European Strategy for Particle Physics: 2026 Update

- Key messages from the Symposium -

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From U. Husemann's talk

European Strategy for Particle Physics

Strategy Secretariat

Karl Jakobs (Chair), Hugh Montgomery (SPC),
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Venice Open Symposium, 27 June 2025

The vision by CERN Council

"The aim of the Strategy update should be to develop a ***visionary and concrete plan*** *that greatly advances human knowledge in fundamental physics through the* ***realisation of the next flagship project at CERN****. This plan should attract and value* ***international collaboration*** *and should* ***allow Europe to continue to play a leading role in the field.****"*

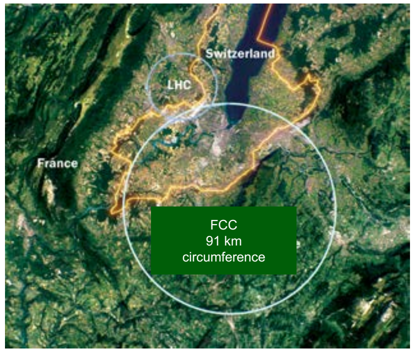
This vision is strongly echoed by the High-Energy Physics communities in Europe and beyond, as testified by the input received from the **national HEP communities**

Many HEP communities support a forward-looking European strategy that **maintains CERN as the global centre for collider physics** and ensures a balanced, ambitious, and innovative research programme.

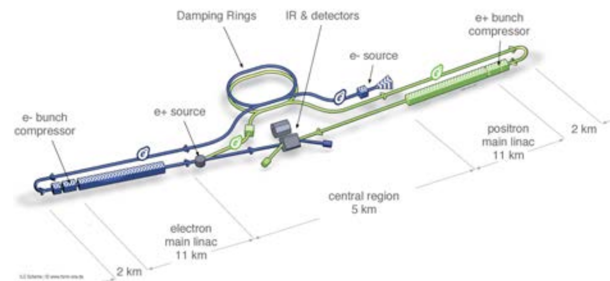
Proposed large-scale projects at CERN, ~ 2045

e^+e^- colliders
("Higgs factories")

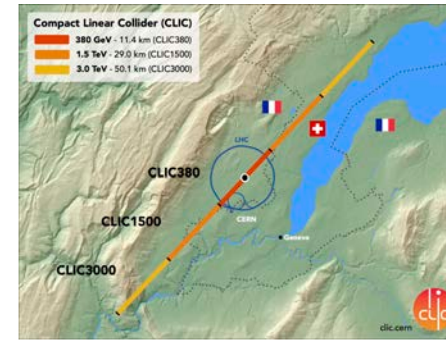
FCC-ee (e^+e^-, circular, 91 – 365 GeV)



LCF (e^+e^-, linear, 91 – 240, 550 GeV)



CLIC (e^+e^-, linear, 380 GeV, 1.5 TeV)

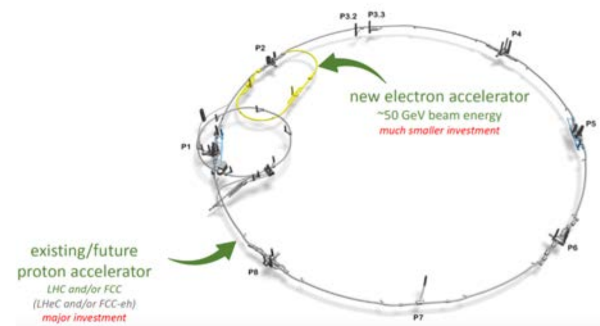


Intermediate projects

(Leave room (time, budget, resources) for further development of THE machine that can probe directly the energy frontier at the 10 TeV parton scale)

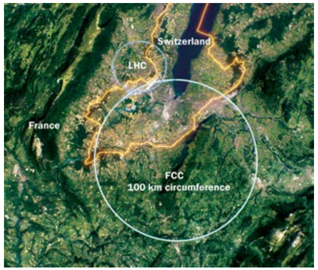
LEP3 (e^+e^-, circular, 91 – 230 GeV)

LHeC (ep, circular, electron ERL, 50 GeV e^-, > 1 TeV ep collisions)



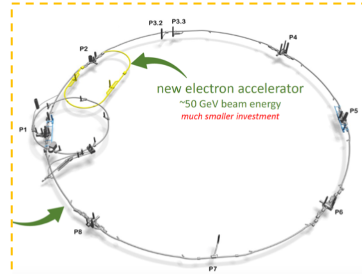
Potential for development: future 10 TeV parton-scale collider options

FCC-ee



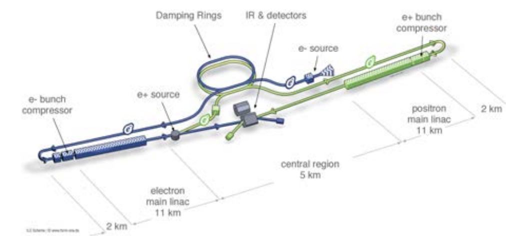
LEP3

LHeC

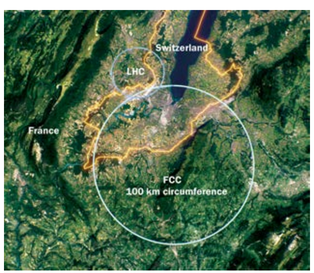


PERLE

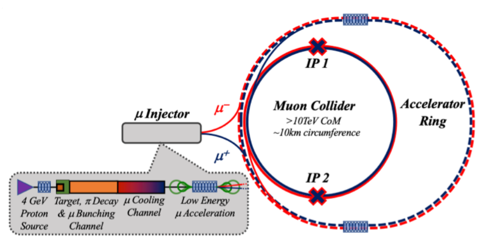
LCF, CLIC



R&D



FCC-hh,
baseline 85 TeV (→ 120 TeV)
+ possibility for HI collisions



Muon Collider (3, 10 TeV)

e^+e^- with improved acceleration technologies
LCF, C^3 (→ 1 TeV), CLIC (1.5 TeV), HALHF, …
→ plasma acceleration for higher energies
(can $\mathcal{O}(10)$ TeV be reached? on what timescale?)

The view of the national HEP communities

- **Completing the full HL-LHC programme** is essential and must remain a high priority for CERN;

  It is paramount to fully exploit the High-Luminosity LHC (HL-LHC) to maximise scientific returns

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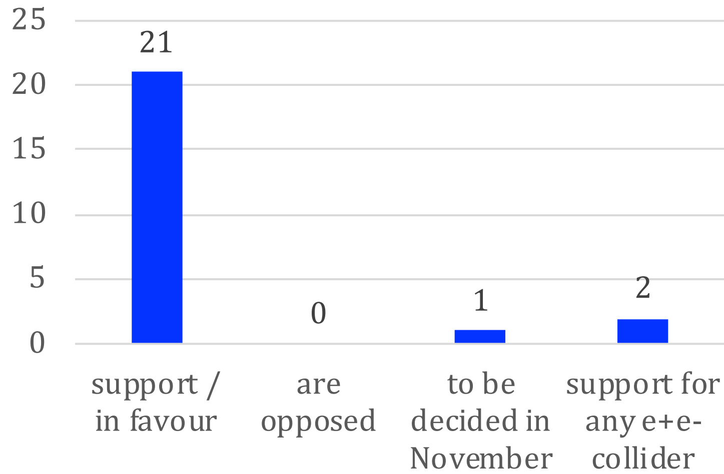
- It is important that the **next flagship collider supports a broad physics programme**, given that it is not clear where new physics will show up.

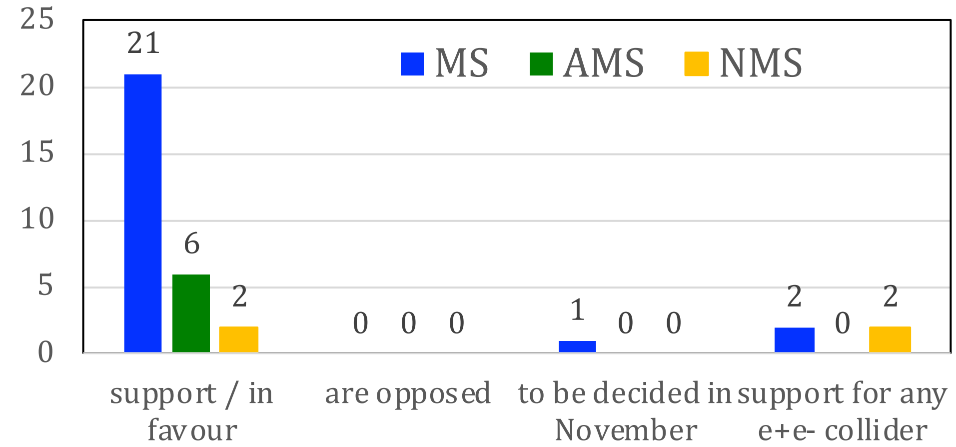
- Should a dedicated energy-frontier collider or a high-luminosity e^+e^- machine not prove feasible or face significant delays, **intermediate collider projects** such as LHeC and LEP3 are recognised as strategically valuable by some member-states HEP communities

What is the preferred large-scale accelerator for CERN

CERN Member States (MS)



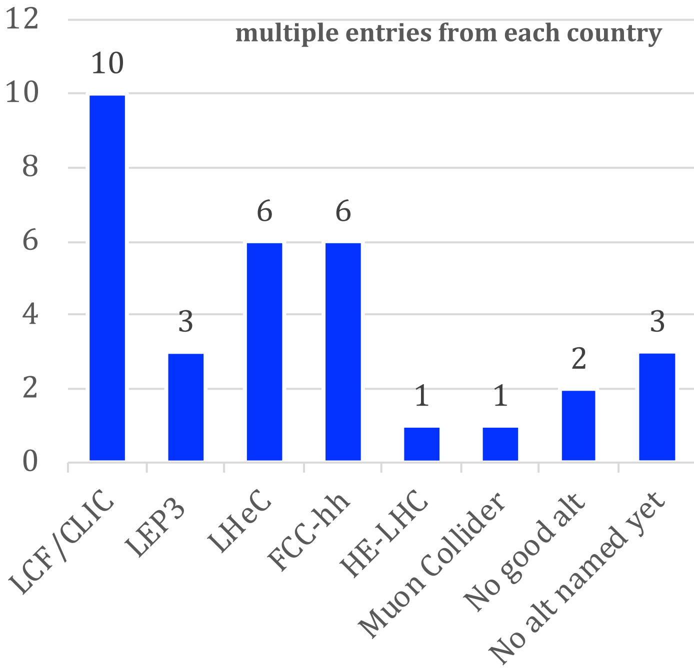
… incl. Associate- and Non-Member States (MS)



- Overwhelming support (21/24 CERN MS HEP communities) in favour of the integrated FCC-ee/hh programme

- Support as well from Associate Member states (AMS) and Non-member states (NMS)

What is the alternative if the preferred option is not feasible?



CERN Member States (MS) (multiple entries allowed)

- 10 MS HEP communities list a Linear Collider (LCF, CLIC) as second best choice
  (LCF is preferred to be realised with 550 GeV)
- 3 MS HEP mention LEP3 as a genuinely less costly alternative to FCC-ee
- 6 MS HEP communities support LHeC
- 6 MS HEP communities support a lower-energy hadron collider
- 2 MS HEP see no reason for another option, as they would be equally costly.

FCC Feasibility Study

- Layout converged on an optimised placement, chosen out of ~ 100 initial variants;

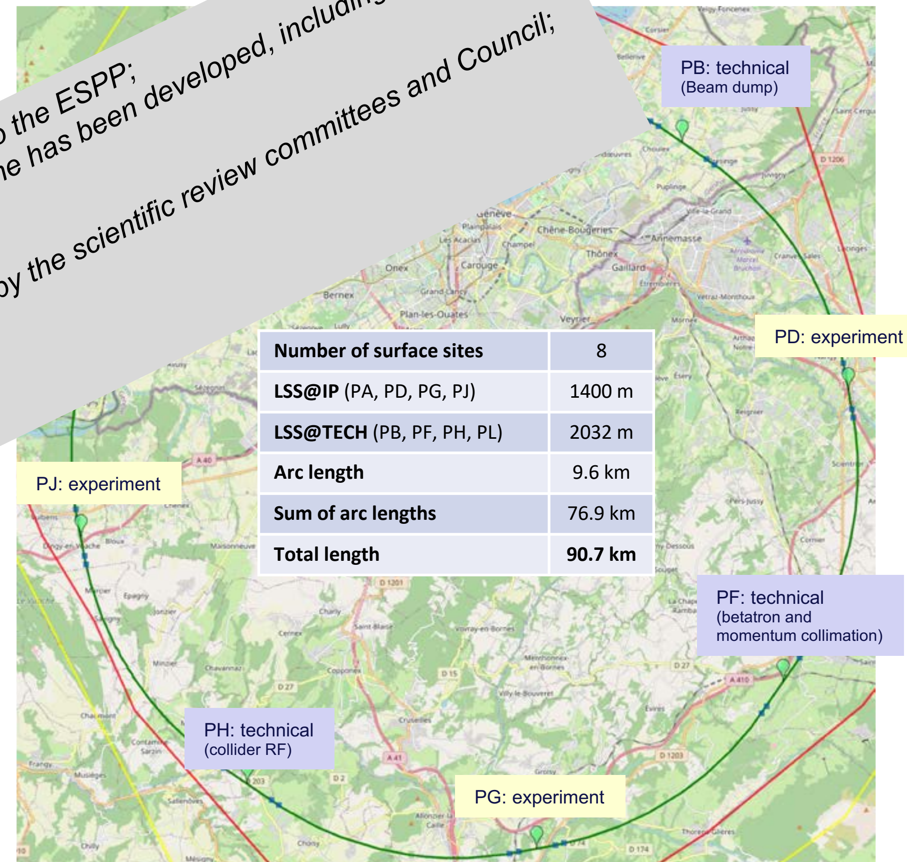
(based on **geology** and **surface constraints** (land availability, access to roads, etc.), **environment,** (protected zones), **infrastructure** (water, electricity, transport), **machine**

- 90.7 km ring, 4-fold symmetry
  8 surface

Whole project

- Feasibility Study has been concluded; final report submitted to the ESPP;
  → coherent baseline design for the FCC integrated programme has been developed, including a well advanced territorial implementation scenario.
- Technical feasibility demonstrated, pending final review by the scientific review committees and Council;
- Work on the Financial Feasibility ongoing

95% in molasse geology → minimising tunnel construction risk



Number of surface sites	8
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 km
Total length	**90.7 km**

Accelerator Challenges

Circular Colliders (e^+/e^-)

Beam is recirculated, enabling high luminosity, but synchrotron radiation (SR) losses constrain the energy

- High luminosity is achieved with **advanced but challenging schemes (e.g. crab waist)**
- High-luminosity goals may be constrained by **beam-beam and intensity effects**

  Lumi / bunch pair (different machines: E, # bunches)

  (SuperKEKB^{2024}: 2.2x10^{31} $cm^{-2}s^{-1}$ → FCC-ee Z: 1.3x10^{32} $cm^{-2}s^{-1}$)

- Smaller circumference imply strong quadrupoles / sextupoles to maintain luminosity (e.g. LEP3)
- Simulation benchmarking with reliable input parameters and diagnostics are required (SuperKEKB and DAΦNE experience/test are very valuable)

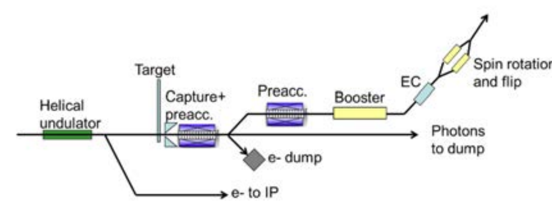
Linear Colliders

No SR but beam energy dumped after a single collision

- **High acceleration gradients** needed for cost efficient accelerators with reasonable length
- **Beamstrahlung constrains** beam parameters at IP
- The small beams needed for high luminosity require stabilisation and extremely tight optics control and correction capabilities
- **Positron production** and capture at high intensity is critical

  (SLC: ~6 × 10^{12} e^+/s

  LCF: ~4-8 × 10^{14} e^+/s) → R&D needed



Accelerator Challenges

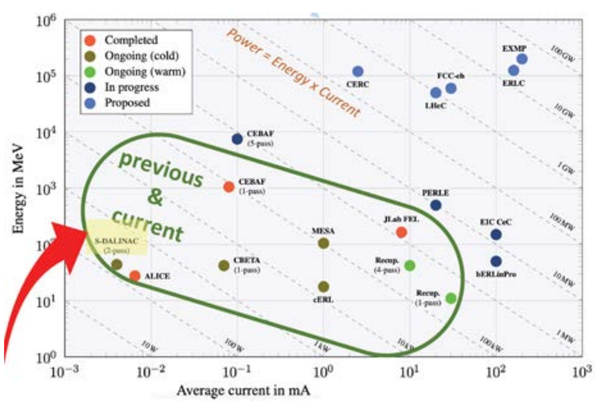
LHeC / Energy Recovery Linacs

Allow high luminosity for ep collisions

- Very high currents; recirculation efficiency is critical

  (25 mA@ 50GeV → 1.25 GW circulating power)

- R&D on superconducting linac technology:
  - high power couplers
  - fast reactive tuners
  - HOM suppression
- Comprehensive beam dynamics simulations needed to ensure performance



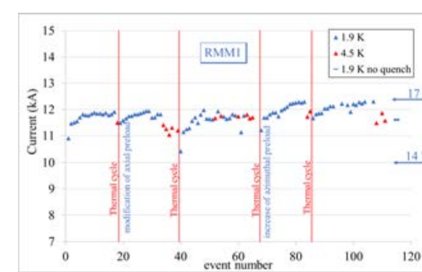
FCC-hh

Highest energy hadron collider

- **High-field magnets 14-20 T needed;**

  High priority R&D on HTS/LTS to identify the best solution

- Magnets need sophisticated system integration to ensure high field strength and acceptable field errors, but also efficient heat removal from SR deposition, good vacuum conditions for beam
- Increase of circulating beam energy by more than order of magnitude compared to LHC challenges machine protection and collimation
- **Superconductor supply and cost are critical**

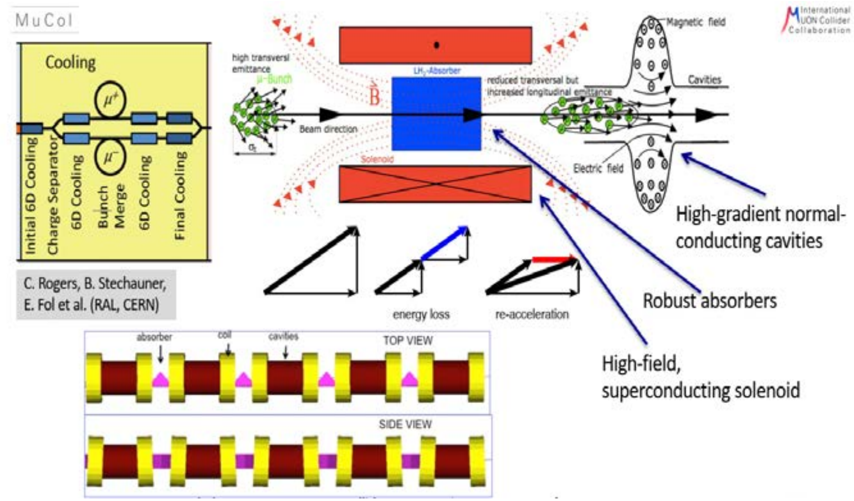


Accelerator Challenges

Muon Colliders

Muon colliders provide a path towards high energy lepton collisions but are not at the level of maturity of the other proposals at present.

- Demonstration of the **6D-cooling technology** is critical
- **Technological challenges are associated with the various acceleration steps**, in particular s.c. magnets, RF systems, fast cycling magnets
- Reliable start-to-end simulation tools need to be further developed to validate and optimise the overall performance
- Mitigation of **neutrino flux** and resulting secondary radiation remains a critical issue



Cost Estimates

FCC-ee

FCC-ee cost estimate (FSR 2025)

Capital cost (2024 CHF) for construction of the FCC-ee is summarised below. This cost includes construction of the entire new infrastructure and all equipment for operation at the Z, WW and ZH working points.

Domain	Cost [MCHF]
Civil engineering	6,160
Technical infrastructures	2,840
Injectors and transfer lines	590
Booster and collider	4,140
CERN contribution to four experiments	290
FCC-ee total	**14,020**
+ four experiments (non-CERN part)	1,300
FCC-ee total incl. four experiments	**15,320**

Note: Upgrade of SRF (800 MHz) & cryogenics for ttbar operation corresponds to additional cost of 1,260 MCHF

LCF / CLIC

Unit: MCHF	LCF 250 (LP)	Δ LCF 550 (FP)	CLIC 380	Δ CLIC 1500
Collider	3864	4204	2471	4684
Main Beam inj./transfer	1181	86	1046	23
Drivebeam inj./transfer	-	-	1060	302
Civil Engineering	2338	0	1403	703
Technical Infrastructure	1109	1174	1361	1404
Sum	**8492**	**5464**	**7341**	**7116**

LEP3

Cost Element	2 new Xpts	2 Exist Xpts
Accelerator	2705	2705
Injectors and Transfer Lines	295	295
Technical Infrastructures	435	435
Experiments	130	60
Civil Engineering	165	165
LHC Removal/LEP3 Installation	140	140
Total CERN (MCHF)	**3870**	**3800**
Experiments non-CERN part	900	270

FCC-hh
(after FCC-ee)

Cost summary table in 2024 MCHF for the construction of FCC-hh.

Domain	FCC-hh Cost [MCHF]
FCC-ee dismantling	200
Collider*	13400
Injectors and transfer linear	1000
Civil Engineering	520
Technical infrastructures	3960
Experiments	N/A
Total	**19080**

*target price of 2.0 MCHF per 14.3 m long magnet with 1.0 MCHF of conductor, 0.5 MCHF for assembly, and 0.5 MCHF for components

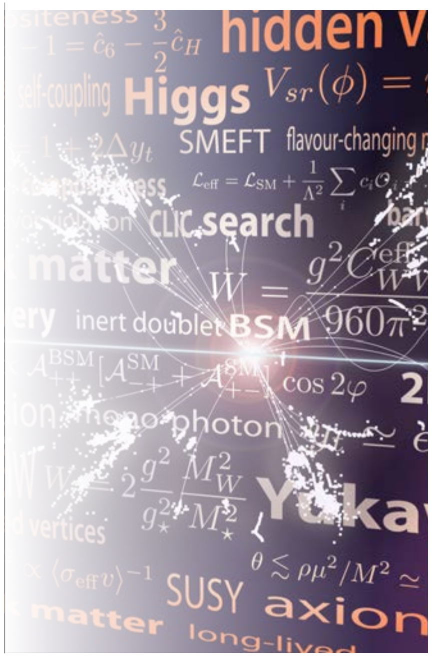
Muon Collider

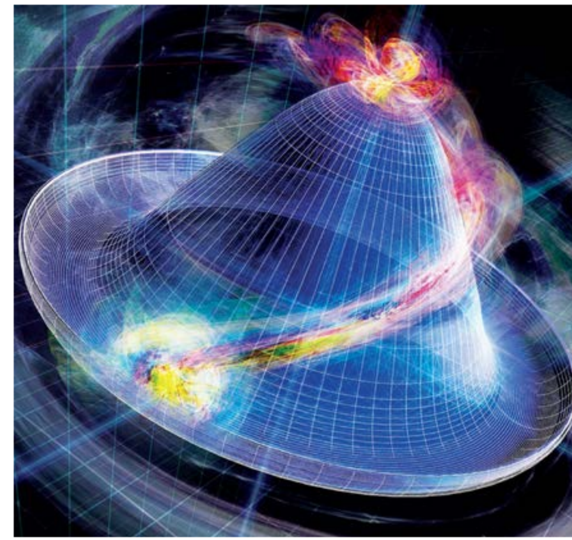
LHeC
(cost estimate 2018, 60 GeV e-)

Budget Item	Cost
SRF System	805MCHF
SRF R&D and Proto Typing	31MCHF
Injector	40MCHF
Magnet and Vacuum System	215MCHF
SC IR magnets	105MCHF
Dump System and Source	5MCHF
Cryogenic Infrastructure	100MCHF
General Infrastructure and installation	69MCHF
Civil Engineering	386MCHF
Total	1756MCHF

→ ~2 BCHF (2025)

Physics Potential





*The **physics potential** is for all national HEP communities the driving motivation for their first choice, followed by **long-term prospects** of covering the precision and the energy frontier*

Electroweak Physics

- The **HL-LHC** will provide legacy measurements for top, ttH, λ_3 and rare decays until a top and high energy run

- **Multiple energy points in e^+e^- colliders** are important to Higgs precision (i.e. width, HWW, λ_3)

- **Tera-Z brings highest overall sensitivity to el.weak**

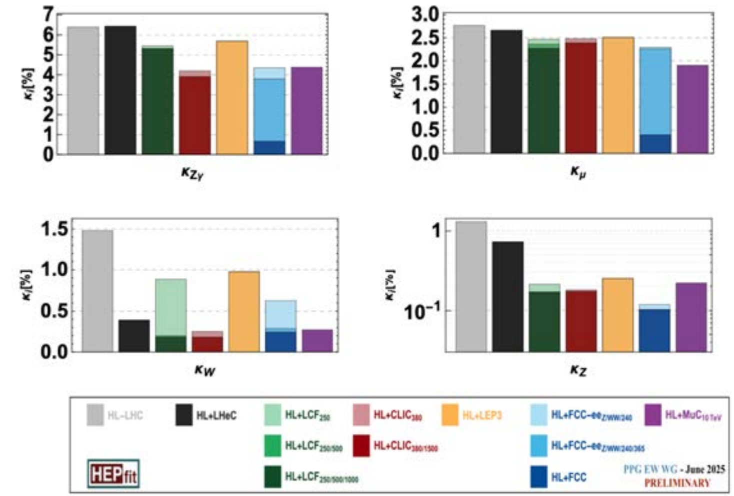
- Significantly improved high-precision tests of the el.weak sector are vital to guide future direct searches of new physics

- Precision and energy are strongly complementary

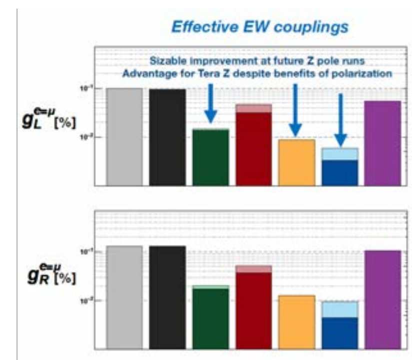
- A focus on both precision (→ smaller effects) and breadth (→ characterization of any eventual signal) is important in the search of the unknown.

- Fundamental advancements in theory techniques and tools needed

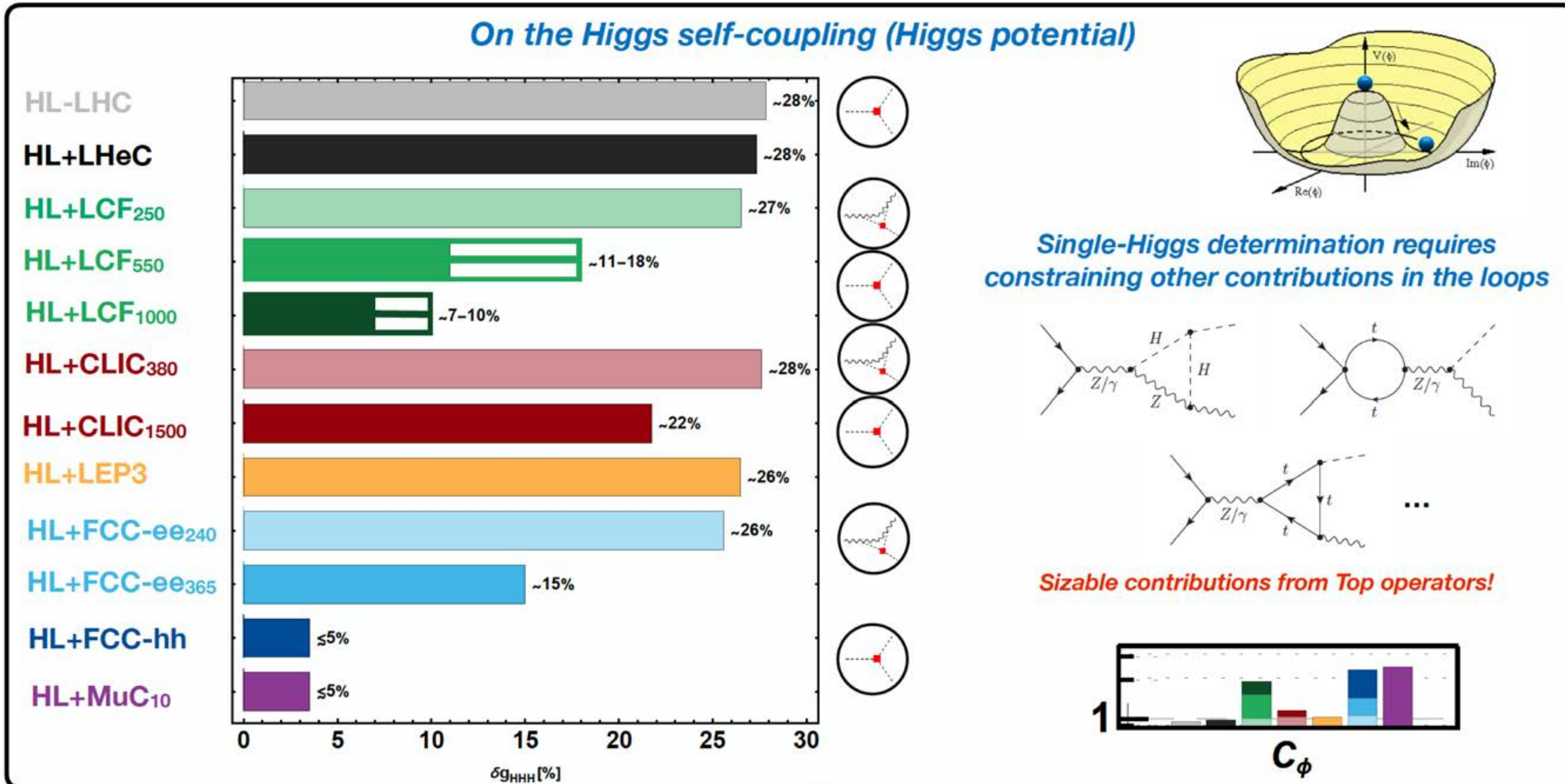
Higgs physics



Z pole physics



Electroweak Physics

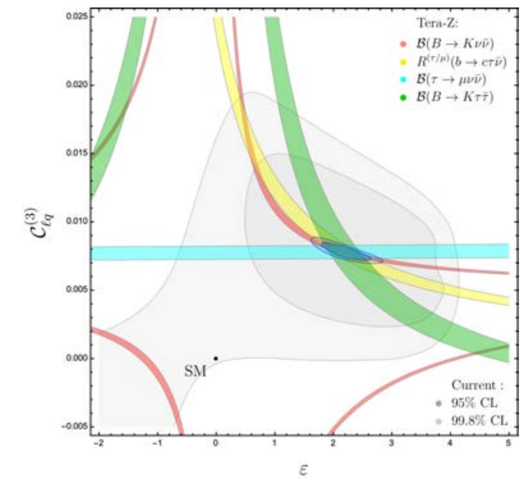


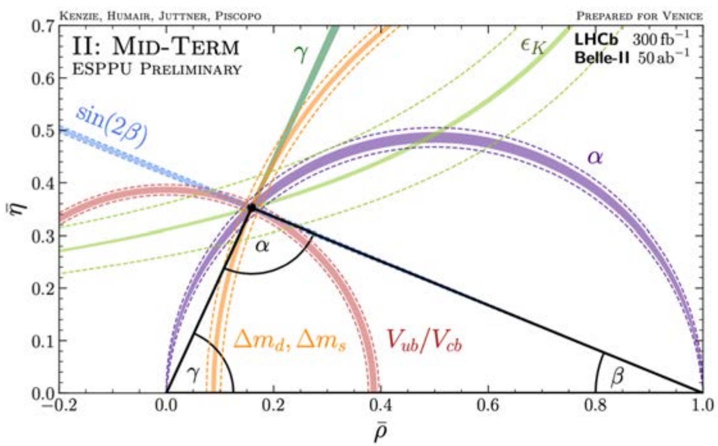
Flavour Physics

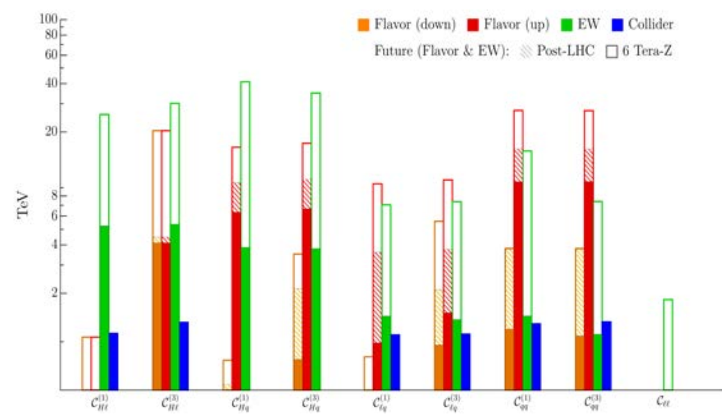
- Precision Higgs, electroweak, and flavour physics are three facets of for indirect discoveries
  → their **synergy is essential to maximise the discovery potential**

- B/D/tau physics: major improvements from full exploitation of available facilities up to 2040s (LHCb-II, ATLAS/CMS, Belle-II)
  Beyond that, **$6 \cdot 10^{12}$ Z^0 would provide a further major step forward**
  Giga-Z is not an option for flavour physics

- Support needed for theory (key role of Lattice QCD)



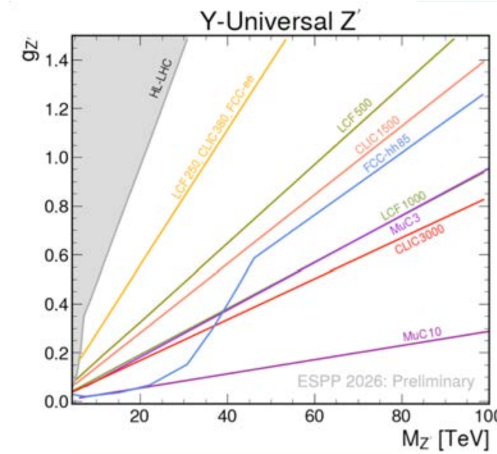




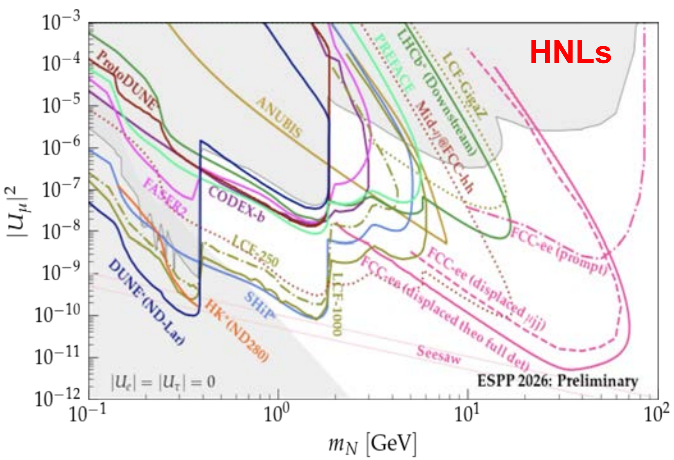
Searches for BSM Physics

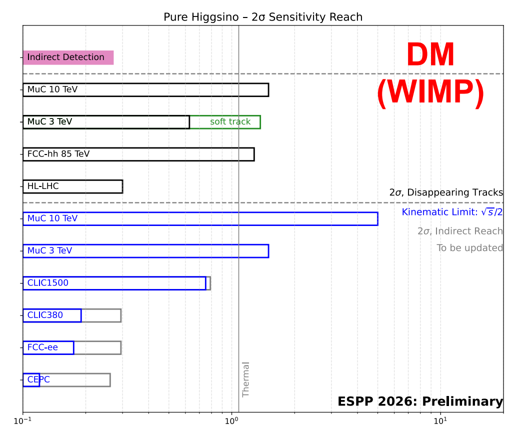
- Need for a future collider programme that can fully leverage both ***precision and energy****, covering the widest range of observables at different scales* – below, at and above the weak scale –

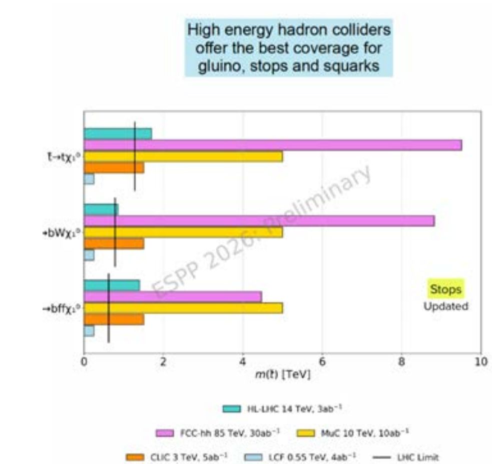
- Sensitivity to new physics below the EW scale, typically feebly interacting particles, requires strong synergy with dedicated experiments and fixed target experiments to provide maximal coverage



Exclusion reach of different colliders on the Y-universal Z' model parameters



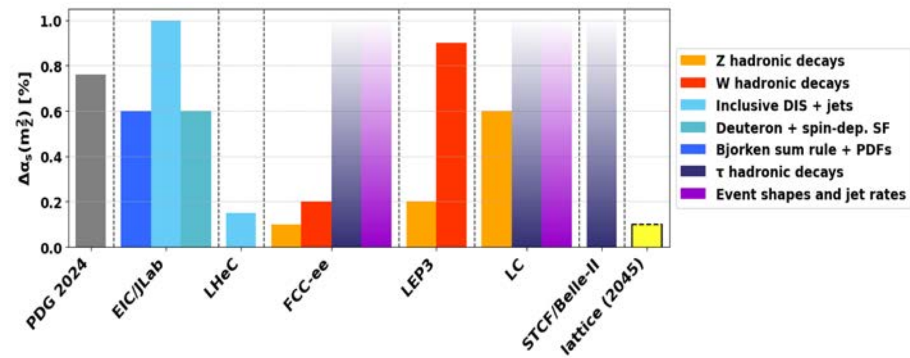




Precision QCD and partonic structure of protons

- The **strong coupling** is the least known amongst the four forces

  → Reaching 0.1% requires
  FCC-ee (10^{12} Z bosons), Lattice, LHeC, theory



- Significant progress in **higher order calculations** (N^nLO+N^nLL pQCQ) and in the understanding of non-perturbative QCD (hadronisation, colour reconnection) required

  → stress test of the SM (el.weak, Higgs, top, …)

- **Hadron structure** is of fundamental scientific interest;
  Uncertainties limit important Higgs and el.weak measurements at hadron colliders

  → significant improvements could / will be achieved at LHeC / EIC

Hot and dense QCD and QCD connections

- **HL-LHC:** rich physics programme in non-perturbative QCD
  (full exploitation already encouraged in 2020 strategy, ongoing)

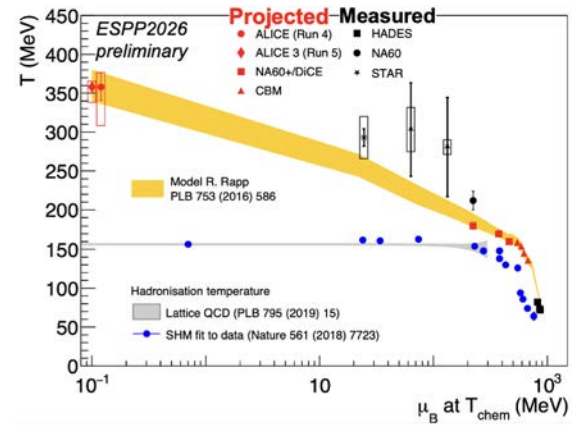
  - **High-temperature QCD**
    → quark-gluon plasma equilibration with heavy quarks,
    temperature and its time evolution

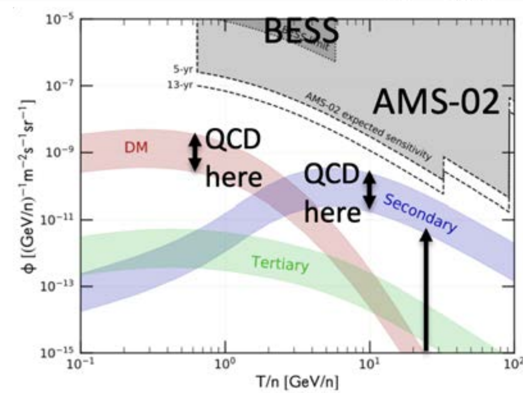
  - Hadron nature (exotica) and interactions
    (very relevant for astro(particle) physics)

- **Post-HL-LHC**: programme **at SPS** essential to keep HI activities ongoing at CERN, in addition to FAIR
  -complementary to LHC (high baryon-density)

  long-term goal: **continue HI-physics at FCC-hh**
  → allow for novel studies in high-T QCD

- Complementary possibilities: FPF, HIE-ISOLDE





Towards the recommendations on the next CERN flagship project

(1) Physics Potential

Physics Briefing Book (→ 30 Sept. 2025)

→ Assessment of overall Physics Potential **(ESG Working Group)**

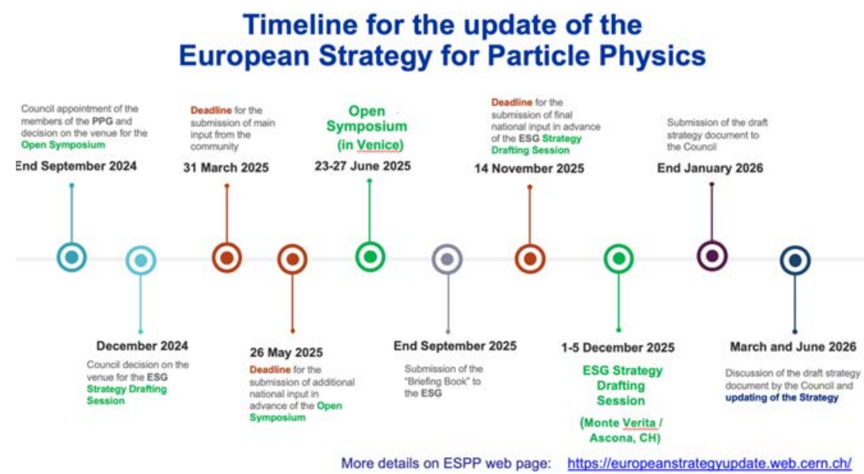
(2) Project assessment

(Technical feasibility, required R&D, risks, timeline, costs and human resources (including estimates for the associated detectors), environmental impact

(ESG working group)

(3) Final input by the National HEP communities

(→ 14 Nov. 2025)

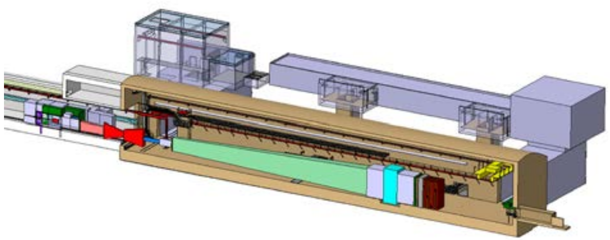


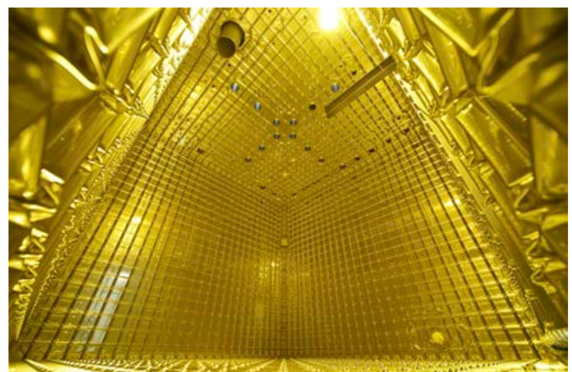
Diversity in the Physics Programme

Keeping **diversity in the particle physics** programme is essential: the next collider project should not come at the expense of a diverse scientific programme in Europe in terms of resources.

Ensuring a diverse and comprehensive physics programme is crucial for addressing fundamental physics questions, including fixed-target, neutrino, flavour, astroparticle and nuclear physics experiments

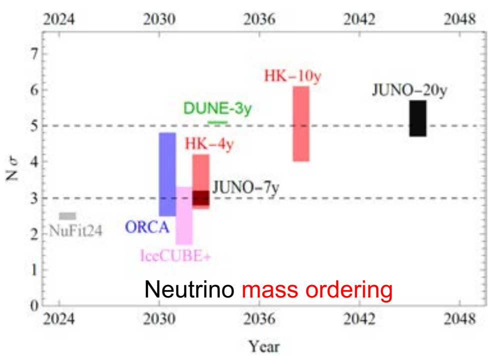
We do not know where new physics might be hiding → potential for groundbreaking discoveries

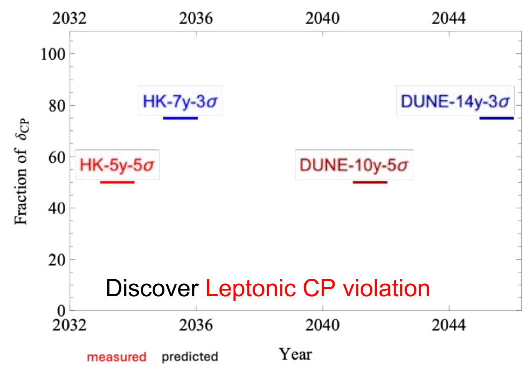


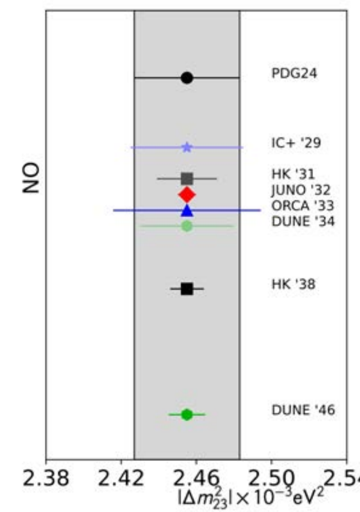


Neutrino Physics

- Neutrino sector is unfinished, compelling connection to new physics: major discoveries and high-impact science expected in the next decade!
- Neutrino experiments: unique facilities to search for new physics (both at high energy and feably interacting sectors) leading to rare events: proton decay, light sterile neutrinos, heavy neutral leptons, …

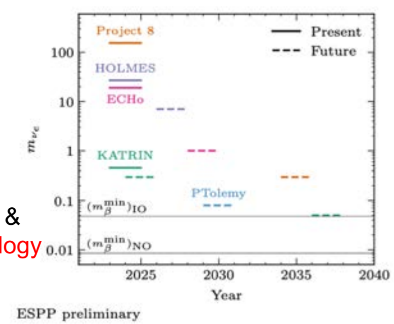


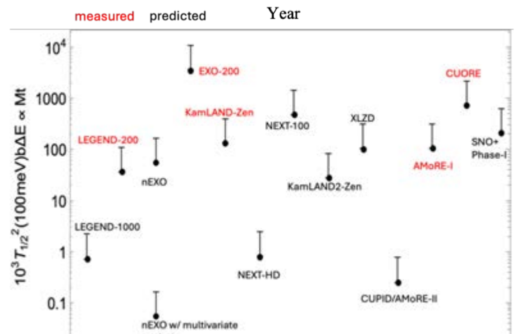




≤% precision in flavour parameters

Neutrino mass scale & interplay with cosmology





Majorana nature of neutrinos?
→ a new physics scale!

Challenges:
- Taming systematic uncertainties on fluxes and σ
- R&D for ultimate neutrino mass and $\beta\beta0\nu$

Dark Matter Searches

- Dark Matter is an important feature of particle physics;
  Both non-accelerator and accelerator searches are needed in any scenario

- **Key messages:**
  - Flexibility should be kept on the experimental side to be able to respond to new developments in phenomenology

  - No one facility or approach can do it all. Important progress will continue to be made by relatively small / rapid projects

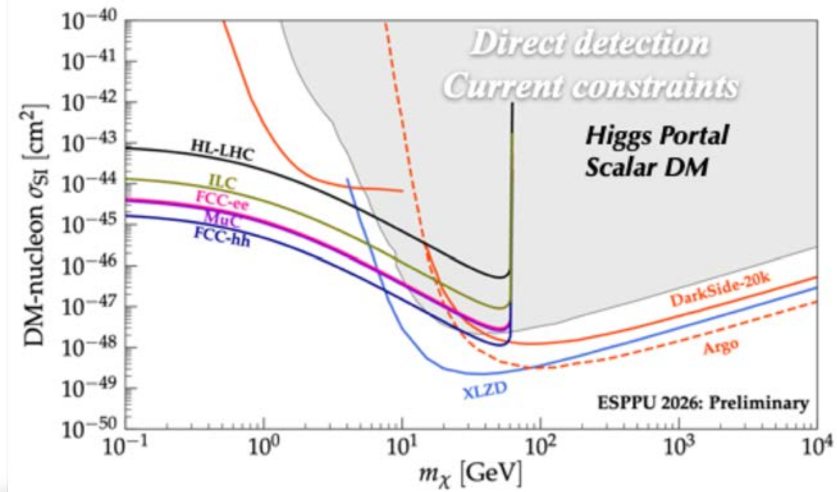
  - A convincing discovery will require **confirmation by multiple experiments and techniques** with independent systematics

- A mix of small and large projects is required

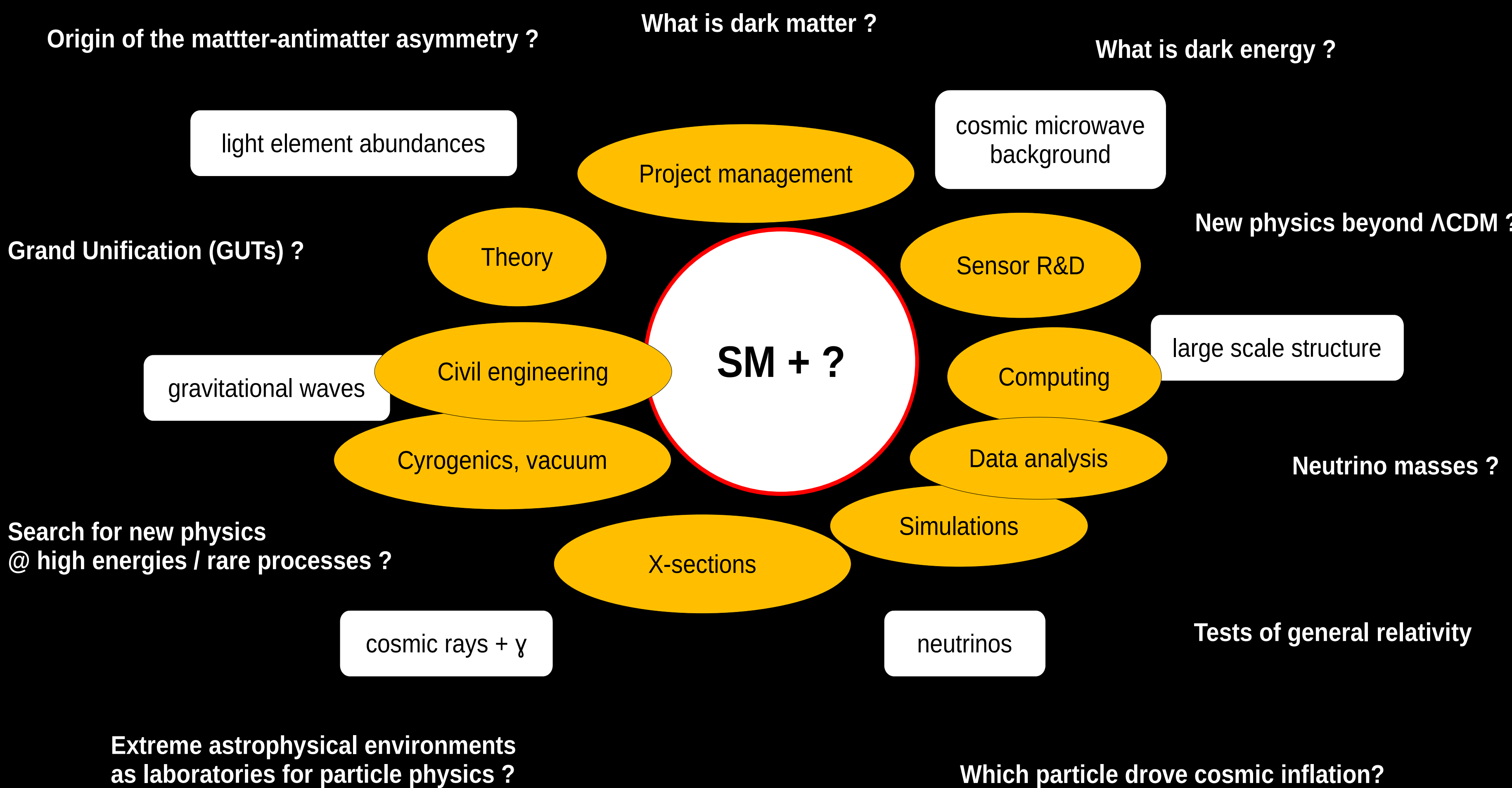
  - Major initiatives in the "traditional" dark matter thrusts in liquid nobles and axion haloscopes

  - A plethora of small scale approaches are a strong technology incubator and relatively small/rapid searches

  - Complemented by searches at colliders



Cosmic messengers for particle physics



R&D on Accelerator Technologies

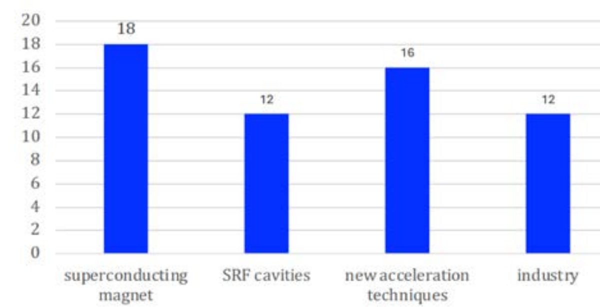
2020 Strategy Update:

Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders.
It is It is also a powerful driver for many accelerator-based fields of science and industry. The technologies under consideration include **high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs.**

Accelerator R&D remains a high-priority research field!

Priorities as seen by the national HEP communities:

- **Superconducting magnet technology:**
  (especially high-temperature superconductors, HTS)
- **High-performance SRF cavities**
  (optimisation, higher gradients, quality factors, ..)
- **New acceleration techniques**
  (plasma wakefields, muon colliders, energy recovery linacs, ...)



Priorities as seen by the national HEP communities

Key messages on Accelerator R&D

- Accelerator R&D on **technologies** (magnets, RF systems, …) remains a **high priority** and appropriate investments have to be made; the developments on **advanced concepts** should continue with adequate effort to prepare future projects

- The European Accelerator Roadmap of LDG should be continued with an updated program; **future R&D lines must be aligned with the needs of the highest priority projects** defined in the 2026 strategy

- It is essential to set up a **coherent programme between CERN, the Large National Laboratories in Europe and with international partners** to address the major topics (ESG Working Group)

- Industry needs to be involved **as early as possible** and production be industrialised wherever possible

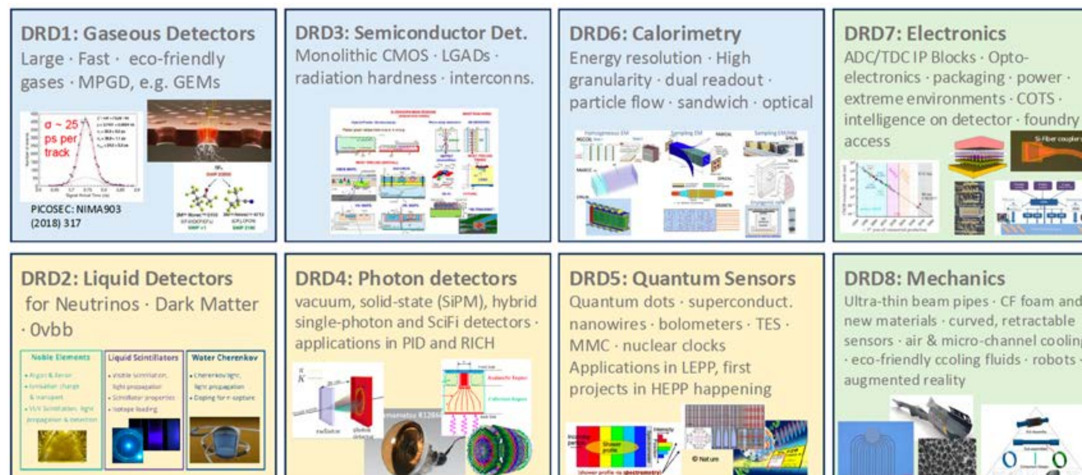
- Besides of key performance parameters also **energy efficiency and sustainability aspects** must be optimized with high priority

R&D on Detector Technologies

2020 Strategy Update:

The ***success of particle physics experiments relies on innovative instrumentation and state-of-the-art infrastructures.*** *To prepare and realise future experimental research programmes, the community must* ***maintain a strong focus on instrumentation****.* ***Detector R&D programmes and associated infrastructures should be supported at CERN, national institutes, laboratories and universities****. Synergies between the needs of different scientific fields and industry should be identified and exploited to boost efficiency in the development process and increase opportunities for more technology transfer benefiting society at large.*

- Eight **Detector R&D Collaborations** (DRDs) have been set up, following the ECFA Detector R&D Roadmap, **focussing on strategic R&D**
- Still in infancy, but expected to grow, once HL-LHC is built
- **General Strategic recommendations** have not yet all been implemented



Key messages on Detector R&D

- Detector R&D remains a **high priority** and adequate investments have to be made, also for detectors beyond colliders

- DRD Collaborations successfully established, however, **more solid funding support** needs to be secured

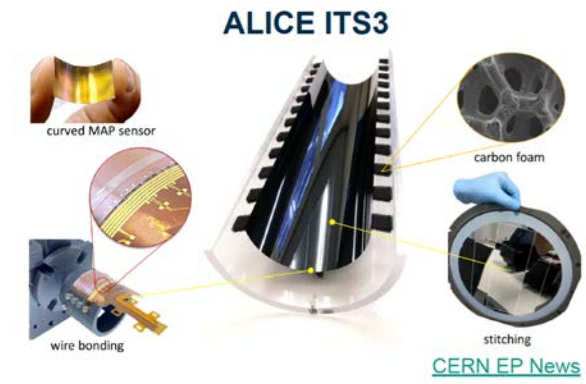
- Significant **technological limitations and challenges** to overcome for future projects;

  - Integration into and extensions of DRDs to be considered
    (superconducting exp. magnets, new TDAQ methods, microelectronics,…)

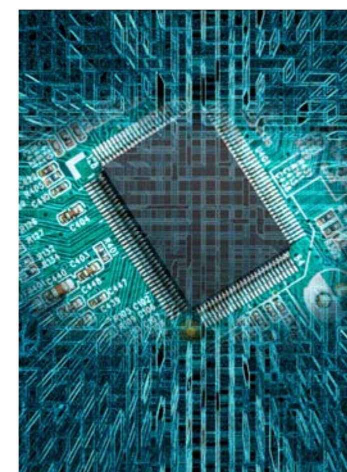
  - Implementation of **General Strategic Recommendations** should be completed, maybe even extended with new ones;

  - Strengthening industrial partnership
    (→ helps to access key technologies, microelectronic challenge)

- **New ideas**, may turn out as potential **game changers** (AI, second quantum revolution)

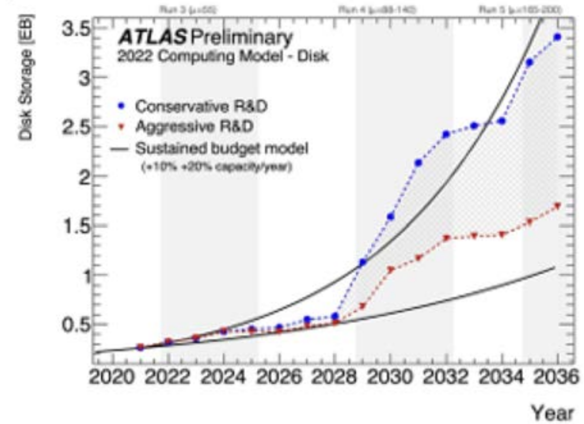


Ongoing upgrades also provide technology demonstrators



Future HEP Computing

The goal of the ongoing software and computing development is to facilitate the successful and timely delivery of the best possible physics results



- HL-LHC computing is not an easy journey, but it should be feasible, provided an **intense and uninterrupted R&D** is carried out.
- Likewise, for any future project chosen, the required software and computing should be feasible, **provided adequate person power and funding are available**
- **Successful projects and collaborations** such as WLCG, GEANT, ROOT, KEY4HEP, … and their deliverables and services **need to be sustained**
- Make sure not to miss the opportunities to **adopt new new technologies**, particularly GPUs and AI, as well as Quantum Computing on a longer timeframe.
- We may not have a clear picture what our computing environment will look like 40 years from now, **but we have an excellent record to adapt and use whatever is available to its full potential.**

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A collaborator setting up the event display, showing an HL-LHC event in 1955

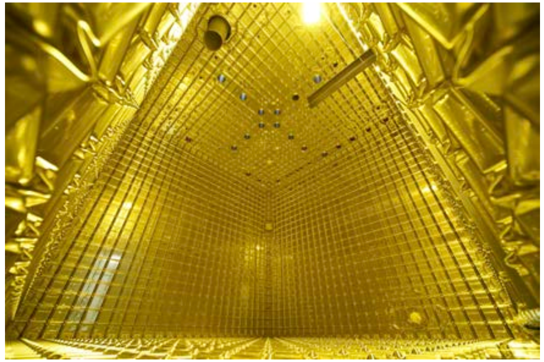
4.5 megabytes of data in 62,500 punched cards (1955) = 1 HL-LHC RAW event (collected at 10 kHz)

From T. Boccali & B. Kersevan

Relations to other fields of physics

- Many projects in neutrino and astroparticle physics stress the importance of CERN's support for this science.
  Projects in these areas grow in scale and complexity
  (neutrino telescopes, neutrinoless double β decay, Dark Matter and Gravitational Wave detectors)

- It is argued that an expansion of CERN's support for these neighbouring fields could help to exploit the synergies further by transferring CERN's technical and managerial knowhow.



- CERN already has a strong Nuclear Physics programme and is involved in astroparticle physics projects through its unique technologies

- Most Member States national communities advocate maintaining the involvement at the present level; CERN must focus and successfully realise the core activities on accelerator-based particle physics
  (HL-LHC, phase-II detector upgrades, future collider project, ..)

- The technical/engineering/purchasing capabilities of CERN are already much stressed. A significant engagement into other areas would require as well a change of the CERN convention
  → The issue will be further discussed by the Strategy Group

Education, Career Development, Outreach

General guiding principles

Outreach and Communication

- Strengthen public trust in science through outreach that fosters critical thinking, counters misinformation and inspires future scientist
- Boost interest in STEM by expanding outreach
- Communicate effectively and transparently to build public and political support for the next European flagship project

Training and Education

- Strengthen training in instrumentation
- Establish closer ties with industry
- Integrate modern physics into school curricula

Open Science

- Promote Open Access to scientific knowledge
- Encourage the use of Open Data in education, outreach, and citizen science

Many good practices and suggestions received; they will be further discussed by ESG

Important: - Strengthen training in instrumentation
- Closer ties with industry

- Regarding Career Development: short-term contracts, frequent relocations, and uncertain job perspectives are perceived as major issues

Sustainability

- Awareness has reached the community / CERN / institutes / labs
- The evaluation of future HEP projects should take into account principles of environmental sustainability

  (Life Cycle Analyses)

- Many good examples of R&D efforts of the HEP community revolving around technological advances (accelerators, detectors, computing…) towards mitigating CO_2 emissions as much as possible;

  These efforts must be continued and strengthened;

  Sustainability issues are already addressed in the proposed flagship accelerator projects

Domain	Value in reference year (2018)	Current status	Target for 2030
Scope 1 emissions (tCO_2e)	192 100	170 100 (2023)	➢ Reduce by 50% w.r.t. 2018
Electricity consumption (GWh)	1252	1142 (2023) 1290 (estimation 2024)	➢ Max 1500 ➢ 10% renewable
Gas consumption (GWh)	61 (average 2016-2018)	39 (2024)	➢ Reduce by 60% w.r.t. 2018

Photo Trevor Sherwin

From F. Gianotti‘s talk

Photo Trevor Sherwin

Final Words

Over the past years very significant progress has been made towards the realisation of the next flagship project at CERN

- FCC: Successful completion of the Feasibility Study; No technical showstoppers identified

- Overwhelming support for the integrated FCC-ee/hh programme by the HEP communities in the CERN Member and Associate Member states and beyond;

  The strong support is largely based on the superb physics potential and the long-term prospects (FCC-ee /hh)

- Discussions on the financial feasibility are ongoing (CERN management and Council)

Photo Trevor Sherwin

Final Words

Discussions on the prioritisation of alternative options are ongoing

- Linear colliders (LCF, CLIC) present as well mature options for a Higgs factory at CERN
- LEP3 and LHeC could be considered as “intermediate” collider projects
- The differences in the physics potential (→ Physics Briefing Book), review of the technical readiness and the final input from the national HEP communities (due by 14 Nov.) will be important ingredients in the final recommendations by the European Strategy Group

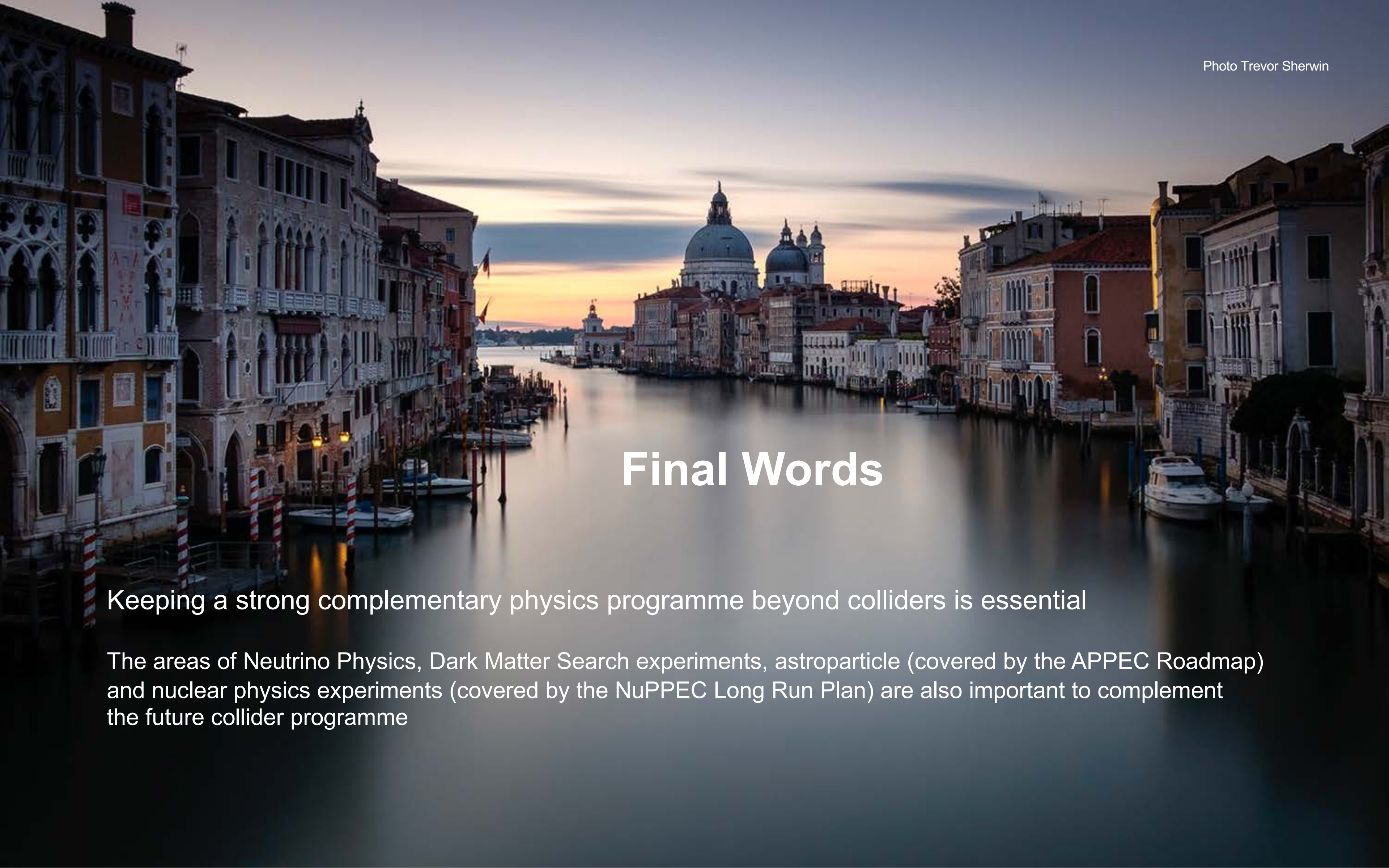


Photo Trevor Sherwin

Final Words

Keeping a strong complementary physics programme beyond colliders is essential

The areas of Neutrino Physics, Dark Matter Search experiments, astroparticle (covered by the APPEC Roadmap) and nuclear physics experiments (covered by the NuPPEC Long Run Plan) are also important to complement the future collider programme

Photo Trevor Sherwin

Huge Thanks to

- **All participants** for the active and constructive participation in this important symposium

- All **members of the PPG working groups**, especially the **co-conveners, scientific secretaries** and **discussion leaders** for the excellent preparation of the programme and for their impressive talks on physics and technologies

- **Sandra Malvezzi** and the **Local Organising Team**, and **INFN** for the great hospitality and for the excellent organisation of the symposium

Huge Thanks!

Physics Preparatory Group, co-conveners, scientific secretaries, and the Working Groups

Thanks to Ulrich Husemann for the “technical support”

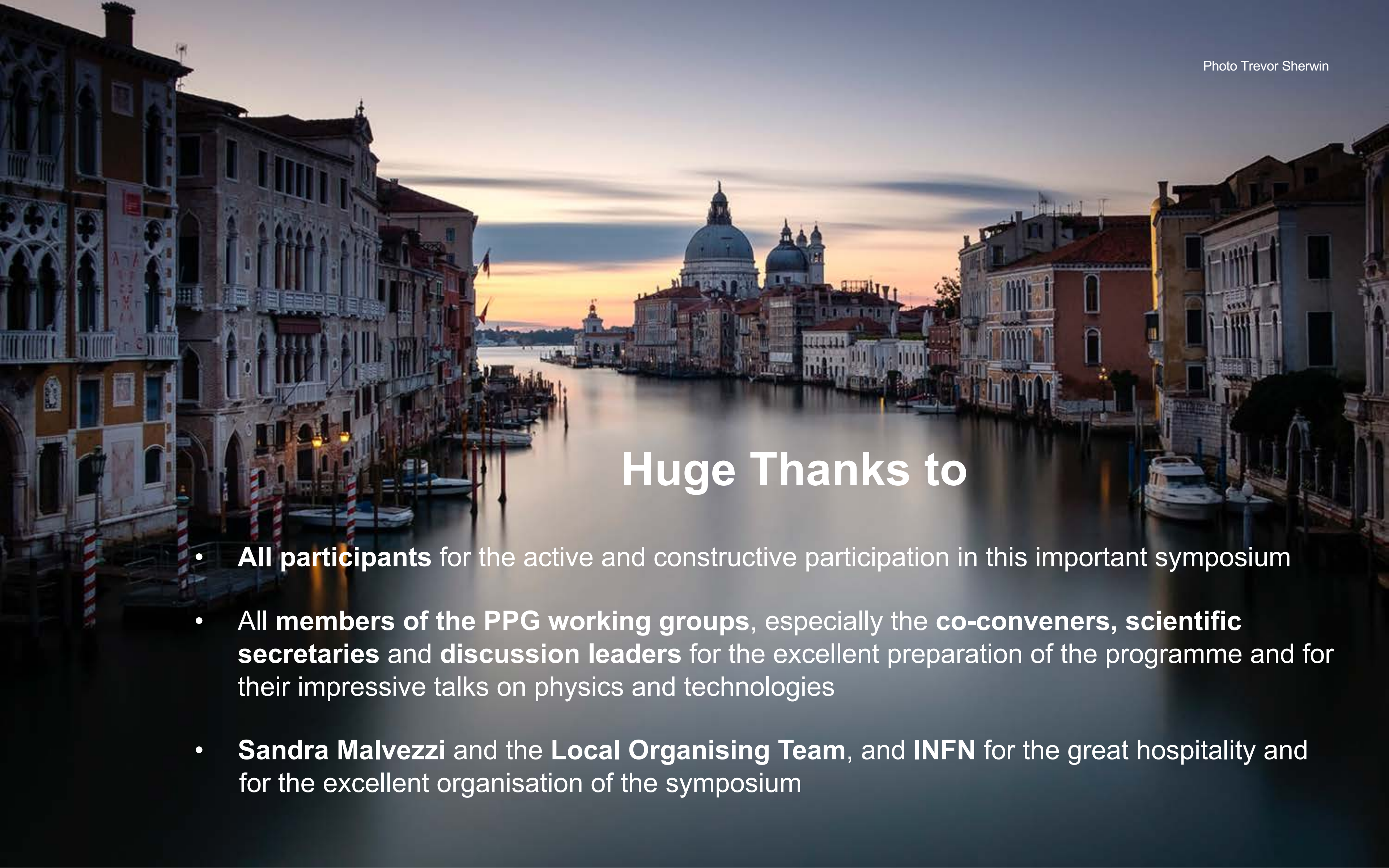


Photo Trevor Sherwin

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