡ GPD and TMD in nuclei (He-3, Deuteron, Carbon, Lead)

Many theoretical questions: ➡ many-body nuclear structure (wave functions, spectral functions)
➡ nuclear medium corrections, coherence effects (saturation etc)

Forward scattering amplitudes, small-x resummation and Glauber exchange

- Forward amplitudes, small-x resummation, and Glauber exchanges are crucial to extending **QCD factorisation theorems** into the low-x, high-density regime—precisely the domain where high-energy particle theory and nuclear physics converge.

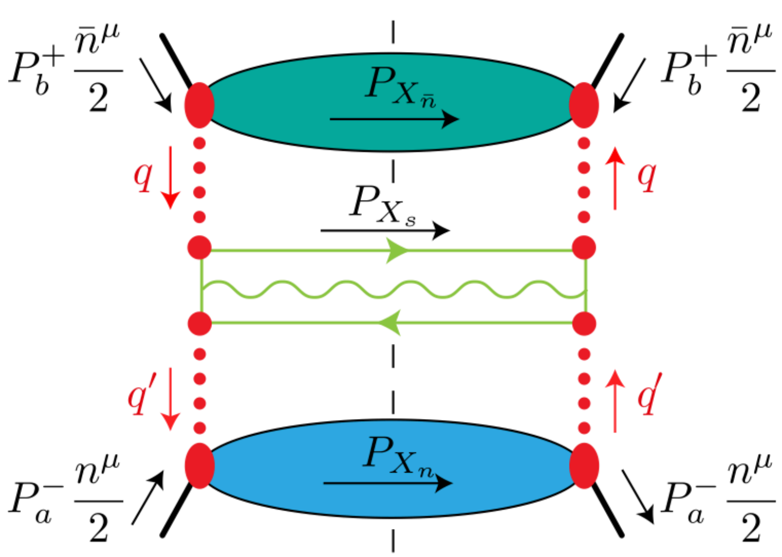
- Nuclear targets enhance gluon densities and multiple scattering effects, forcing us to go beyond standard DGLAP and collinear factorisation. Understanding this interface, through tools like BFKL, CGC, and hybrid factorisation, is essential for a coherent description of hadronic and nuclear structure at the EIC and LHC forward programs.

Frank Krauss

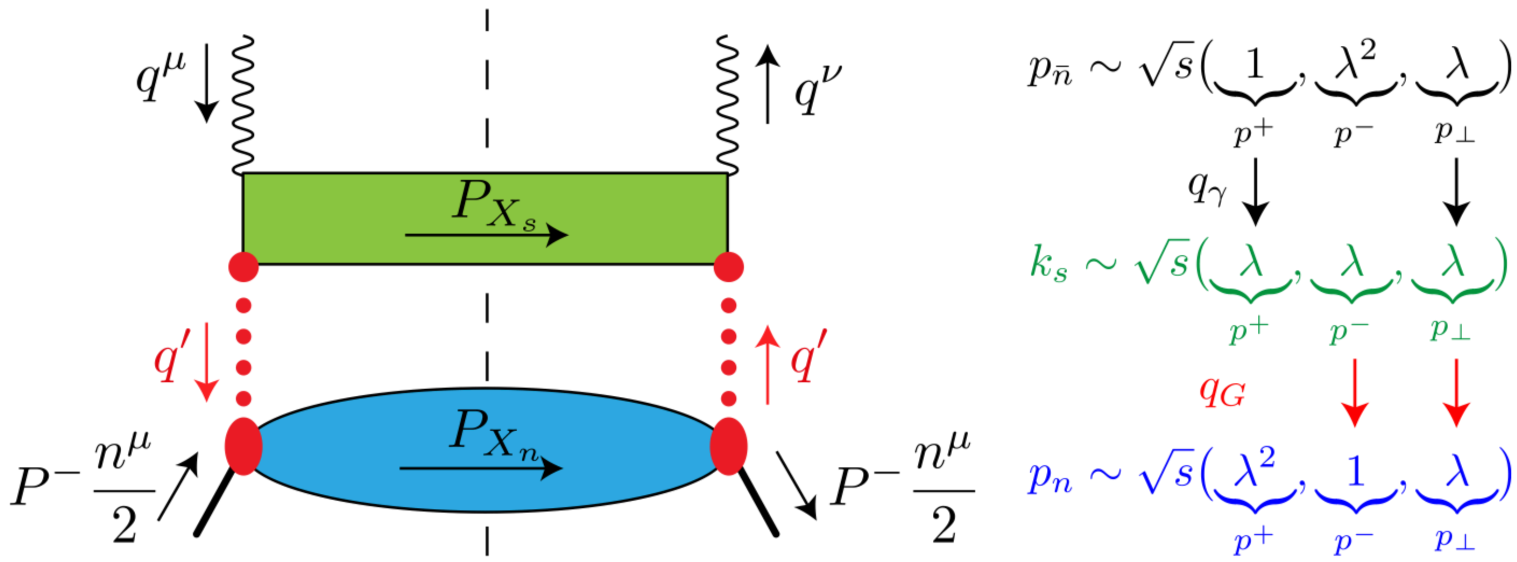
Stephen Jones

Valery Khoze

Peter Richardson



Forward scattering in Drell-Yan



Factorization at lowest order in Glauber exchange

Hadron Physics

From the **flavour physics** perspective, **hadron physics** is essential because the quark-level processes (e.g., weak decays) are embedded in strongly interacting, nonperturbative final states.

- **Pions, kaons, and their mixtures** dominate light-flavour transitions (especially for V_{us}, V_{ud}).
- Understanding **final-state interactions** among these hadrons is crucial for the precision extraction of CKM elements.

Stefan Schacht

Danny van Dyk

V_{us} **from** $K \to \pi \ell \nu$ **(semileptonic kaon decays)** requires knolwedge of **vector form factor** $f_+(0)$

V_{ud} **from superallowed nuclear beta decays** from decays between $0^+ \to 0^+$ isospin analog states

➡ **Nuclear theory input key: nuclear structure corrections dominate uncertainty budget now (PDG).**

Joint methodological interest: Dispersion relations, conformal mapping and expansion

This is a **textbook case** of **nuclear and particle physics co-dependence**:

- Nuclear theory must provide reliable estimates of structure-dependent corrections, with uncertainties
- Recent work (e.g., J.C. Hardy et al. [INSPIRE 1821327], Czarnecki et al. [INSPIRE 1743986]) uses dispersive methods to compute nuclear radiative corrections — previously modeled more crudely
- Connection to nuclear beta decay experiments is direct and quantitative

Neutrino scattering

Jessica Turner

Ivan Martinez-Soler

As neutrino experiments transition from discovery mode to **precision measurements**:

- CP-violation phase δ_{CP},
- mass ordering,
- mixing angles with per cent-level uncertainties,

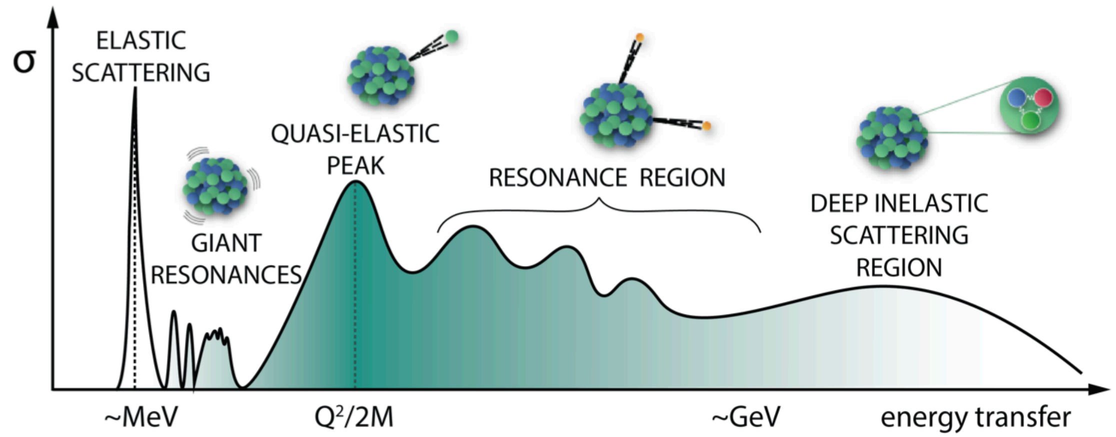
dominant **theoretical uncertainty** no longer oscillation theory but **neutrino-nucleus interactions**.

$$N_{\text{events}}(E_\nu) = \Phi(E_\nu) \cdot P_{\alpha\to\beta}(E_\nu, L) \cdot \sigma_{\nu_\beta N}(E_\nu) \cdot \epsilon(E_\nu)$$

- Neutrino beams are **not monoenergetic**, so one must reconstruct the neutrino energy from the **final state particles**, e.g. lepton kinematics.
- This reconstruction **depends sensitively** on assumptions about how the neutrino interacts with the target nucleus.

Nuclear physics controls:

- **Fermi motion, nucleon correlations, meson exchange currents, final-state interactions (FSI)**
- **transition from quasielastic (QE) to resonance (RES) to DIS** regimes



Neutrinoless double β decay - $0\nu\beta\beta$


Jessica Turner


Ivan Martinez-Soler

- **0νββ decay** is the **only feasible experimental probe** of whether neutrinos are **Majorana particles**, i.e., their own antiparticles.
- It also probes **lepton number violation (LNV)**, which is required for most mechanisms of **baryogenesis** via **leptogenesis**.
- If observed, it would have **far-reaching consequences** for the SM and BSM physics — including neutrino mass mechanisms and CP violation.

See also: Jordy de Vries CERN colloquium, February 2025

The **rate** for 0νββ decay is proportional to the **square of the nuclear matrix element** (NME), multiplied by a phase space factor and the square of the **effective Majorana mass** $m_{\beta\beta}$:

$$\left[T_{1/2}^{0\nu}\right]^{-1} \propto |M^{0\nu}|^2 \cdot \left(\frac{m_{\beta\beta}}{m_e}\right)^2 \cdot G^{0\nu}(Q,Z) \longleftarrow \text{phase factor (well known)}$$

Thus, to extract (or even constrain) $m_{\beta\beta}$, we **must know** $M^{0\nu}$ — the nuclear matrix element — **accurately**.

Nuclear effects are **Fermi motion**, **nucleon-nucleon correlations**, **meson exchange currents**, and **fs interactions**

- Many-body nuclear structure methods disagree significantly. Some progress has been made recently
- Alternative: extract NME from 2νββ at DM experiments and next-gen 0νββ

Uncertainties factor 5, leads to factor 25 on lifetime

Large nuclei, complicated matrix elements

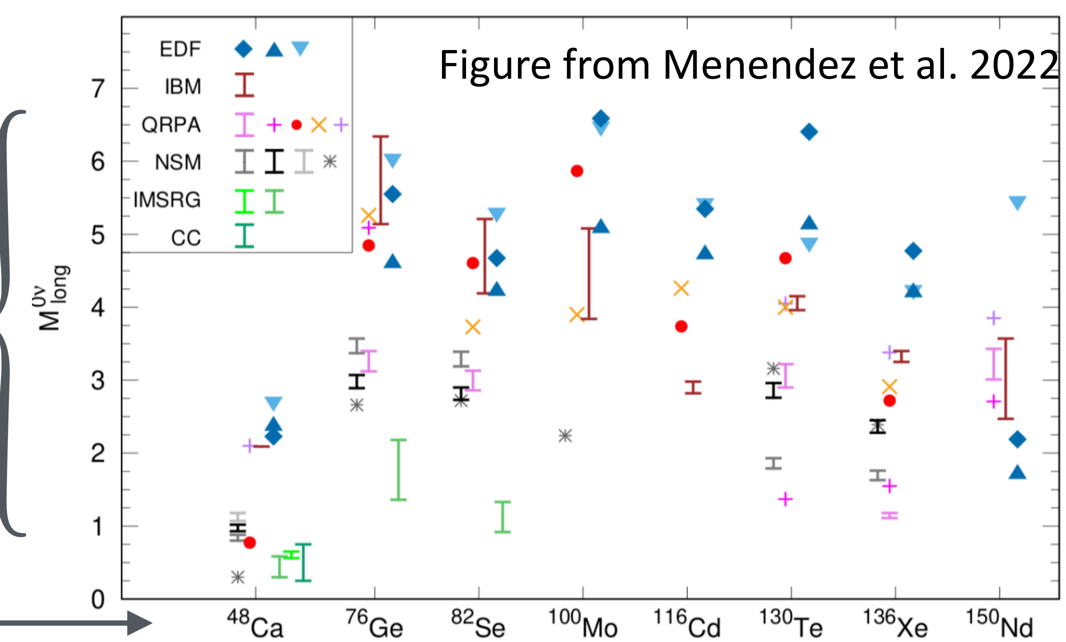


Figure from Menendez et al. 2022

Nuclear rates limit BBN bounds


Martin Bauer


Djuna Croon

BBN describes the synthesis of light nuclei (D, He-3, He-4, Li-7, etc.) in the first few minutes of the Universe, when temperatures dropped below $T \sim \mathrm{MeV}$.

It is sensitive to new physics because:

- It occurs at times $t \sim 1 - 10^3\,\mathrm{s}$, energies $E \sim \mathrm{MeV}$
- It is well understood theoretically, with well-measured nuclear reaction rates,
- It depends on the expansion rate, radiation content, and neutrino sector at the time.

So, comparing predicted vs observed abundances allows us to constrain deviations from the Standard Model in the early Universe.

Nuclear Reaction Rates:

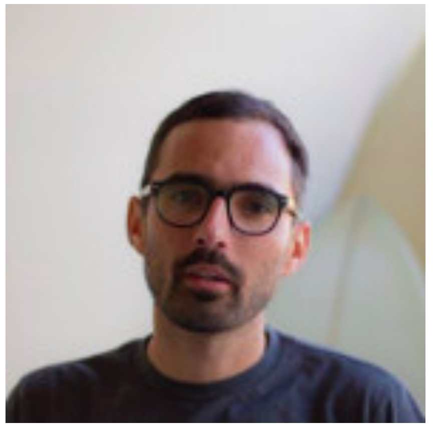
BBN predictions depend critically on the rates of a handful of key nuclear reactions, such as

$$\mathrm{n} + \mathrm{p} \to \mathrm{D} + \gamma, \quad \mathrm{D} + \mathrm{D} \to \mathrm{He}^3 + \mathrm{n}, \quad \mathrm{He}^3 + \mathrm{He}^4 \to \mathrm{Li}^7 + \gamma$$

Uncertainties in these rates directly translate into abundance prediction uncertainties.

→ Some rates not well known … → Limits BBN as cosmological probe

Dark matter direct detection



Rodrigo Alonso

Djuna Croon

Especially important for light DM:

- Light DM (with mass $m_\chi \lesssim 10\,\mathrm{GeV}$) imparts **very low recoil energies** ($\lesssim 1\,\mathrm{keV}$) to nuclei.

- As a result, the **nuclear and detector response** must be understood at **very low energy thresholds** — a regime where **nonperturbative nuclear effects dominate**.

Quenching factors: How much of the recoil we see

- When a nucleus recoils from a DM hit, not all of its kinetic energy is converted into **detectable signals** (light, charge, phonons). The quenching factor tells us what fraction is observed.

Depends on:
- **Target material** (e.g. xenon, germanium, argon)
- **Recoil energy** (nonlinear at low energies)
- **Ionisation vs phonon production vs scintillation**

Uncertainties in quenching directly translate to **uncertainties in recoil energy**, and thus in the **inferred DM mass and cross section.**
Nuclear physics and condensed matter input is needed to **calibrate and model** these effects, often at the **few-percent level**.

Nuclear Form Factors: Internal Structure of the Target

For DM–nucleus scattering, especially at **nonzero momentum transfer**, the **nuclear form factor** enters the cross section:

$$\frac{d\sigma}{dE_R} \propto F^2(q^2)$$

distribution of nucleons inside nucleus

Calculated via **ab initio nuclear theory**, e.g. chiral EFT, coupled cluster, shell model

Migdal Effect: Inelastic Channels for light dark matter

The Migdal effect is a quantum mechanical process where a DM-induced nuclear recoil causes atomic ionization or excitation. It opens up a detectable **electron recoil channel**, even when the nuclear recoil is too small to see.

Calculating the Migdal amplitude requires understanding the coupling between nuclear motion and electron orbitals. This is a challenging **many-body problem**, requiring nuclear + atomic physics input

High energy astroparticle physics

Francesca Chahda-Day

Martin Bauer

Many constraints on light BSM physics (axions, sterile neutrinos, dark photons, millicharged particles, …) rely on stellar, supernova, or cosmic-ray observables, whose interpretation hinges on nuclear reaction rates.
Nuclear uncertainties thus directly limit our ability to probe and constrain new physics.

Cosmic Rays: Spallation and Secondary Production

High-energy cosmic rays (protons, nuclei) collide with interstellar gas and produce:

- **Light elements** (e.g. Li, Be, B via spallation),
- **Pions** → which decay into neutrinos and gamma rays.

This is essential for:

- **Dark matter indirect detection** (e.g. positrons, antiprotons, gamma rays from DM annihilation),
- **High-energy neutrino flux predictions** (e.g. IceCube)
- Modeling **cosmic-ray propagation and backgrounds**

→ Precise cross sections for **nuclear fragmentation and pion production** on light elements (C, O, N, H) are needed. Many of these are still **poorly measured**

Helium Burning: Triple-α and $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$

These two reactions control the carbon-to-oxygen ratio in stellar cores:

Triple-α: $3\alpha \rightarrow ^{12}\mathrm{C}$ and Alpha-capture: $^{12}\mathrm{C} + \alpha \rightarrow ^{16}\mathrm{O} + \gamma$

These reactions determine the outcome of stellar evolution, supernova energetics, and element production, i.e. **final mass of stars**, conditions in **pair-instability supernovae** and late **stages of star burning**

→ $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ remains one of the most important yet least certain nuclear reaction rates — it's very hard to measure at astrophysical energies ($\sim 300\,\mathrm{keV}$).

r-process Nucleosynthesis and Kilonovae

The r-process (rapid neutron capture) is responsible for producing heavy elements beyond iron, such as gold, platinum, and uranium

Predicting abundances requires:

- **Neutron capture rates** on **unstable, neutron-rich isotopes**,
- **Fission barriers**, **beta-decay rates**, **mass models**, and **neutrino interactions**
- Often far from experimental reach → needs **nuclear theory extrapolations**.

→ NP could show up in cooling channels (axions), mod. neutrino opacities etc

Computational Methods

Tensor networks, **machine learning**, and **quantum computing** offer complementary and increasingly essential capabilities for addressing some of the hardest problems in theoretical physics — especially where standard methods break down.

Steve Abel

Michael Spannowsky

Tensor Networks

These are variational ansätze for quantum states with entanglement structure encoded in the geometry of the network.

➡ **Lattice QCD at finite density**: Tensor networks provide sign-problem-free formulations in 1+1D and progress in 2D

➡ **Nuclear many-body theory**: Tensor networks can compactly represent low-entanglement wavefunctions.

Quantum Computing

While still in early stages, quantum computing targets problems intractable on classical machines, particularly for:

➡ **Hamiltonian simulation for real-time evolution, non-equilibrium QFT, finite density systems etc**

Science-exchange facilitation

Plenty of expertise in hosting workshops, conferences and schools

Workshops	‣ each year ~15 small to mid-size meetings ‣ often meetings supported by associateships
Conferences	‣ each year 3-5 conferences ‣ ATM, Planck, Top, Pascos, SM@LHC, …
Schools	‣ each year ~3 PhD schools ‣ YTF, YETI, STFC summer school

IPPP contributes to workshops that are organised outside Durham

Reach out to the IPPP if you want to organise conference/workshop

Fellowships and Associateships

Awarded by Steering Committee twice a year (March & September)

Senior Experimental Fellowship

https://www.ippp.dur.ac.uk/senior-fellowships/

- Funds, up to £15k for senior UK-based experimenters
- For entire group to collaborate with IPPP members, organise workshops etc

IPPP Associateship

https://www.ippp.dur.ac.uk/associateships/

- £3k in support of joint research projects with IPPP members

Durham International Visitor Award (DIVA)

https://www.ippp.dur.ac.uk/diva-program/

- Nomination by UK-based host
- £5k to bring international researcher to the UK.

For more information, please watch our showreel https://youtu.be/v7Px_T1tetc

Institute for Particle Physics Phenomenology

Please engage with the IPPP

https://www.ippp.dur.ac.uk/