Preparing for the Future

The 2026 Update of the European Strategy for Particle Physics

Ulrich Husemann
Karlsruhe Institute of Technology
Frauenwörth Abbey, September 14–19, 2025

Image credit: Adobe Stock

Lecture Outline

… and some preliminary remarks

A **difficult lecture** to give:

- Lots of material, and a moving target
- No textbook or blueprint
- Isn't lecturing about structures and processes super boring?

Three parts:

I. Where will particle physics be in 2040?

II. What is strategic planning and why should I care?

III. Update of the European Strategy for Particle Physics: what's going on now?

Image credit: Adobe Stock

A Word of Caution

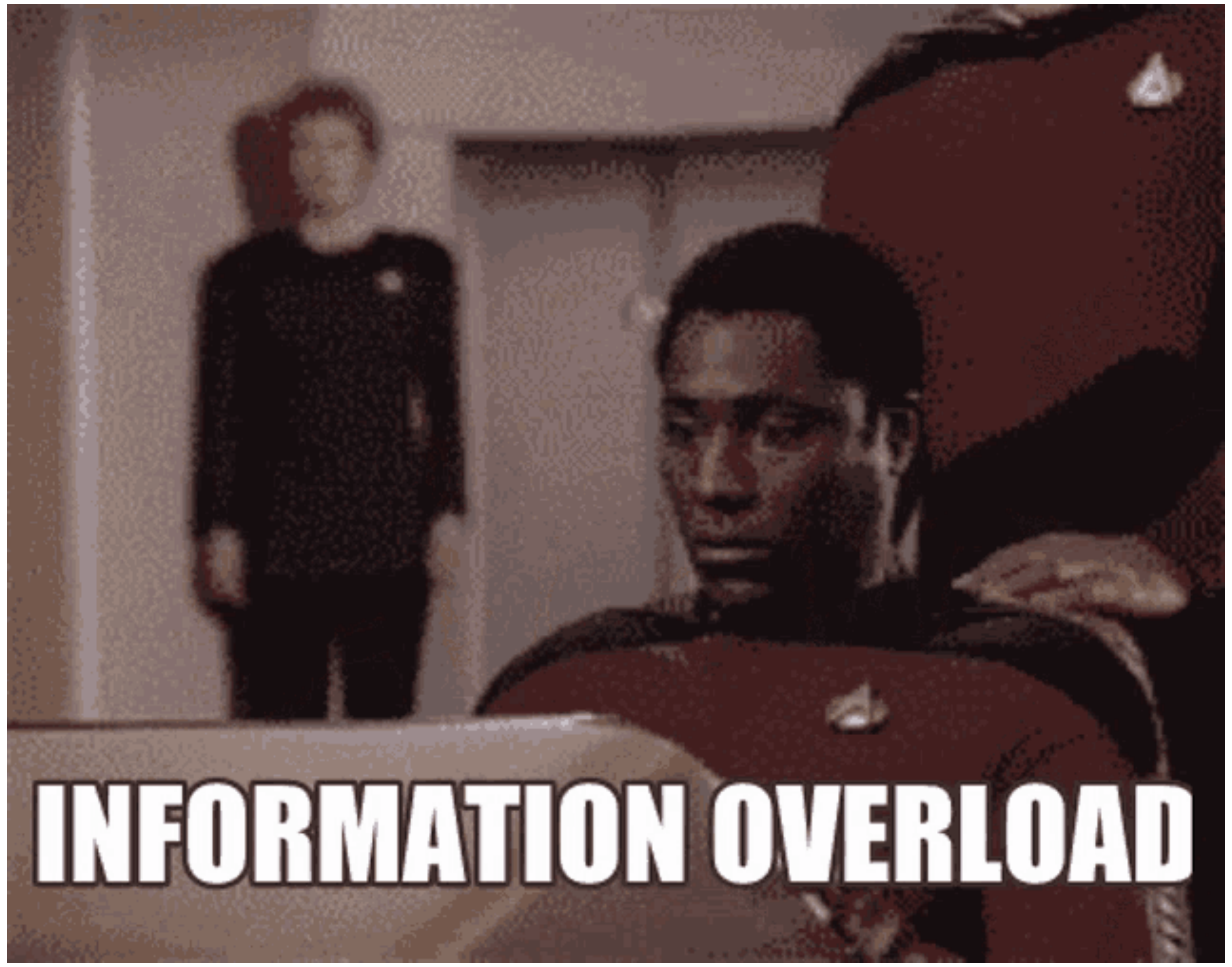
This Lecture May Be Information Overload!

Need **broad physics knowledge** to understand today's particle physics landscape

In just three lectures, I will often have no choice but to **drop names with little explanation**
→ please **ask questions** at any time!

Please feel encouraged to:

- **Stay informed** about the full field (don't focus on your thesis topic too narrowly)
- Talk to your fellow doctoral researchers and **educate yourselves** (peer instruction is fun and extremely effective)



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Part I: Where will particle physics be in 2040?

European Strategy
for Particle Physics

Open Questions in Particle Physics

In 2025

What is the **structure of the vacuum**?

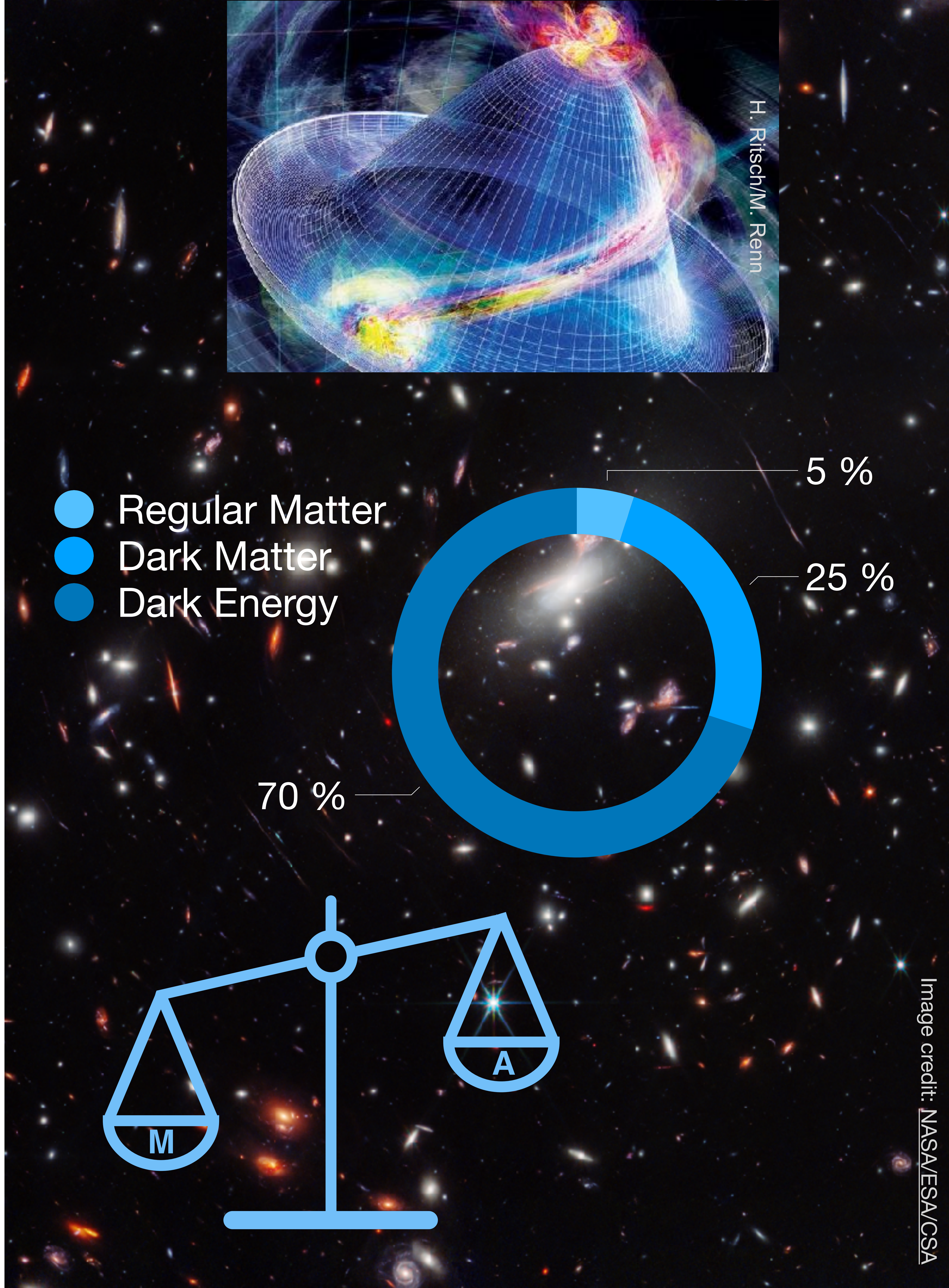
The Higgs potential.

What is the **energy content** of the universe?

Dark matter and dark energy.

Why is there so much **more matter than antimatter** in the universe?

Violation of the charge-parity (CP) symmetry.



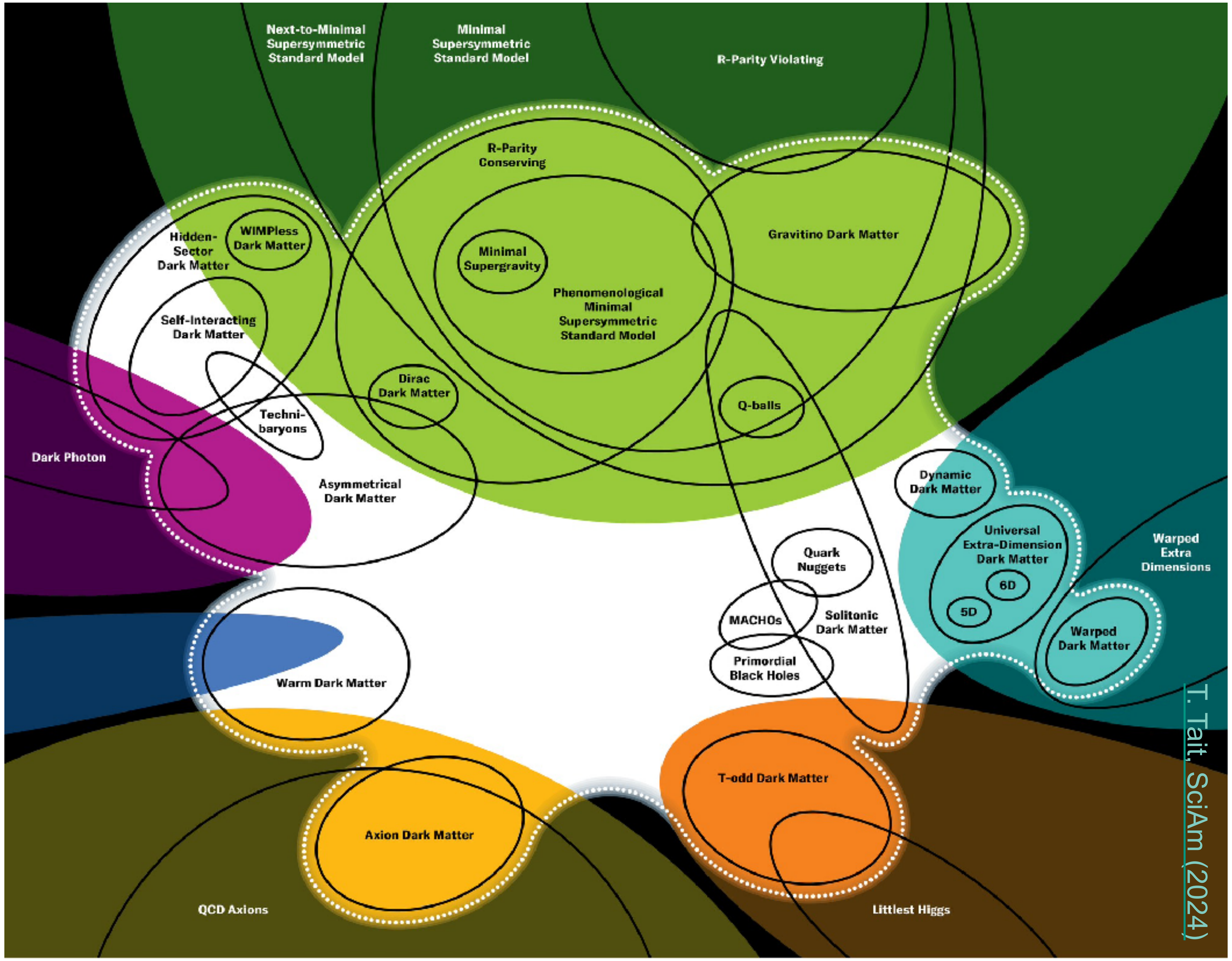
Standard Model and Beyond

The Physics Landscape

Traditional split of topics:

- **Electroweak** physics (incl. Higgs)
- **Strong** interactions (QCD)
- **Heavy flavor** physics (incl. CP)
- **Neutrino** physics (incl. CP?)
- **Beyond** the standard model (BSM)
- **Dark matter** (DM) and dark sector

Many **connections** between these topics, e.g., standard model (SM) measurements may imply search for BSM physics, DM is BSM physics



T. Tait, SciAm (2024)

Addressing the Open Questions

The Experimental Landscape

Experiments **at particle accelerators**:

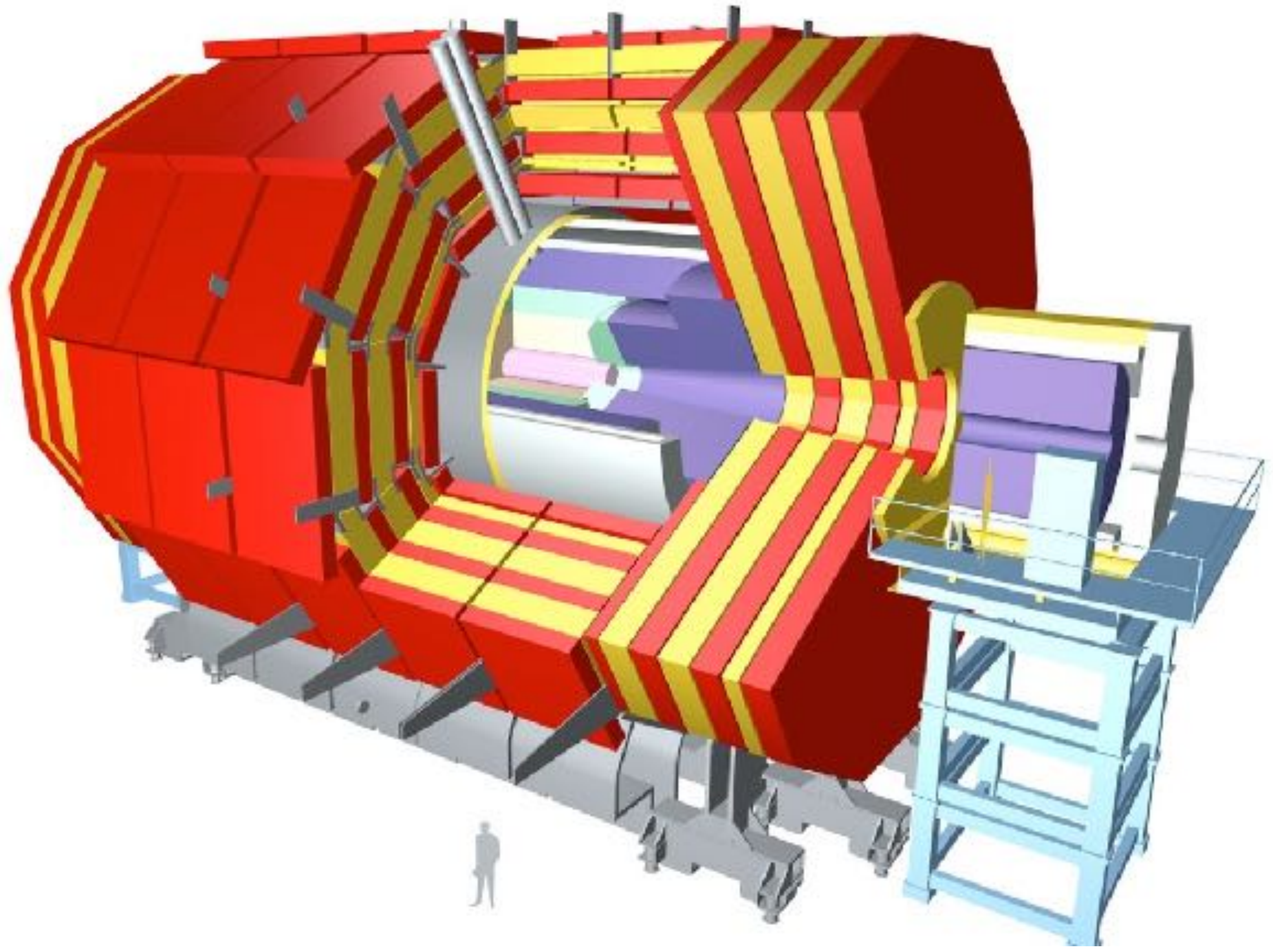
- Big **particle colliders**: the LHC (since 2009/2010)
- Much more diverse landscape: **flavor factories** (beauty and charm); **pion**, **kaon** and **muon beams**; **beam dumps**

Experimental program **beyond accelerators** even more diverse: dark sector, neutrinos, rare event searches

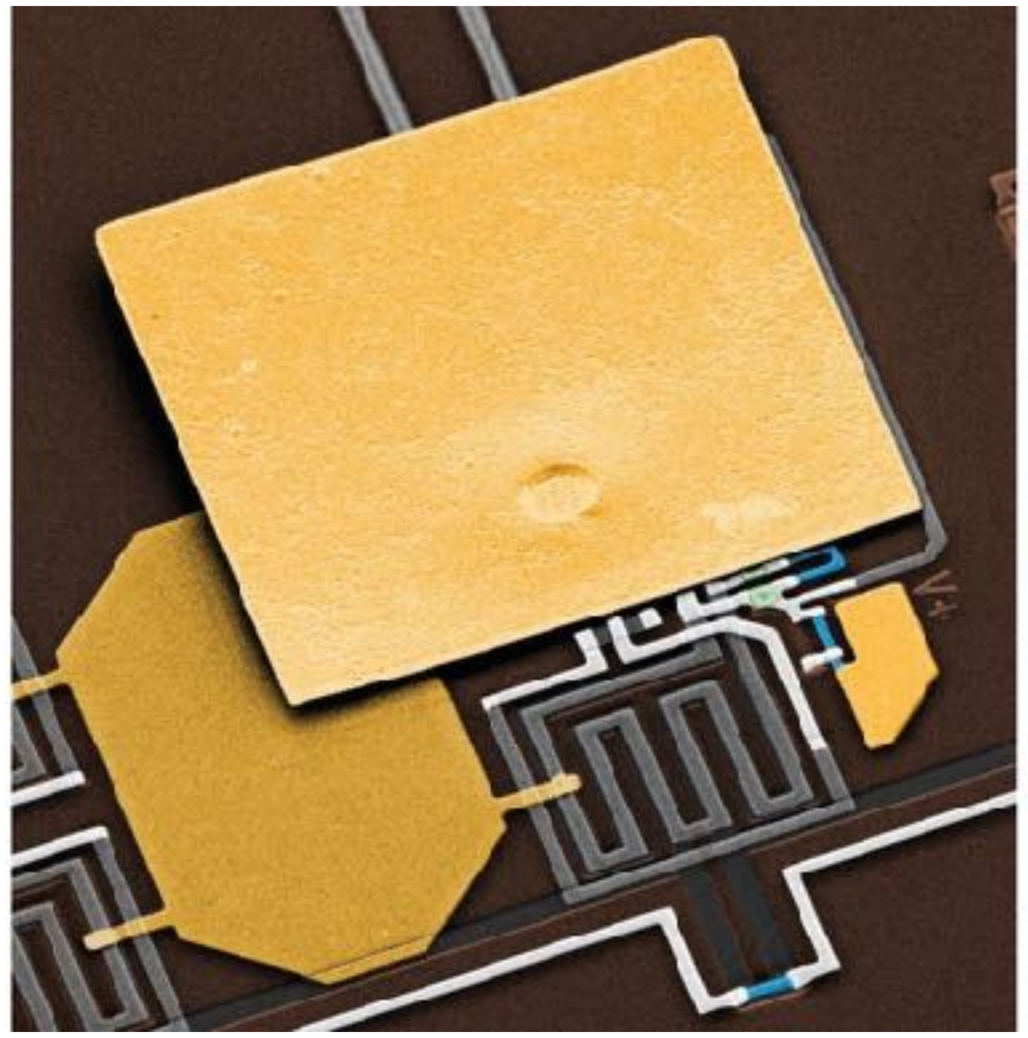
Instrumentation and **computing** technologies: broad range of experimental requirements and challenges

Detector physics is also physics!

CMS Experiment



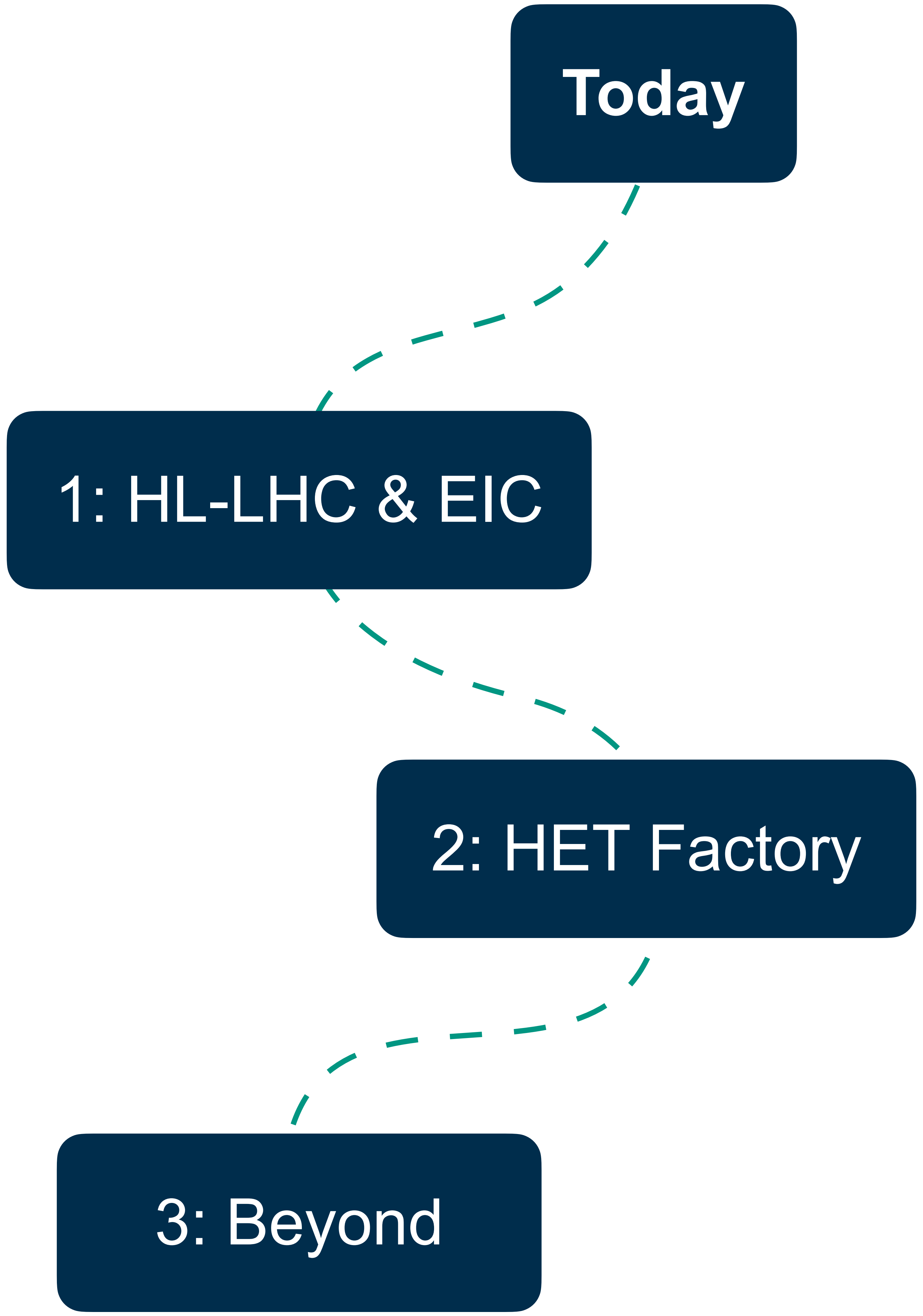
Quantum Sensor (MMC)

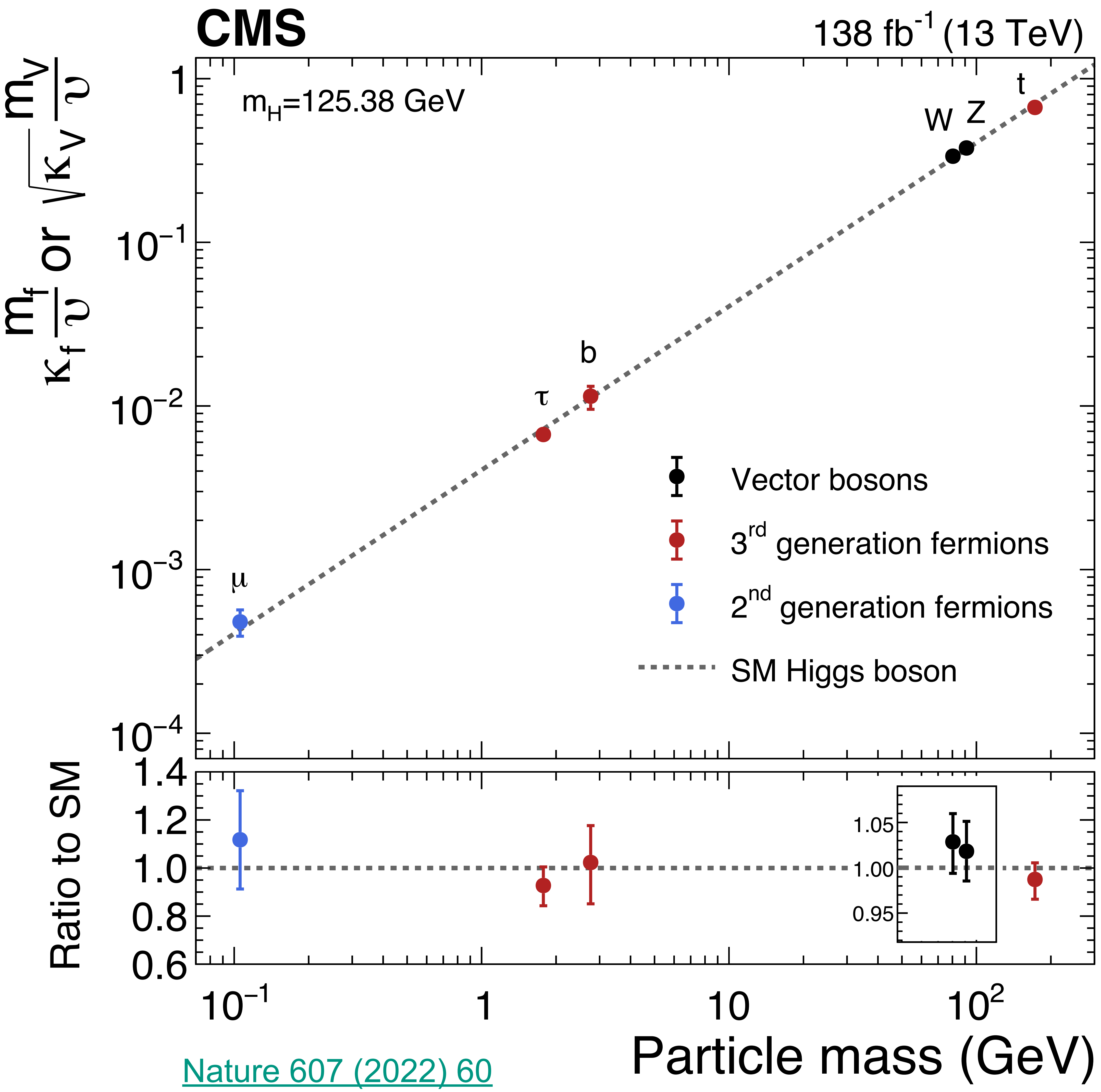


App.Phys.Lett. 124 (2024) 032601

Where are we right now in particle physics?

Higgs-Boson: Coupling vs. Mass

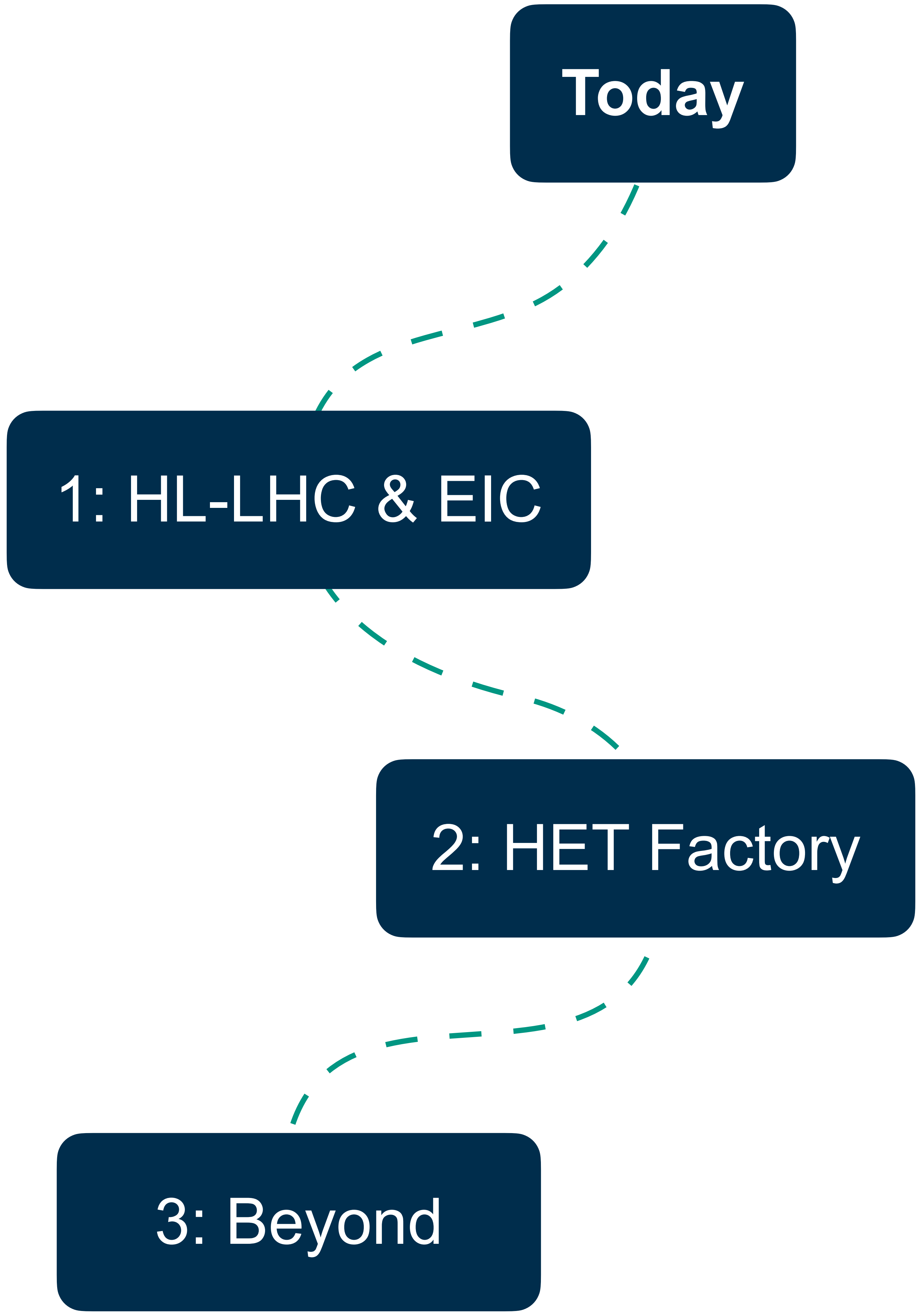


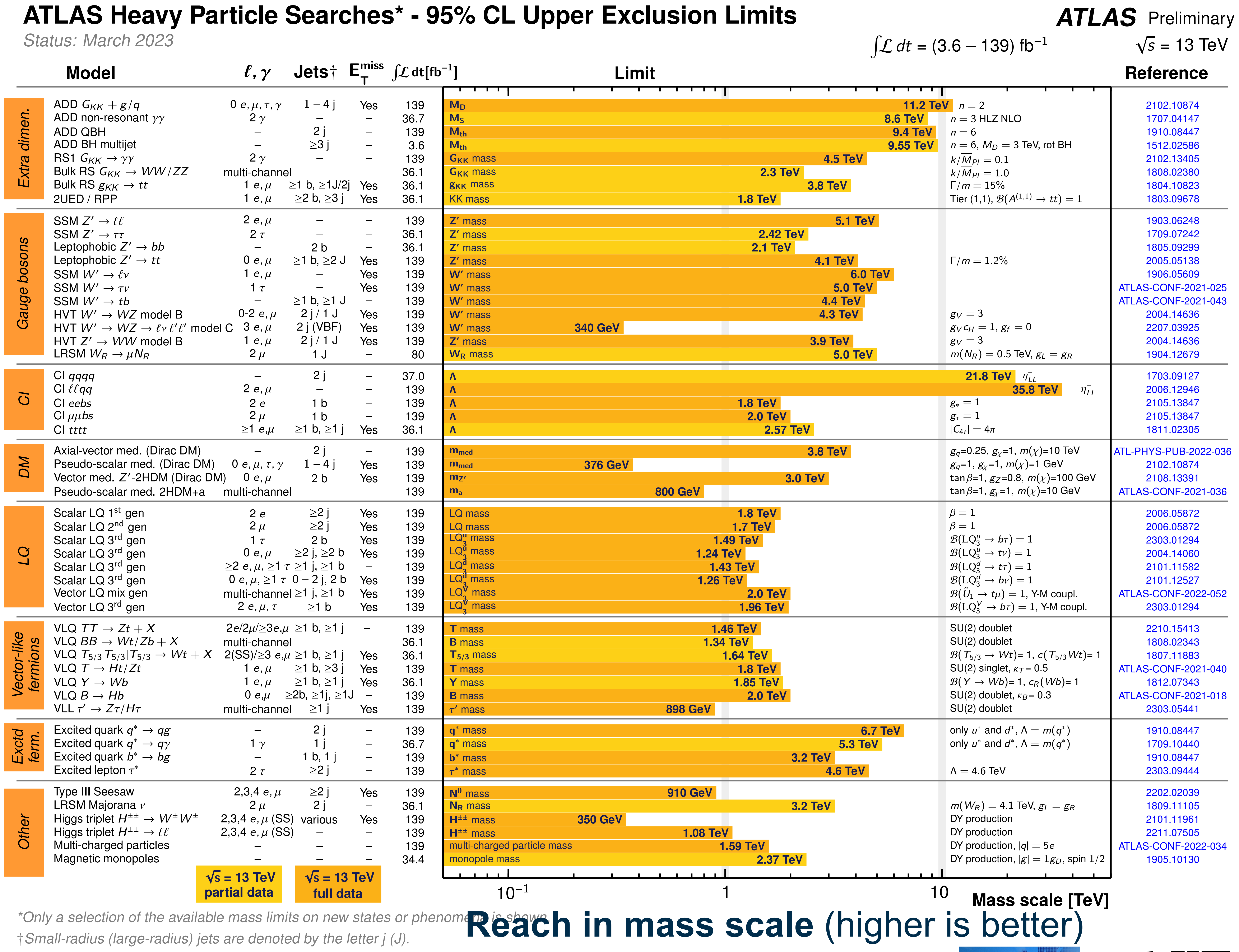


Nature 607 (2022) 60

Where are we right now in particle physics?

Heavy Particle Mass Limits





Reach in mass scale (higher is better)

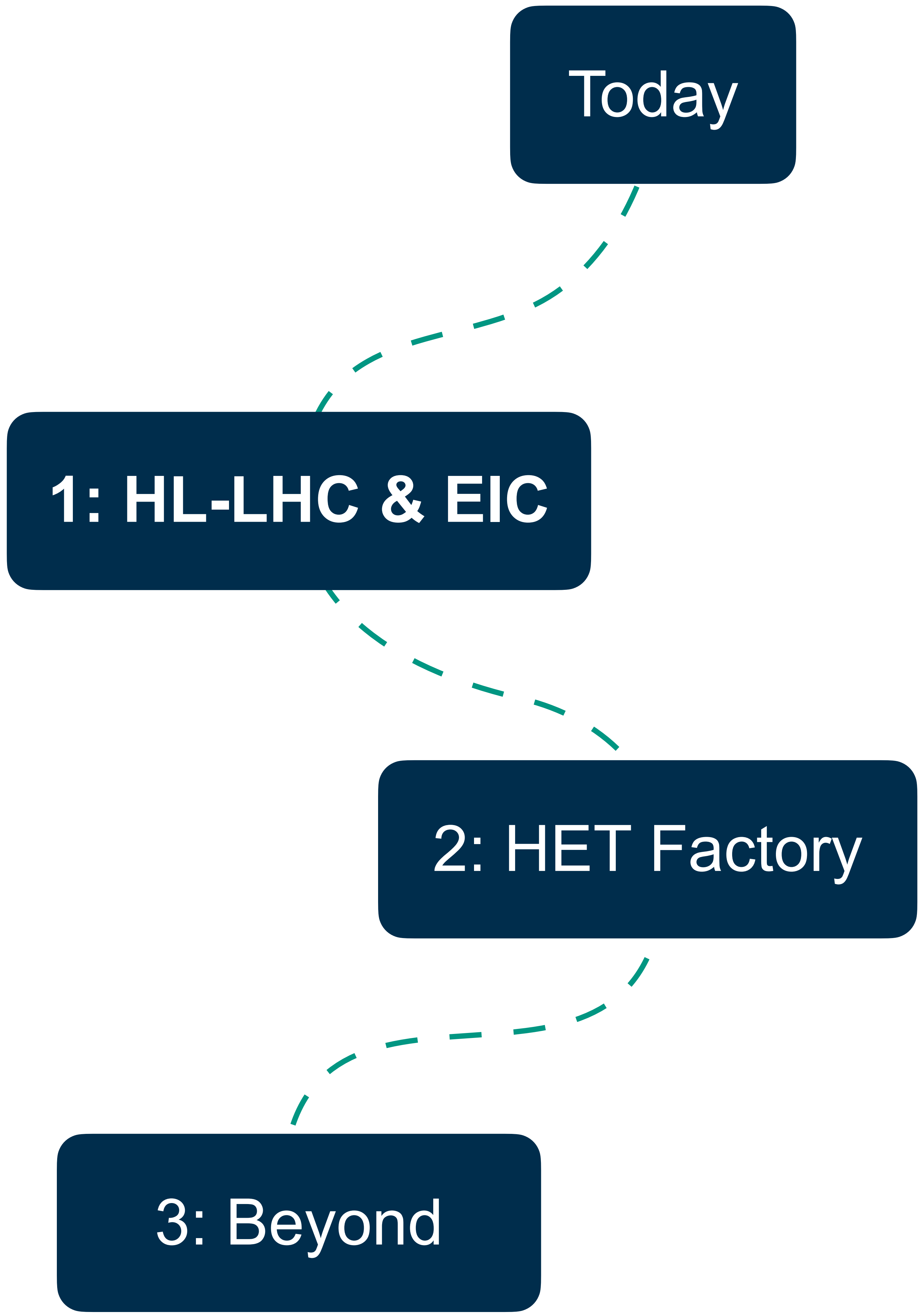
ATL-PHYS-PUB-2023-008

Where will particle physics be in the 2040s?

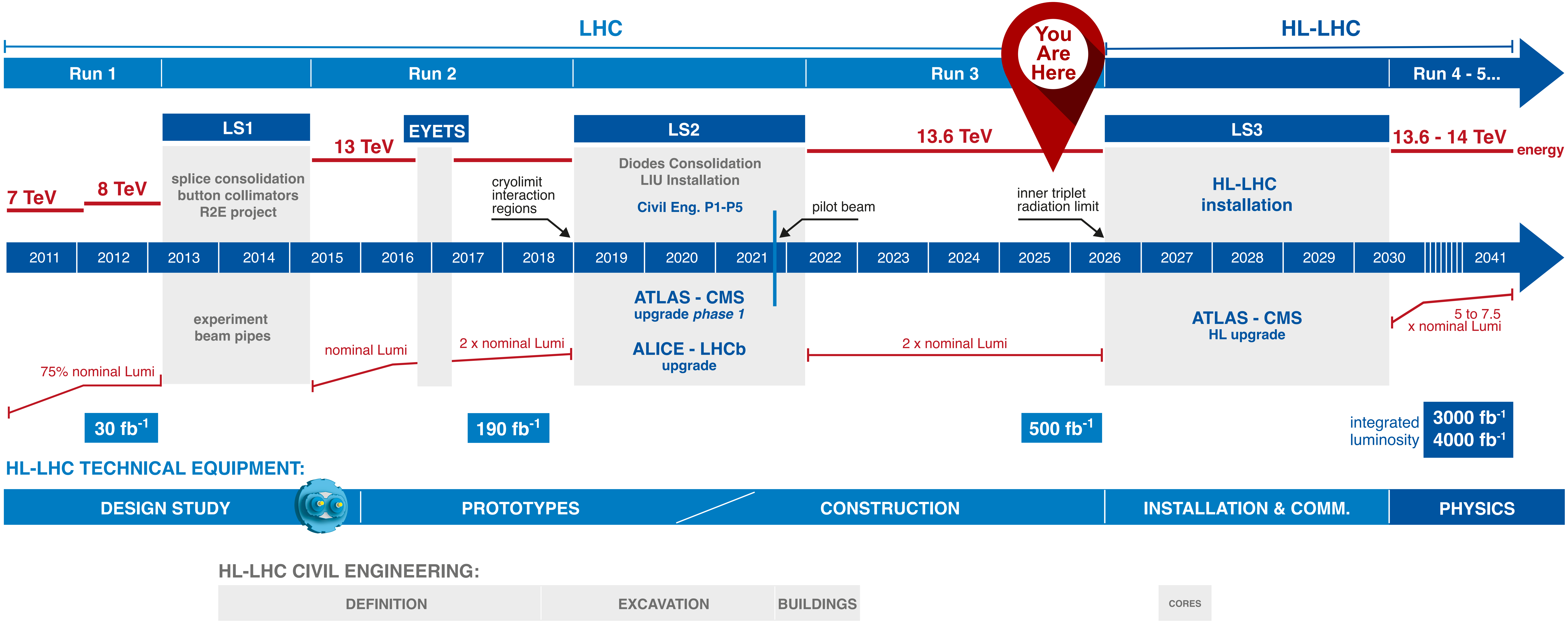
Colliders

European flagship: **HL-LHC** @ CERN
→ high-luminosity upgrade of the LHC

- LHC **accelerator upgrades**
  → 3.5× instantaneous luminosity, 7× integrated luminosity
- LHC **detector upgrades**: keep up with accelerator upgrades, introduce **innovative instrumentation**



LHC / HL-LHC Plan



https://hilumilhc.web.cern.ch/content/hl-lhc-project

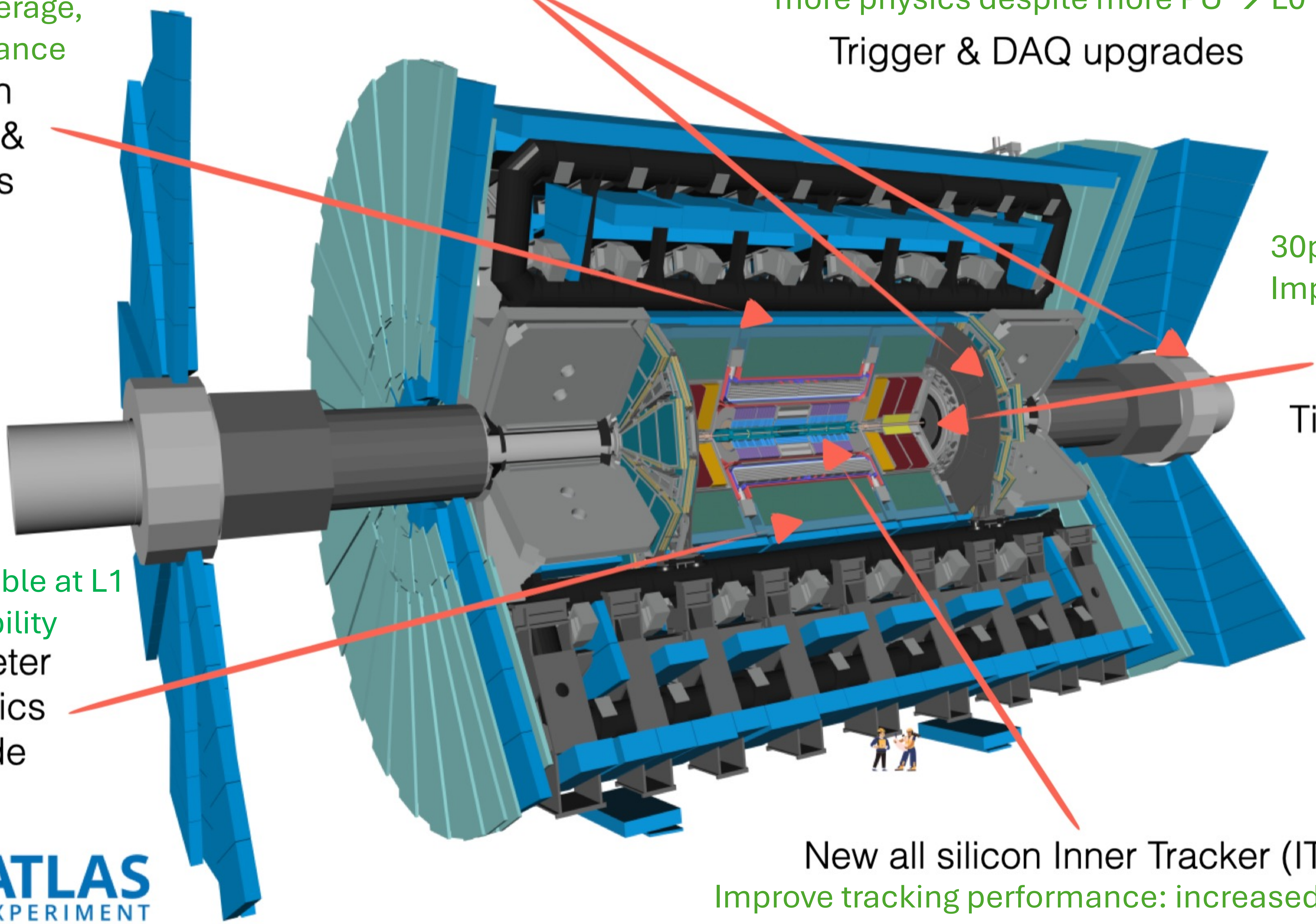
The Phase II upgrade program

ATL-UPGRADE-PUB-2025-001/

1% luminosity accuracy
New and upgraded forward and luminosity detectors

Improve trigger performance/rate:
more physics despite more PU → L0 trigger at 1 MHz, EF 10kHz
Trigger & DAQ upgrades

Improve muon trigger coverage, electronics and performance
New muon chambers & electronics



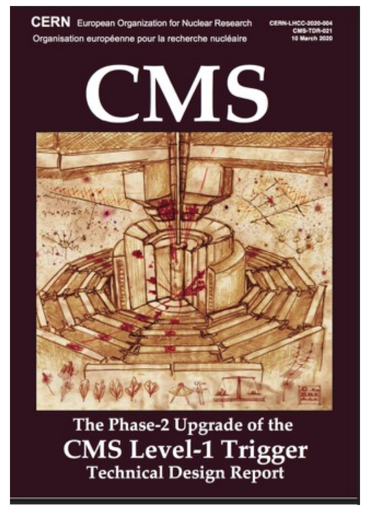
30ps time resolution per track
Improve PU rejection in forward region
New High Granularity Timing Detector (HGTD)

Full granularity data accessible at L1 trigger, increased rate capability
Calorimeter electronics upgrade

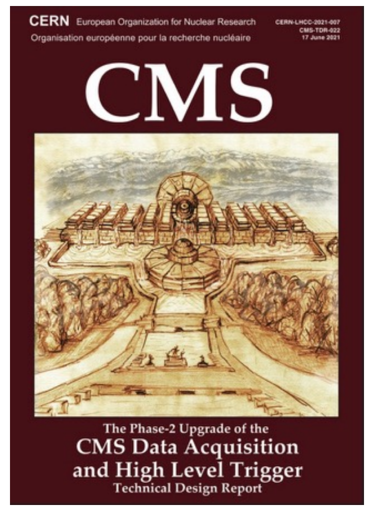
New all silicon Inner Tracker (ITk)
Improve tracking performance: increased coverage, reduced occupancy, better track p_T resolution

F. Cerutti, EPS HEP 2025

CMS Upgrade Projects

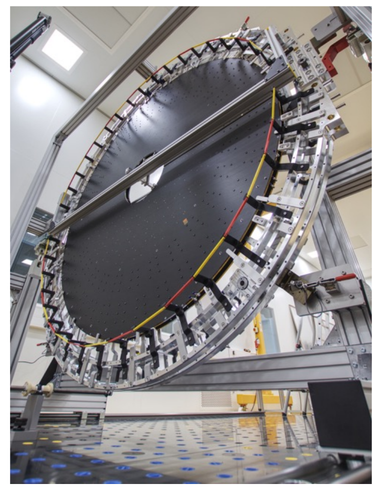


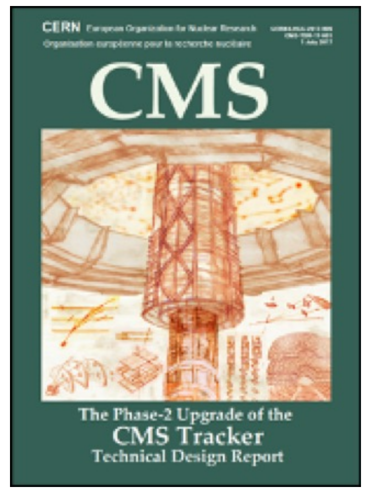
L1-Trigger
https://cds.cern.ch/record/2714892
- Tracks in L1-Trigger at 40 MHz
- Particle Flow selection
- 750 kHz L1 output
- 40 MHz data scouting



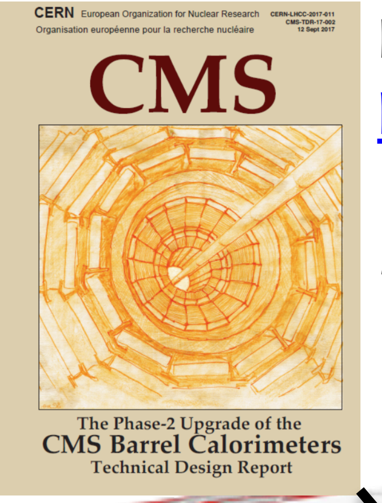
DAQ & High-Level Trigger
https://cds.cern.ch/record/2759072
- Full optical readout
- Heterogenous architecture
- 60 TB/s event network
- 7.5 kHz HLT output

First double disk





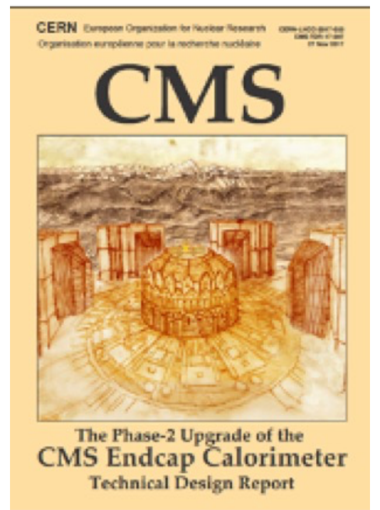
Tracker
https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Design for tracking in L1T
- Extended coverage to $\eta \simeq 3.8$

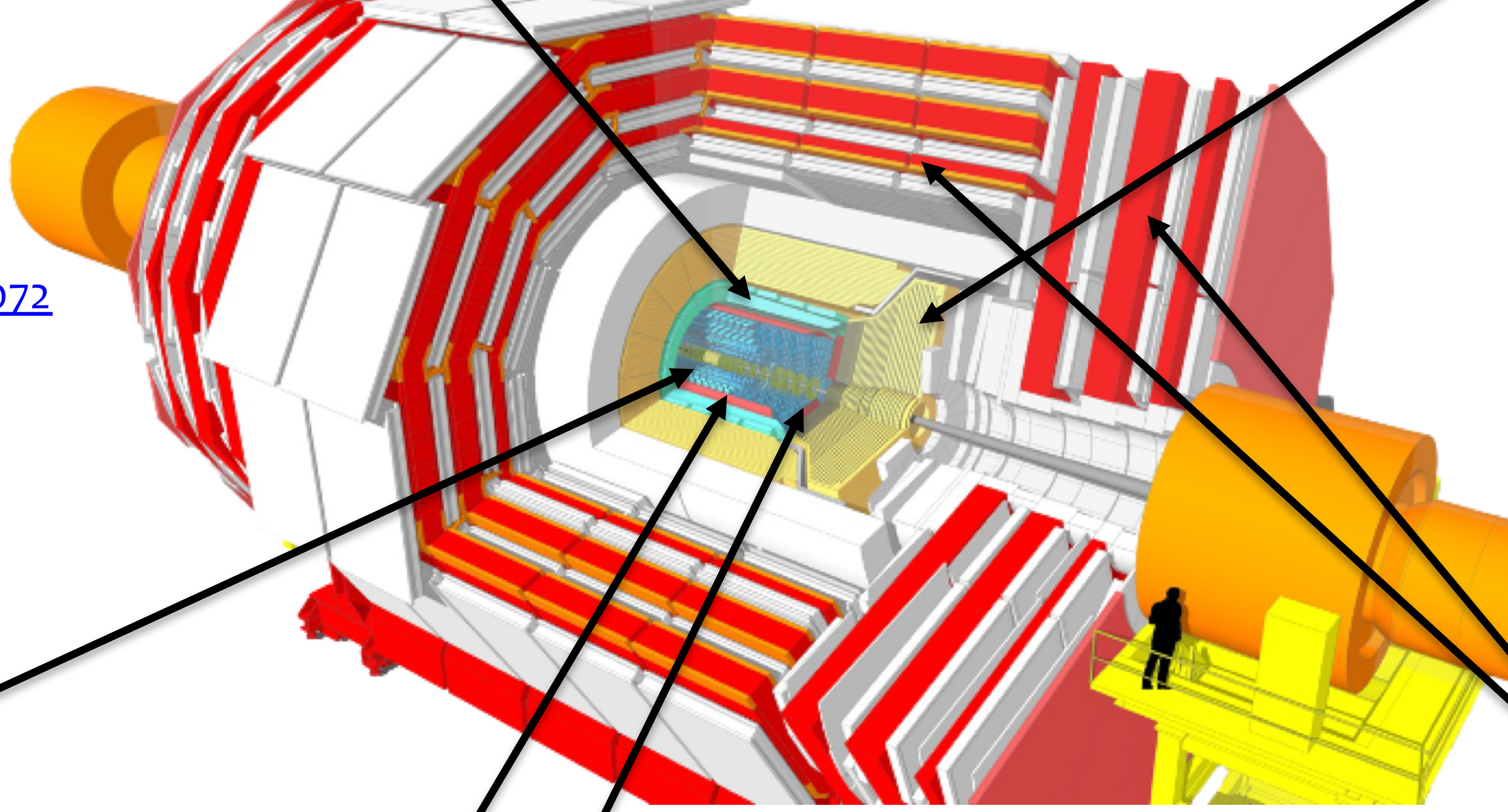


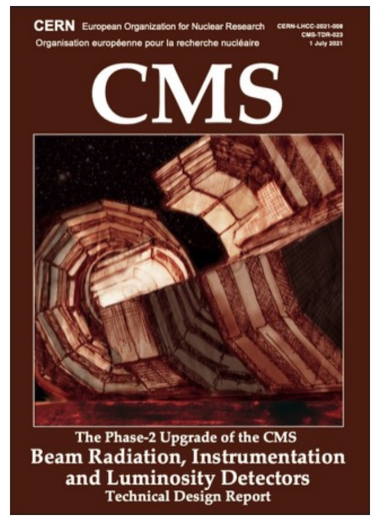
Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

Absorber (~1 endcap)

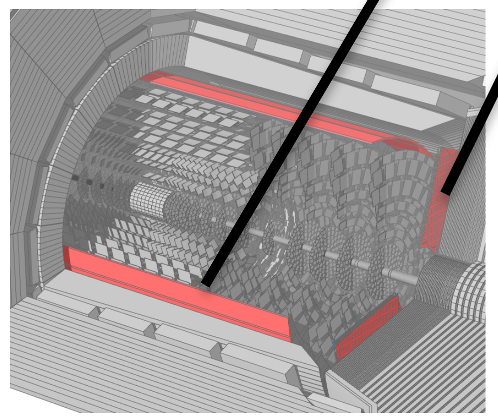
Calorimeter Endcap (HGCal)
https://cds.cern.ch/record/2293646
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS



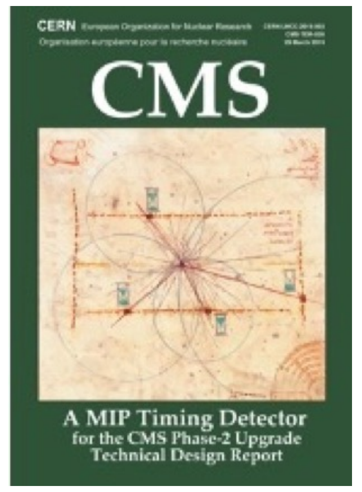


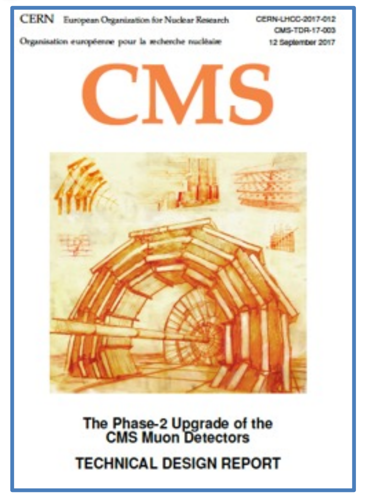


Beam Radiation Instr. and Luminosity
http://cds.cern.ch/record/2759074
- Beam abort & timing
- Beam-induced background
- Bunch-by-bunch lumi: 1% offline, 2% online
- Neutron and mixed-field radiation monitors



MIP Timing Detector
https://cds.cern.ch/record/2667167
Precision timing with:
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes





Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC 1.6 < η < 2.4
- Extended coverage to $\eta \simeq 3$

R. Salerno, EPS HEP 2025

Towards the HL-LHC

Proposed for after 2035: LHCb Upgrade II

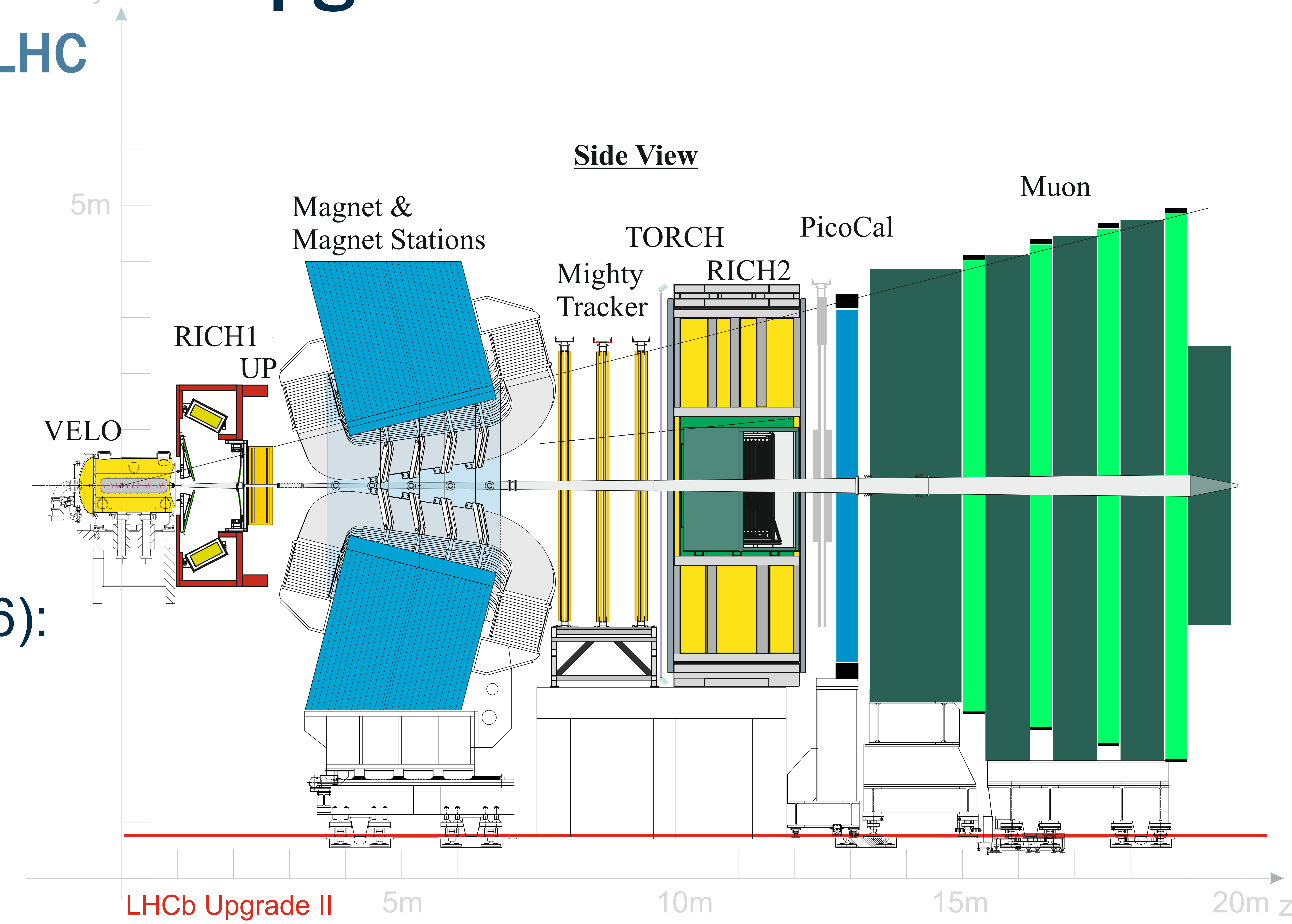
Flavor Physics and More at the HL-LHC

Physics **objectives**:

- Reduce statistical and systematic uncertainties of many measurements, e.g. ultimate precision of CKM triangle
- Exploit unique LHCb reach for ions, baryons, and exotic hadrons

Upgrade for LHC Run 5/6 (from 2036):

- Full **four-dimensional tracking** with larger acceptance, precision **timing**
- Improved **particle ID**
- Data processing **in real time**: reconstruction, calibration, alignment



Proposed for after 2035: ALICE 3

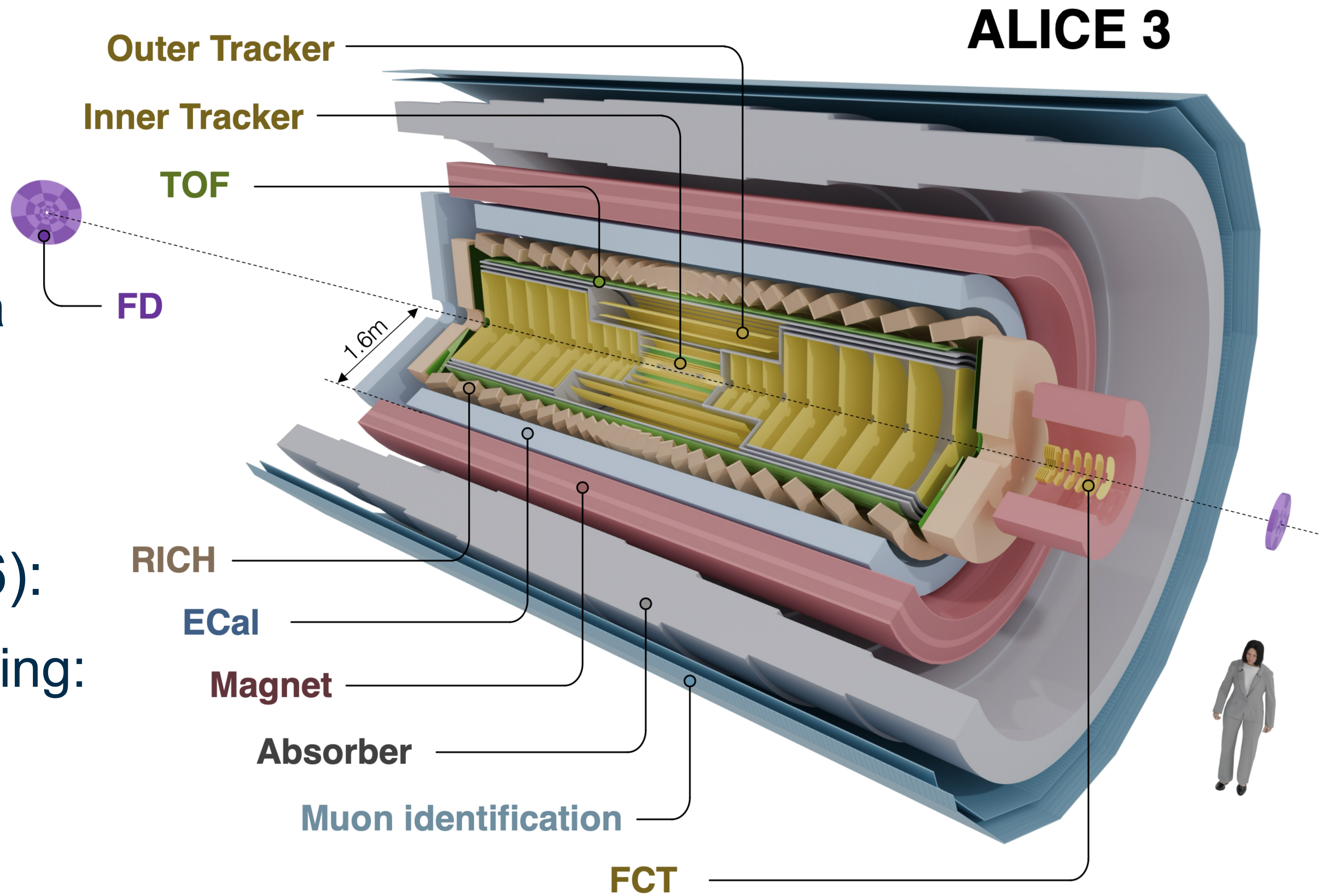
Heavy Ion Physics at the HL-LHC

Physics **objectives**:

- **Dielectrons** as temperature probes
- Properties of the **quark-gluon plasma** (QGP) with **heavy-flavor hadrons**
- **QCD phase transition**

New detector for Run 5/6 (from 2036):

- **Low-mass** all-silicon vertexing & tracking: excellent vertex reconstruction, wide acceptance
- **Particle ID** in wide p_T range
- High readout rate & **online reconstruction**



I. Altsybeev, EPS HEP 2025

Remark: Future Data Processing

Dealing with the Data Deluge

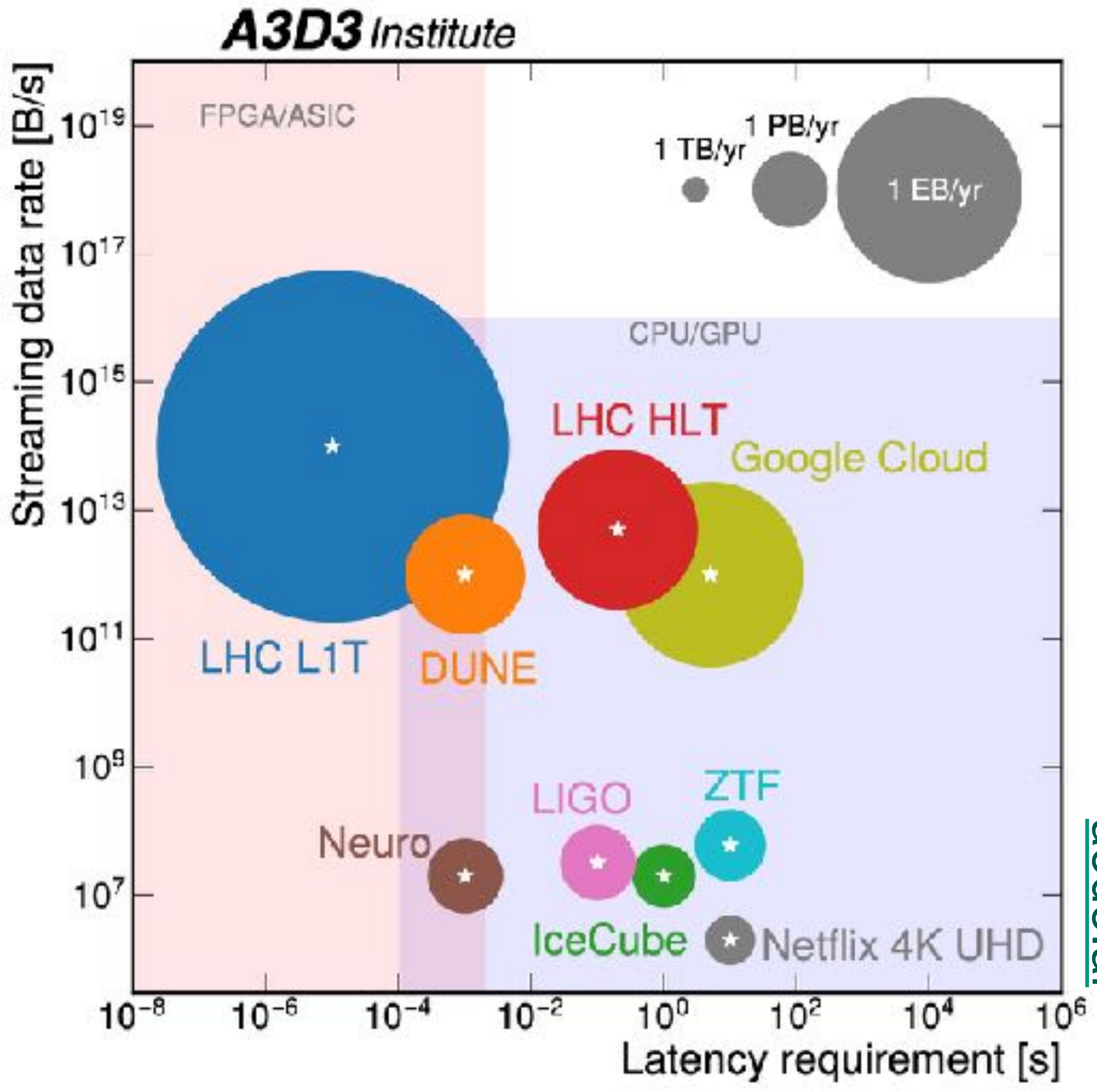
Particle physics: **unique requirements** for streaming **data rates** and processing **latency**

Recent trend: **“triggerless” operation**
→ pioneered by LHCb and ALICE for LHC Run 2/3

Trigger, **data acquisition**, and **computing** challenges:

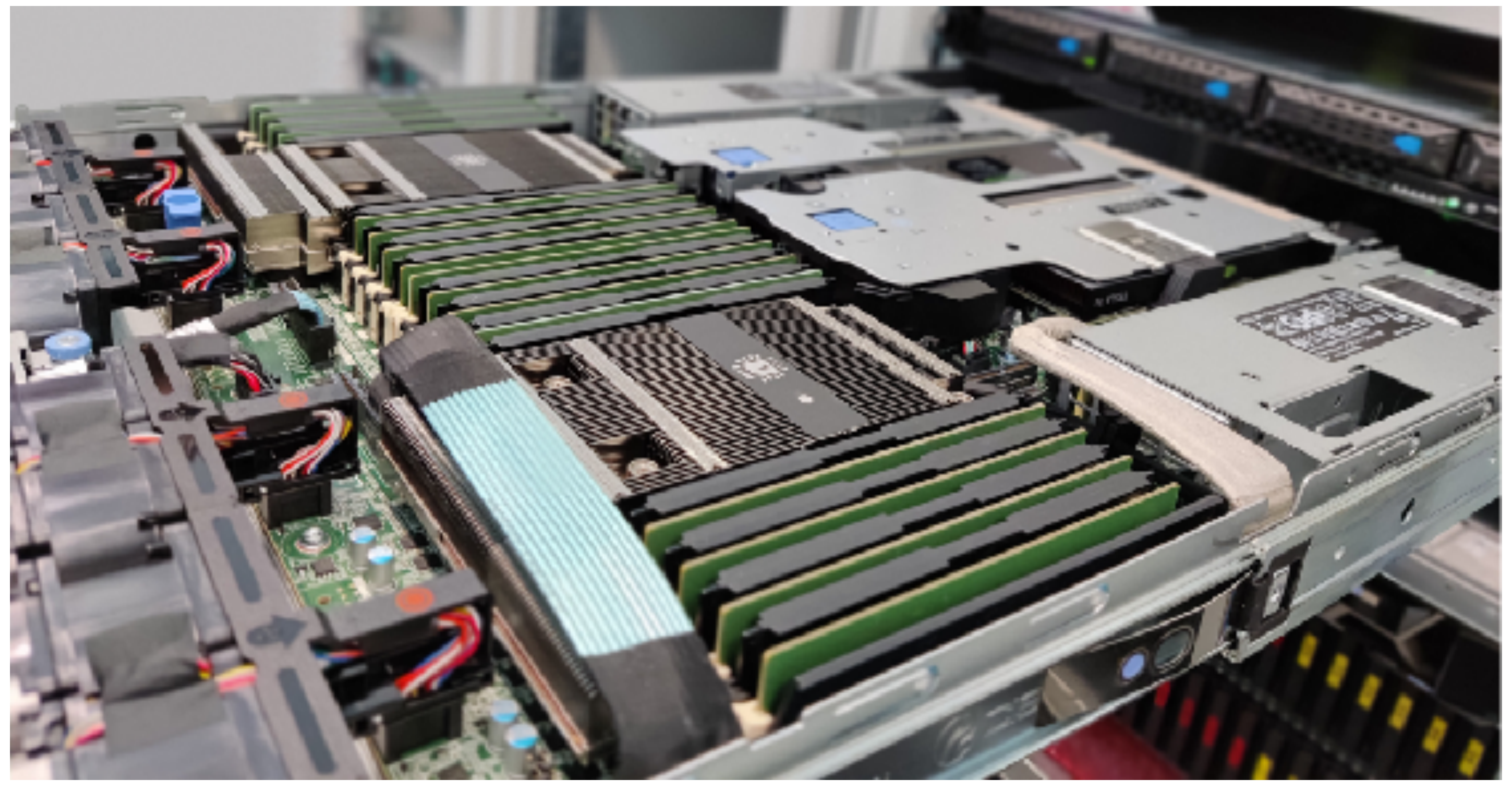
- Avoiding **rate bottlenecks** along data processing chain
- **Heterogeneous computing** on different CPU architectures, GPUs, programmable logic (FPGAs)
  → risk of **vendor lock-in**
- Long-term **maintenance** of particle physics code base (10s of millions lines of code)

Rate/Latency Requirements



a3d3.ai

CMS HLT Node: CPU + GPU



cms.cern

Where will particle physics be in the 2040s?

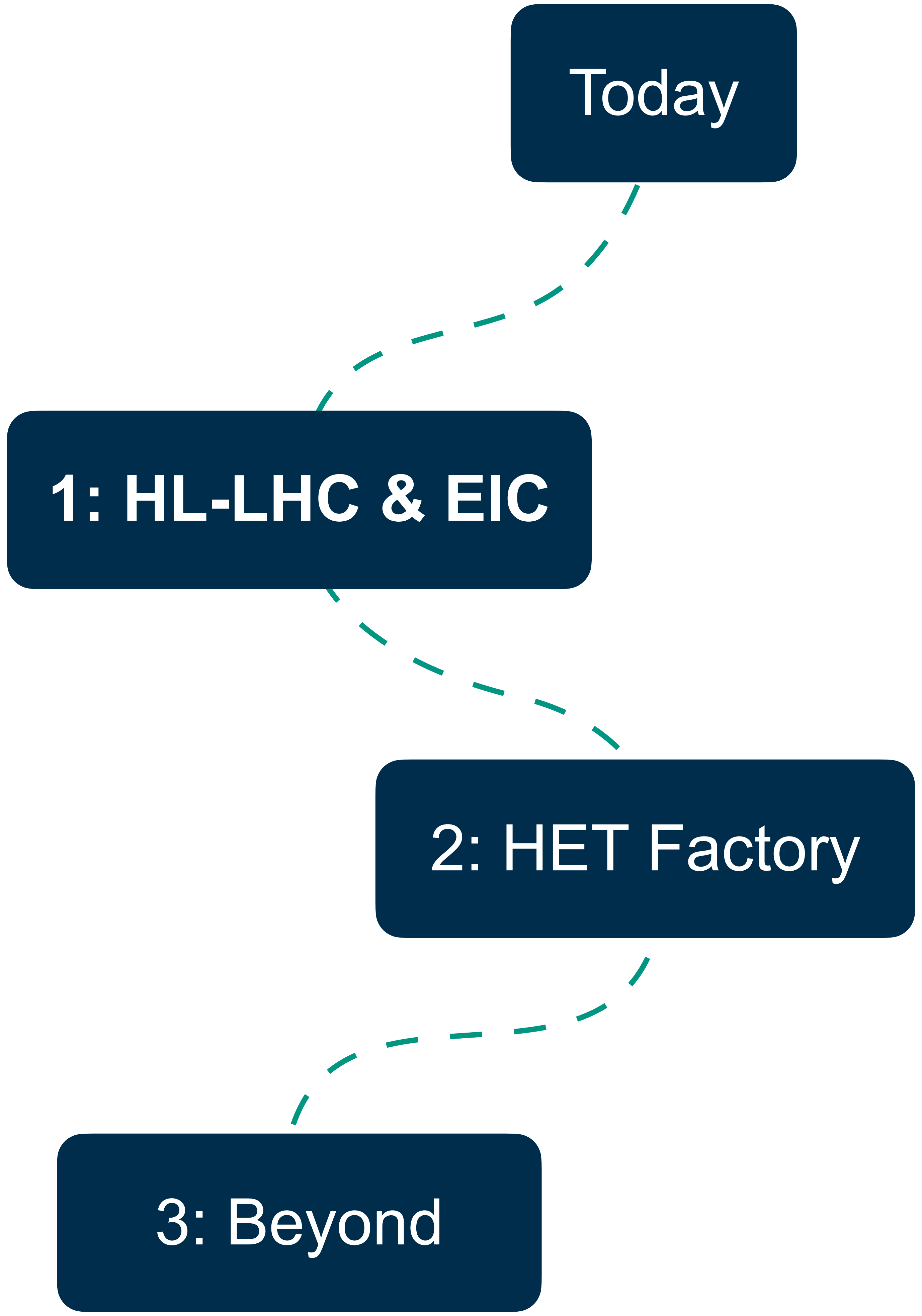
Colliders

European flagship: **HL-LHC** @ CERN
→ high-luminosity upgrade of the LHC

- LHC accelerator upgrades
  → 3.5× instantaneous luminosity, 7× integrated luminosity
- LHC detector upgrades: keep up with accelerator upgrades, introduce **innovative instrumentation**

Further **major colliders and experiments** globally:

- **Belle II** at the SuperKEKB B factory at KEK in Japan
- **ePIC** at the Electron-ion Collider (EIC) at Brookhaven National Lab (BNL) in the US
- DAΦNE in Italy, BEBC in China, VEPP in Russia, …



Since 2019: Belle II

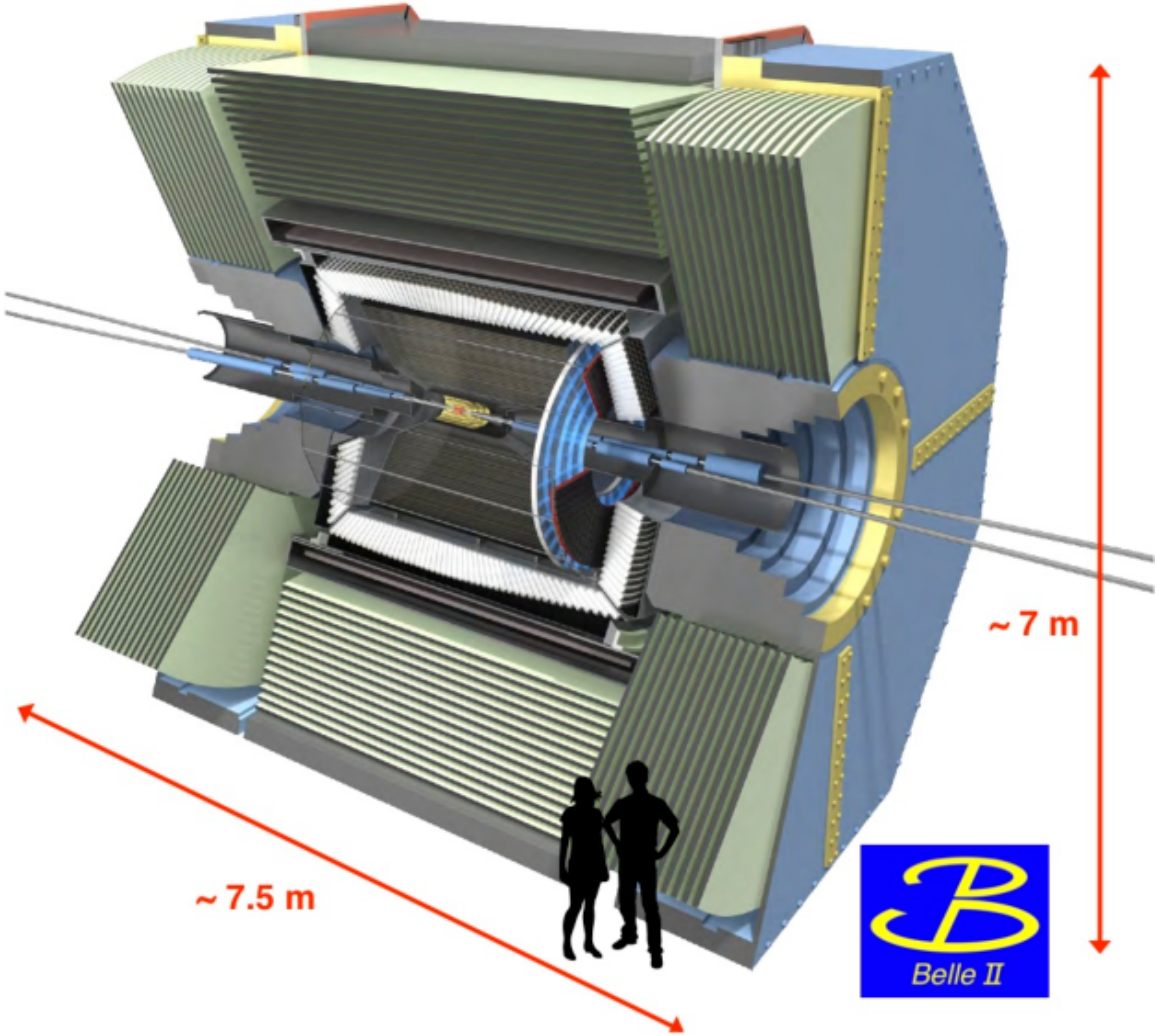
SuperKEKB Asymmetric e^+e^- Collider, KEK, Japan

Physics objectives (examples):

- CKM **unitarity triangle**: angle ϕ_2/α
- **CP violation** in charm-meson decays
- **Rare tau** lepton decays

Detector upgrades planned for SuperKEKB Run 3 (from 2034):

- Redesign of **interaction region** (reduction/mitigation of beam backgrounds)
- New 5–6 layer silicon pixel **vertex detector**
- Upgrades to drift chamber and particle ID



Beyond 2035: ePIC

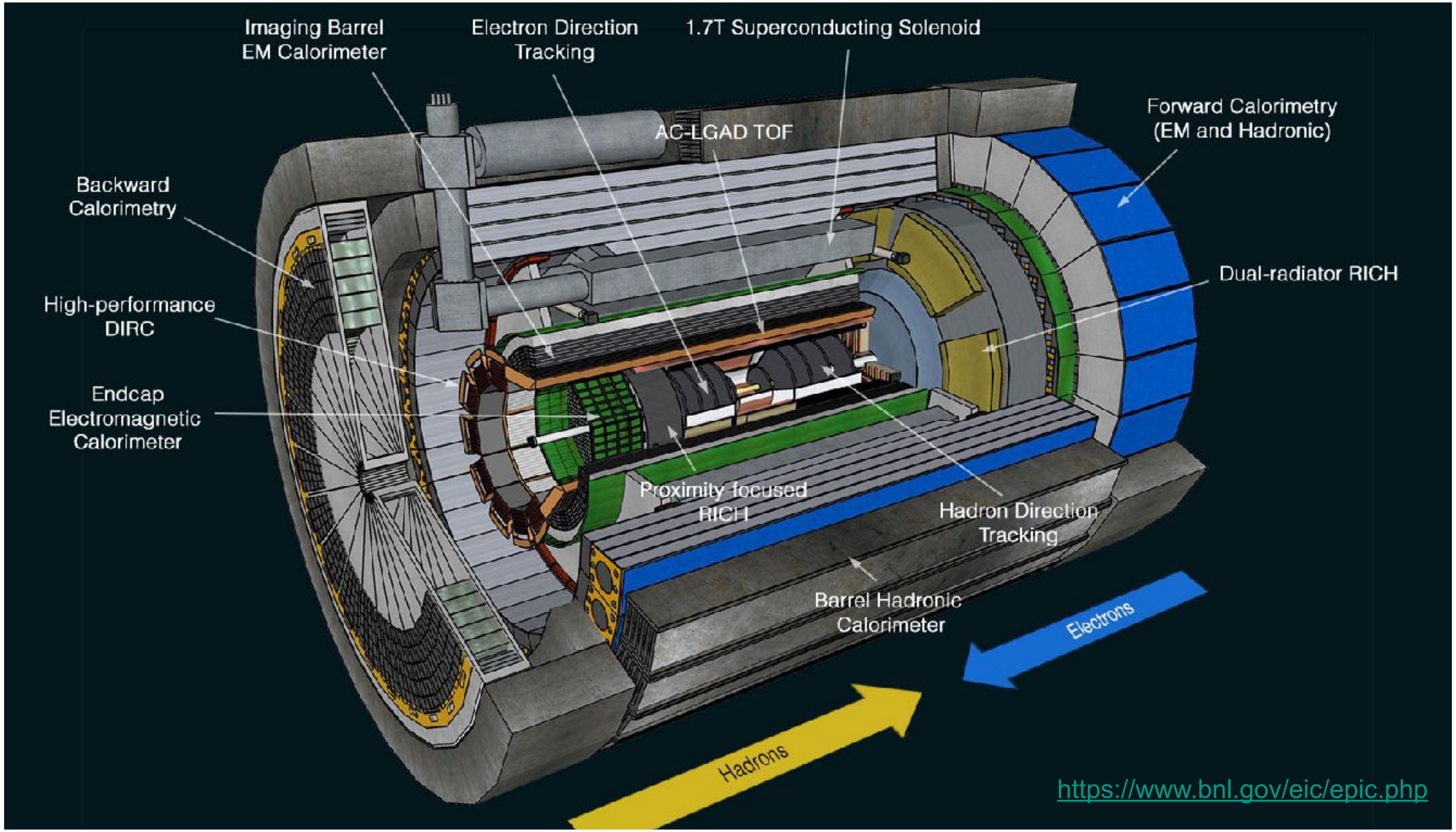
Electron-ion Collider (EIC), Brookhaven National Laboratory, US

Physics objectives:

- 3D structure of protons and nuclei
- Gluon saturation
- Confinement

Detector:

- Modern 4π detector
- **Latest advances** in tracking, timing, and particle ID



https://www.bnl.gov/eic/epic.php

What can we expect beyond the 2040s?

The Next Flagship Collider

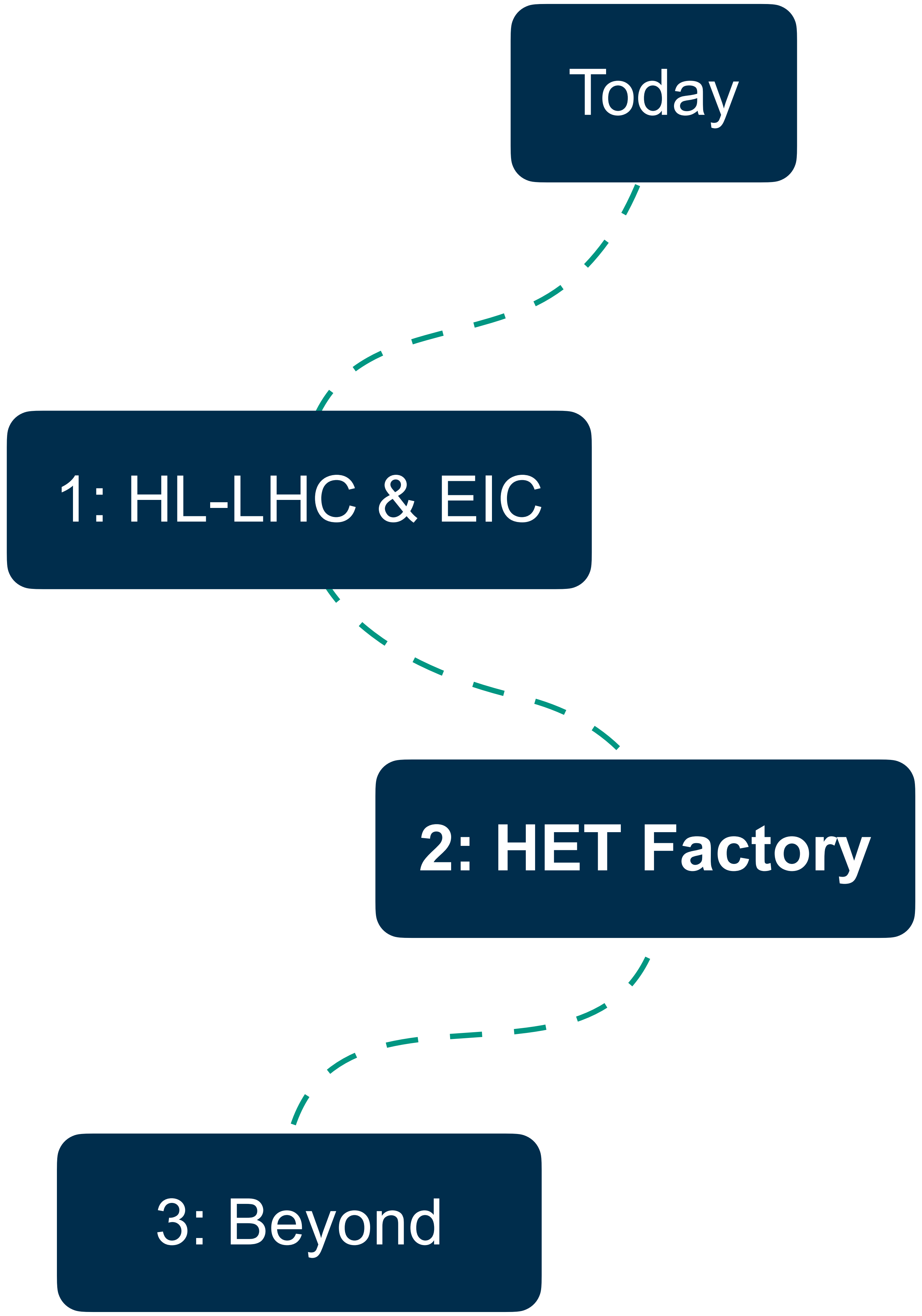
General consensus: **e^+e^- collider** covering Higgs-boson, electroweak, and top-quark physics
→ **Higgs/EW/Top Factory** (“HET Factory”)

How can a **HET factory** be implemented **at CERN**?

- Future **Circular** e^+e^- Collider (FCC-ee)
- **Linear** Collider Facility (LCF)

Remarks:

- There are also plans for a HET factory in China (Circular Electron-Positron Collider, CEPC)
- Various other “intermediate” options, e.g., LEP3, LHeC



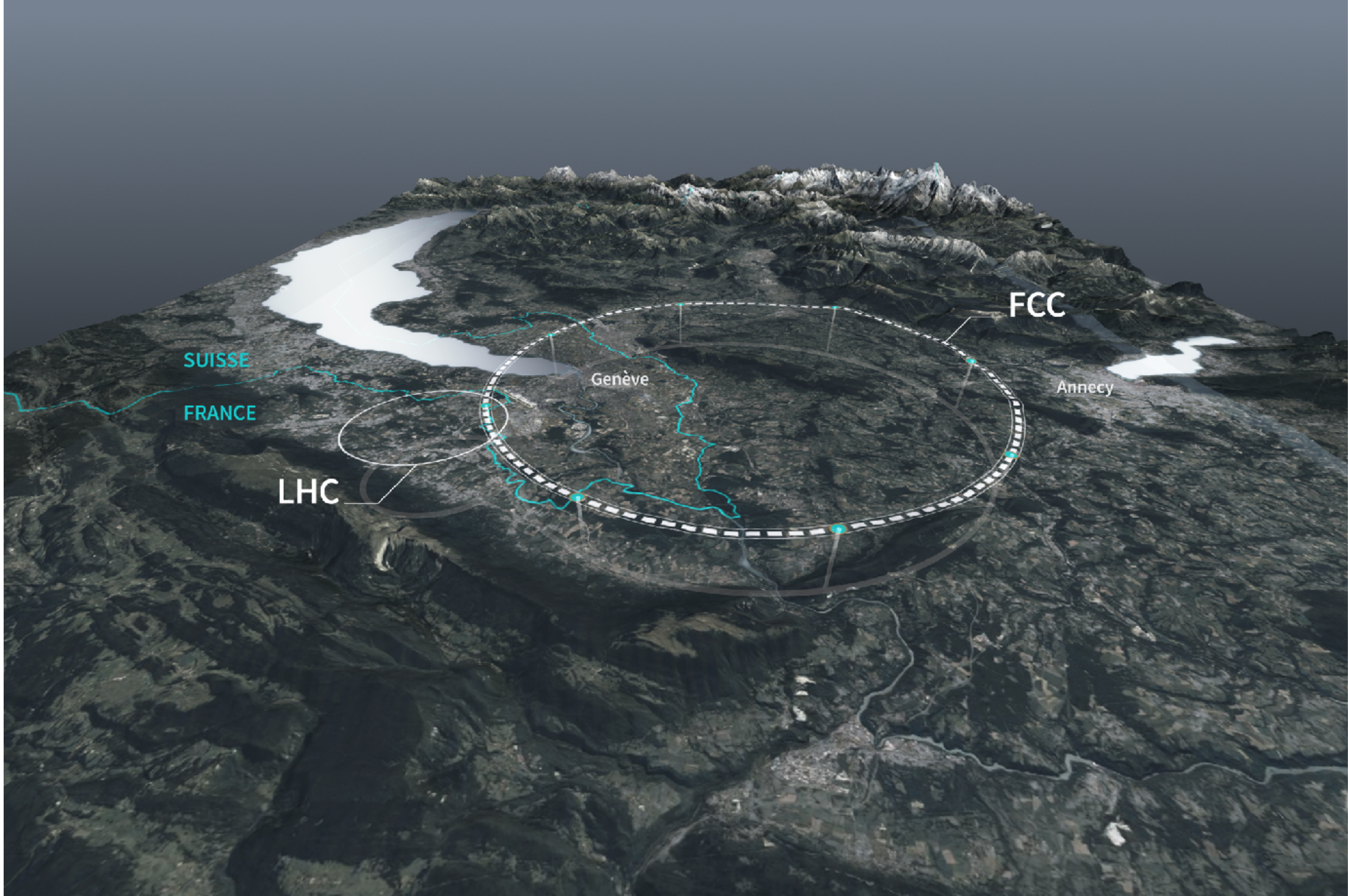
FCC-ee

The Circular Option

90.7 km ring,
e^+e^- center-of-mass energies:

- 91.2 GeV (Z)
- 160 GeV (WW)
- 240 GeV (ZH)
- 365 GeV ($t\bar{t}$)

Integrated program: hadron collider in FCC tunnel after FCC-ee completion (like LEP → LHC)



https://fcc.web.cern.ch/fcc-layout-aerial-view

LCF at CERN

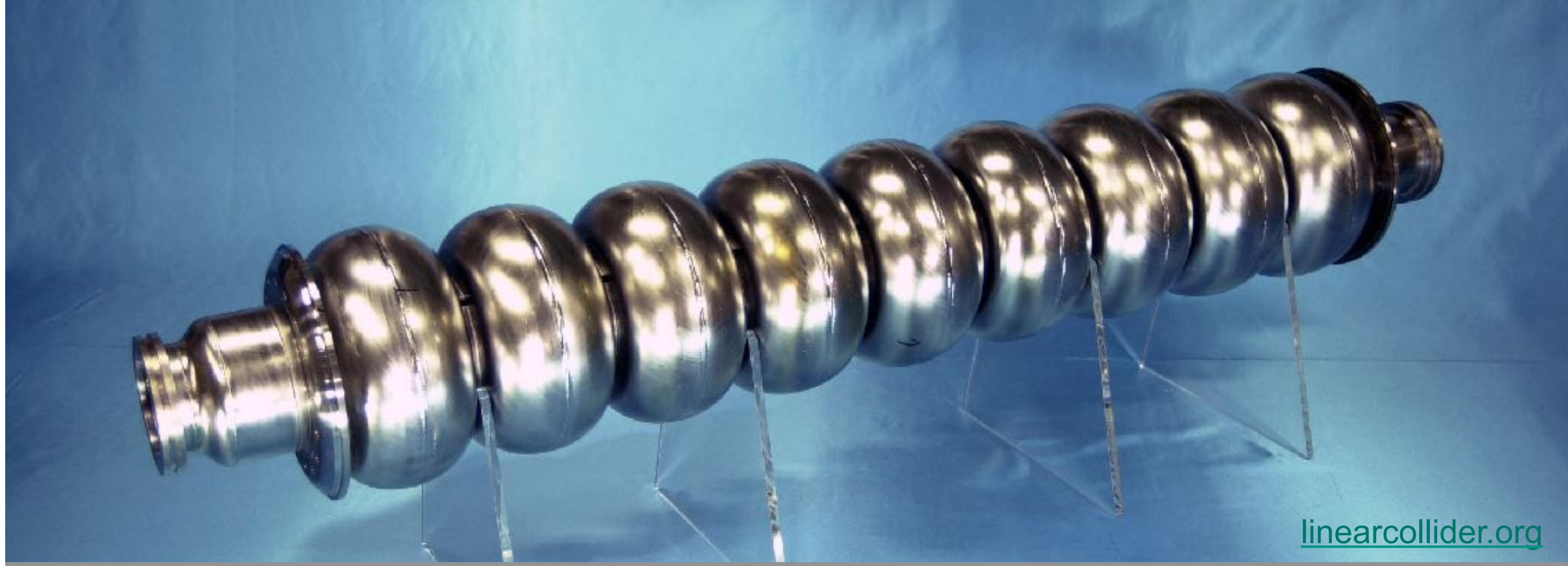
The Linear Option

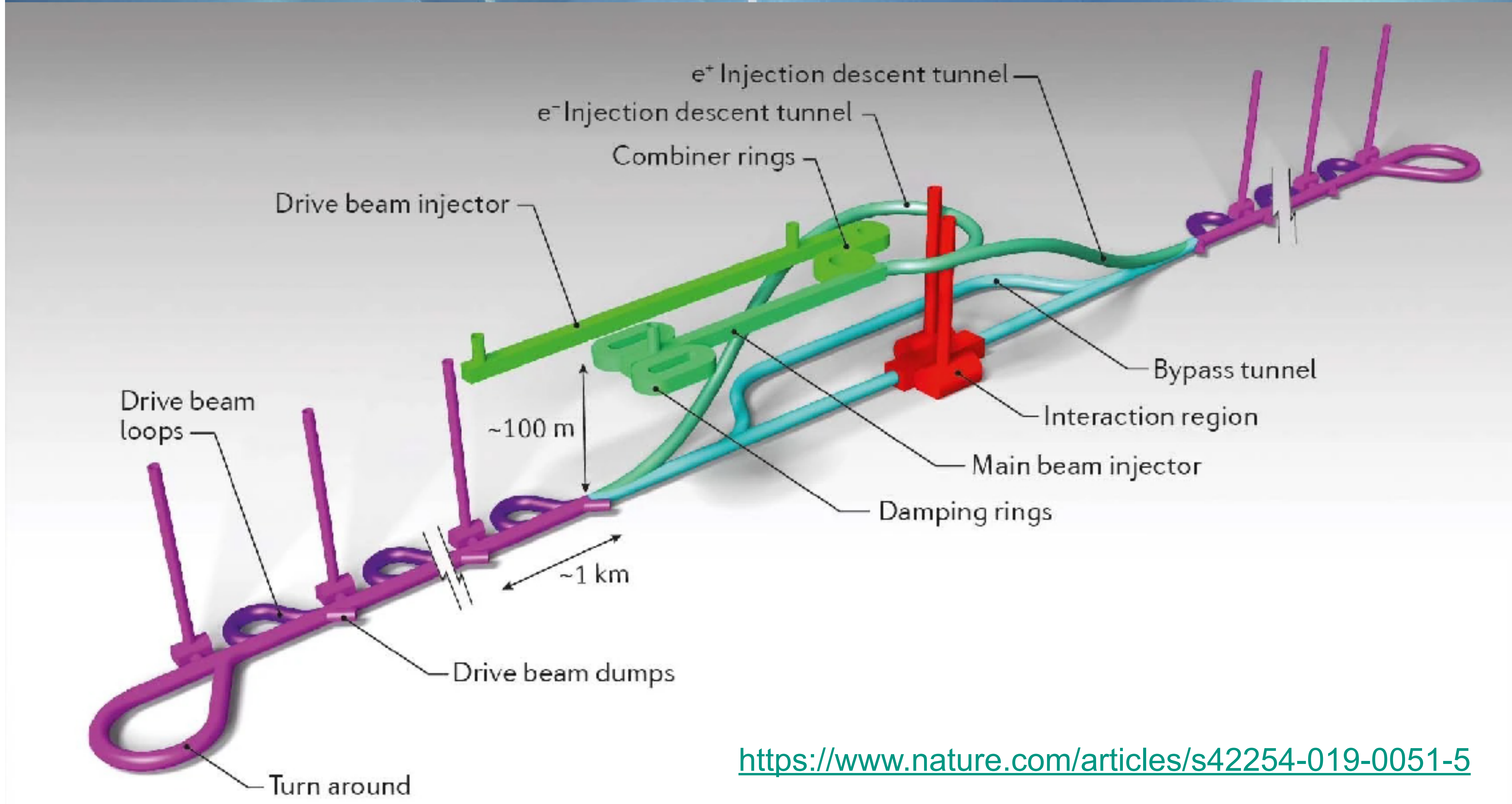
ILC technology:

- Acceleration: **superconducting** radiofrequency (RF) cavities (XFEL technology)
- Center-of-mass energies: 250 GeV, 550 GeV (up to 1 TeV)

CLIC technology:

- Acceleration: normal-conducting RF cavities and **drive beam**
- Center-of-mass energies: 380 GeV, 1.5 TeV





https://www.nature.com/articles/s42254-019-0051-5

Linear or Circular?

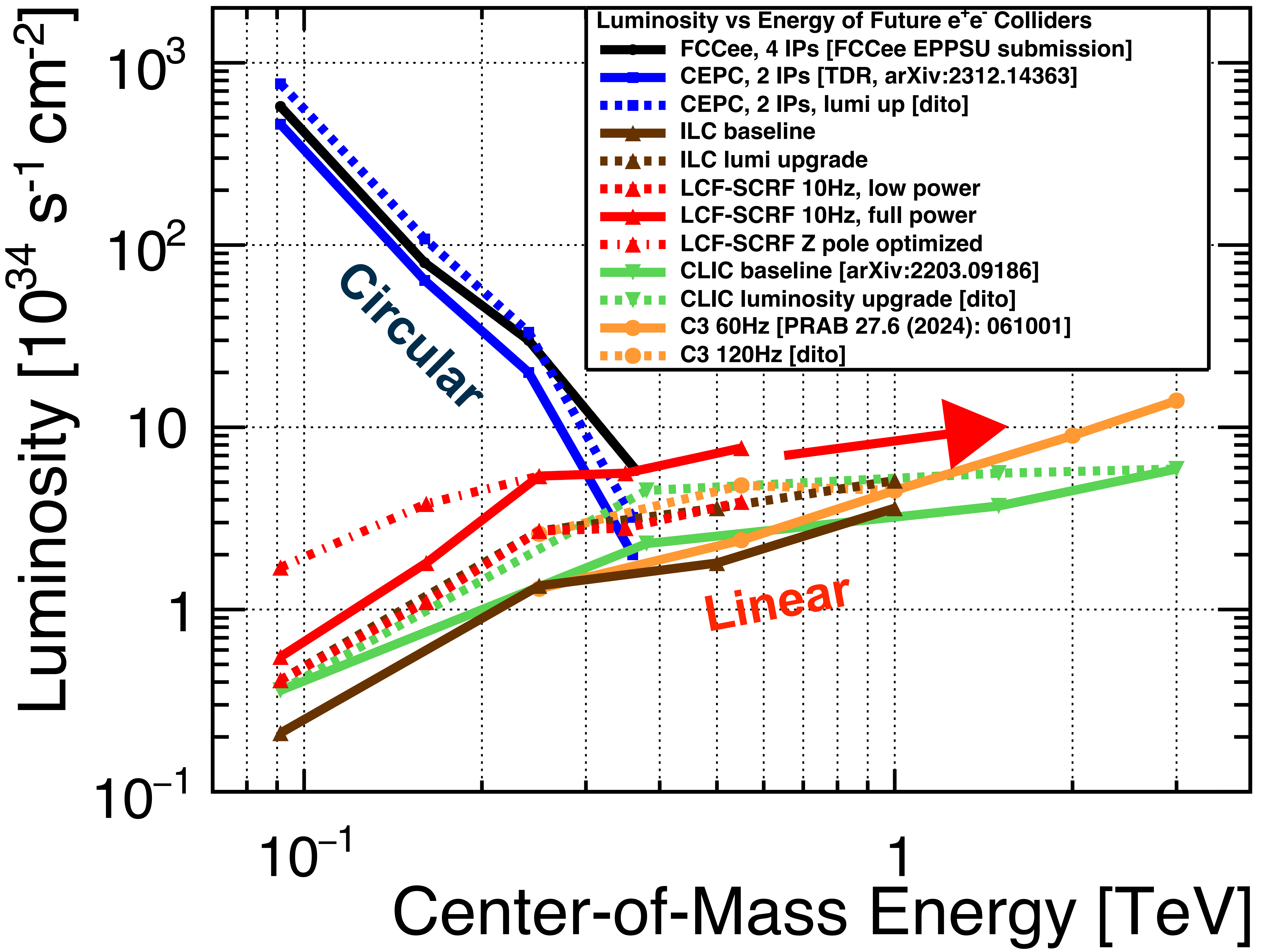
Luminosity vs. Center of Mass Energy

Key for physics potential: **luminosity**

- **Circular** colliders: highest luminosity at **lowest** center of mass energies
  → ideal for Z-pole operation
- **Linear** colliders: highest luminosity at **highest** center of mass energies
  → advantages at/above $t\bar{t}$ threshold

Many other criteria:

- Power consumption
- Flexibility of infrastructure
- …



https://arxiv.org/abs/2503.19983

Comparison of Proposed Flagship Projects: Performance

ESG Work in Progress

	FCC-ee				LCF LP	LCF FP		CLIC 380
Tunnel Length (km)	90.7				33.5			11.4
Number of Experiments	4				2			2
Synch. Rad. Power per Beam (MW)	50				–			–
Center-of-mass Energy (GeV)	91.2	160	240	365	250	91.2	250	380
Longitudinal Polarization for e^-/e^+ (%)	–				80/30			80/–
Years of Operation	4	2	3	5	5	1	3	10
Integrated Lumi Full Program (ab^{-1})	205	19.2	10.8	3.1	0.72	0.067	1.44	2.56
Peak Power (MW)	251	276	297	381	143	123	182	166
Consumption per Year (TWh)	1.2	1.3	1.4	1.9	0.8	0.7	1.0	0.82

Numbers shown at the ESPP Open Symposium by G. Arduini

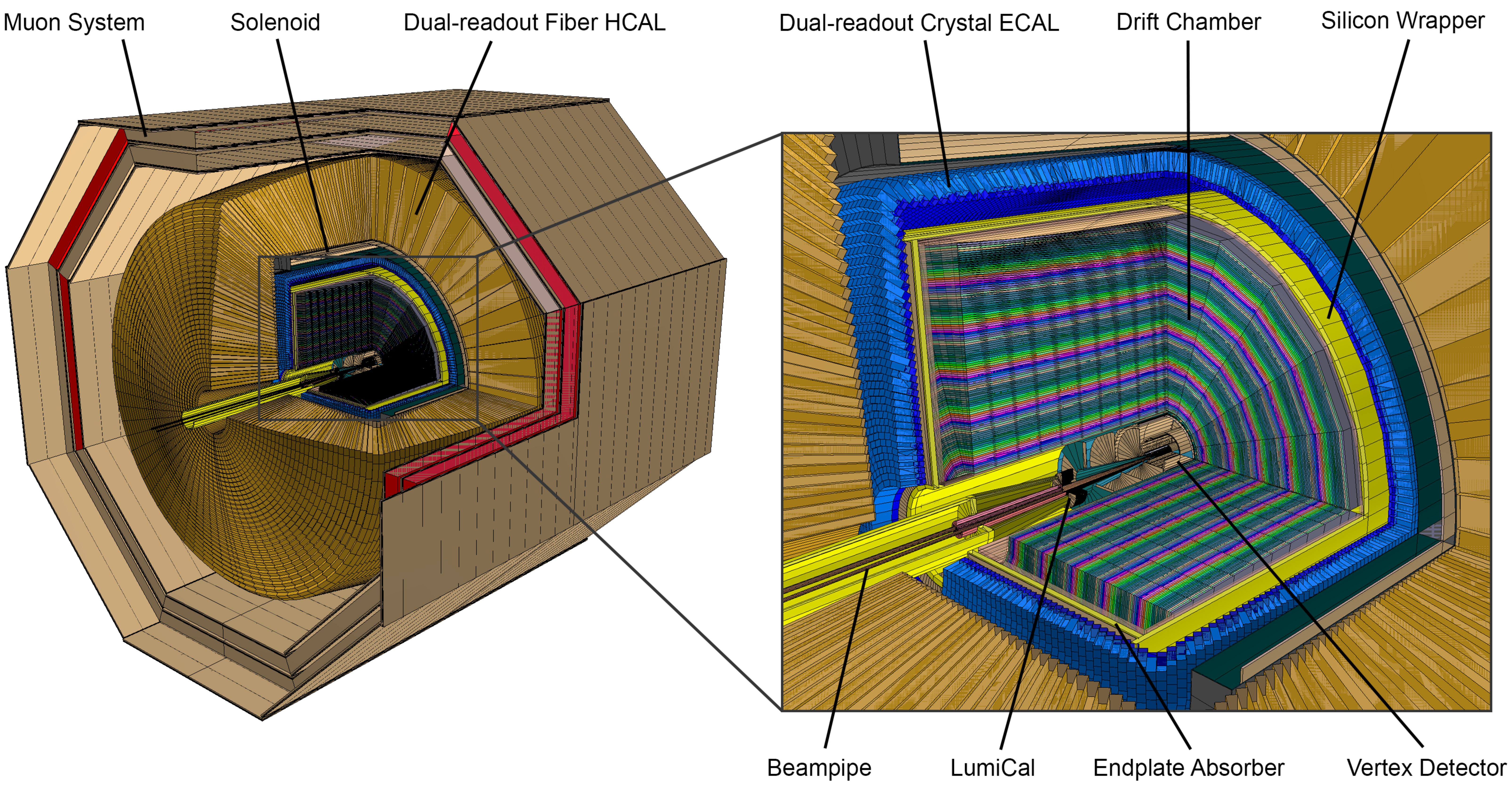
LP = Low Power (1312 bunches/train), FP = Full Power (2625 bunches/train)

Detector Concepts for a Higgs/EW/Top Factory

Example: IDEA – Dual Readout Calorimetry for the FCC-ee

Key subdetectors:

- **Dual readout** calorimeters: detect scintillation **and** Cherenkov light → constrain electromagnetic fraction in hadronic showers
- Light weight **drift chamber**: tracking & particle identification using cluster counting (d*N*/d*x*)
- **Silicon wrapper**: precision 3D space point + sub 100-picosecond timing



https://arxiv.org/pdf/2502.21223

Detector Concepts for a Higgs/EW/Top Factory

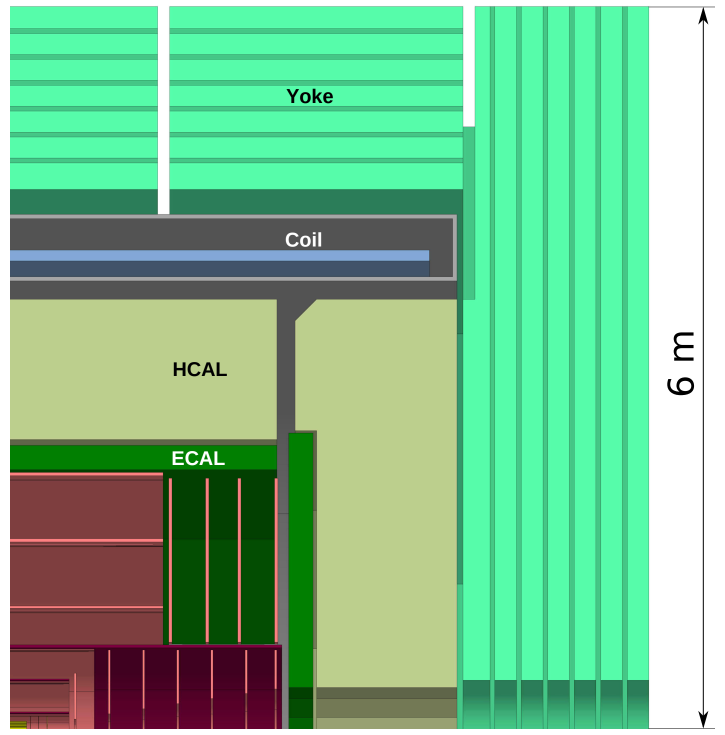
A Link between Requirements and Technology

Concept	SiD	ILD'*	CLD*	IDEA	ALLEGRO
Vertexing	Silicon MAPS	Silicon MAPS	Silicon MAPS	Silicon MAPS	Silicon MAPS
Tracking/ PID	Silicon Strips	Time Projection Ch.	Silicon, RICH option	Gaseous	Gaseous, Silicon+ RICH
Calorimetry	Silicon/ Scintillator	Silicon/ Scintillator, Gaseous	Silicon	Dual Readout	Noble Liquids
Muon System	Scintillator	Scintillator	Gaseous	Gaseous	Gaseous
Magnet	5 T	3.5 T	2 T	2 T	2 T

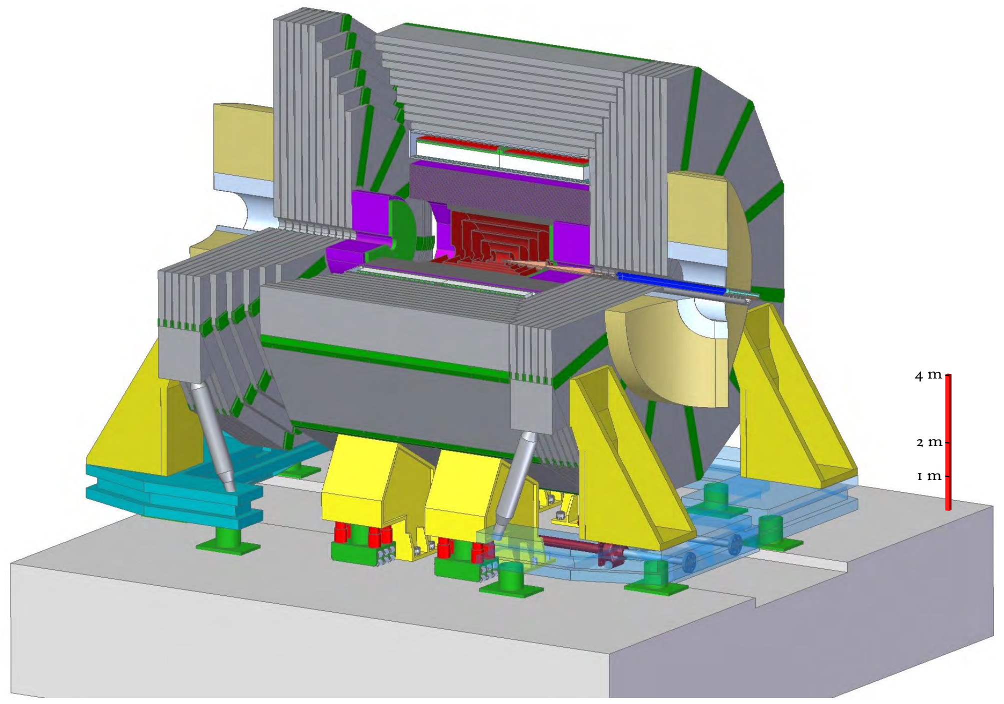
*evolutions from detector concepts for CLIC and ILC

→ **guide R&D**, maintain **freedom to combine** technologies later

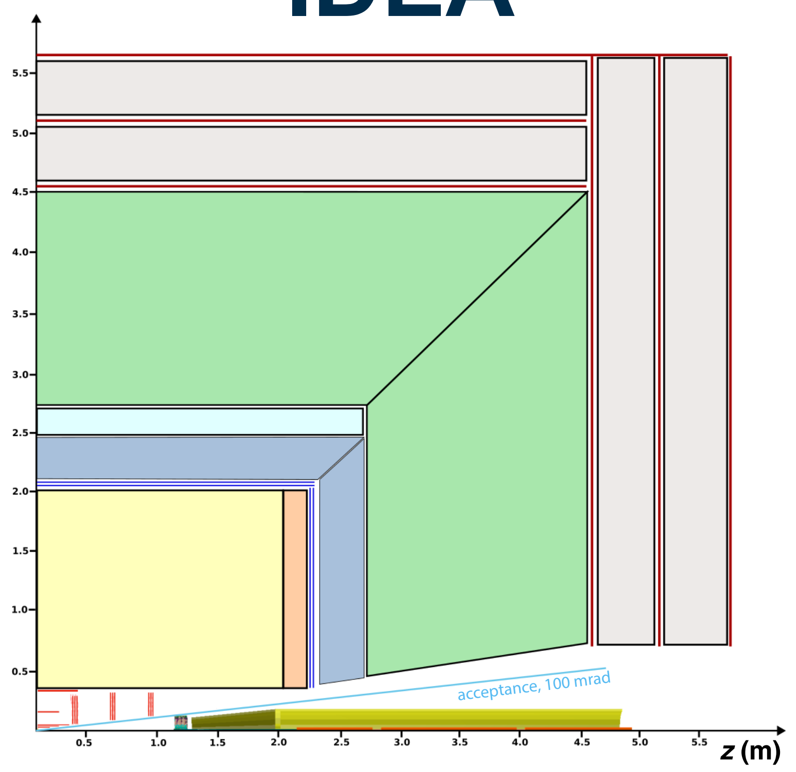
CLD



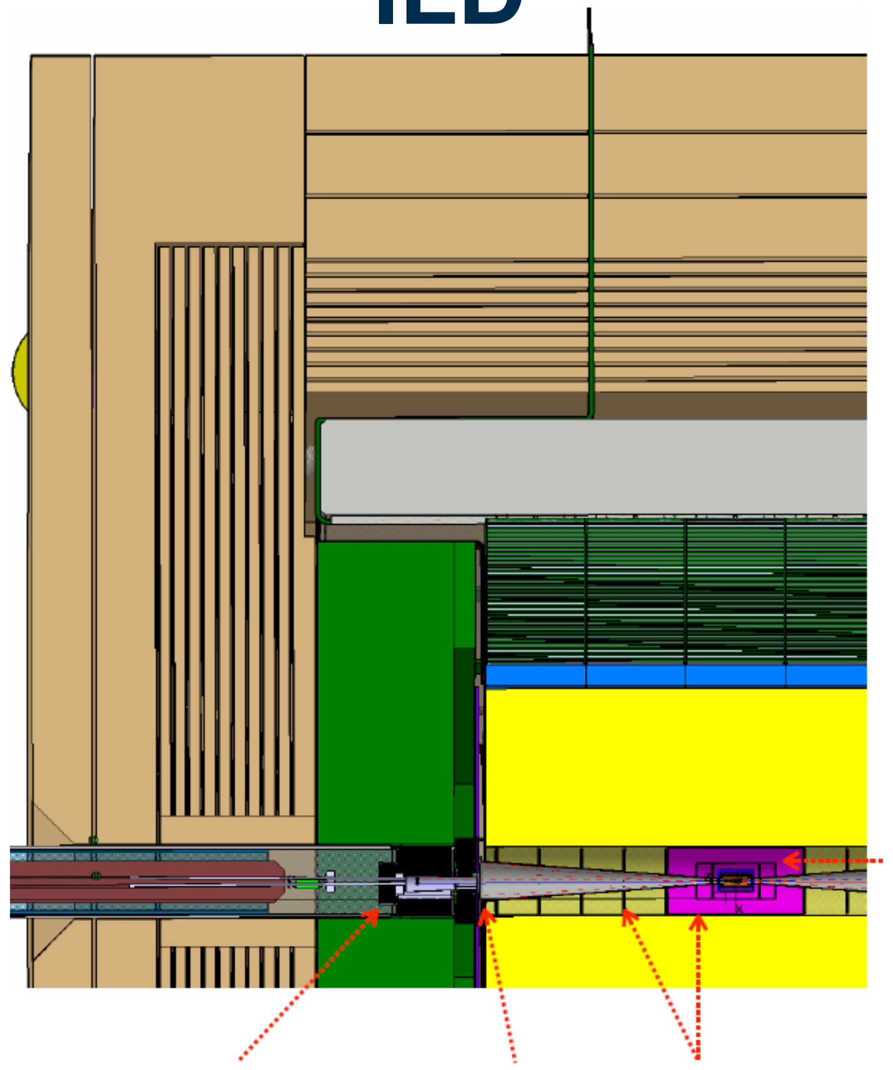
SiD



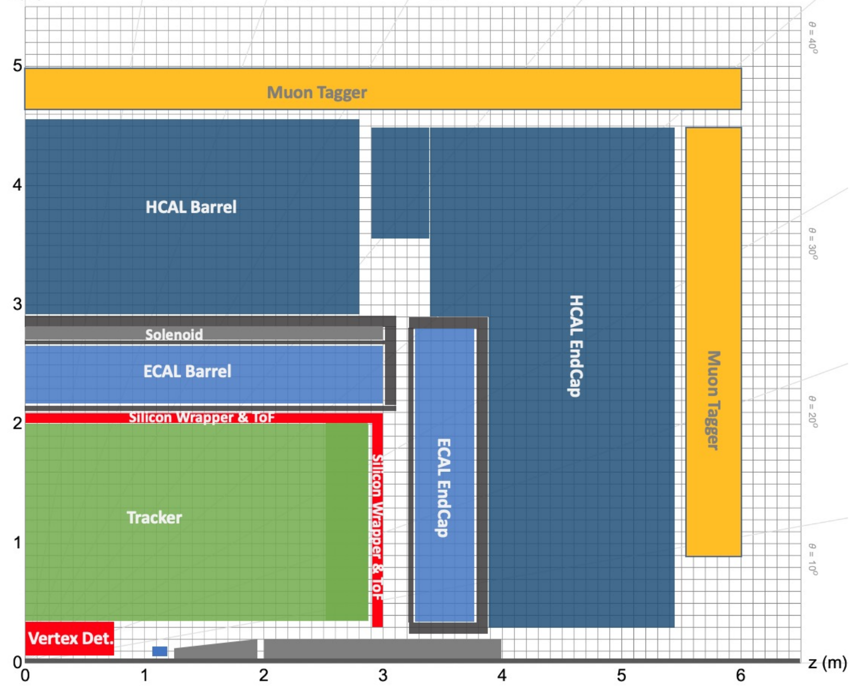
IDEA



ILD



ALLEGRO



Which projects should we pursue?

And on which criteria should our decision be based?

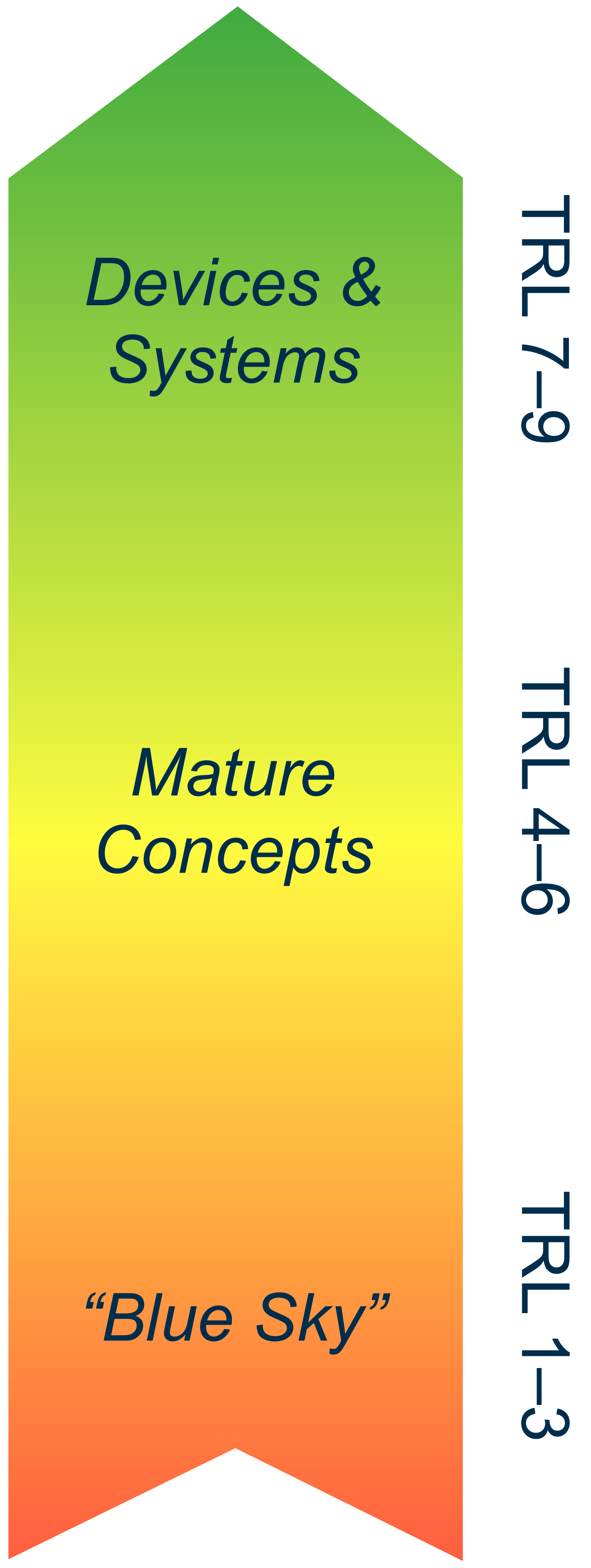
Science-driven decision-making on prioritization of projects:

- Which projects does the community find **most interesting**?
- Which projects have the **largest scientific impact**?

Additional factors to be considered:

- When can the projects be implemented?
  → **Technology Readiness Levels** (TRLs, à la NASA)
- Are there political will, money, and people to implement the projects?
  → **political** and **financial** feasibility, trained workforce
- Does the project fulfill all standards and boundary conditions?
  → **environmental** and **societal** impact

More in **Part II** of this lecture…



Comparison of Proposed Flagship Projects: Cost

ESG Work in Progress

Stage 1 → Stage 2 (LCF 250 (LP) → Δ LCF 550 (FP)); Stage 1 → Stage 2 (CLIC 380 → Δ CLIC 1500)

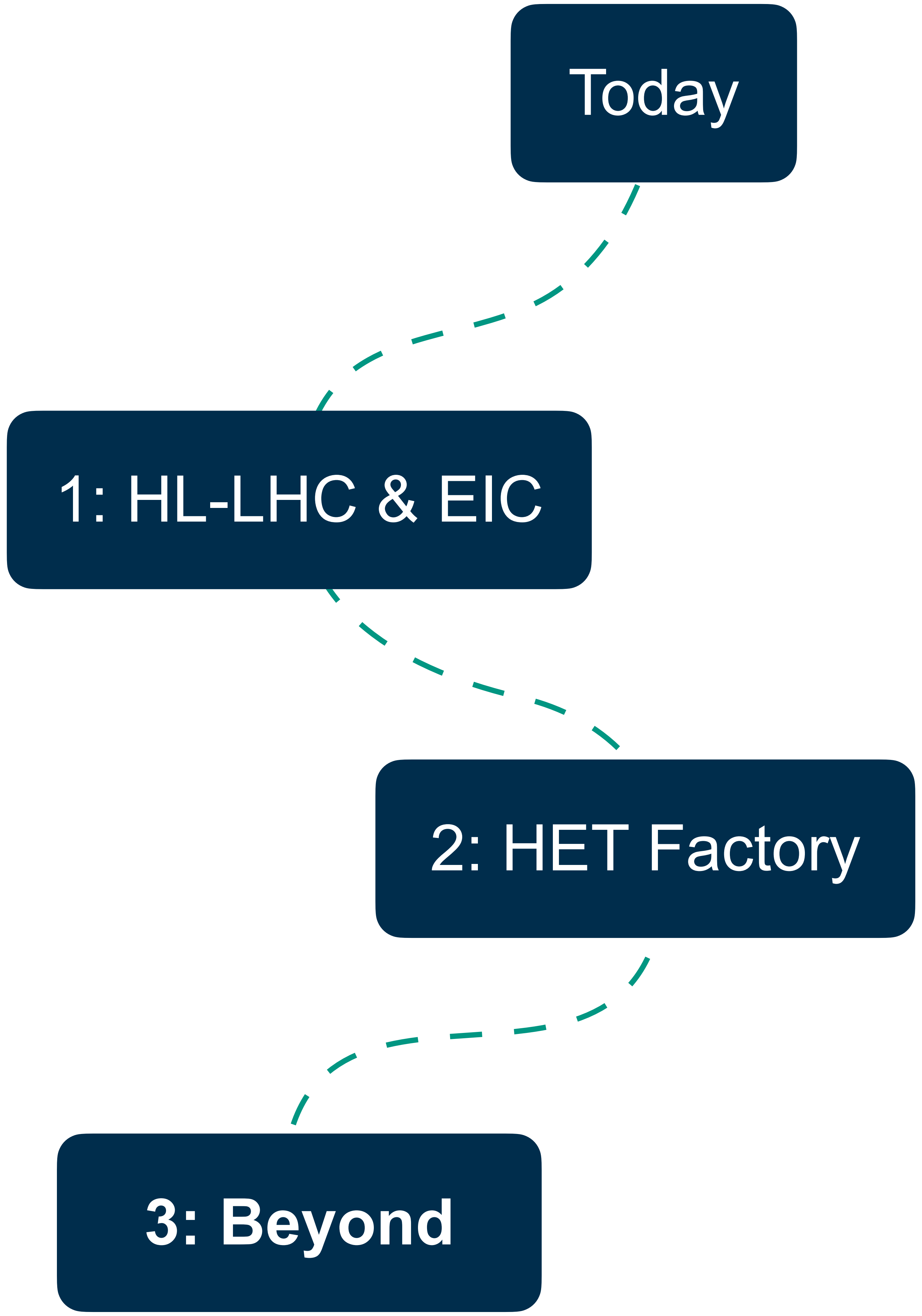
Cost in MCHF	FCC-ee	LCF 250 (LP)	Δ LCF 550 (FP)	CLIC 380	Δ CLIC 1500
Civil Engineering	6,160	2,338	+ 0	1,403	+ 703
Technical Infrastructure	2,840	1,109	+ 1,174	1,361	+ 1,404
Injection, Transfer, Collider	4,730	5,045	+ 4,290	4,577	+ 5,009
Total	**13,730**	**8,492**	**+ 5,464**	**7,341**	**+ 7,116**

+ costs for experiments: approx. 400 MCHF per experiment

Based on numbers presented at ESPP Open Symposium by M. Benedikt and S. Stapnes

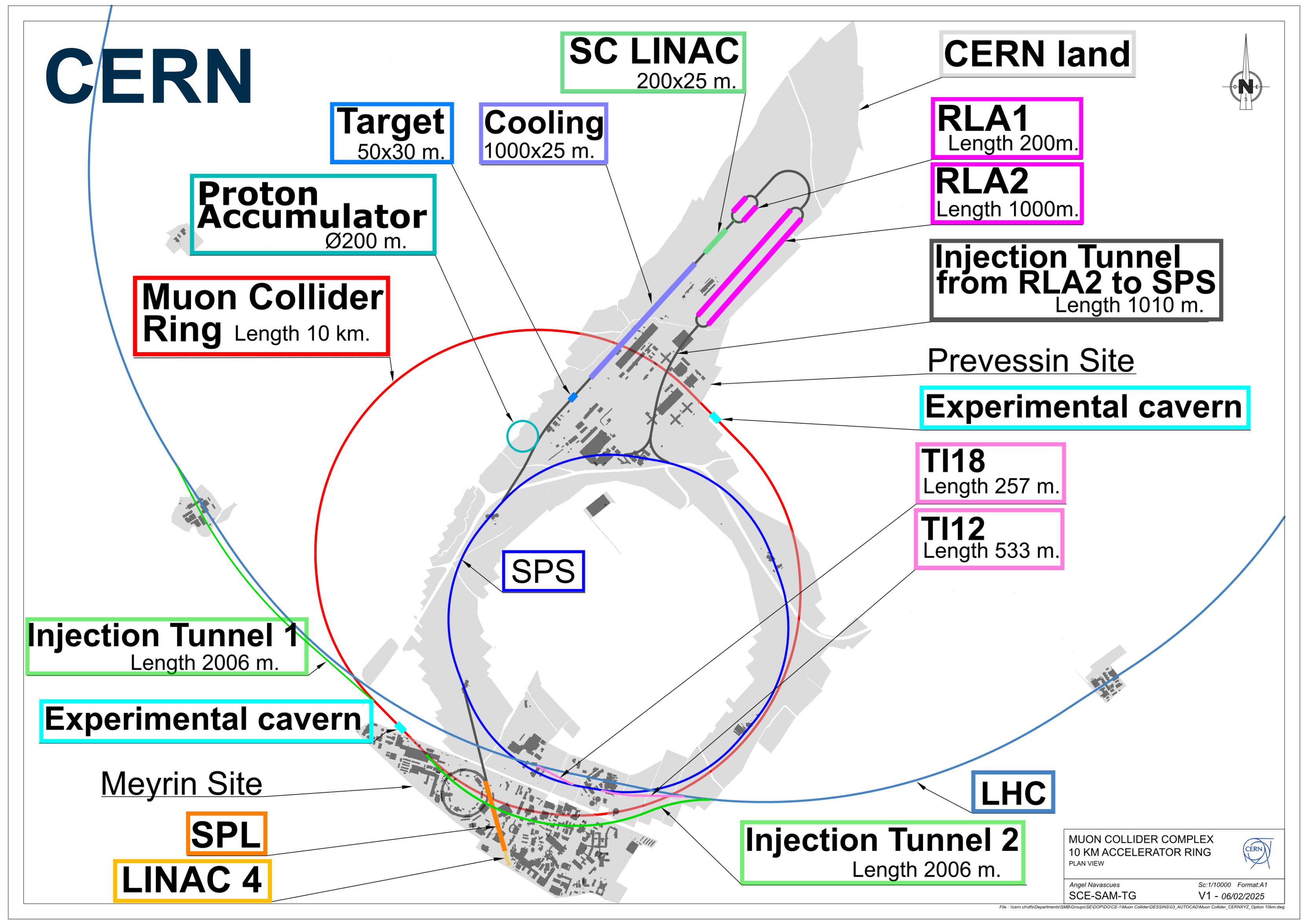
What can we expect in the 2050s and beyond?

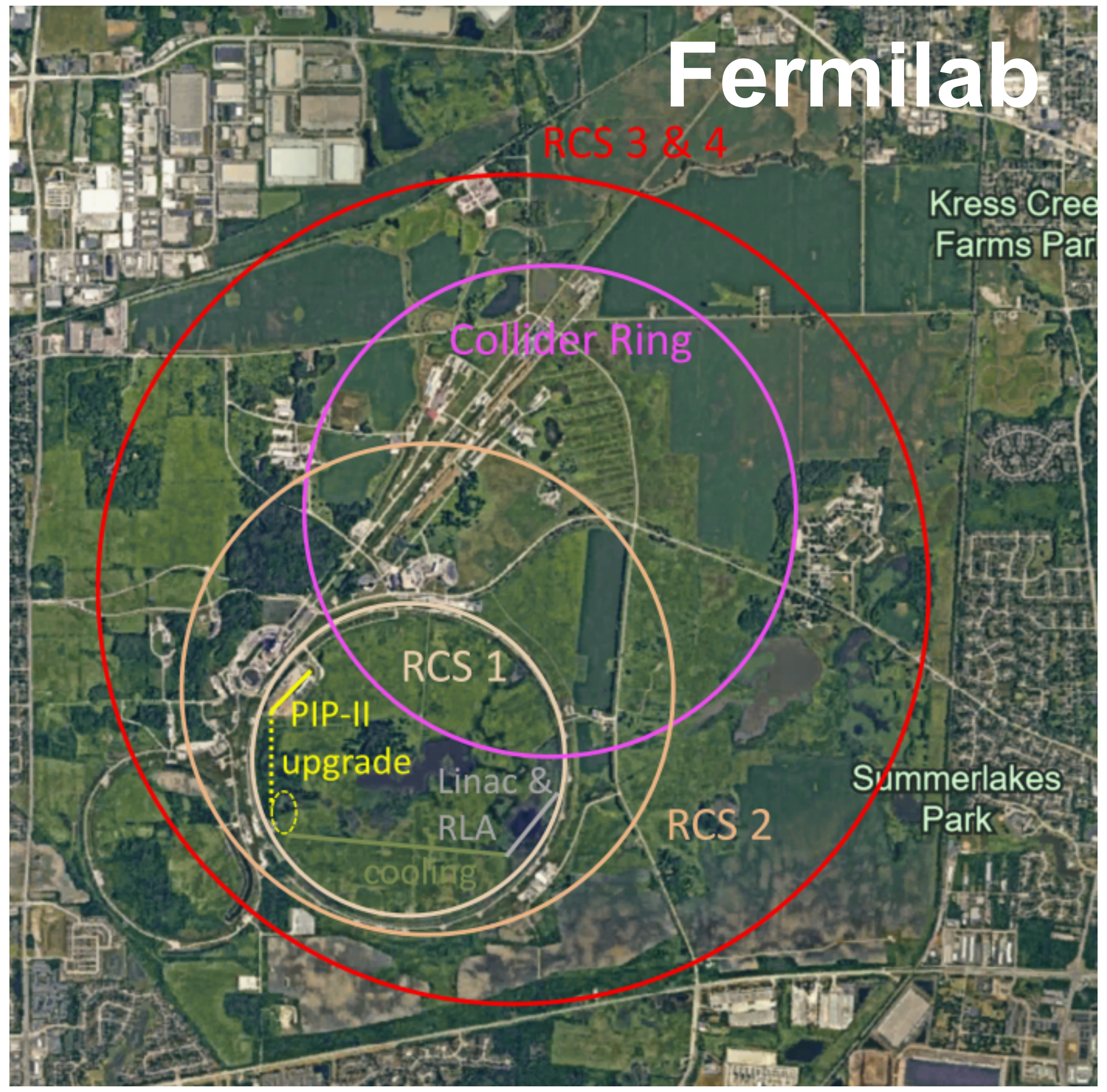
The Next-to-next Flagship Collider



Broad consensus: collider providing **at least 10 TeV** partonic center-of-mass energy

- FCC-hh: **80 TeV hadron collider** as second part of integrated FCC program
- Concepts for a **10 TeV muon collider**





https://arxiv.org/pdf/2504.21417

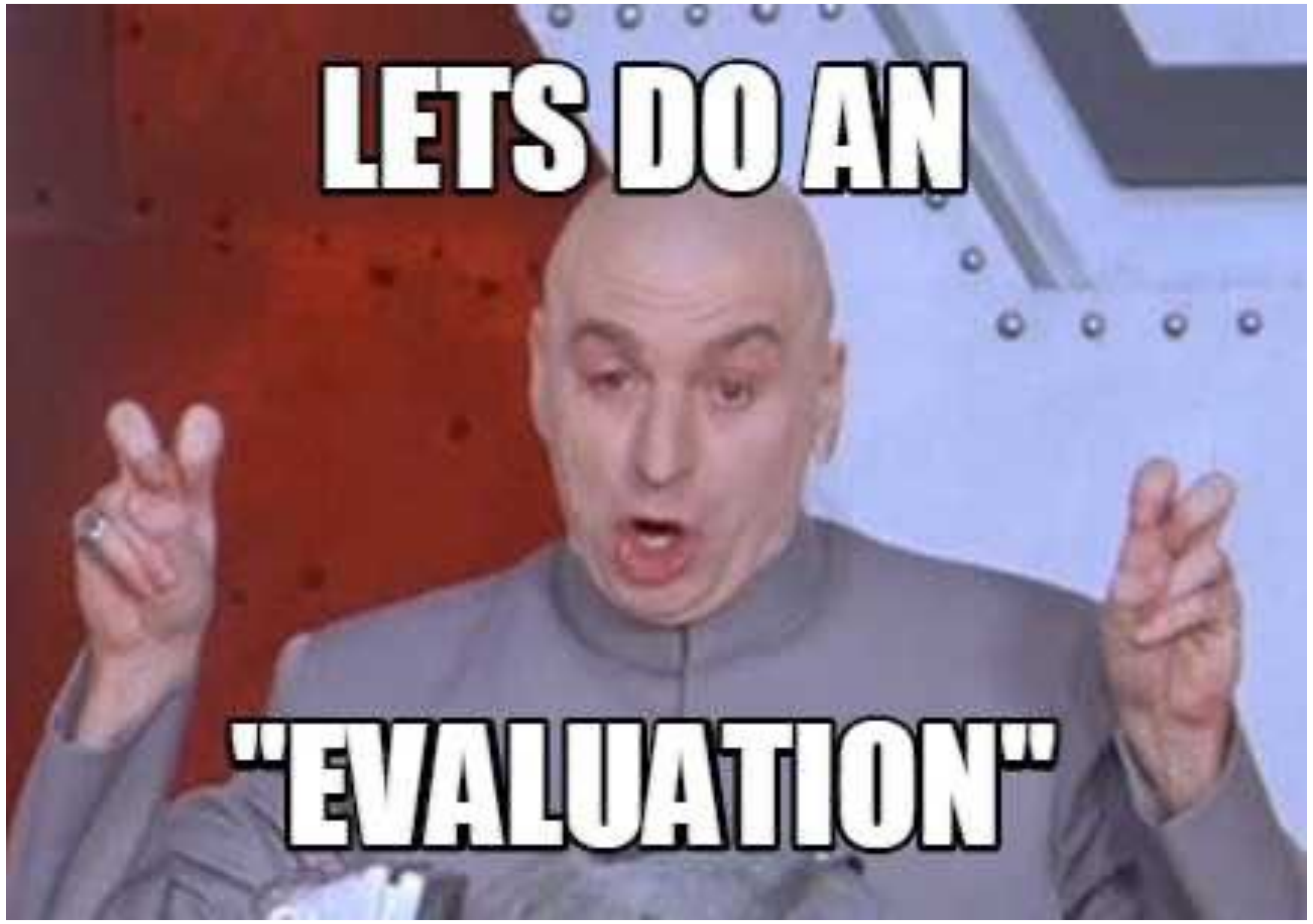
Evaluating and Comparing Future Projects

Finding the Right Metric

Important: need **apples-to-apples comparison** of competing projects

- Compare **physics reach** (e.g., sensitivity on parameters, energy/ mass scales to be probed)
- Required: meaningful and well-defined **benchmark physics processes**
- Evaluate **impact** of projects on **global interpretation** of data

Evaluation is usually based on a few **assumptions** → read the fine print!



https://www.mihaileric.com/posts/model-evaluation/

Physics Benchmarks: Couplings

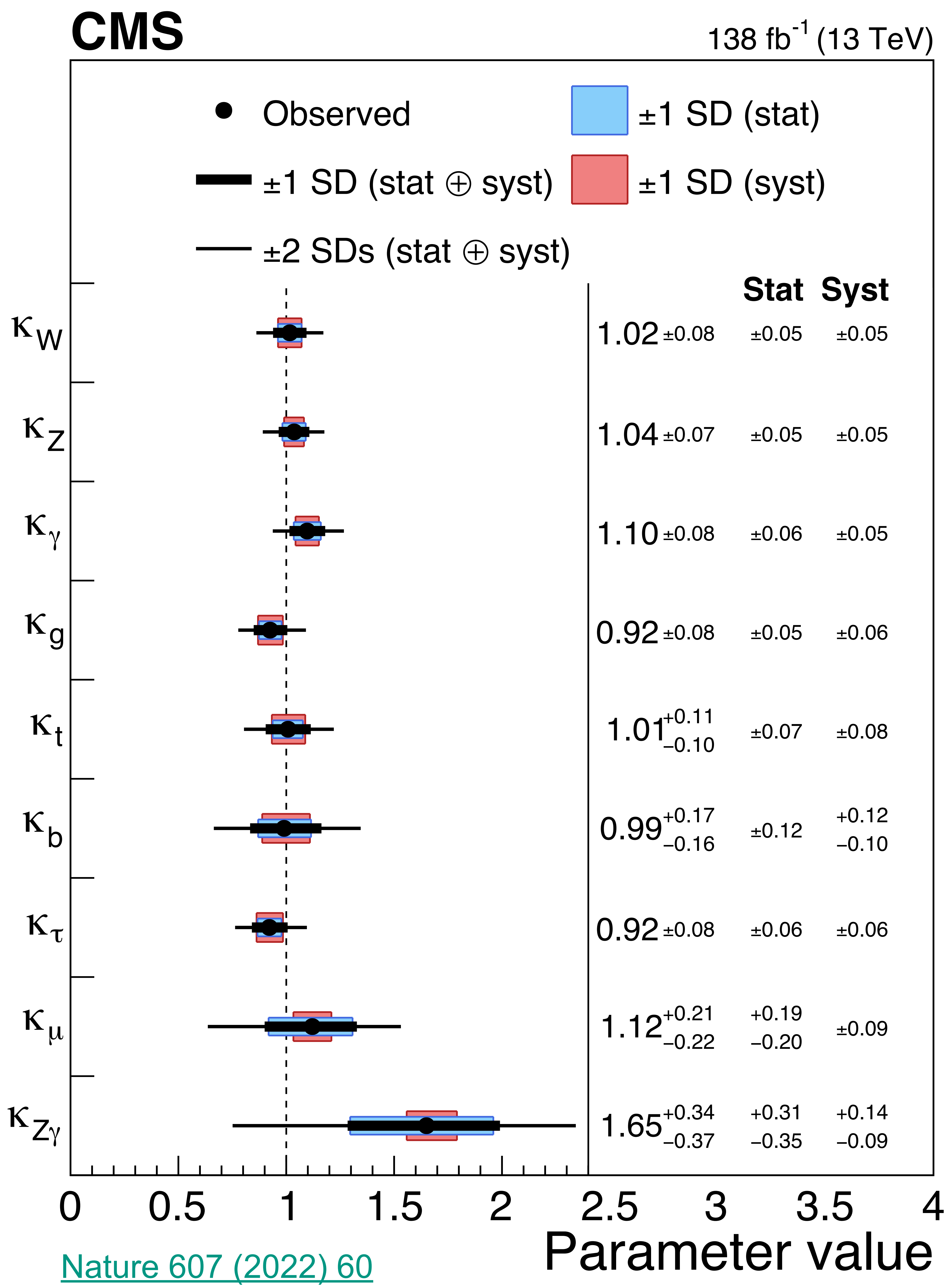
Example: Higgs Boson Couplings

Couplings of the Higgs boson to other particles:

- Couplings: theory parameters, **not observables**
- **Measure** (differential) cross sections of processes and **interpret** them as couplings

Typical **assumptions**
(example: Higgs-boson couplings)

- Higgs-boson production and decay processes **factorize** ("narrow width approximation")
- **BSM physics affects** production **cross sections** and decay **branching fractions**, but **does not affect** kinematic distributions



Nature 607 (2022) 60

Physics Benchmarks: Couplings

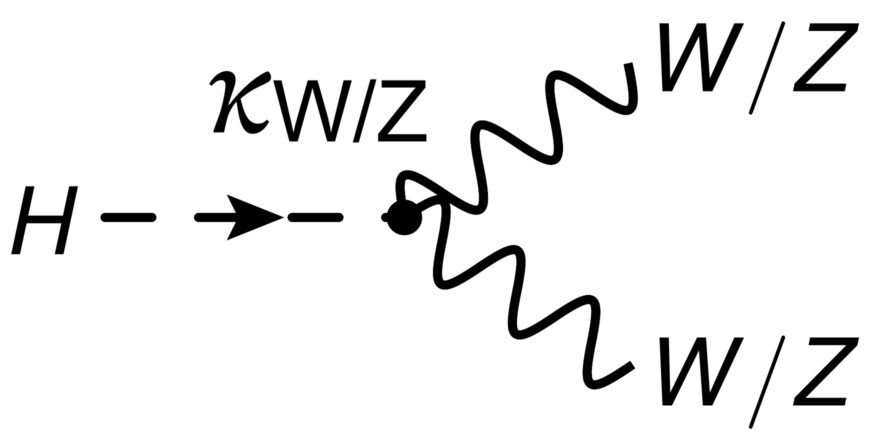
Example: Higgs Boson Couplings

Simplest observable:
signal strength modifier μ –
production cross section and/or branching fraction relative to SM

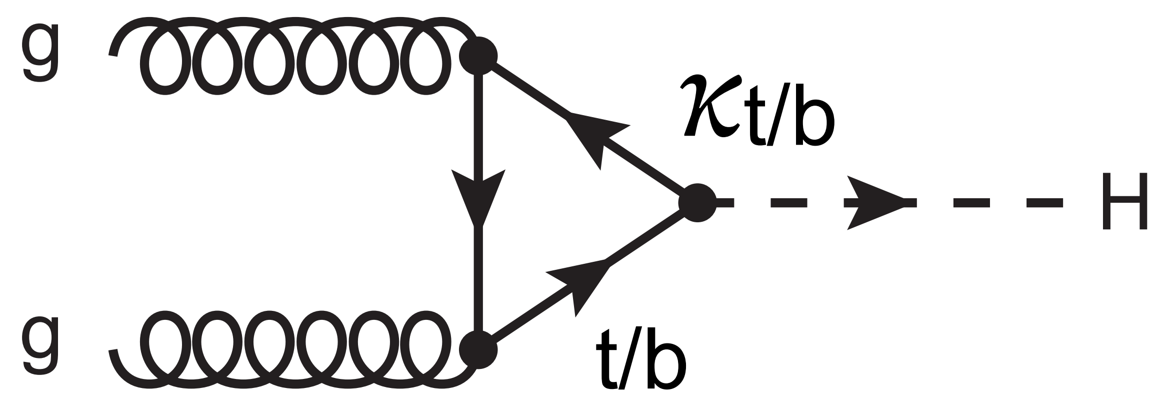
$$\mu(\mathrm{pp} \to \mathrm{H}(\to Y) + X) = \frac{\sigma(\mathrm{pp} \to \mathrm{H} + X)}{\sigma(\mathrm{pp} \to \mathrm{H} + X)^{\mathrm{SM}}} \cdot \frac{B(\mathrm{H} \to Y)}{B(\mathrm{H} \to Y)^{\mathrm{SM}}}$$

→ $\mu = 1$ for SM expectation

Slightly more advanced: **scale factors** κ_i ("coupling modifiers")
for couplings to all SM particles, with $\kappa_i = 1$ for SM coupling, e.g.



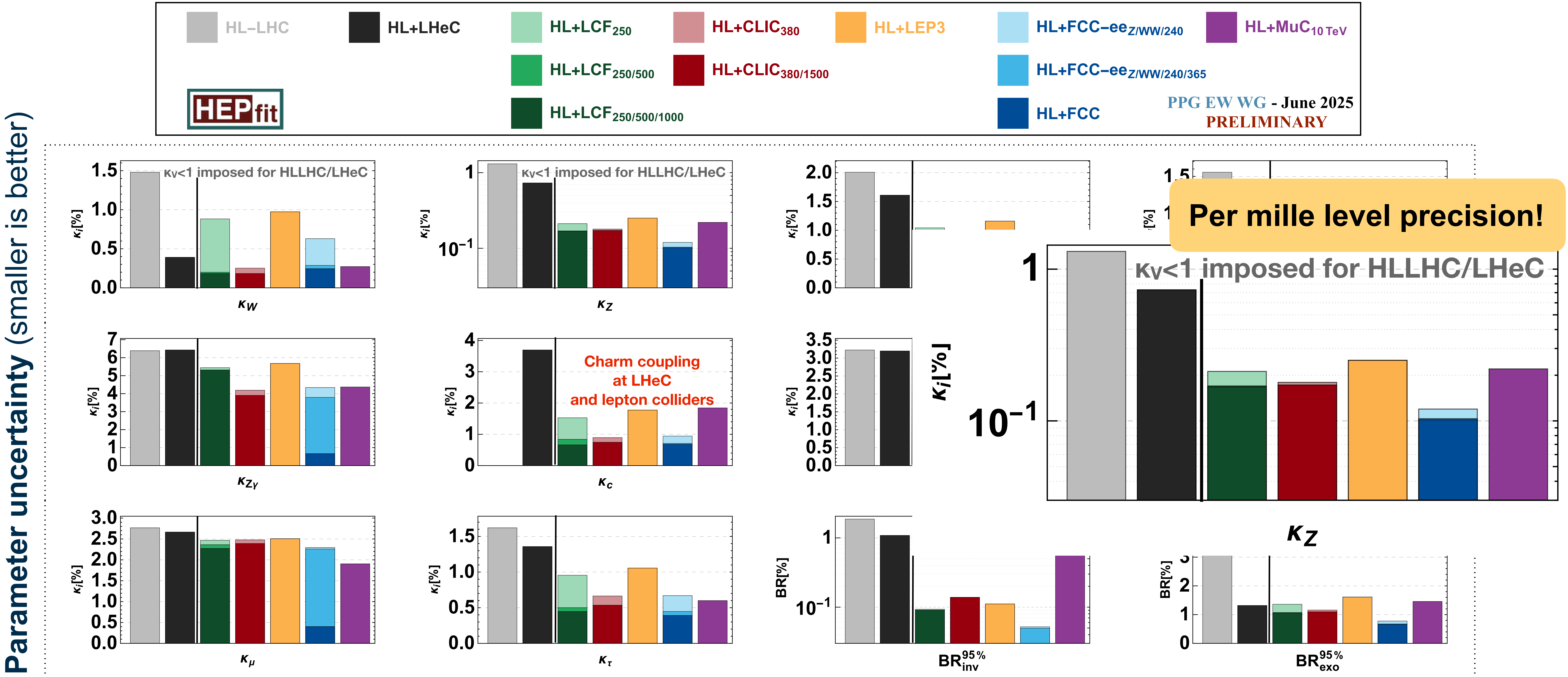
$$B(\mathrm{H} \to \mathrm{ZZ}) \propto \kappa_{\mathrm{Z}}^2$$



$$\sigma(\mathrm{gg} \to \mathrm{H}) \propto 1.06\kappa_{\mathrm{t}}^2 + 0.01\kappa_{\mathrm{b}}^2 - 0.07\kappa_{\mathrm{t}}\kappa_{\mathrm{b}}$$

Physics Benchmarks: Couplings

Example: Higgs Boson Couplings



Global Interpretation of Experimental Data

Effective Field Theory (EFT)

EFT: systematic way to calculate effects of BSM particles **too heavy to detect** on low-energy observables

General approach: add **all possible QM operators** $\mathcal{O}_i$ with mass/energy dimension d > 4 to SM Lagrangian

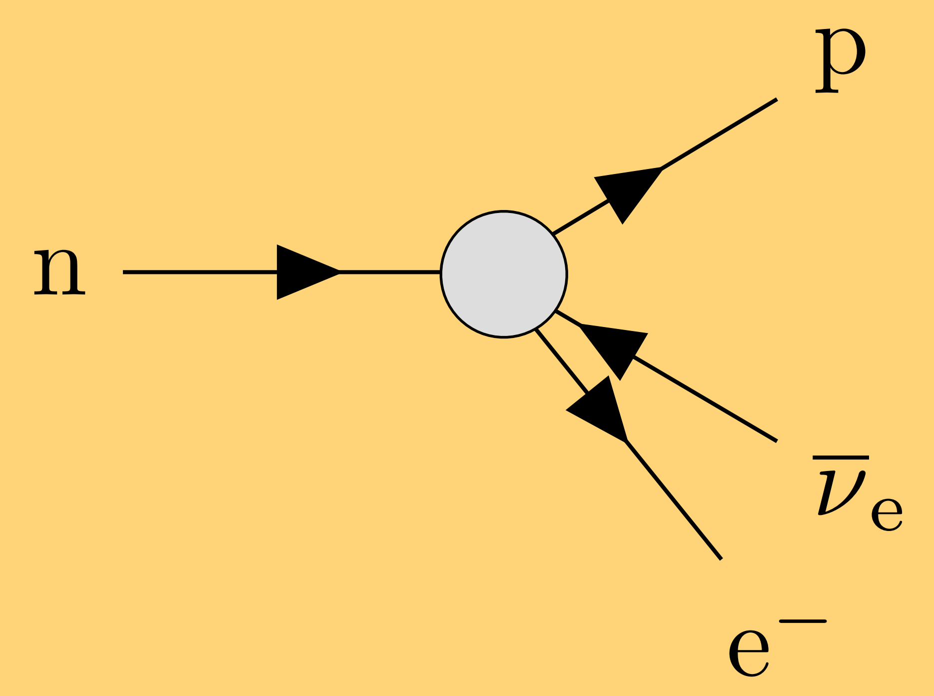
$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i}{\Lambda^2}\mathcal{O}_i^{d=6} + \sum_i \frac{C_i}{\Lambda^4}\mathcal{O}_i^{d=8} + \ldots$$

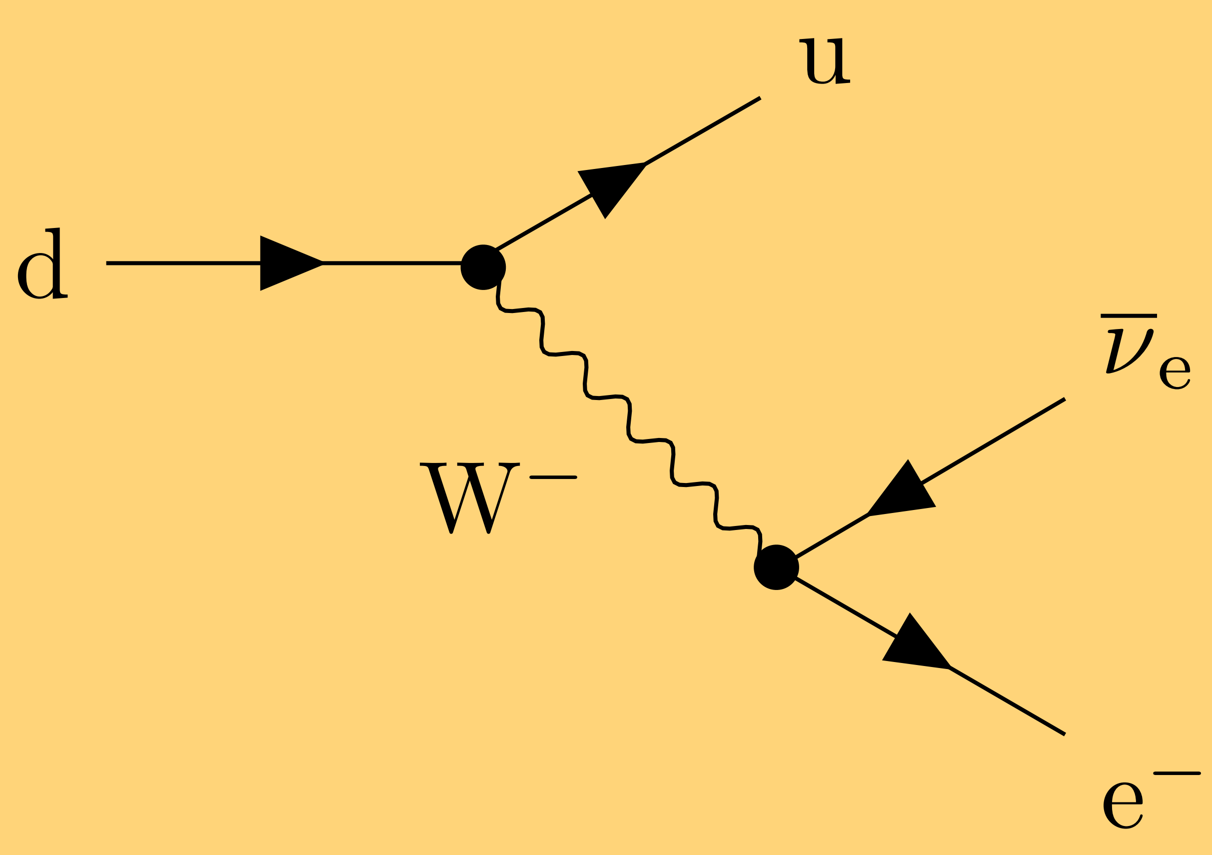
→ C_i ("Wilson coefficients") contain BSM effects

Often considered: **SMEFT** = standard model EFT

- Full SMEFT: **2499 operators** at d = 6
- Operators can be expressed in different **bases**

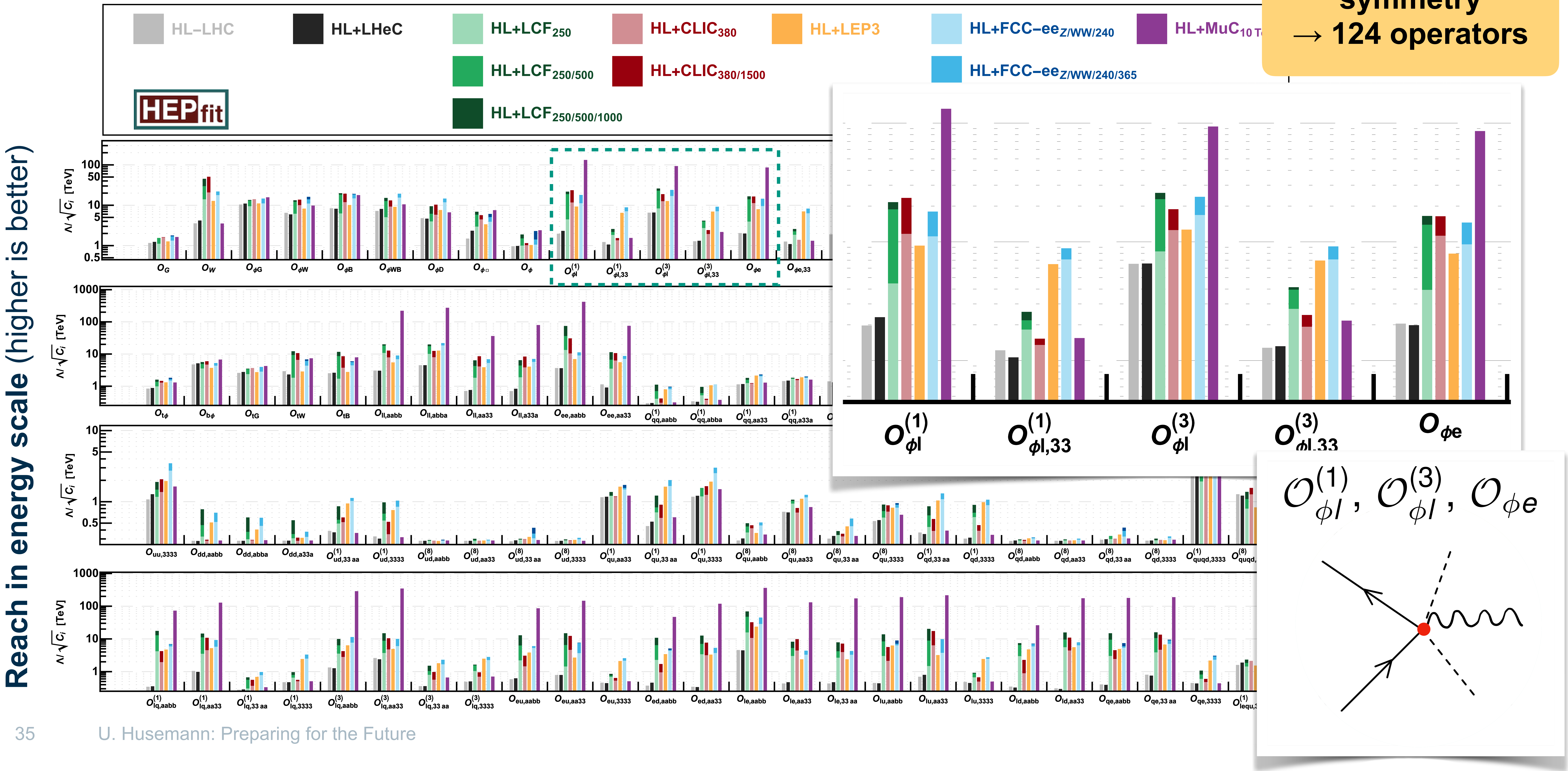
Classic Example:
Fermi Theory of Beta Decay





Global SMEFT Fit 2025: Energy Scale Sensitivity

SMEFT assuming $U(2)^5$ flavor symmetry → 124 operators



Physics Benchmarks: CKM

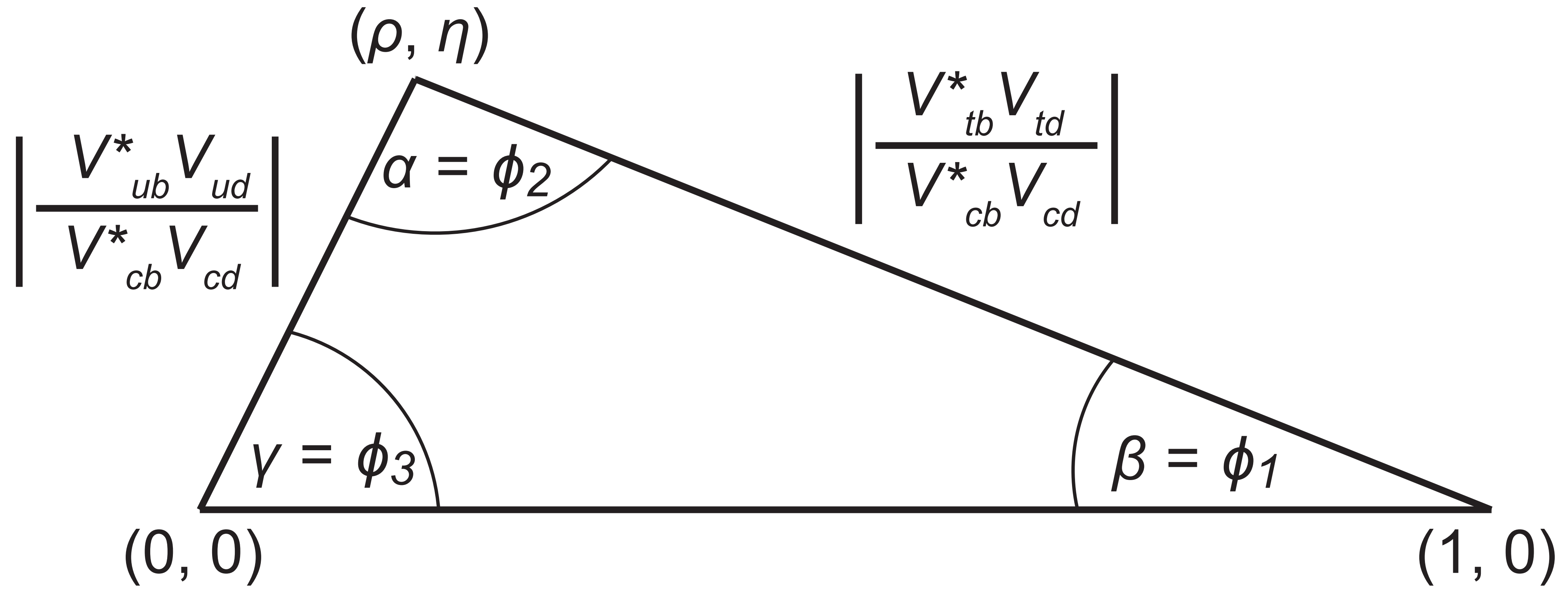
Unitarity Triangle Today and Tomorrow

CKM Matrix & Wolfenstein Parameterization

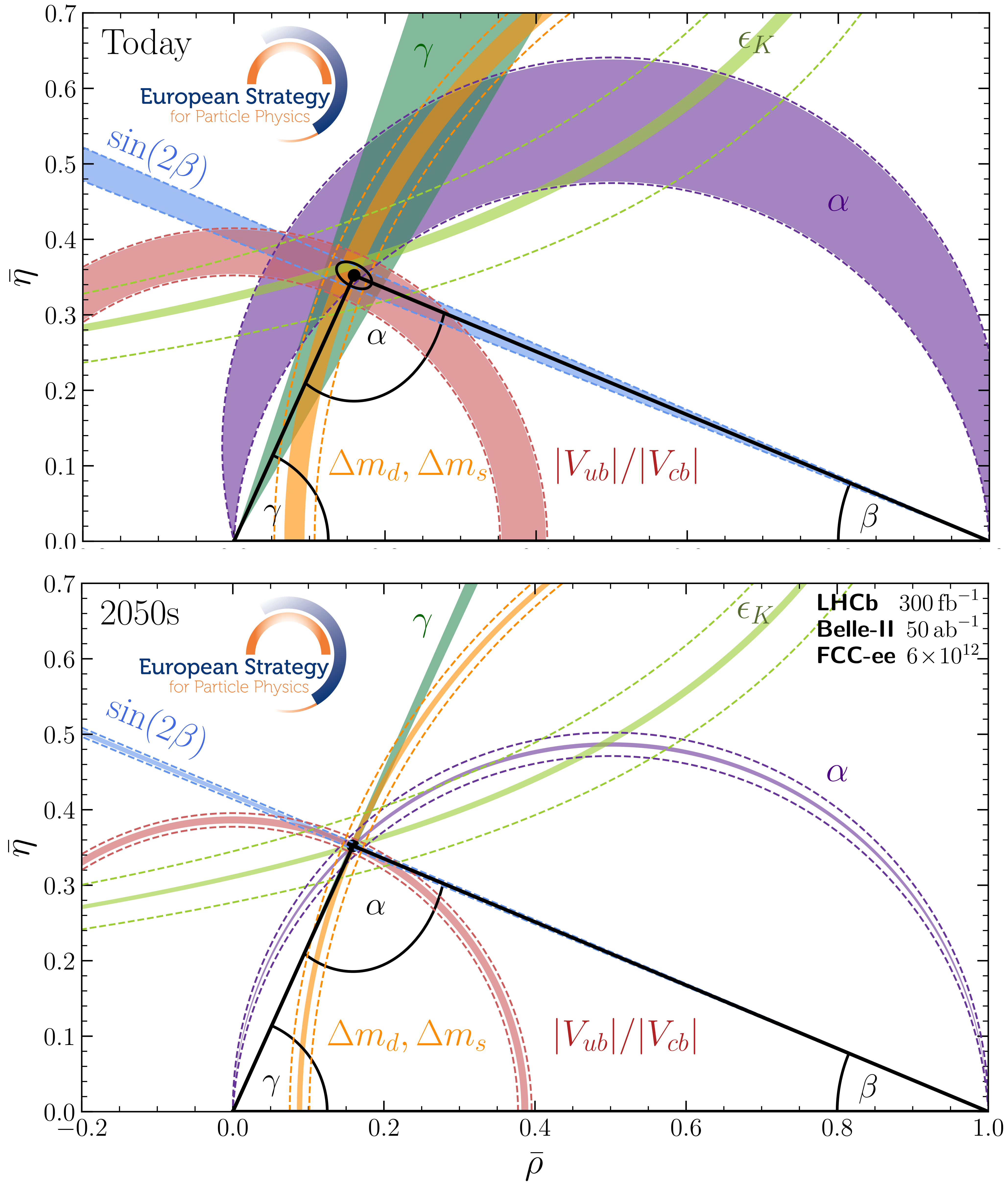
$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

→ **Unitarity Triangle**: first column × (third column)* = 0



PPG Flavour WG Preliminary – Sep 2025



Neutrino Physics

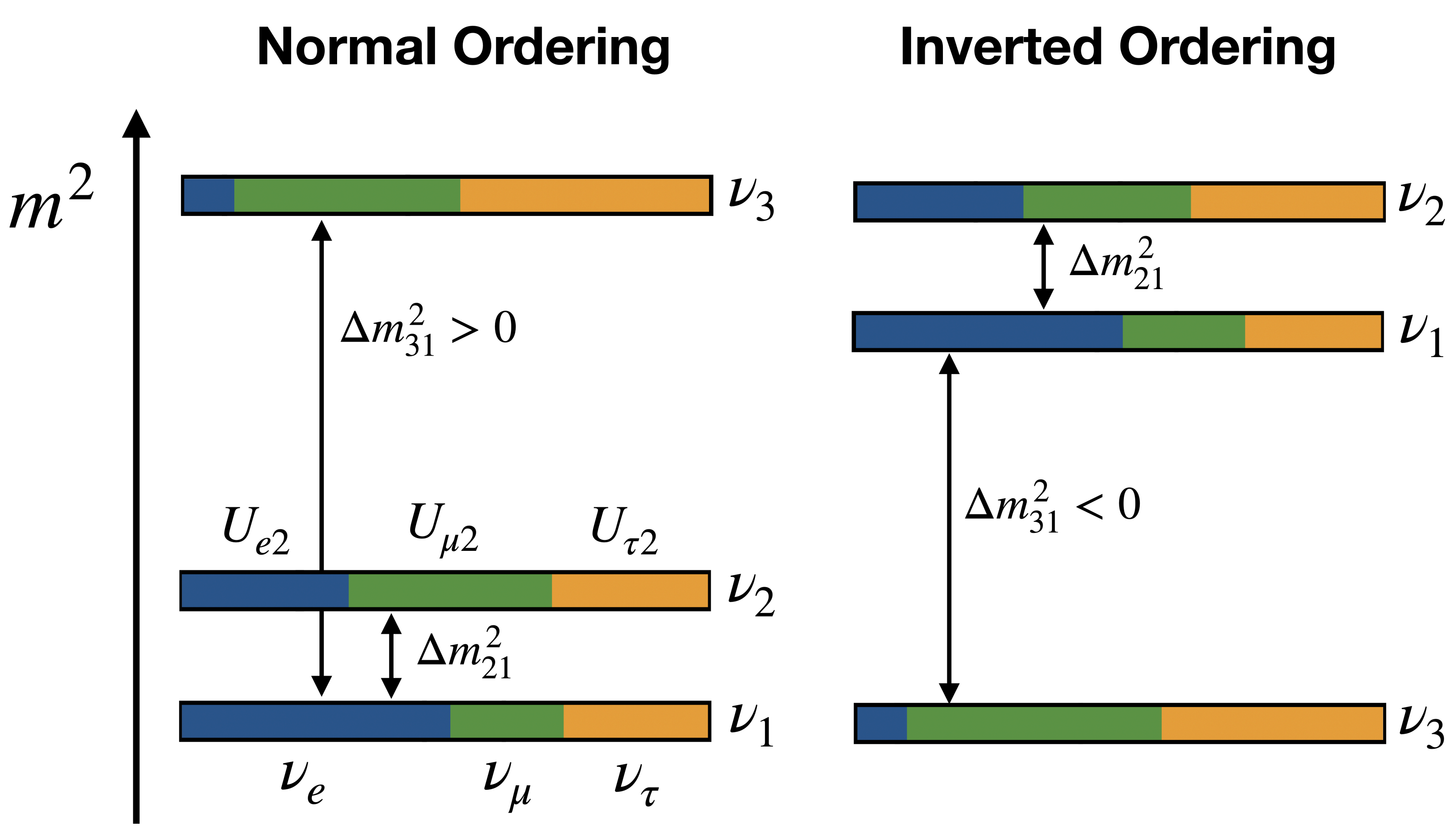
Global Fit of Neutrino Oscillation Data

Sources: **atmospheric** and **solar** neutrinos, **accelerator** and **reactor** neutrinos

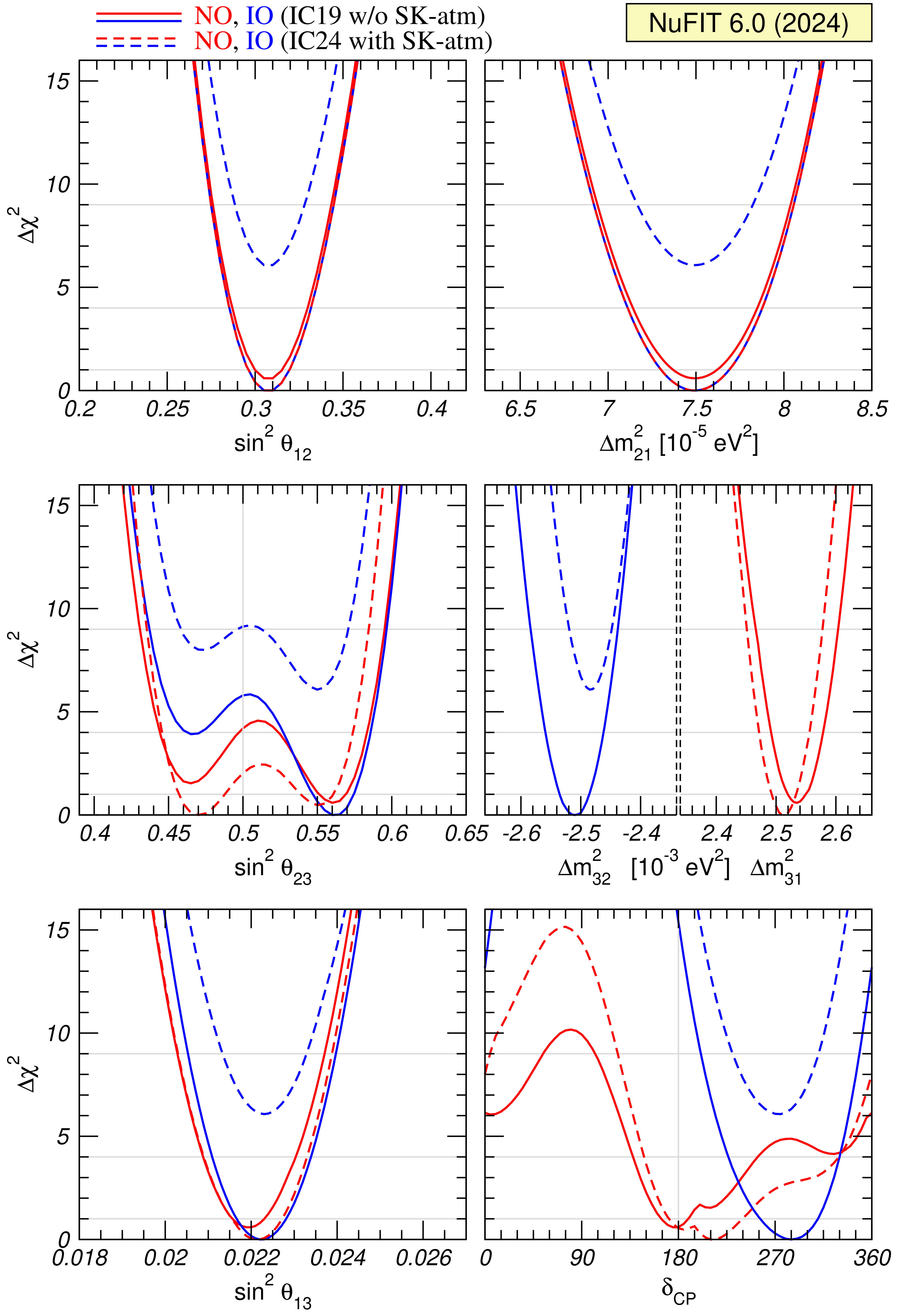
Parameters: **mass differences Δm^2 and mixing parameters sin² θ, CP violating phase δ_{CP}**

$$P_{osc} = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L\,[\text{km}]}{E\,[\text{GeV}]}\right)$$ (for two flavors)

Mass hierarchy: **normal** and **inverted** ordering



https://www.mdpi.com/2673-9984/8/1/7



JHEP12 (2024) 216, http://www.nu-fit.org/

Neutrino Physics

Neutrino Mass

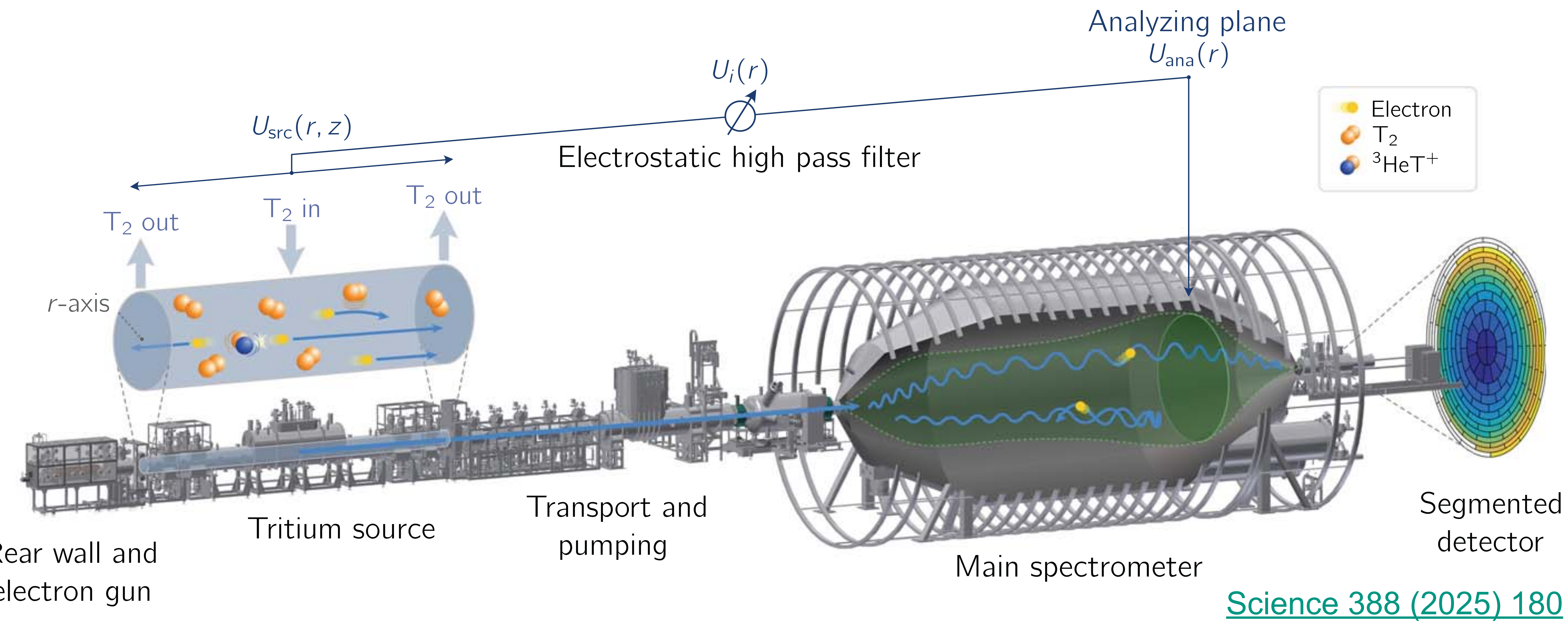
Neutrino oscillations: at least one neutrino mass eigenstate must have **non-zero mass**

Today's flagship: **KATRIN**

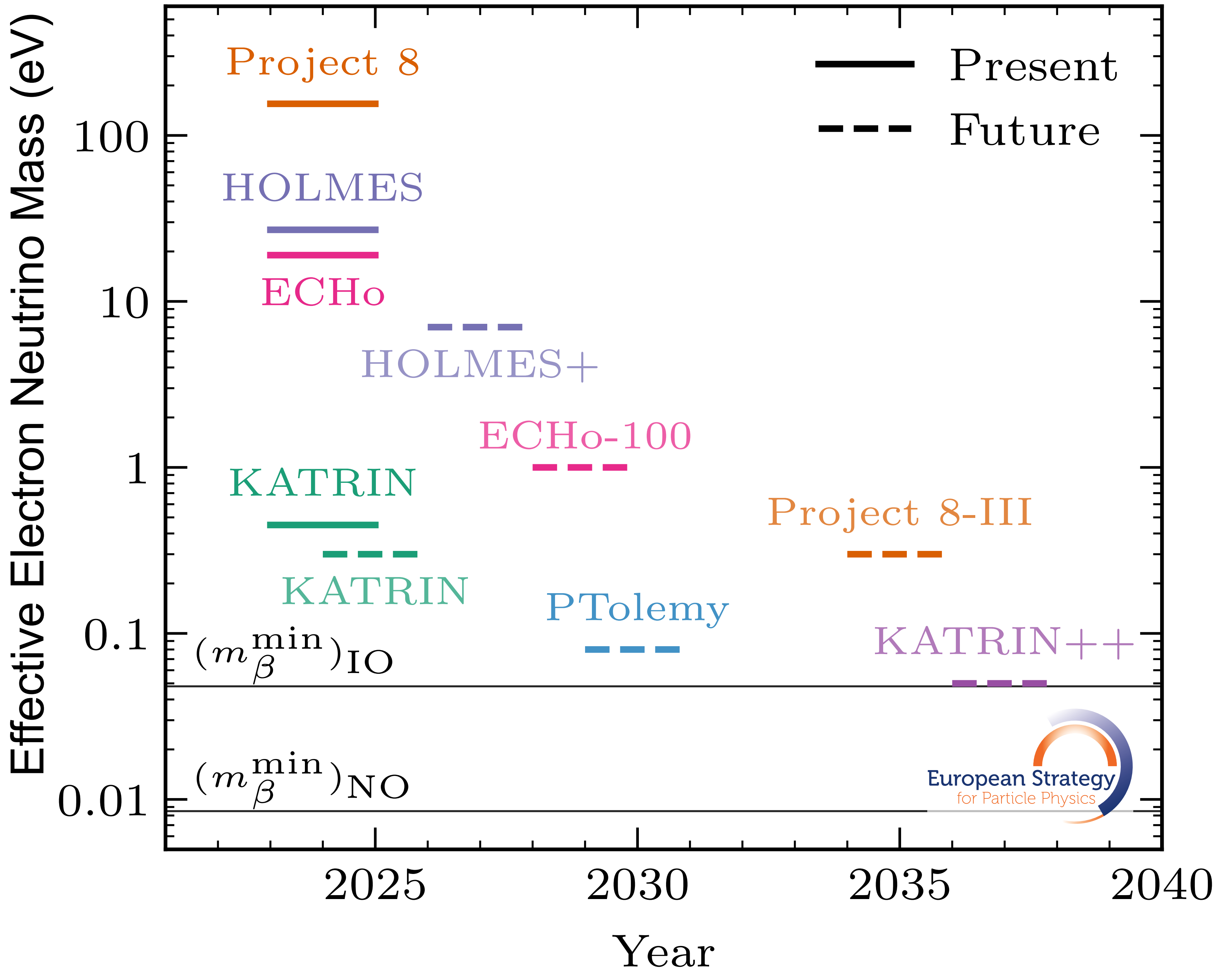
- Kinematics of **tritium beta decay**
- Observable: effective mass of electron neutrino, independent of neutrino nature

Future directions:

- Different **isotopes** (e.g., electron capture in Ho)
- **Atomic** tritium & **quantum sensors**
- Novel detection methods: **cyclotron radiation emission spectroscopy** (CRES)



Science 388 (2025) 180



Neutrino Physics

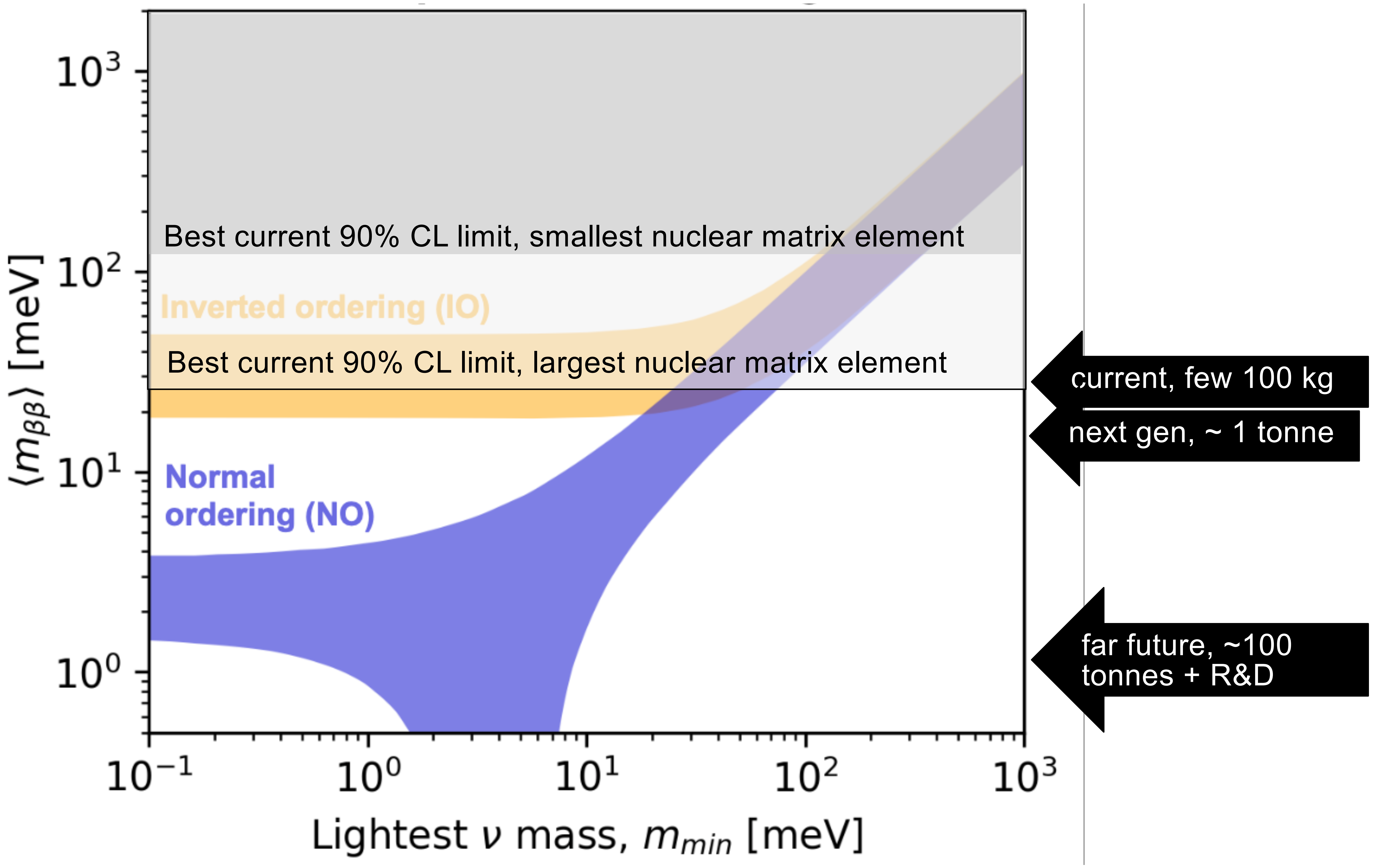
Neutrino Nature: Dirac or Majorana?

Neutrino oscillations: at least one mass eigenstate must have non-zero mass

Search for **neutrinoless double-beta decay** ($0\nu\beta\beta$):

- Very rare **two-body** decay, only possible if neutrinos are **Majorana fermions**, but **model dependent** (nuclear physics!)
- Observable: $0\nu\beta\beta$ **half-life $T_{1/2}$** → effective Majorana mass $\langle m_{\beta\beta} \rangle$
- Search for **peak** in energy spectrum of ultrapure Ge, Se, Te, Mo, Xe isotopes

$$\frac{1}{T_{1/2}} = \underbrace{|\mathcal{M}|^2}_{\text{(nuclear matrix element)}^2} \times \frac{|\langle m_{\beta\beta} \rangle|^2}{m_e^2} \times \underbrace{\phi}_{\text{phase space}}$$



K. Scholberg, EPS HEP 2025

Dark Sector

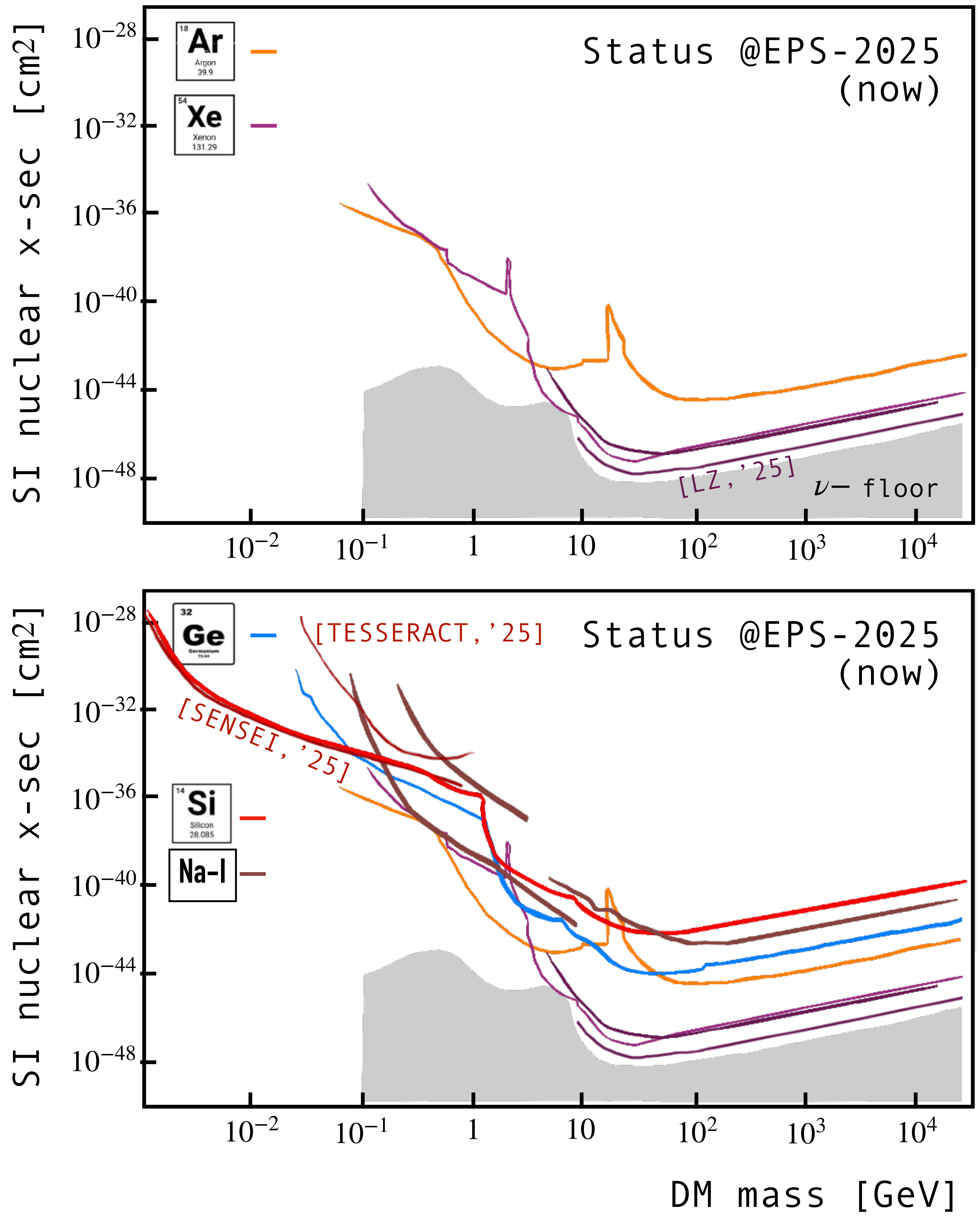
The GeV/TeV Scale: WIMP Dark Matter

Standard model of cosmology: **ΛCDM**

- **Cold** (i.e. non-relativistic) **dark matter** (DM) plus **cosmological constant Λ** as dark energy
- Energy content of the universe: 5% baryonic matter, **70% dark energy, 25% dark matter**

10+ years ago: **WIMP paradigm**

- **Weakly interacting massive particle** (WIMP) with GeV to TeV mass
  → **ideal DM candidate** (stable, dark, cold)
- Supersymmetric (SUSY) theories naturally provide WIMP candidate, e.g., lightest neutralino (superpartner of Z, γ, H^0)



C. Morgui (EPS HEP 2025)

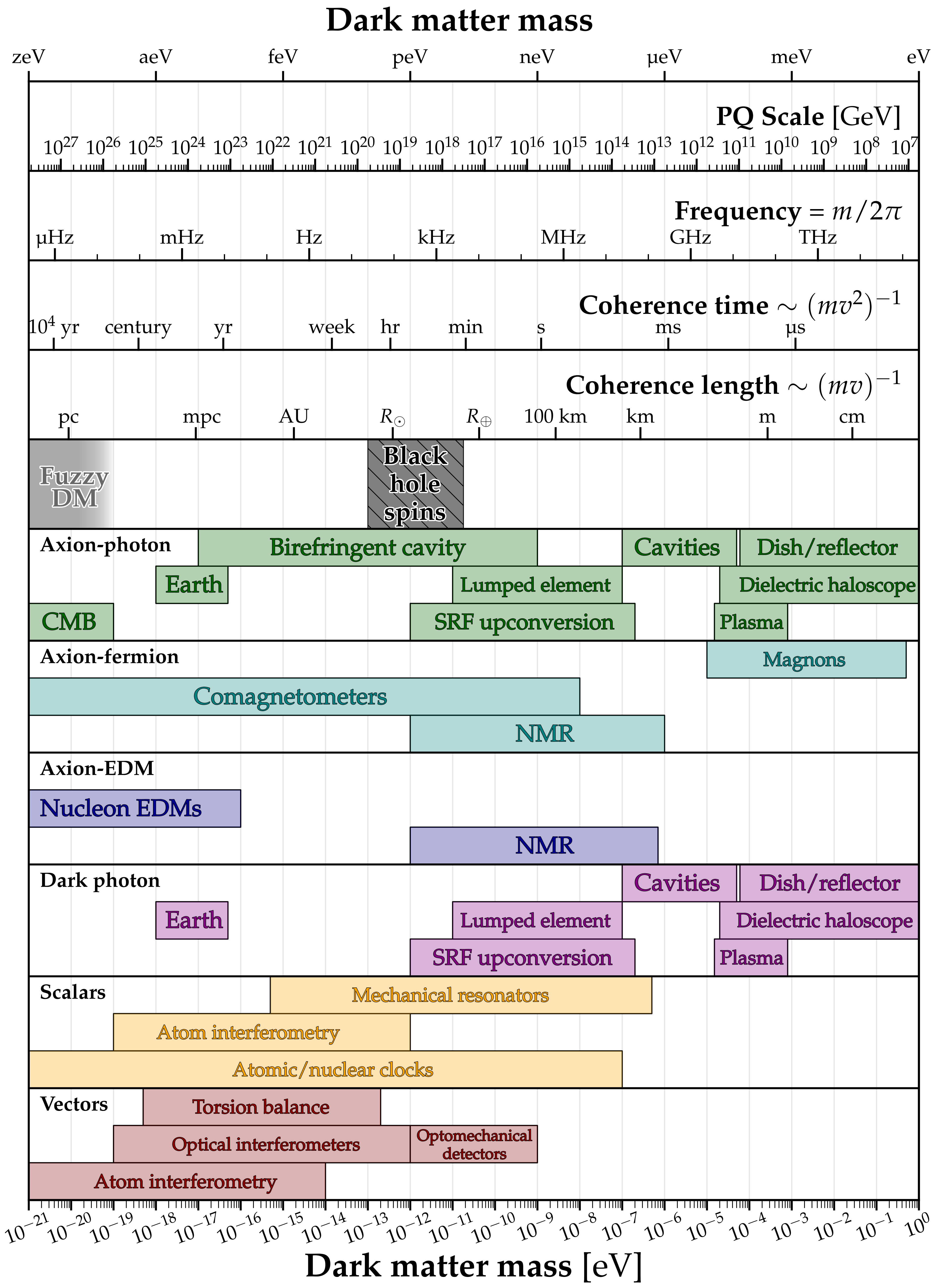
Dark Sector

The Sub-eV Scale: Axion Dark Matter

Initial science question: why is there
no matter-antimatter asymmetry in QCD?
(“strong CP problem”)

Solution: **axions – “cleaning the vacuum”**
(Peccei & Quinn, Wilczek, Weinberg, 1977/1978)

- Well motivated SM extension: solves strong CP problem and provides **viable DM candidate**
- Plausible mass range of axion-like particles (ALPs) beyond the QCD axion: **>20 orders of magnitude!** → wide variety of of experimental techniques



https://cajohare.github.io/AxionLimits/

Where will particle physics be in 2040?

Summary of Part I

Collider-based particle physics:

- **Harvest of the HL-LHC**: phase-2 upgrades of ATLAS and CMS and significant upgrades proposed for LHCb and ALICE
- **Flavor** factories, e.g. Belle II, and **electron-ion collisions** at the EIC
- Preparation of the next flagship project in full swing: **Higgs/Electroweak/Top Factory** (circular or linear)

Particle physics **beyond colliders**:

- **Neutrino** properties: oscillations, CP, mass, …
- **Dark sector**: 24+ orders of magnitude in mass

Image credit: Adobe Stock


Image credit: Adobe Stock

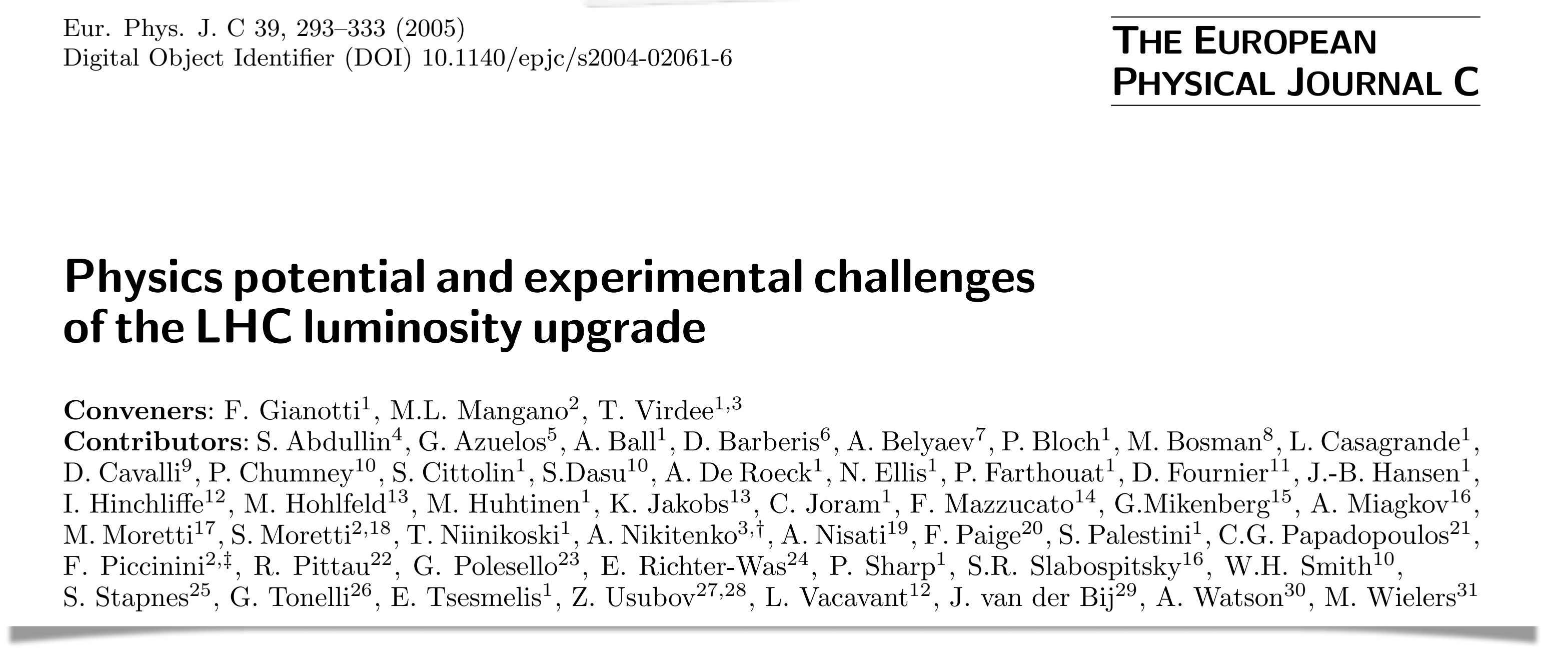
Part II: What is strategic planning and why should I care?

European Strategy
for Particle Physics

Preparing for Future Projects

Time Scales for Big Projects

Example: **Phase-2 upgrades** of the ATLAS and CMS detectors for the HL-LHC


Eur. Phys. J. C 39, 293–333 (2005)
Digital Object Identifier (DOI) 10.1140/epjc/s2004-02061-6

THE EUROPEAN PHYSICAL JOURNAL C

Physics potential and experimental challenges of the LHC luminosity upgrade

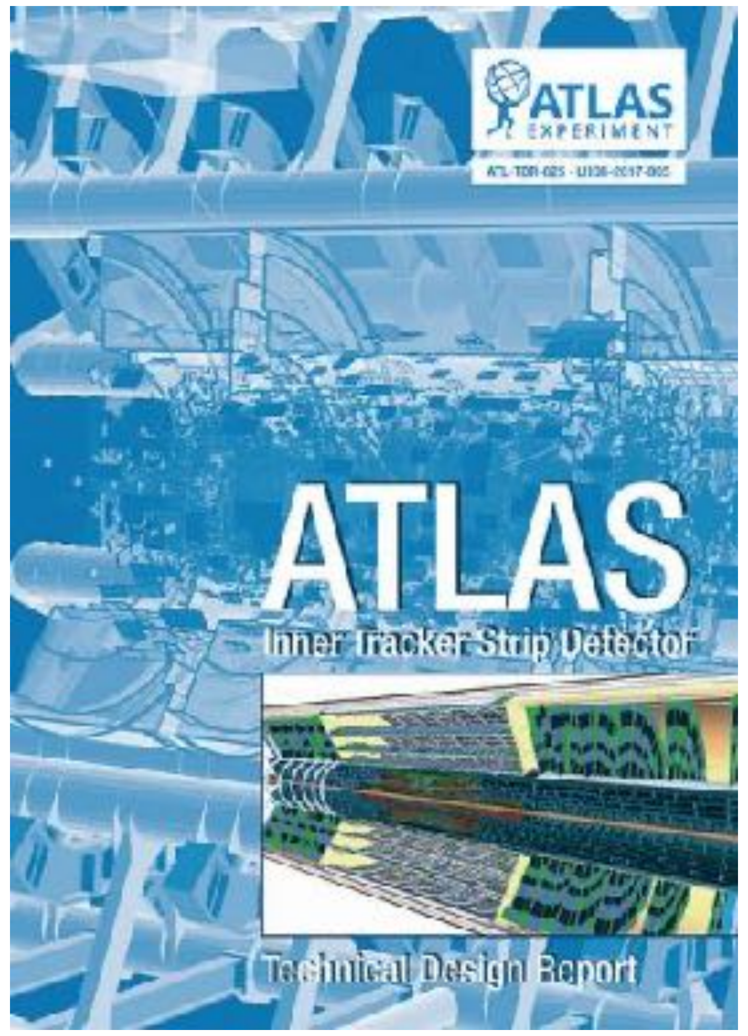
Conveners: F. Gianotti[1], M.L. Mangano[2], T. Virdee[1,3]
Contributors: S. Abdullin[4], G. Azuelos[5], A. Ball[1], D. Barberis[6], A. Belyaev[7], P. Bloch[1], M. Bosman[8], L. Casagrande[1], D. Cavalli[9], P. Chumney[10], S. Cittolin[1], S.Dasu[10], A. De Roeck[1], N. Ellis[1], P. Farthouat[1], D. Fournier[11], J.-B. Hansen[1], I. Hinchliffe[12], M. Hohlfeld[13], M. Huhtinen[1], K. Jakobs[13], C. Joram[1], F. Mazzucato[14], G.Mikenberg[15], A. Miagkov[16], M. Moretti[17], S. Moretti[2,18], T. Niinikoski[1], A. Nikitenko[3,†], A. Nisati[19], F. Paige[20], S. Palestini[1], C.G. Papadopoulos[21], F. Piccinini[2,‡], R. Pittau[22], G. Polesello[23], E. Richter-Was[24], P. Sharp[1], S.R. Slabospitsky[16], W.H. Smith[10], S. Stapnes[25], G. Tonelli[26], E. Tsesmelis[1], Z. Usubov[27,28], L. Vacavant[12], J. van der Bij[29], A. Watson[30], M. Wielers[31]

First ideas and workshops — Early 2000s

Letters of Interest/ Technical Proposals — 2012–2015

Technical Design Reports — 2017–2021

Production & Commissioning — 2022–2030



Smaller-scale experiments: **shorter** development cycles, more **agile**

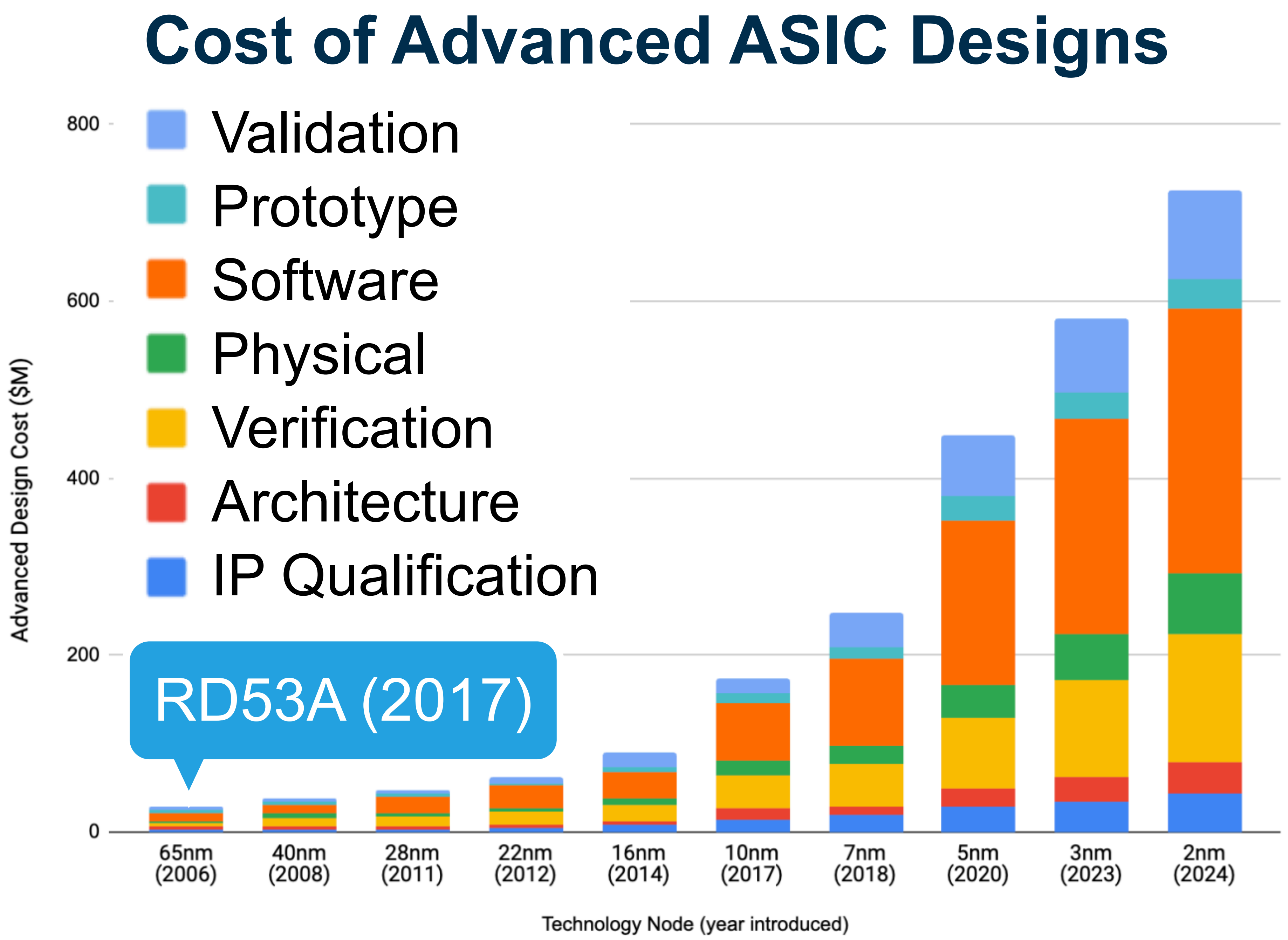
How do we stay at the forefront?

Long-term Projects in a Rapidly Changing World

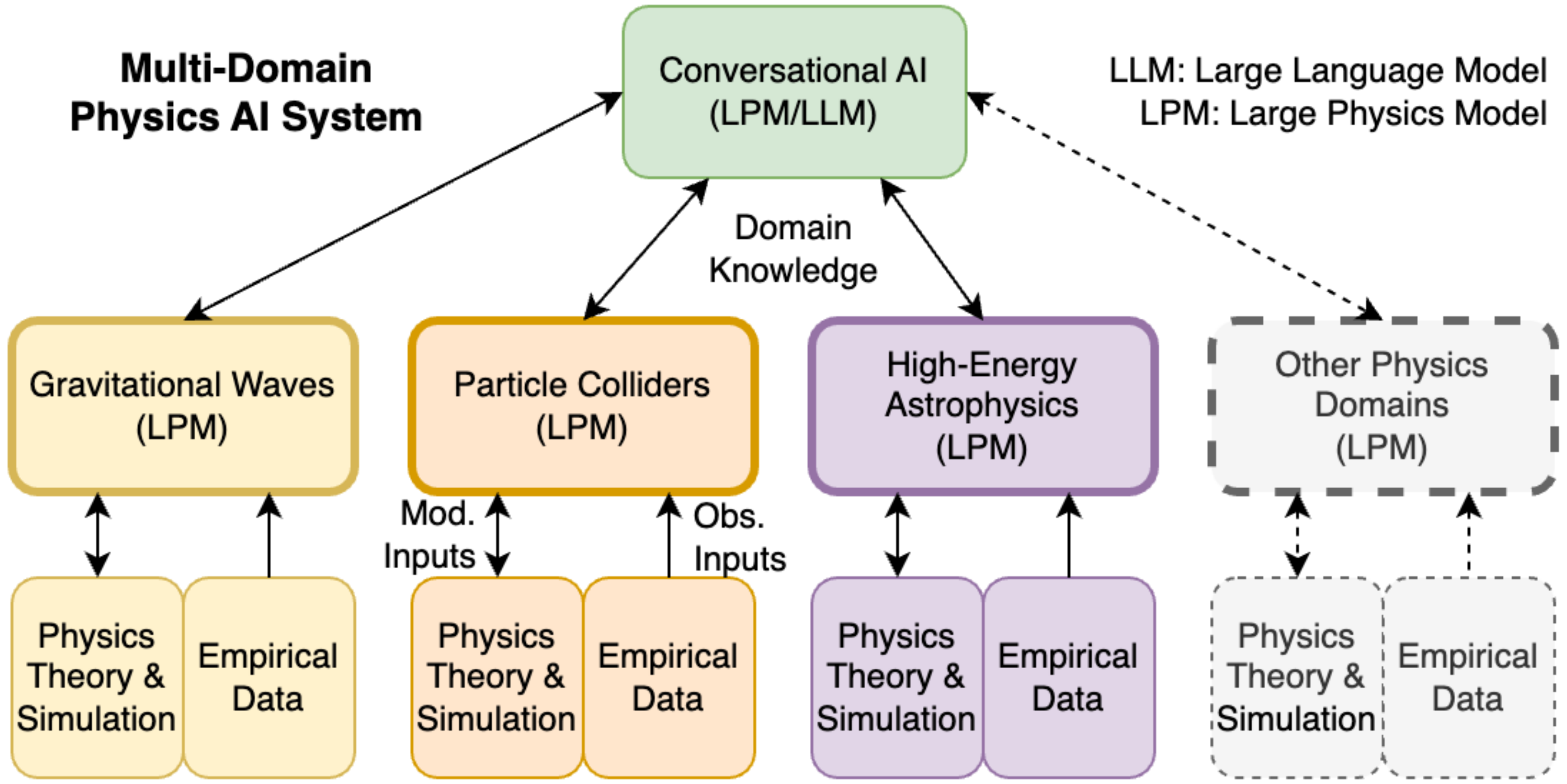
The world is **changing fast** around us new, e.g.:

- **Microelectronics**: 2 nm chips (HL-LHC: 65 nm)
- **Materials science** and **additive manufacturing**
- Second **quantum revolution**: quantum materials, quantum sensing, quantum computing
- **AI revolution**: machine learning, large language models, foundation models, …

Possible solution: **collaborate outside particle physics bubble** → other fields of physics and engineering, industry partnerships, …



Dario Soatto (Data source: International Business Strategies)



https://arxiv.org/abs/2501.05382

Big Science – Small Brains?

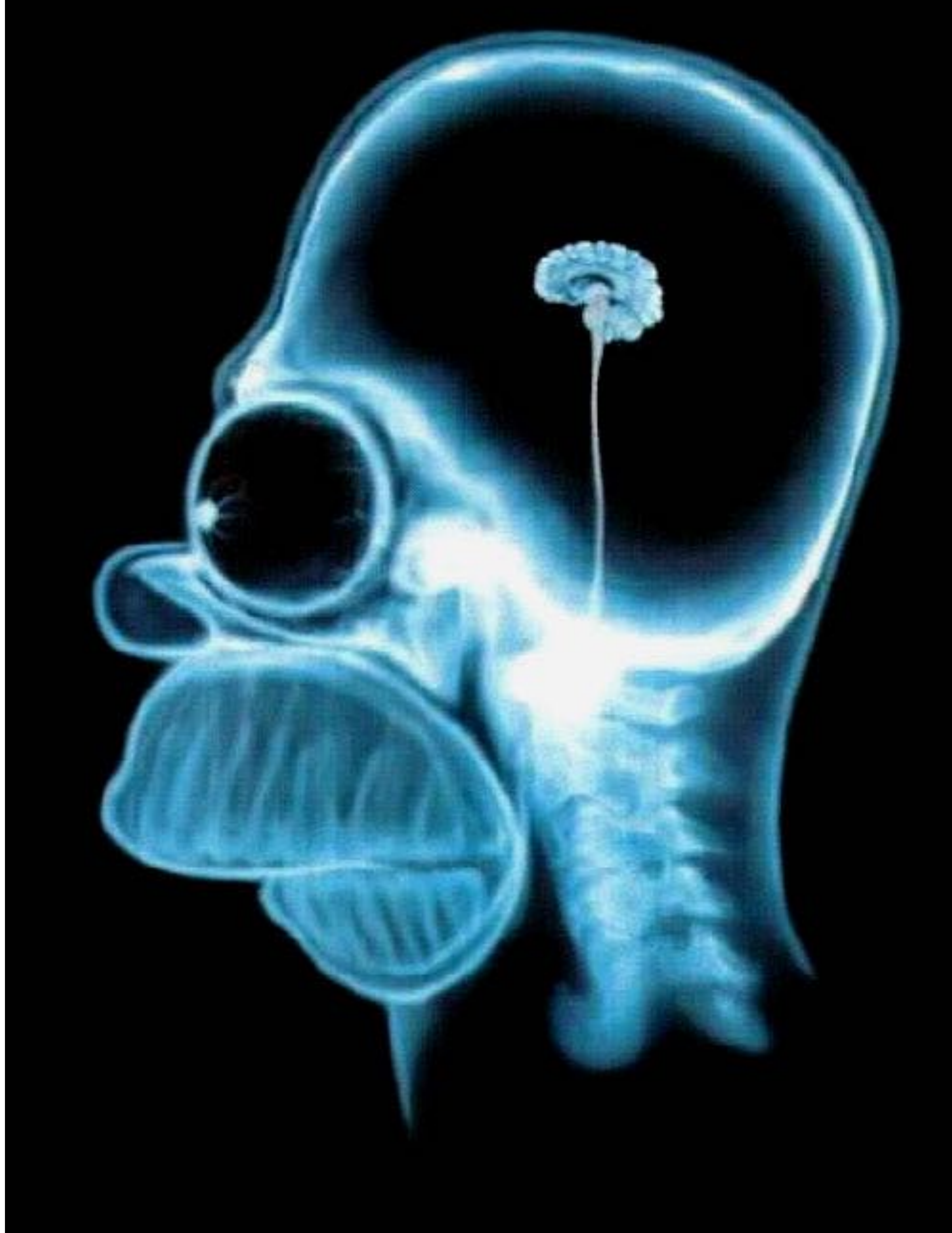
The Role of Big Research Infrastructures

Major **infrastructure investments**:

- Above “magic limit” of about a **billion euros**: involves high-level **political decisions**
- Helpful: **vision** for **long-term usage** (historical example: LEP → LHC → HL-LHC = 50+ years)

Possible decision/prioritization **criteria**:

- **Answers to big questions**: large scientific **interest** and **impact**
- Financial and societal **feasibility**, skilled **workforce**
- Reasonable **return on invest** for society: industry return, technology transfer, expert training



What IS a strategy, anyway?

Let's look at the Military and Management

Etymology: στρατηγία (stratēgia) = "art of the general"

Various **definitions** of strategy in **military theory** and **management theory**, e.g.:

- C.P.G. von Clausewitz (1780–1831): **strategy** = "doctrine of the use of individual battles for the purpose of war" vs. **tactics** = "the doctrine of using armed forces in combat"
- Wikipedia (2025): "**strategic management** involves the formulation and implementation of the major goals and initiatives taken by an organization's managers … based on consideration of resources and an assessment of the internal and external environments"

Strategic Analysis of New Projects

SWOT: Strengths, Weaknesses, Opportunities, Threats

SWOT: standard project evaluation procedure, also in science

- Identify **internal** and **external factors** influencing strategic position of project → assist decision-making
- Internal: **strengths** and **weaknesses** (personnel, equipment, funding, knowledge, reputation, …)
- External: **opportunities** and **threats** (trends in science and society, economy, funding sources, legislation, …)

Why You Should Care About Strategy

if you are an Early Career Researcher today

Today's Early Career Researchers (ECRs)…

- … will be **tomorrow's leaders** in science, industry, politics, …
- … will make projects **sustainable**
- … will define how we **work together**
- … deserve **interesting and challenging projects**, as well as a working **talent pipeline** and **recognition** for their work

→ should **participate** in today's decisions

N.B.: a good strategy opens up many **attractive career paths**

ECR Open Symposium 2025

C. Dimitriadi, U. Einhaus, ESPP Open Symposium 2025

The Political Dimension

Technological Sovereignty and Competitiveness

Recent political discussions on science influenced by, e.g.:

- The future of European competitiveness ("Draghi report"):

  The CERN success story
  A notable example of the remarkable returns from the joint collaboration of European countries is the creation of the European Organization for Nuclear Research (CERN) in 1954. […] The pooling of country-specific resources allowed single countries to share the considerable risks and uncertainty inherent to fundamental innovative research. Its collaborative effort has yielded remarkable successes, including two most notable discoveries: the invention of the World Wide Web, invented at CERN 35 years after its inception, and the discovery of the Higgs Boson particle, announced on 4 July 2012. CERN scientific leadership spans various domains, including superconductivity, magnets, vacuum, radio frequency, precision mechanics, electronics, instrumentation, software, computing and Artificial Intelligence. CERN's technologies have generated significant societal benefits, including advancements in cancer therapy, medical imaging, autonomous driving with artificial intelligence, and environmental applications of superconducting cables.
- Much more than a market ("Letta report")

The Global Context

Relations to Other World Regions

LHC: very successful model of **worldwide scientific collaboration**

Boundary conditions became more difficult in recent years:

- **Multipolar** world order, strong **competition**
- **Hot war** in Europe between states active at CERN
- Tendencies **against evidence-based science**
- **Tight budget situation** in many parts of the world
- **Other scientific fields** have large-scale projects as well

Image source: Adobe Stock

Future projects: use synergies and partnerships in **global particle physics network**

What is strategic planning and why should I care?

Summary of Part II

Challenge: planing and deciding on **decades-long projects** in a **rapidly changing world**

Long-term **strategic planning**:

- **Distinguish strategy** from vision and tactics/implementation
- **Evaluate internal** and **external factors** (e.g., SWOT analysis)
- **Prioritize** projects: interest – impact – capability – feasibility
- **Interact** with other branches of science and industry
- **Reach out** to society and politics → **science communication**

Image credit: Adobe Stock

Image credit: Adobe Stock

Part III: European Strategy for Particle Physics – What’s Going On?

European Strategy
for Particle Physics

KIT

European Strategy for Particle Physics

Cornerstone of European Decision-making on the Long-Term Future of Particle Physics

Challenge: decision-making with $O(10^4)$ scientists

Mandate from **CERN Council**
(“supreme decision-making authority of CERN”)

Broad **consultation** in CERN member states, associate member states, and beyond

Development of **strategic recommendations** for CERN Council (≠ project approval)

CERN Council decides on strategy

European particle physics community **implements** strategy

- 2006: Original Strategy
- 2013: First Update
- 2020: Second Update
- 2026: Third Update

The ESPP does make a difference

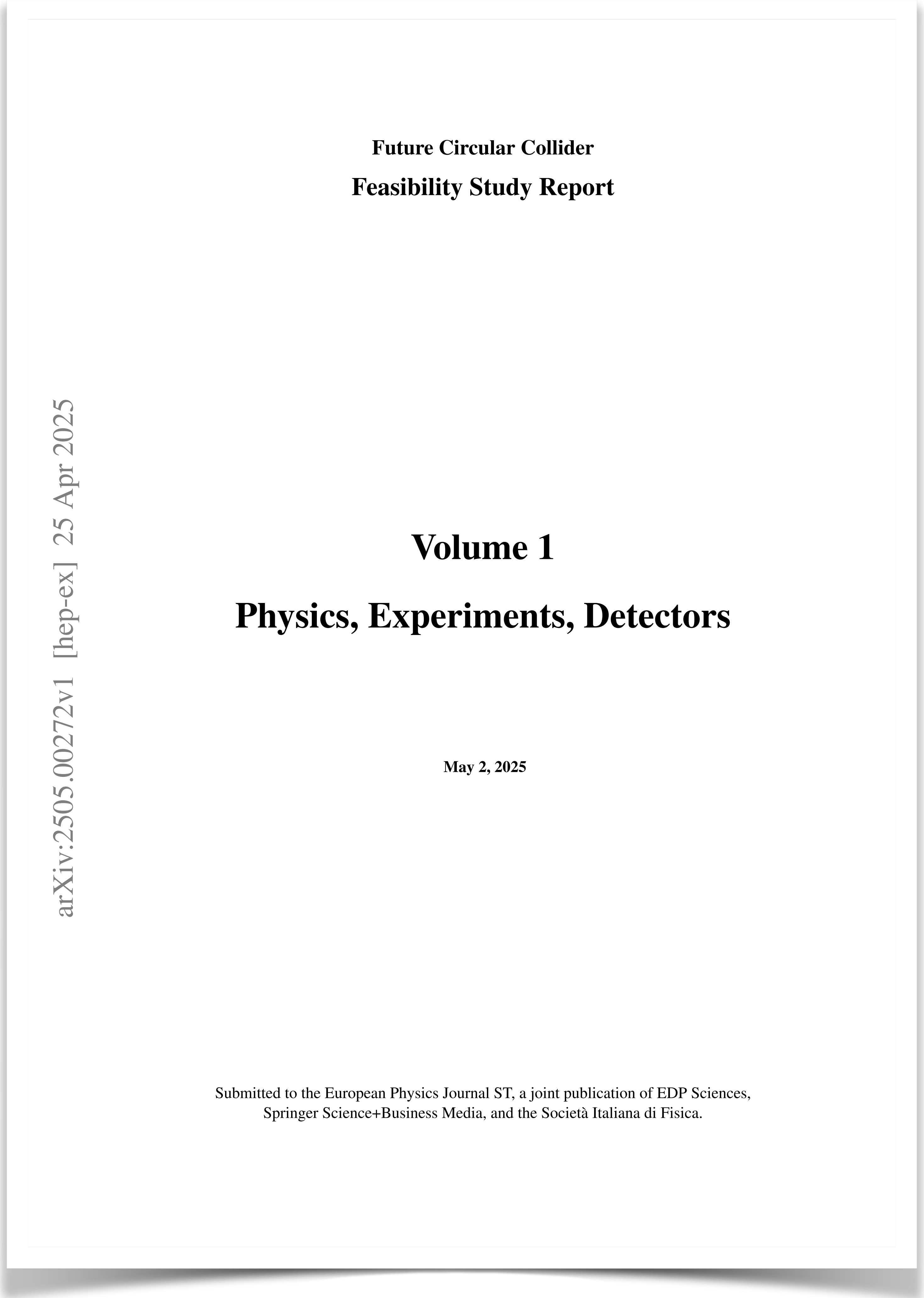
Example: Feasibility of the Future Circular Collider at CERN

2020 ESPP Update: **FCC Feasibility Study**

- Charge for 2021–~~2027~~ 2025: investigate technical and financial viability of an FCC facility at CERN
- Consider scientific, technical, administrative, financial issues, e.g.: geologic, environmental impact, infrastructures, civil engineering

Feasibility Study Report released March 31, 2025:

- Vol. 1: Physics and Experiments
- Vol. 2: Accelerators, Technical Infrastructure and Safety
- Vol. 3: Civil Engineering, Implementation and Sustainability
- Further details: https://fcc.web.cern.ch/overview


Future Circular Collider
Feasibility Study Report

arXiv:2505.00272v1 [hep-ex] 25 Apr 2025

Volume 1

Physics, Experiments, Detectors

May 2, 2025

Submitted to the European Physics Journal ST, a joint publication of EDP Sciences, Springer Science+Business Media, and the Società Italiana di Fisica.

The ESPP does make a difference

Example: Strategic R&D on Particle Detectors

2020 ESPP Update: **ECFA Detector R&D Roadmap**

- Series of **bottom-up workshops** to identify requirements, technologies, time scales, expert training, …
- Comprehensive **roadmap document**
- New **DRD** (Detector R&D) **collaborations** → **strategic R&D**

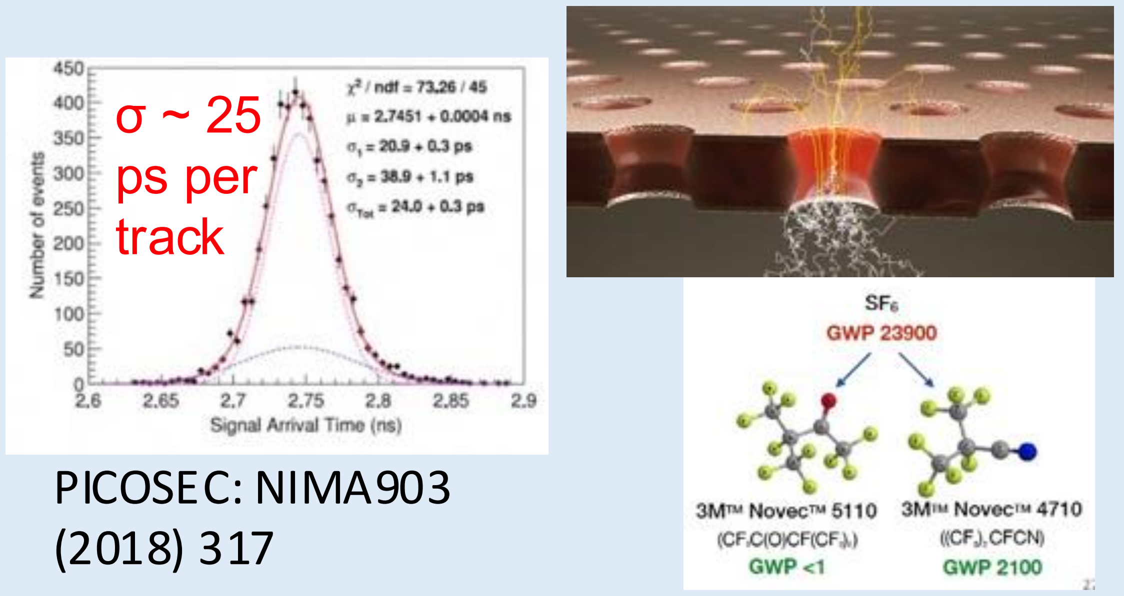
CERN-ESU-017

ECFA Detector R&D Roadmap 2021: DRD Collaborations

+ close collaboration and efforts in the US, Japan, and China

DRD1: Gaseous Detectors

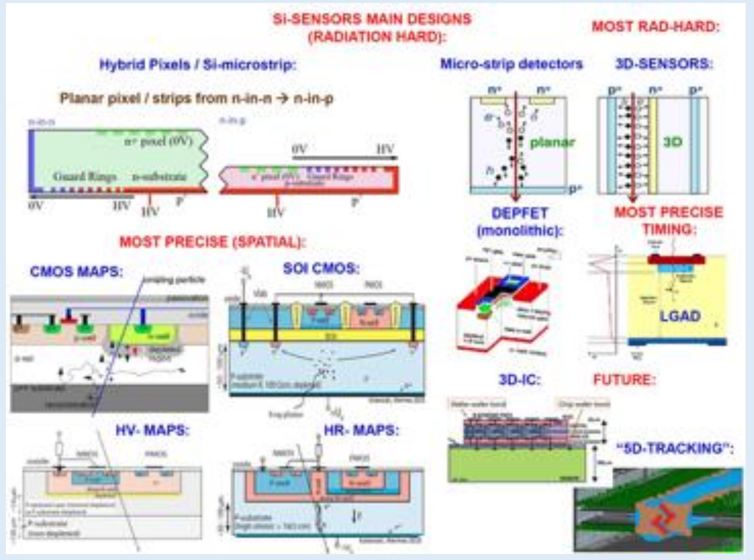
Large · Fast · eco-friendly gases · MPGD, e.g. GEMs



PICOSEC: NIMA903 (2018) 317

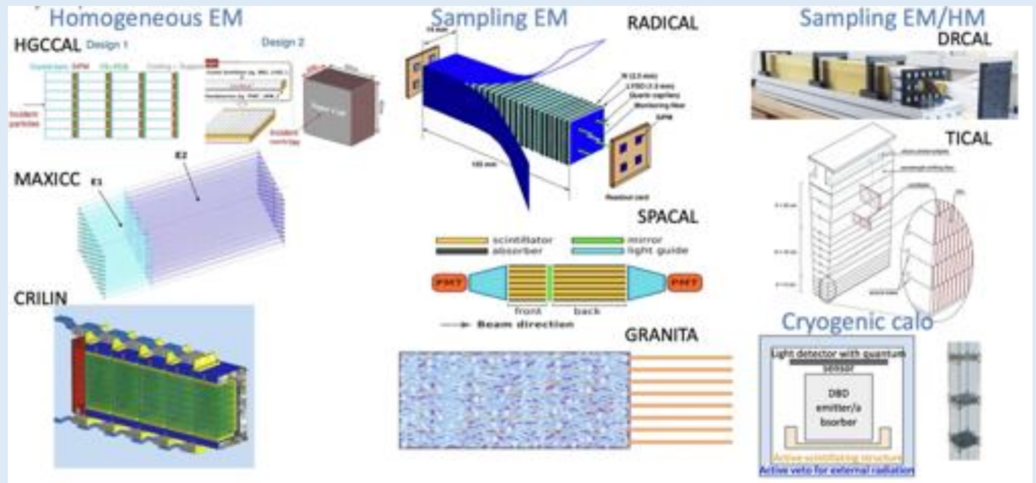
DRD3: Semiconductor Det.

Monolithic CMOS · LGADs · radiation hardness · interconns.



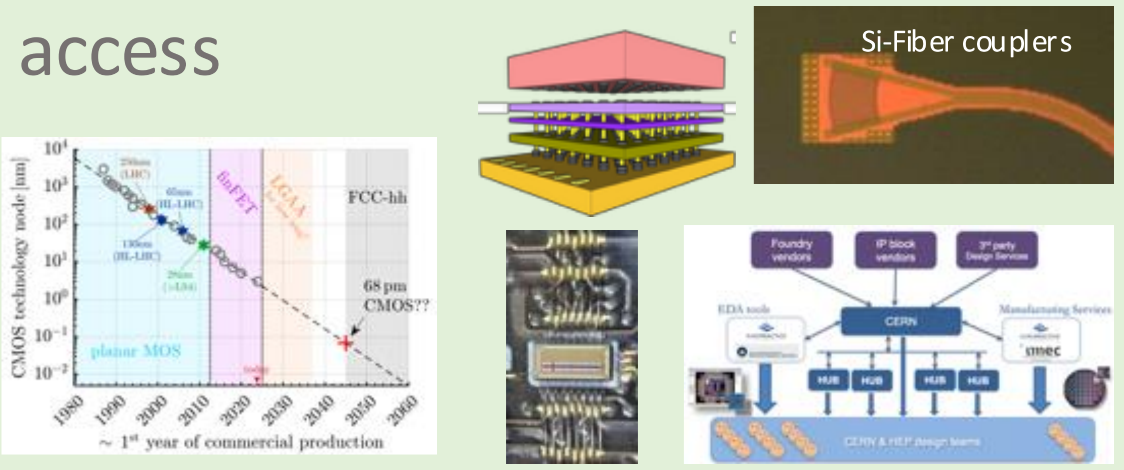
DRD6: Calorimetry

Energy resolution · High granularity · dual readout · particle flow · sandwich · optical



DRD7: Electronics

ADC/TDC IP Blocks · Opto-electronics · packaging · power · extreme environments · COTS · intelligence on detector · foundry access

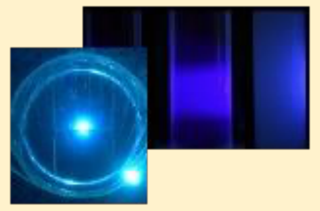


DRD2: Liquid Detectors

for Neutrinos · Dark Matter · 0vbb

Noble Elements
- Argon & Xenon
- Ionisation charge & transport
- VUV Scintillation, light propagation & detection

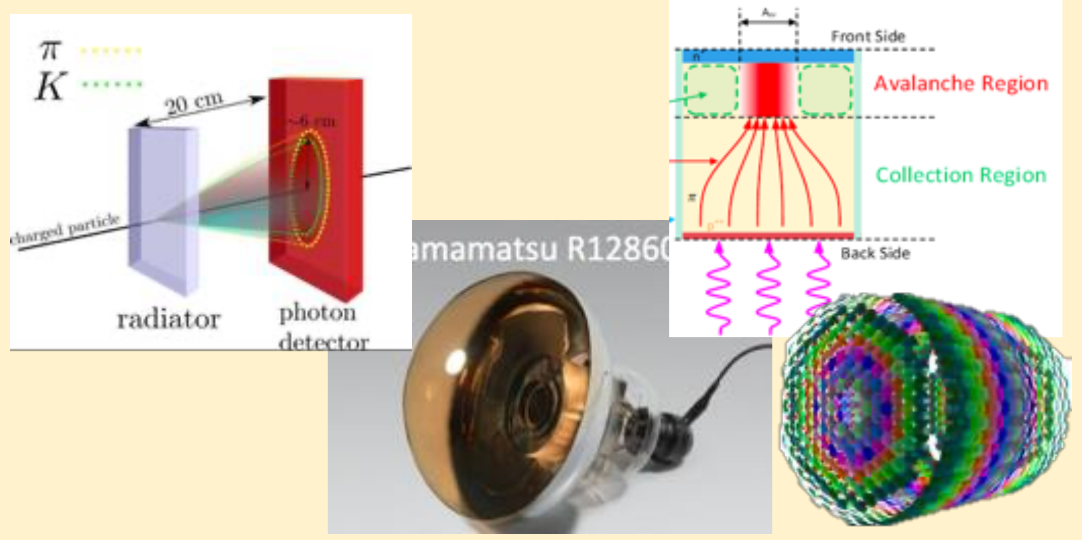
Liquid Scintillators
- Visible Scintillation, light propagation
- Scintillator properties
- Isotope loading



Water Cherenkov
- Cherenkov light, light propagation
- Doping for n-capture

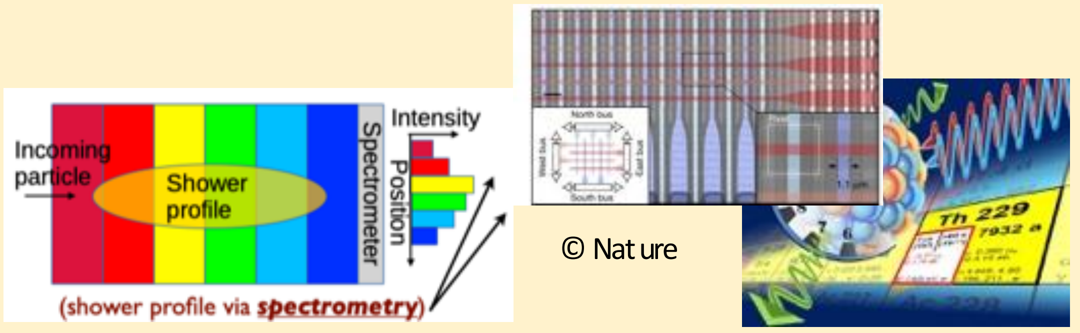
DRD4: Photon detectors

vacuum, solid-state (SiPM), hybrid single-photon and SciFi detectors · applications in PID, RICH, tracking



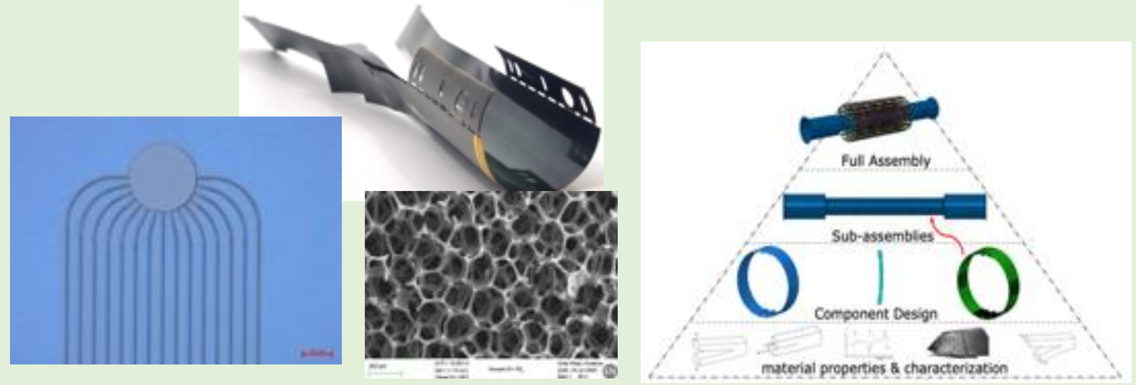
DRD5: Quantum Sensors

Quantum dots · superconduct. nanowires · bolometers · TES · MMC · nuclear clocks
Applications in LEPP, first projects in HEPP happening



DRD8: Mechanics

Ultra-thin beam pipes · CF foam and new materials · curved, retractable sensors · air & micro-channel cooling · eco-friendly cooling fluids · robots · augmented reality



T. Bergauer

The ESPP does make a difference

Instrumentation

2020 ESPP Update: **ECFA Detector R&D Roadmap**

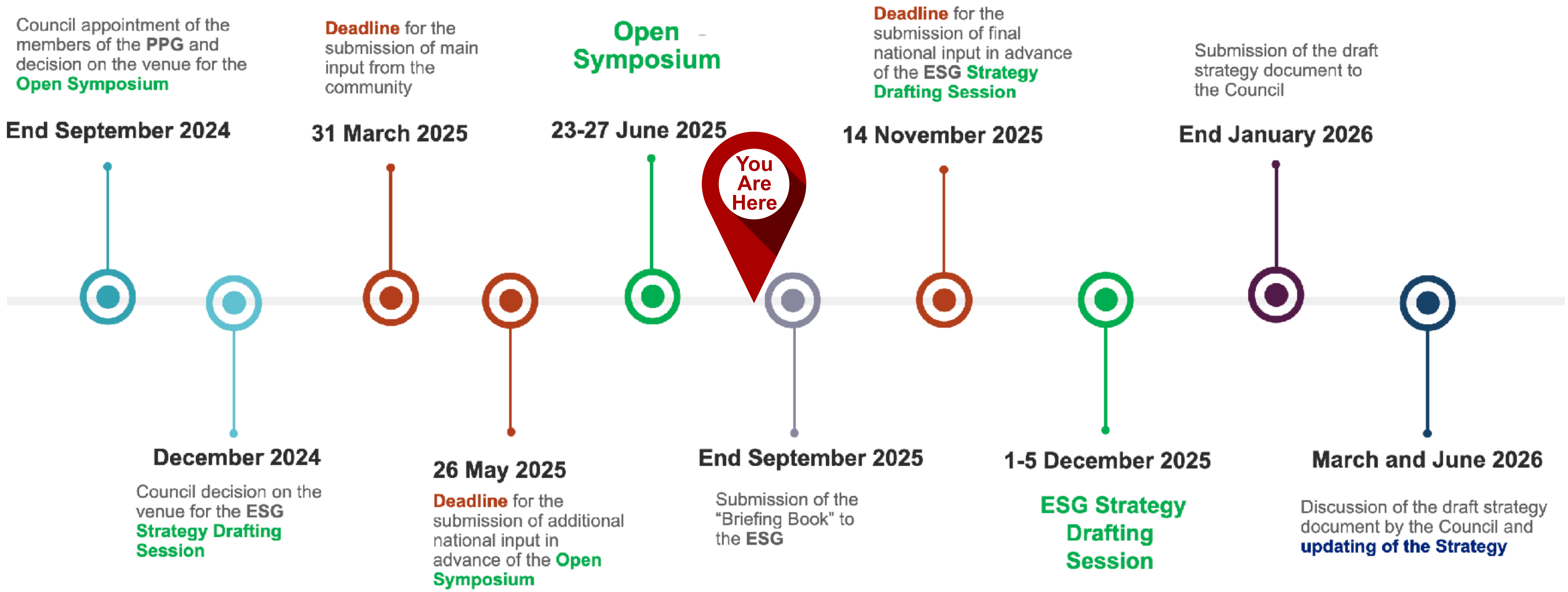
- Series of **bottom-up workshops** to identify requirements, technologies, time scales, expert training, …
- Comprehensive **roadmap document**
- New **DRD** (Detector R&D) **collaborations** → **strategic R&D**

2026 ESPP Update:

- **New/updated requirements** and **recent developments**
- Not (yet fully) considered: detector **magnets**, **quantum** detectors for rare event searches, **“intelligent”** trigger and data acquisition – electronics and software tools
- New **R&D collaborations for AI**? (“AI-RD collaborations”)

CERN-ESU-017

Timeline for the update of the European Strategy for Particle Physics



https://europeanstrategyupdate.web.cern.ch/process-0

Interlude: Top-Down vs. Bottom-Up Approaches

Which approach is superior in science?

Update of the European Strategy for Particle Physics 2026: mixture of **top-down and bottom-up elements**

Top-down approach: **deduction** from global view to details

Bottom-up approach: **induction** from details to global view

Challenge: what would be your approach to organizing a big project?

https://pingo.scc.kit.edu/events/361709

What are we supposed to do and who is involved?

What is ECFA?

European Committee for Future Accelerators (ECFA):

- **Long-range planning** of European high-energy particle physics facilities – accelerators, large-scale facilities and equipment – adequate for the conduct of a valid high-energy research program
- **Advisory** to CERN Management, CERN Council and its Committees, and to other national/international organizations
- **Plenary ECFA**: "parliament" composed of multiple country representatives + ex-officio member + invitees + observers
- **Restricted ECFA**: one member per country, advise ECFA chair, communicate to national communities

Paris Sphicas, ECFA Chair

What are we supposed to do and who is involved?

The “Remit” (= charge/task) of the European Strategy Group

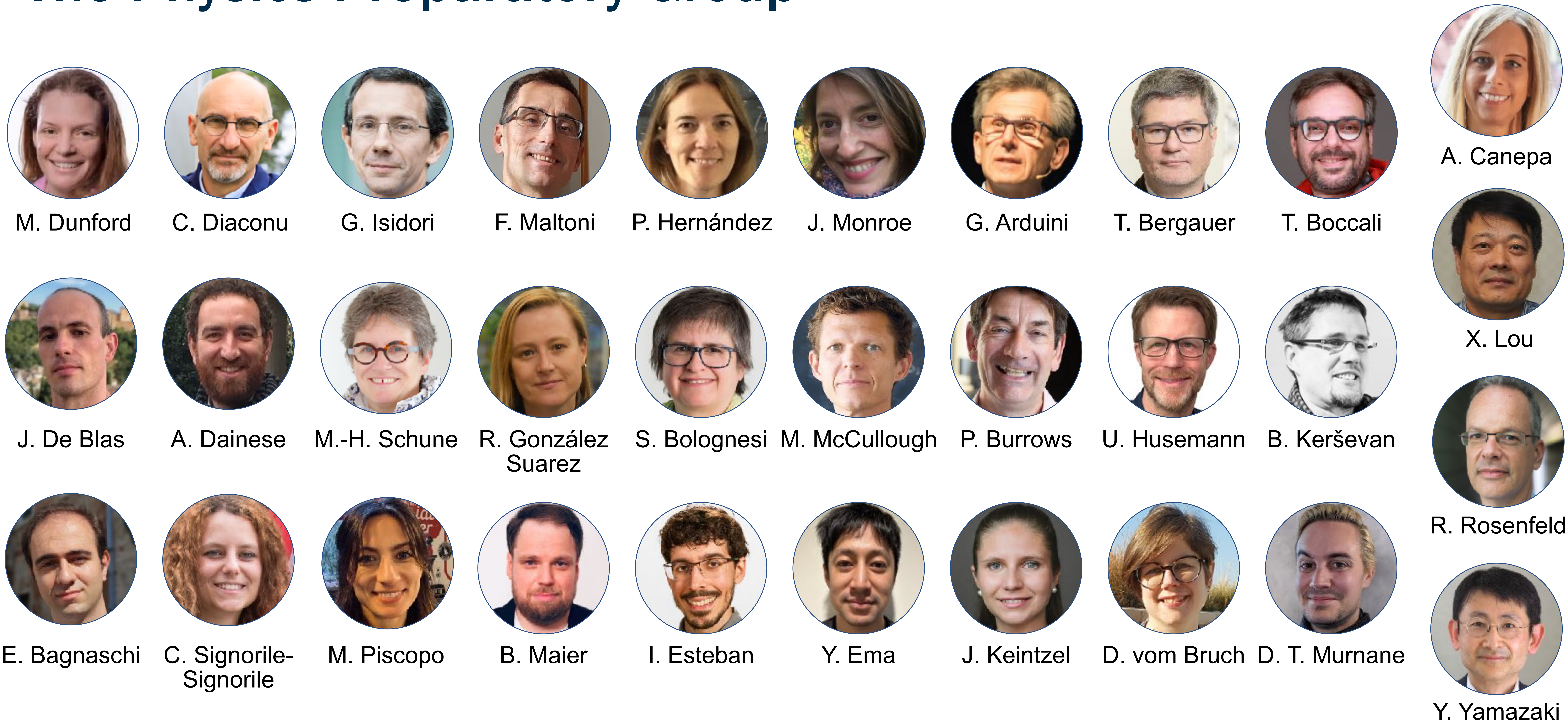
Remit: “The aim of the Strategy update should be to develop a **visionary and concrete plan** that greatly advances human knowledge in fundamental physics through **the realisation of the next flagship project at CERN**. This plan should attract and value **international collaboration** and should allow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

Key players and their roles:

- **Strategy Secretariat**: organize the strategy process
- **European Strategy Group** (ESG): establish a proposal for the periodic update of the medium-and long-term priorities of the field
- **Physics Preparatory Group** (PPG): prepare the scientific contribution to the work of the ESG, based on the input it gathers from the community

Karl Jakobs, Strategy Secretary

The Physics Preparatory Group



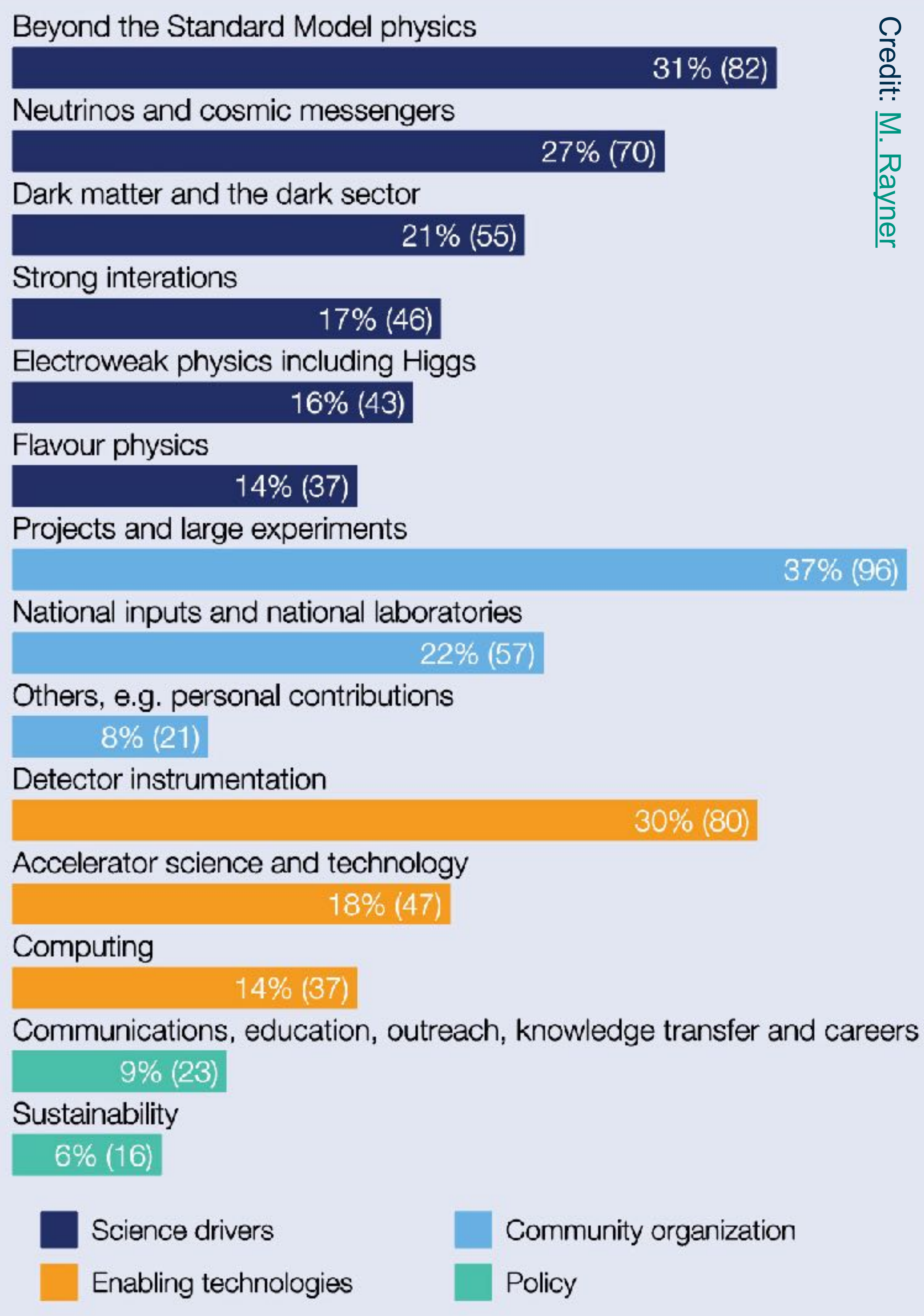
Input from the Scientific Community

A Big Reading Assignment

266 contributions received:
(10 pages + supplementary material)

- Major **flagship** projects
- Projects in **neighboring fields** of physics
- Input from **national** particle physics **communities**
- Input from European **national laboratories** (e.g., DESY)
- Input from **Early Career Researchers** (ECRs)
- Input from other European expert committees for long-range planning: **astroparticle physics** (APPEC) and **nuclear physics** (NuPECC)

Public link: https://indico.cern.ch/event/1439855/contributions/



Credit: M. Rayner

European Strategy
for Particle Physics

One-week **Open Symposium** in Venice

- Debate scientific **input** → lots of **discussion**
- Define **scientific goals and priorities** for the upcoming generation of facilities and experiments
- Indico link: https://agenda.infn.it/event/44943

Inputs and outcome of discussions
→ **Physics Briefing Book** (due Sep 30, 2025)

23-27 JUNE 2025 Lido di Venezia

Physics Briefing Book

Work in Progress

Structured into **science drivers** and **key technologies**:

- Electroweak physics (incl. Higgs)
- Strong interactions (QCD)
- (Heavy) flavor physics
- Neutrino physics
- Cosmic messengers
- Beyond the standard model (BSM)
- Dark Matter (DM) and dark sector
- Accelerator science and technology
- Detector instrumentation
- Computing

Challenge: ensure that **no topics fall into the cracks**

DRAFT 1v3
3 September 2025

Physics Briefing Book

Input for the 2026 update of the European Strategy for Particle Physics

Electroweak Physics: Jorge de Blas[1], Monica Dunford[2] *(Conveners)*, Emanuele Bagnaschi[3] *(Scientific Secretary)*, Ayres Freitas[4], Pier Paolo Giardino[5], Christian Grefe[6], Michele Selvaggi[7], Angela Taliercio[8] *(Contributors)*

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Beyond the Standard Model Physics: Fabio Maltoni[8,31], Rebeca Gonzalez Suarez[32] *(Conveners)*, Benedikt Maier[33] *(Scientific Secretary)*, Timothy Cohen[7,28,78,*], Annapaola de Cosa[34,*], Nathaniel Craig[35], Roberto Franceschini[36], Loukas Gouskos[37], Aurelio Juste[38], Sophie Renner[13], Lesya Shchutska[28] *(Contributors)*

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European Strategy for Particle Physics

KIT

Next Steps

Towards A European Strategy Update in 2026

September 2025: Physics Briefing Book published

November 2025: Final inputs from national communities

December 2025: European Strategy Group drafts strategy

January 2026: Strategy submitted to CERN Council

March/June 2026: CERN Council updates strategy

European Strategy
for Particle Physics

In Summary...

Particle physics in 2025: **vivid field**, broad range of **physics objectives** and detailed plans for **future projects**

2026 Update of the **European Strategy for Particle Physics**:

- **Structured** and **inclusive** strategy process, influencing particle physics in Europe **for decades to come**
- **Diverse** research field: big **flagship collider projects** complemented with **broad range of smaller projects**
- **Strategic long-range planning**: scientific and societal impact, feasibility, sustainability, return on invest

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