Theoretical Particle Physics

— in Quantum Universe Cluster —

QU Attract Workshop, Hamburg, November 25, 2025

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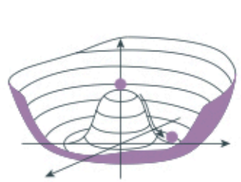
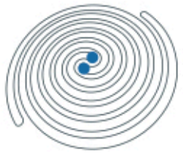
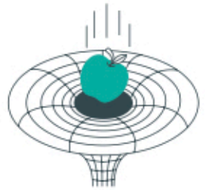
Quantum Universe Cluster

By now, you should already be familiar with the structure of the cluster



Higgs	Dark Matter and Axions	Gravitational Waves	Quantum Gravity
1. Higgs Potential 2. Higgs and the Origin of Matter 3. Tools and New Facilities for Future Higgs Characterization	1. Light Bosonic Dark Matter Searches 2. Astrophysical and Cosmological Probes of Dark Matter 3. Dark Sector Searches at Colliders	1. Gravitational Wave Detection Techniques 2. Multi-Messenger Signatures of Gravitational Wave Sources 3. Gravitational Waves from the Early Universe	1. Holographic Models and Black Holes 2. Constraints on String Geometry and Pheno-menology 3. Cosmological Acceleration in (Quantum) Gravity

Structures, Methods, Advanced Research Technologies (SMART)

1. Algebraic and Geometric Structures

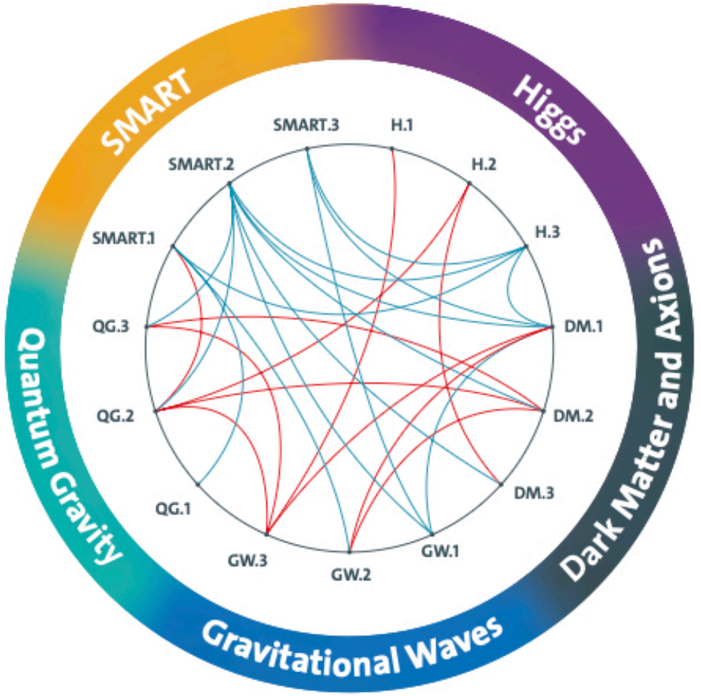
- Feynman Integration Techniques
- Generalized Symmetries
- Derived Structures
- Stable Categorification

2. Artificial Intelligence

- Foundation Models
- Generative AI
- Ultra-Fast Machine Learning Lab
- Advanced Reconstruction Techniques

3. Detectors, Quantum Sensors, and Accelerators

- Detectors for Particle Physics
- Quantum Sensors
- Accelerators for Particle Physics



Our offers/Your shopping list

9 PD + 7 PhD
DESY
theory group

3 fellow positions in strings:
- QG.1.1 Holography
- QG.1.2 Quantum BH
- SMART.1.1 Feynman: Binary

3 fellow positions in pheno:
- H.1 H potential interpretation
- H.2 Higgs and matter/antimatter
- H.2 Precision predictions

3 fellow positions in cosmo:
- GW.3 GW signatures from axion early cosmology
- GW3 GWs from cosmological phase transitions
- QG.2.2 Swampland Phenomenology

1 PhD position in Strings
- SMART.1.1 Feynman: AdS

4 PhD positions in Pheno
- H.1 Higgs EWSB+GW
- DM2 Investigating self-interacting DM
- GW2 Ultra-light dark matter in the sky
- QG.2.2 Positivity

2 PhD positions in Cosmo
- DM2 PBH production
- GW3 Inflaton couplings with GWs

Let’s talk about Physics

Often, the athletes, as the physicists, push the frontiers/break the records.
How high can a human jump with a pole?
Physics (energy conservation) tells us that longer and longer poles don’t help!

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footspeed: 44.72km/h
(Usain Bolt, Berlin, August 2009, between 60m and 80m)

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— Symmetries and Forces —

Over the years, we have learnt a few other conservation laws
that tell us what an athlete/a particle can do or cannot do.

— Remarkable breakthrough in the understanding of Nature: —

"forces among particles are associated to symmetries" (Noether)
conservation of E → invariance by (time)-translation
electro-magnetic forces → (local) invariance by phase rotation of particle wavefunctions

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Philosophical dilemma: how can we be sure there is no heavier particles undiscovered yet?
Technical difficulties (e.g. strong coupling, non-perturbative effects…).
Conceptual obstacles: separation of scales → large logs that endangers perturbative expansions.
Solution: match to EFT and run to lower energies.

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— EFTs are not an option —
— Physics is a succession of EFTs —

It is better to know it and to do it correctly.

BSM Selection Rules

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4}\mathcal{O}_j^{(8)} + \cdots$$

Dimensional arguments impose

$$c_i^{(D)} \sim (\text{coupling})^{n_i - 2}$$

n_i=number of fields in operator $\mathcal{O}_i^{(D)}$
(independant of D)

generically, (coupling ~ g_*) coupling of New Physics to SM
but there might exist "**selection rules**" that lead to other scaling

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Examples of symmetries leading to different selection rules

Operator	Naive (maximal) scaling with g_*	Symmetry/Selection Rule and corresponding suppression
$O_{y_\psi} = \lvert H\rvert^2 \bar{\psi}_L H \psi_R$	g_*^3	Chiral: y_f/g_*
$O_T = (1/2)\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$	g_*^2	Custodial: $(g'/g_*)^2$, $y_t^2/16\pi^2$
$O_{GG} = \lvert H\rvert^2 G^a_{\mu\nu} G^{a\,\mu\nu}$ $O_{BB} = \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	g_*^2	Shift symmetry: $(y_t/g_*)^2$ Elementary Vectors: $(g_s/g_*)^2$ (for O_{GG}) $(g'/g_*)^2$ (for O_{BB}) Minimal Coupling: $g_*^2/16\pi^2$
$O_6 = \lvert H\rvert^6$	g_*^4	Shift symmetry: λ/g_*^2
$O_H = (1/2)(\partial^\mu \lvert H\rvert^2)^2$	g_*^2	Coset Curvature: ϵ_c
$O_B = (i/2)\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\partial^\nu B_{\mu\nu}$ $O_W = (i/2)\left(H^\dagger \sigma^a \overleftrightarrow{D^\mu} H\right)\partial^\nu W^a_{\mu\nu}$	g_*	Elementary Vectors: g'/g_* (for O_B) g/g_* (for O_W)
$O_{HB} = (i/2)\left(D^\mu H^\dagger D^\nu H\right) B_{\mu\nu}$ $O_{HW} = (i/2)\left(D^\mu H^\dagger \sigma^a D^\nu H\right) W^a_{\mu\nu}$	g_*	Elementary Vectors: g'/g_* (for O_{HB}) g/g_* (for O_{HW}) Minimal Coupling: $g_*^2/16\pi^2$

Contino, Falkowski, Goertz, Grojean, Riva '16

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Causality, Locality, Unitarity→Positivity

Not all bona fide IR EFT are extendable in the UV

Pions EFT

$$\mathcal{L} = \partial^\mu \pi \partial_\mu \pi + \frac{c_3}{\Lambda^4}(\partial_\mu \pi \partial^\mu \pi)^2 + \dots$$

UV: $c_3 \geq 0$

QED EFT
Euler-Heisenberg

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \quad a_1 \frac{\alpha^2}{16}(F_{\mu\nu}F_{\mu\nu})(F_{\rho\sigma}F_{\rho\sigma}) + a_2 \frac{\alpha^2}{16}(F_{\mu\rho}F_{\nu\rho})(F_{\mu\sigma}F_{\nu\sigma})$$

UV: $2a_1 + a_2 > 0, \qquad a_2 > 0$

one-loop QED: $\frac{a_1^{\rm QED}}{\Lambda^4} = -\frac{4Q_e^2}{9m_e^4}, \qquad \frac{a_2^{\rm QED}}{\Lambda^4} = \frac{56Q_e^2}{45m_e^4}$

tree-level ALP: $\frac{a_1^{\rm axion}}{\Lambda^4} = -\frac{b_h^2}{\pi^2 f^2 m_h^2}, \qquad \frac{a_2^{\rm axion}}{\Lambda^4} = \frac{2b_h^2}{\pi^2 f^2 m_h^2}.$

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Convex cone fully characterised by its extremal rays. How to determine these extremal rays?

What is the connection with swampland/weak gravity conjecture?

Colliders

Colliders

(LHC = Higgs + Nothing*) ⇒ More energy & More precision

* actually a lot progress in our understanding of the SM:
1) Improved measurements of SM processes; 2) Precise measurements in flavour physics; 3) New frontiers in heavy-ion studies.

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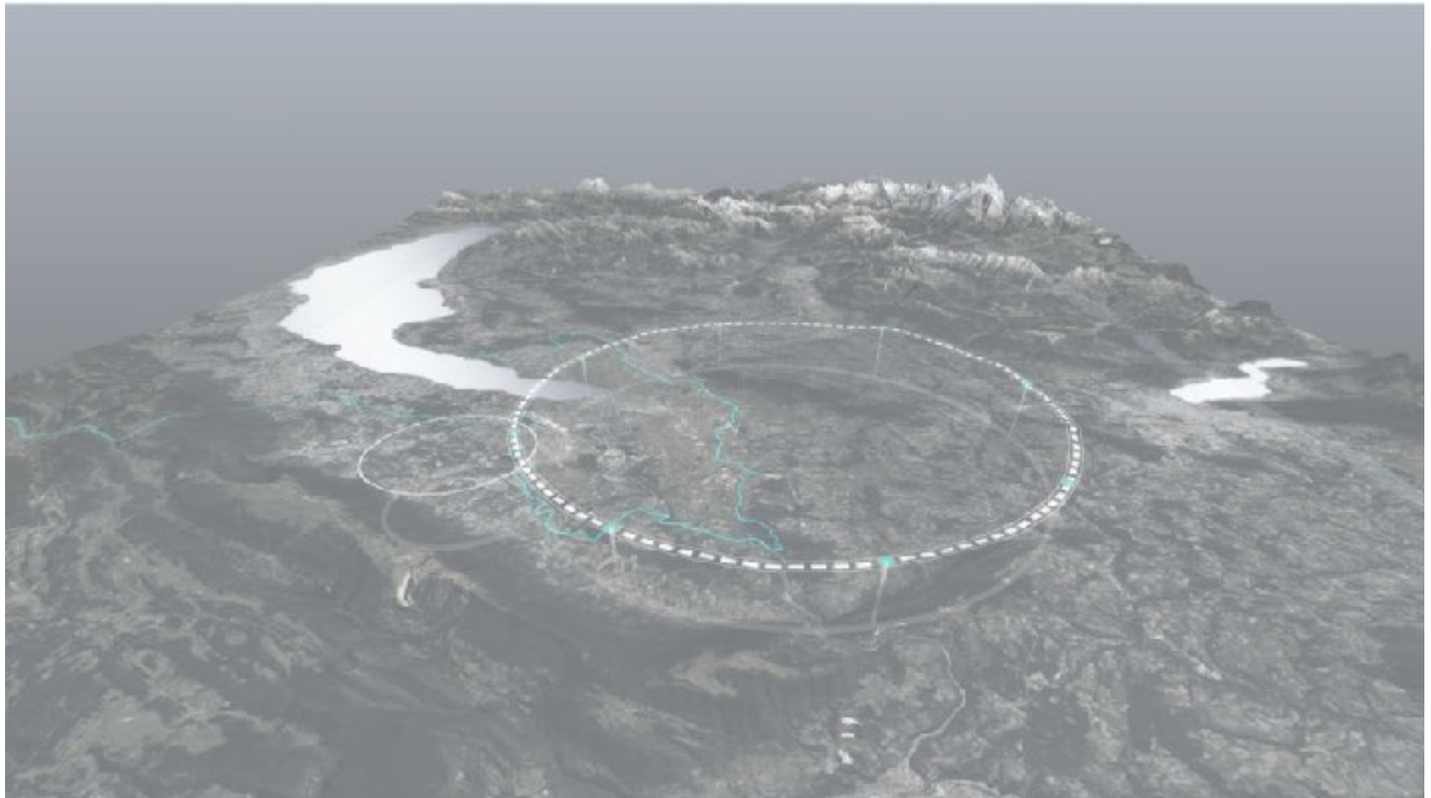
We need a broad and ambitious programme that can
1. sharpen our knowledge of already discovered physics
2. push the frontiers of the unknown at **high** and **low** scales.

The Future Circular Collider integrated programme fits the bill.

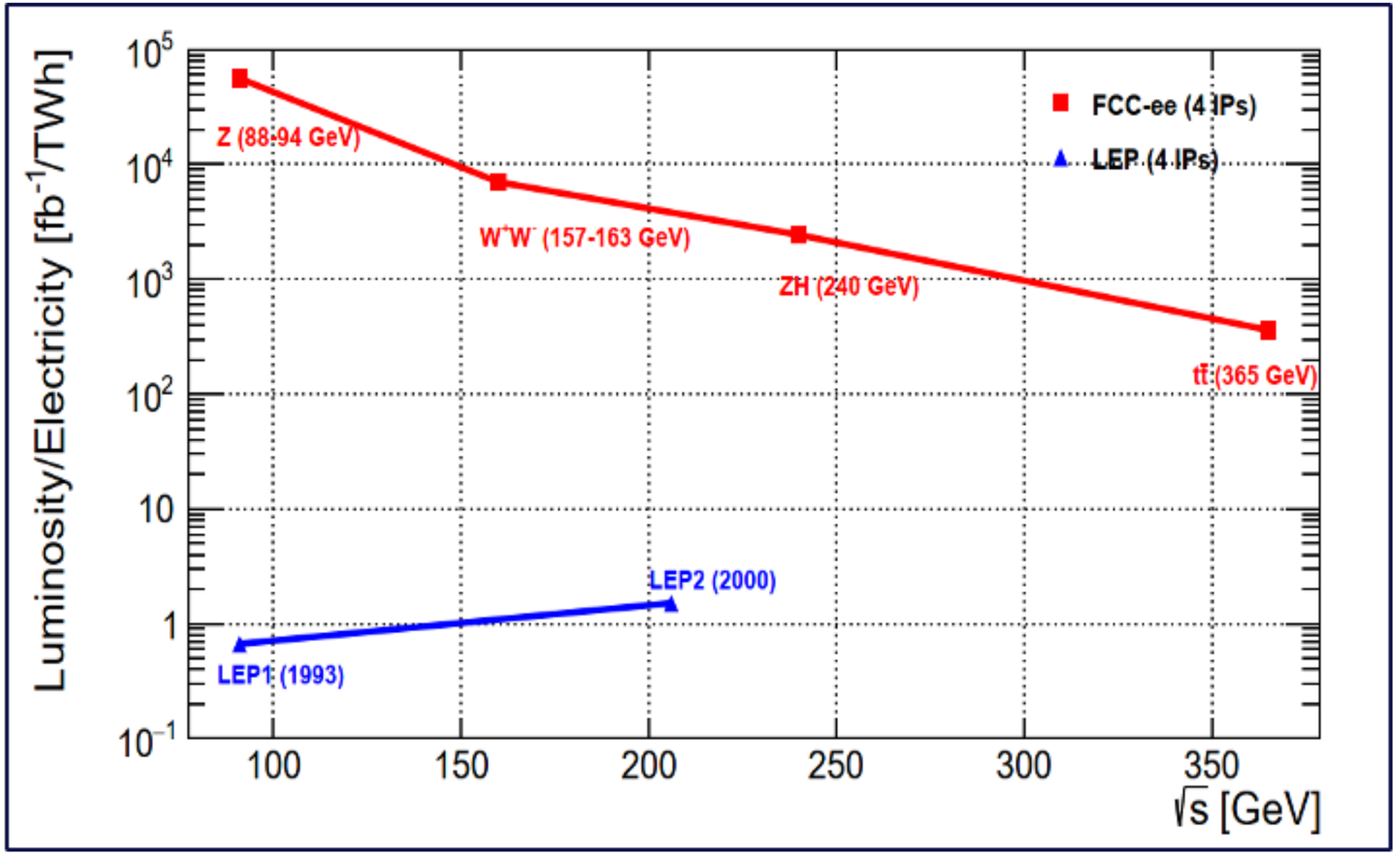
Future Circular Collider

- A versatile particle collider, with four interaction poins, housed in a 200m-underground 91 km ring around CERN.
- Implemented in several stages:
  - an e^+e^- “Higgs/EW/Flavour/top/QCD” factory running at 90-365 GeV ▶ **FCC-ee**
  - followed by a high-energy pp collider reaching 100 TeV ▶ **FCC-hh**

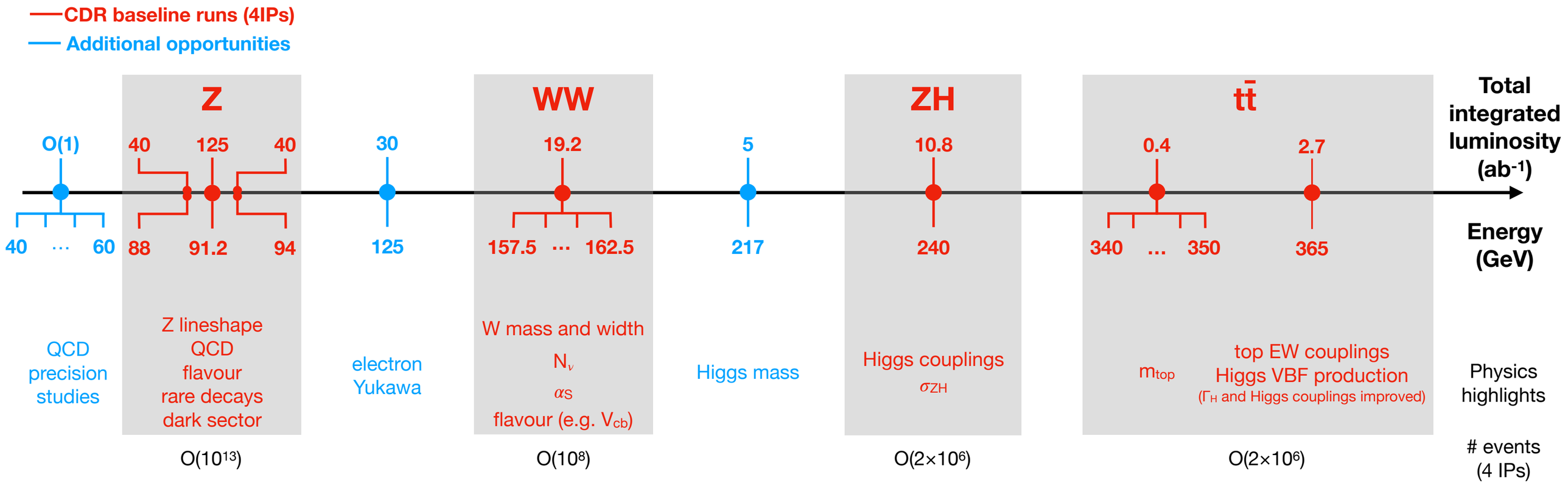


Progress in Accelerator Science

At FCC-ee: LEP1 data accumulated in **every 2 mn**.
(for the same power consumption, i.e. machine 100’000 more efficient).



FCC-ee Physics Programme



- **Opportunities** beyond the baseline plan (√s below Z, 125GeV, 217GeV; larger integrated lumi…)
- **Opportunities** to exploit FCC facility differently (to be studied more carefully):
  - using the electrons from the injectors for beam-dump experiments,
  - extracting electron beams from the booster,
  - reusing the synchrotron radiation photons.

FCC-ee Physics Programme

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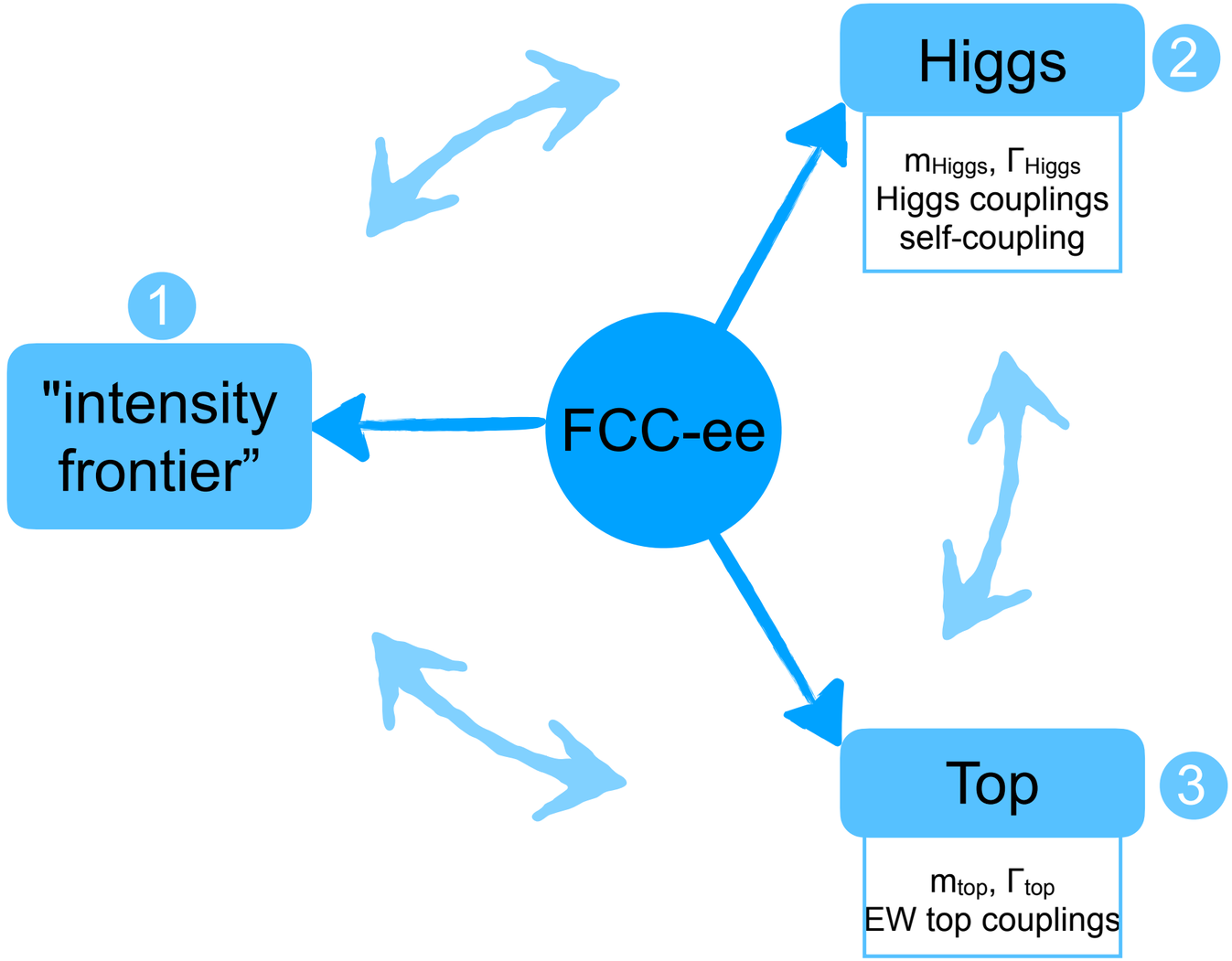

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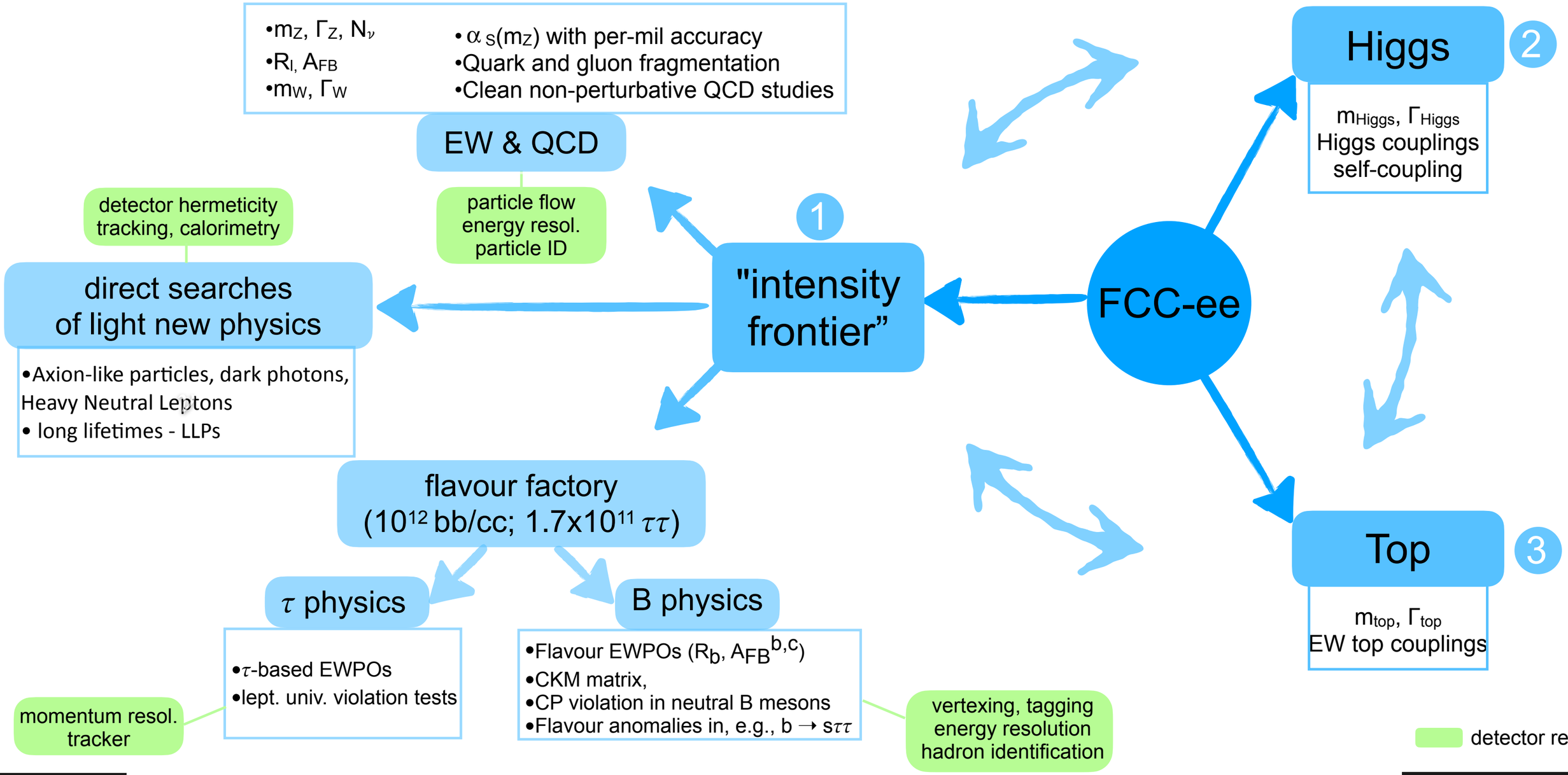
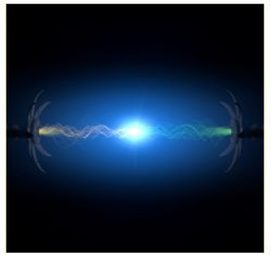


EU Support

- **EU Competitiveness Report: 400-page report made public by Mario Draghi on Monday 9/9/24024:**
  - Handed to Ursula von der Leyen (European Commission president) for subsequent action
  - Urges the EU to invest 800 billion euros annually [with specific guidance] to close the economic gap between the US and China (consistently seen as a threat throughout the report)
  - CERN mentioned 19 times in the report (and FCC 3 times)!
    - *"Refinancing CERN and ensuring its continued global leadership in frontier research should be regarded as a top EU priority."*
    - *"One of CERN's most promising current projects, with significant scientific potential, is the construction of the Future Circular Collider (FCC): a 90-km ring designed initially for an electron collider and later for a hadron collider."*
- **Speech of Ursula von der Leyen at CERN@70 celebration** (Youtube recording from 38'12" onwards)
  - *"CERN has become the centre of the world for particle physics"*
  - *"I am proud that we have funded the FCC Feasibility Study"*
  - *"I want the increase research budget just as you wish, Fabiola"*
- **July 16, 2025: Commission's proposal for the next Multiannual Financial Framework 2028–34 and the European Competitiveness Fund: 410 billion EUR**
  - *FCC is one of the 11 "moonshots" with up-to 20% of the project funded by EU.*

EU Support

Moonshots



Future Circular Collider

What: Sustain Europe's leadership in particle physics by investing in CERN's next-generation collider.

How: Co-invest with other CERN countries, leveraging Horizon Europe funding.

Clean Aviation

What: Lead the world in developing the next generation of CO_2-free aircraft.

How: Develop applications from medicine to climate, solving previously impossible problems for 450 million citizens

Quantum Computing

What: Make Europe the first continent with fully integrated quantum computing in daily life.

How: Develop applications from medicine to climate, solving previously impossible problems for 450 million citizens.

Next Generation AI

What: Model the new AI on the laws of nature and grounded in physics and biology.

How: AI developed by, with, and for European scientists and industry, drawing to Europe the world's best minds.

Data Sovereignty

What: Make Europe the global leader and safest hub for critical research data.

How: Provide access to critical data for researchers, universities and companies, offering competitive advantage in tackling global challenges.

Automated Transport and Mobility

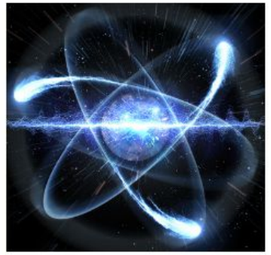
What: Advance safe, inclusive, and emission-reducing automated transport and mobility in Europe.

How: Invest in smart transport systems to improve traffic, reduce emissions, and enhance access.

Regenerative Therapies

What: Deliver breakthrough therapies to improve people's health and lives.

How: Harness Europe's scientific strengths to treat incurable diseases and personalise medicine.



Fusion Energy

What: The first commercial nuclear fusion power plant, generating safe, consistent, and reliable electricity.

How: Overcome the scientific and technological challenges necessary to put fusion on the grid in Europe by 2034.

Space Economy

What: Make Europe the leader in the space economy.

How: Develop the next generation launch vehicles such as reusable rockets, able to deploy massive cargo by 2040.

Zero Water Pollution

What: Move towards zero pollution of water in the EU.

How: Stimulate innovation to build a true water-smart economy which secures sufficient, clean and affordable water and sanitation to all at all times.

Ocean Observation

What: Achieving strategic autonomy in ocean observation infrastructure, data and information services.

How: Developing, connecting, governing and securing the next generation of European ocean observing technologies

Why becoming a physicist?

You can choose the problems you want to work on.

You are interacting with intellectually stimulating people.

You won’t be eternal, but your science can be eternal…
provided you pass it to the next generation!

I wish you all the best for your studies and your scientific career.