

Experimental High Energy Physics

@FlipPhysics workshop (2nd edition)
May 23, 2024

Carlos Escobar Ibáñez
Instituto de Física Corpuscular (CSIC-UV)

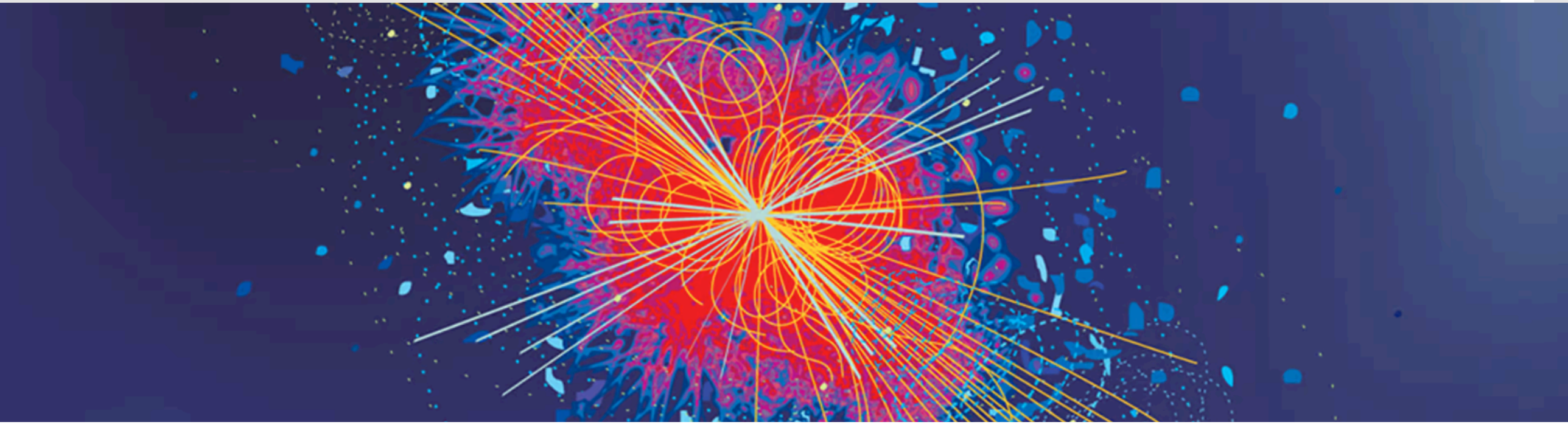
Research project: CNS2022-135718



Experimental High Energy Physics

@FlipPhysics workshop (2nd edition)
25 de may de 2024

Carlos Escobar Ibáñez
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What is High Energy Physics?

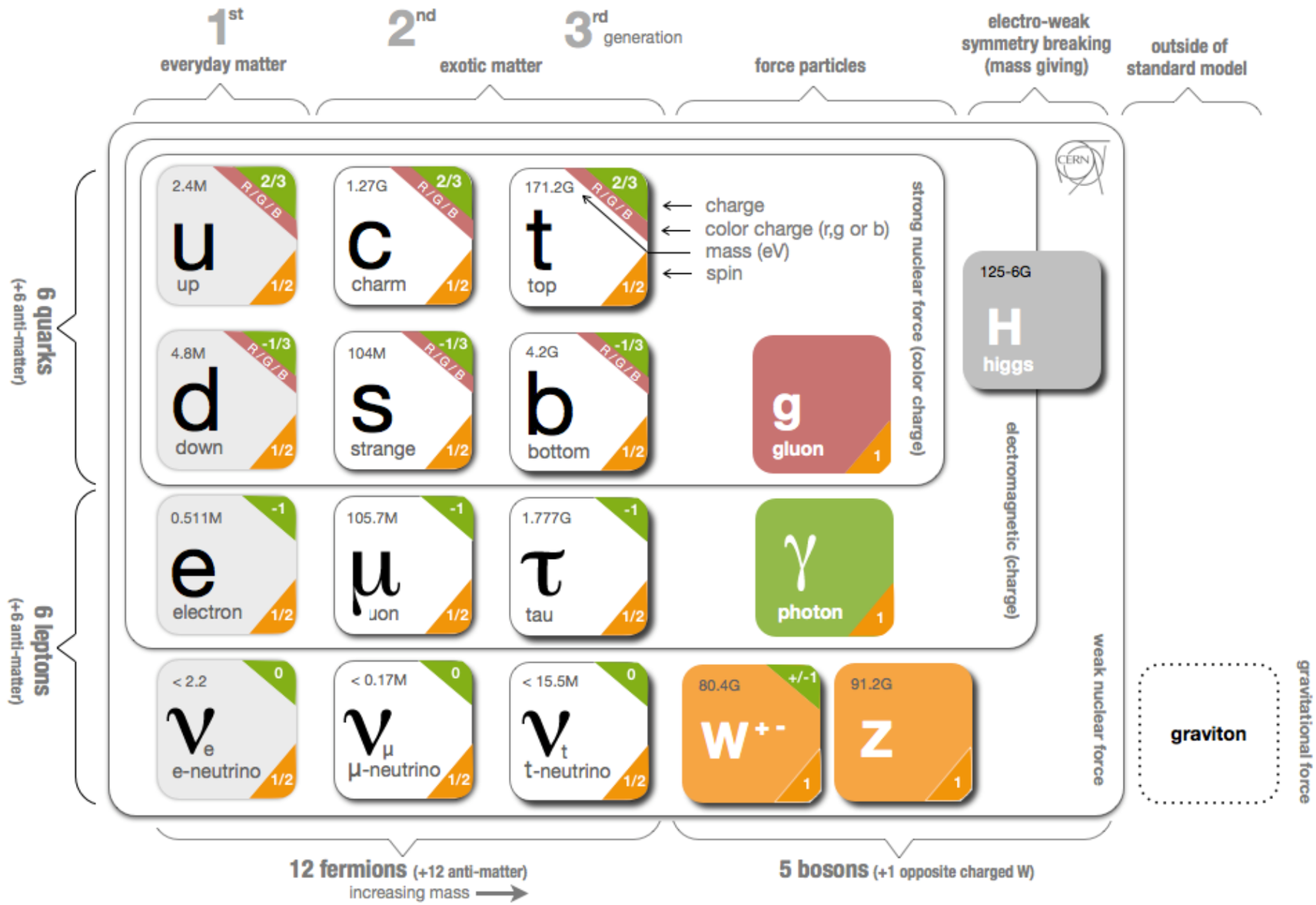
High Energy Physics (HEP) explores what the world is made of and how it works at the smallest and largest scales, seeking new discoveries from the tiniest particles to the outer reaches of space

- Inspired by some of the biggest questions about our universe:
  - What is it made of?
  - What forces govern it?
  - How did become the way it is today?
- Aims to understand the fundamental particles and their interactions providing insight into the basic structure of the universe and its origins

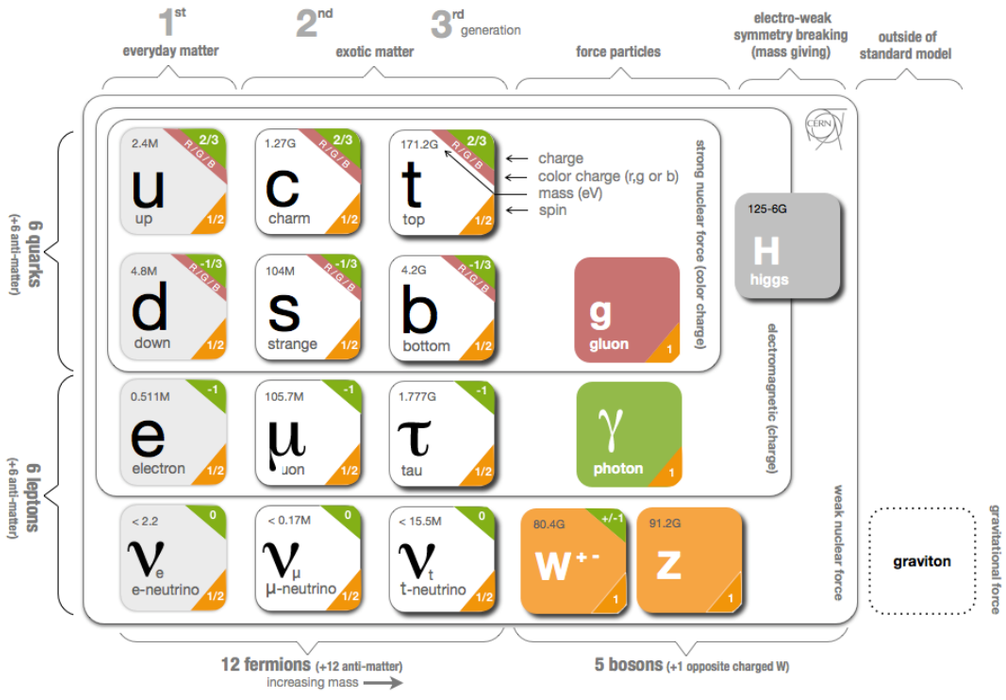
The Standard Model of Particle Physics

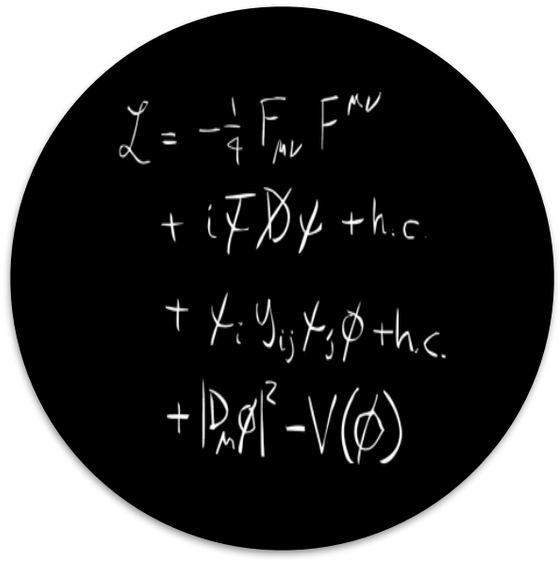
The Standard Model (SM) of Particle Physics is a well-established theoretical framework that describes the fundamental particles and their interactions

- It successfully explains a wide range of phenomena observed in particle physics experiments
  - Measurements agree with SM predictions with remarkable precision!!!



The Standard Model of Particle Physics





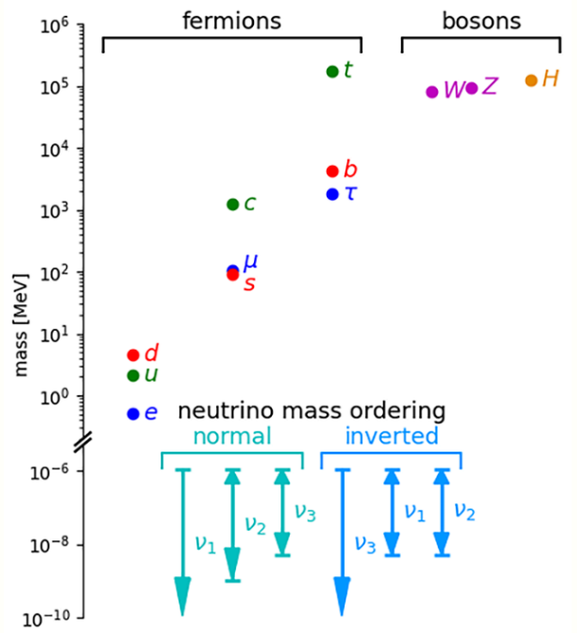
Lagrangian of the SM

The SM has a total of 19 free parameters

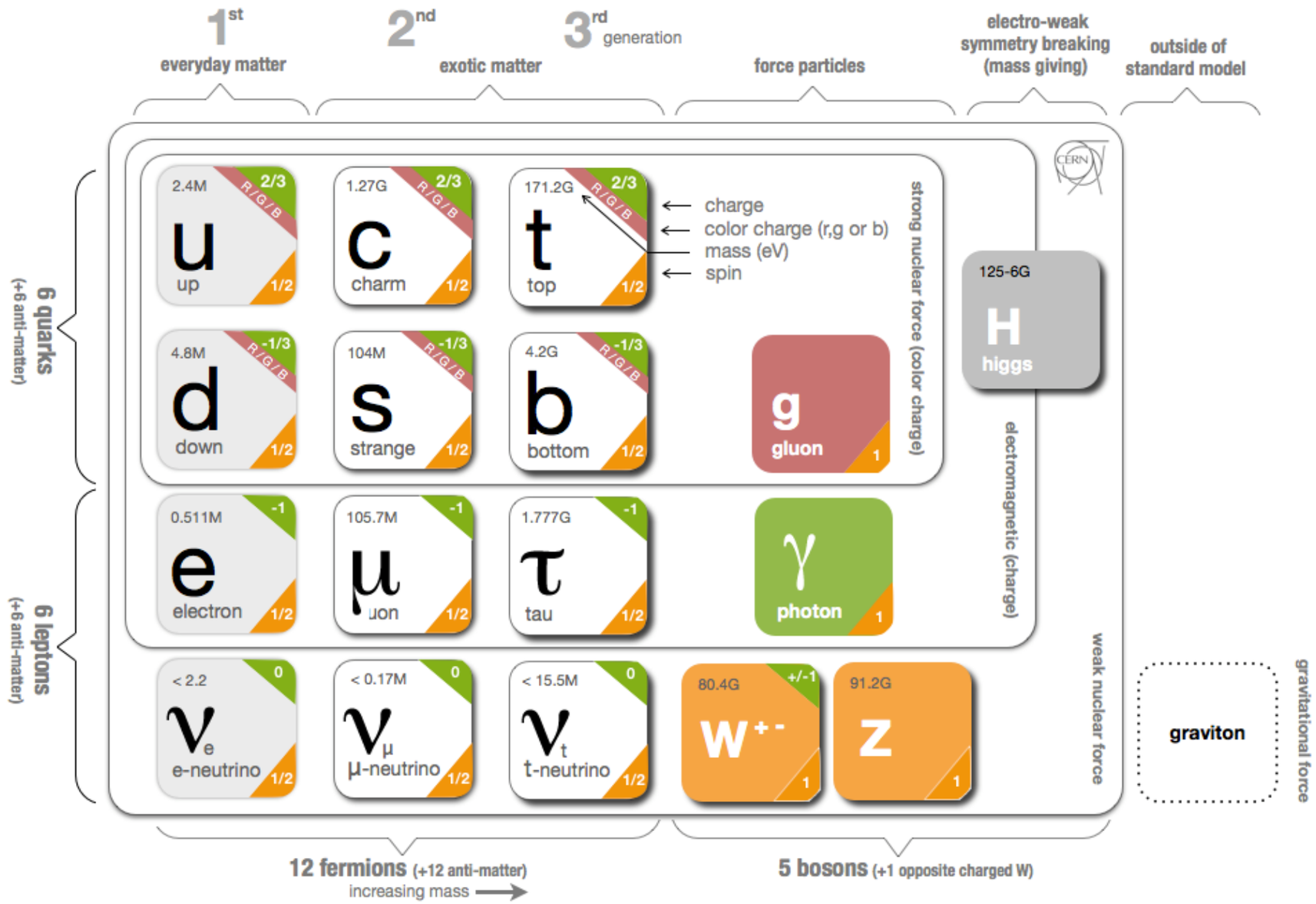
- Gauge coupling constants (weak interaction, electromagnetism, strong interaction)
- Quark masses (up, down, charm, strange, top, and bottom)
- Lepton masses (electrón, muón and tau)
- Quark mixing parameters (CKM matrix) - flavour mixing
- Higgs sector (self-coupling constant, vacuum expectation value and mass)

- If neutrino masses and mixings are considered, it has a total of 26 free parameters
  - Neutrino masses
  - Lepton mixing parameters (PMNS Matrix) - flavour mixing (neutrinos)

- **These parameters must be measured experimentally!**



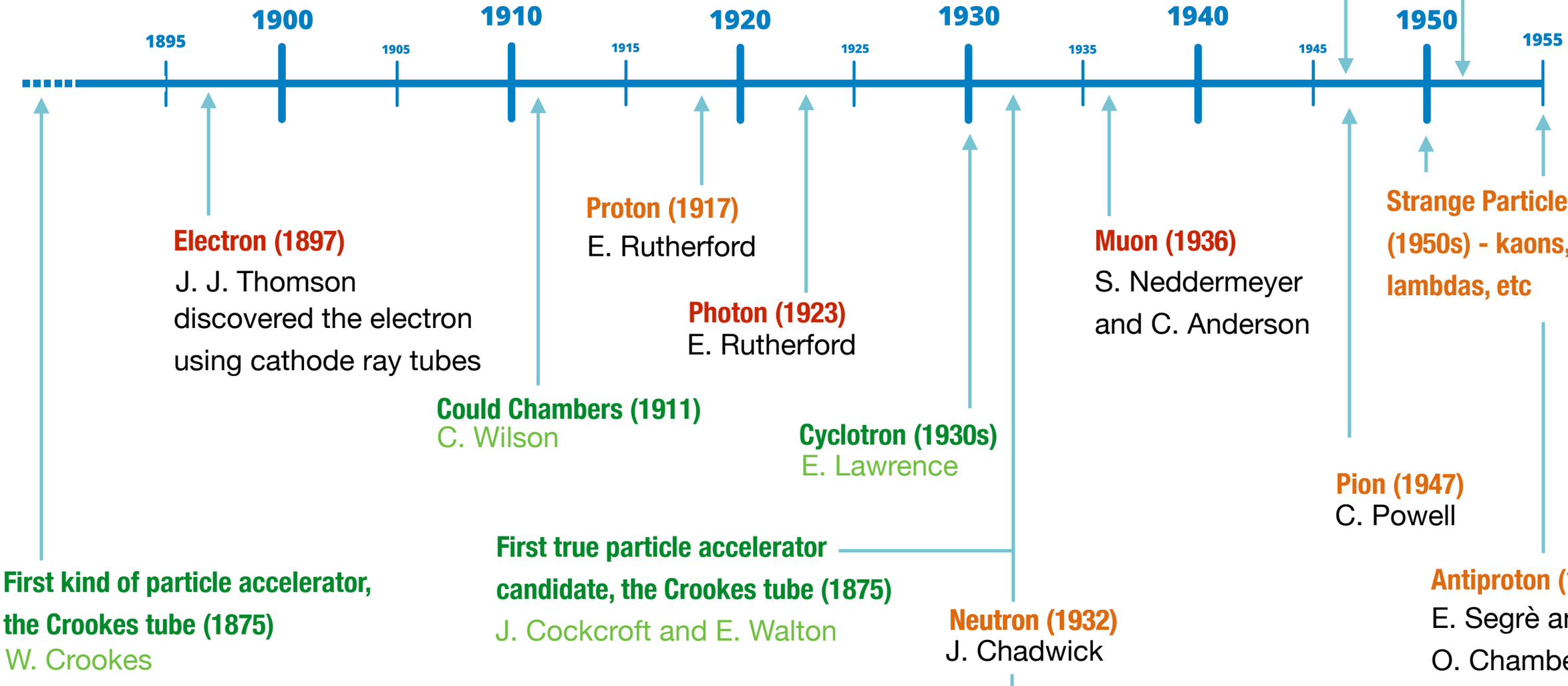
The development of the SM by theoreticians and experimentalists in the latter half of the 20th century was a long and hard road! 🥵



Historical milestones in High Energy Physics

Early discoveries and the birth of particle physics

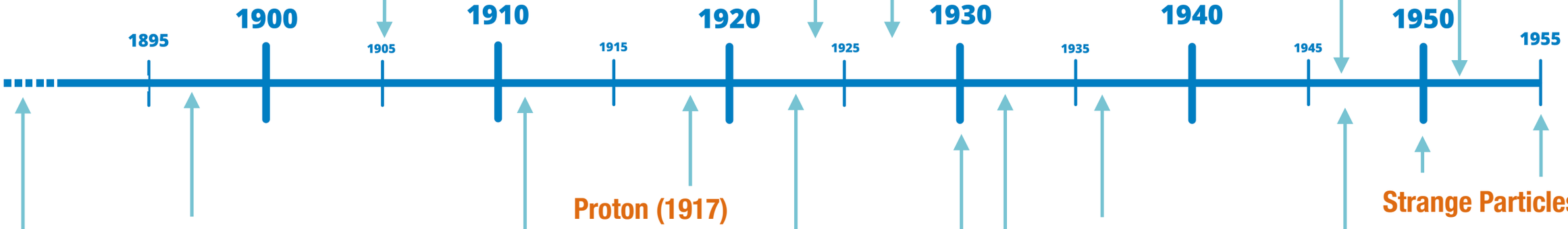
- The development of the SM was a hard road! 🥵



Historical milestones in High Energy Physics

Early discoveries and the birth of particle physics

- The development of the SM was a hard road! 🥵



Quantum Theory
M. Planck's quantization (1900)

A. Einstein's photoelectric effect (1905)

Wave-Particle Duality
de Broglie's hypothesis (1924), confirmed by electron diffraction experiments (1927)

Quantum Electrodynamics (QED)
R. Feynman, J. Schwinger, and S.-I. Tomonaga (1940s)

Nuclear Emulsions (1947)
C. Powell

Bubble Chambers (1952)
D. Glaser

Electron (1897)
J. J. Thomson
discovered the electron
using cathode ray tubes

Proton (1917)
E. Rutherford

Photon (1923)
E. Rutherford

Could Chambers (1911)
C. Wilson

Cyclotron (1930s)
E. Lawrence

Muon (1936)
S. Neddermeyer
and C. Anderson

Strange Particles (1950s) - kaons, lambdas, etc

Pion (1947)
C. Powell

First kind of particle accelerator, the Crookes tube (1875)
W. Crookes

First true particle accelerator candidate, the Crookes tube (1875)
J. Cockcroft and E. Walton

Neutron (1932)
J. Chadwick

Positron (1932)
C. Anderson
discovered the positron
(anti-electron) in cosmic rays

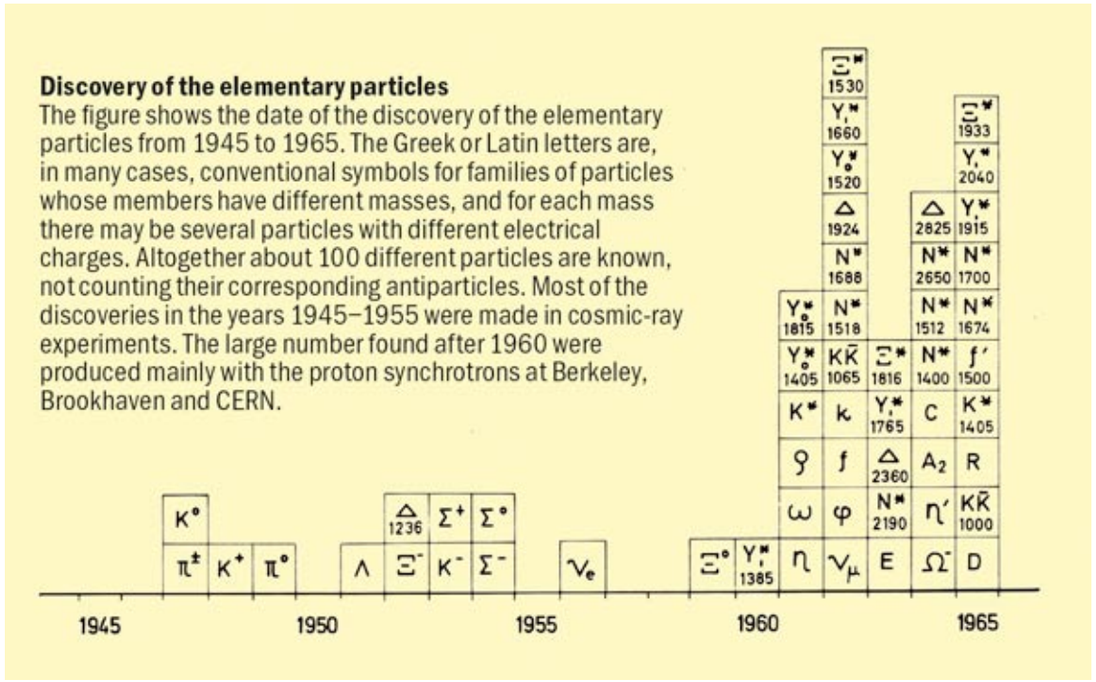
Antiproton (1955)
E. Segrè and
O. Chamberlain

The Particle Zoo

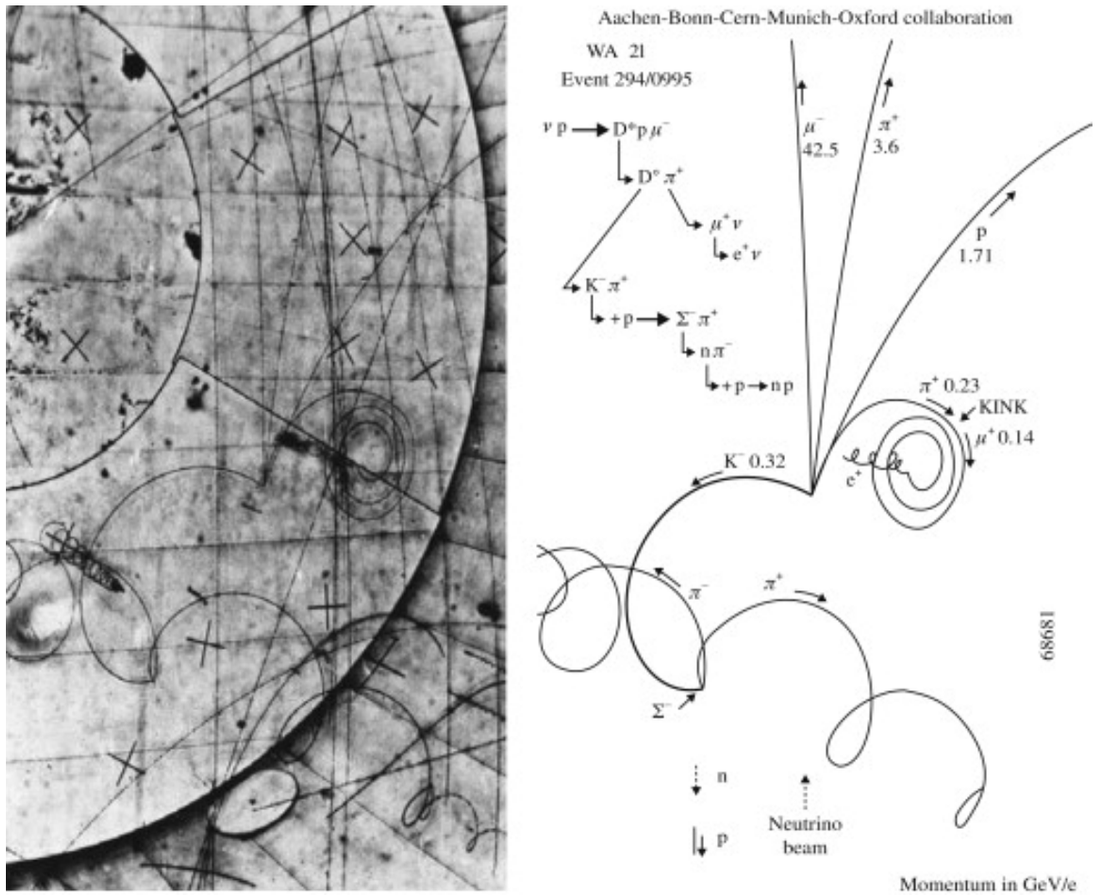
Unveiling the diversity of subatomic particles

- The term "Particle Zoo" emerged (popularized by R. Oppenheimer in 1956) in the mid-20th century when numerous subatomic particles were discovered, which seemed overwhelming in their variety and number 😒
  - *Were all these particles elementary particles?* 🤔
- It was urgently needed a systematic way to categorize them!!! 😱

Particle Zoo :: chaos



Bubble Chambers allowed the visualization of particle tracks, leading to the identification of new particles



Towards the Modern Era: The Standard Model and Beyond

- The development of the SM was a hard road! 🥵

particle accelerators

1956 1960 1965 1970 1975 1980 1985 1990 1995 2000 2005 2010 --?

Electron neutrino (1956)
C. Cowan y C. Anderson

Muon neutrino (1962)
Brookhaven National Laboratory

Quark (up, down, strange) (1969)
SLAC National Accelerator Laboratory

Quark (charm) (1974)
SLAC National Accelerator Laboratory

Tau (1976)
SLAC National Accelerator Laboratory

Gluon (1979)
DESY.

W/Z (1983)
CERN

Quark (bottom) (1977)
Fermilab

Quark (top) (1995)
Fermilab

Tau neutrino (2000)
Fermilab

Higgs (2012)
CERN

Historical milestones in High Energy Physics

Towards the Modern Era: The Standard Model and Beyond

- The development of the SM was a hard road! 🥵

Higgs mechanism (1964)
M. Gell-Mann and G. Zweig

Electroweak Theory (1970s)
S. Glashow, A. Salam, and S. Weinberg

Quantum Chromodynamics (1970s)
M. Gell-Mann, H. Fritzsch, and H. Leutwyler

The Standard Model of Particle Physics 😎

Quark Model (1960s)
M. Gell-Mann and G. Zweig

1956 1960 1965 1970 1975 1980 1985 1990 1995 2000 2005 2010 --?

particle accelerators

W/Z (1983) CERN

Muon neutrino (1962) Brookhaven National Laboratory

Gluon (1979) DESY.

Tau neutrino (2000) Fermilab

Quark (up, down, strange) (1969) SLAC NATIONAL ACCELERATOR LABORATORY

Quark (bottom) (1977) Fermilab

Tau (1976) SLAC NATIONAL ACCELERATOR LABORATORY

Quark (top) (1995) Fermilab

Higgs (2012) CERN

Electron neutrino (1956)
C. Cowan y C. Anderson

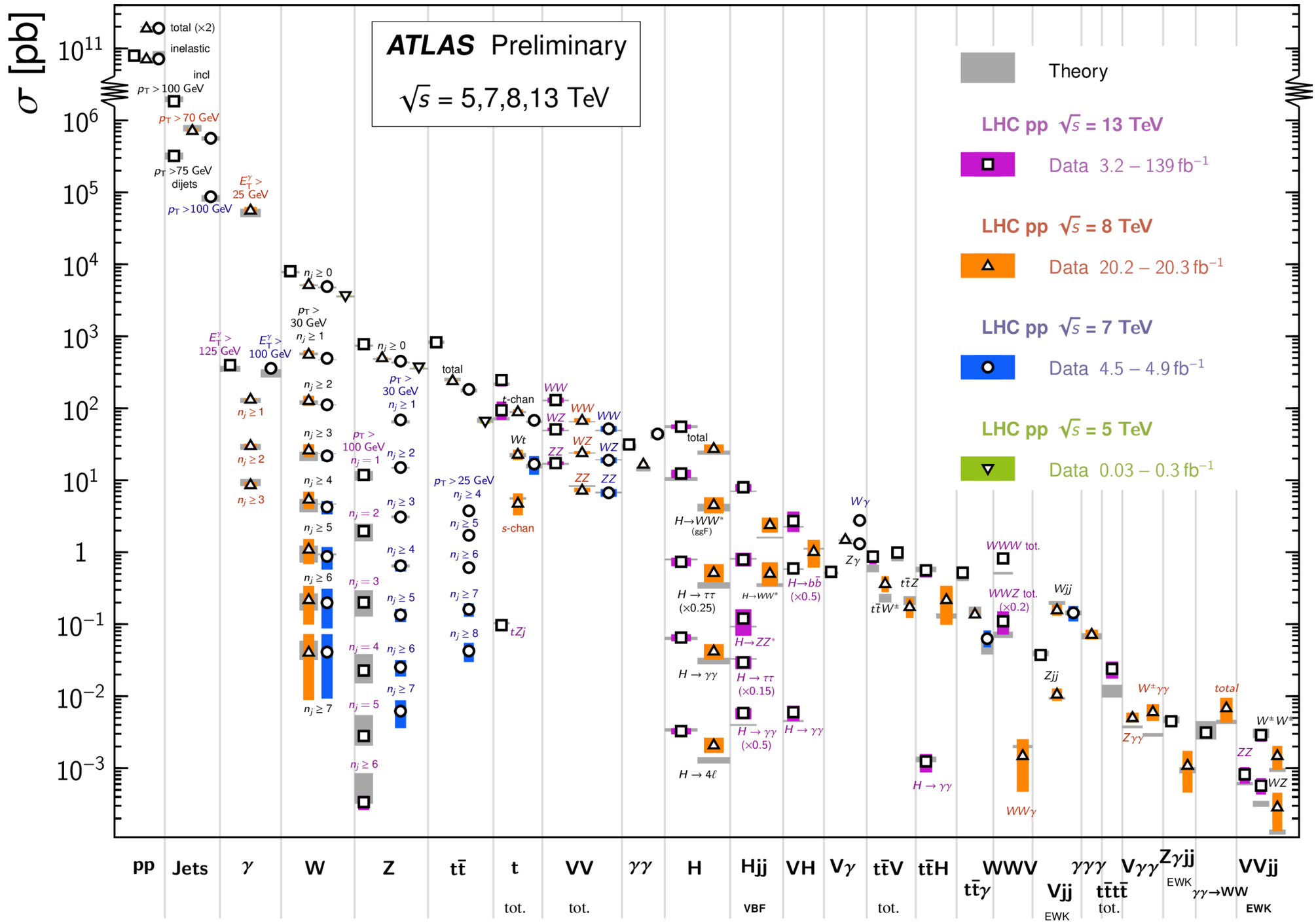
Quark (charm) (1974) SLAC NATIONAL ACCELERATOR LABORATORY



Measurements agree with SM predictions with remarkable precision!!! 😎

Standard Model Production Cross Section Measurements

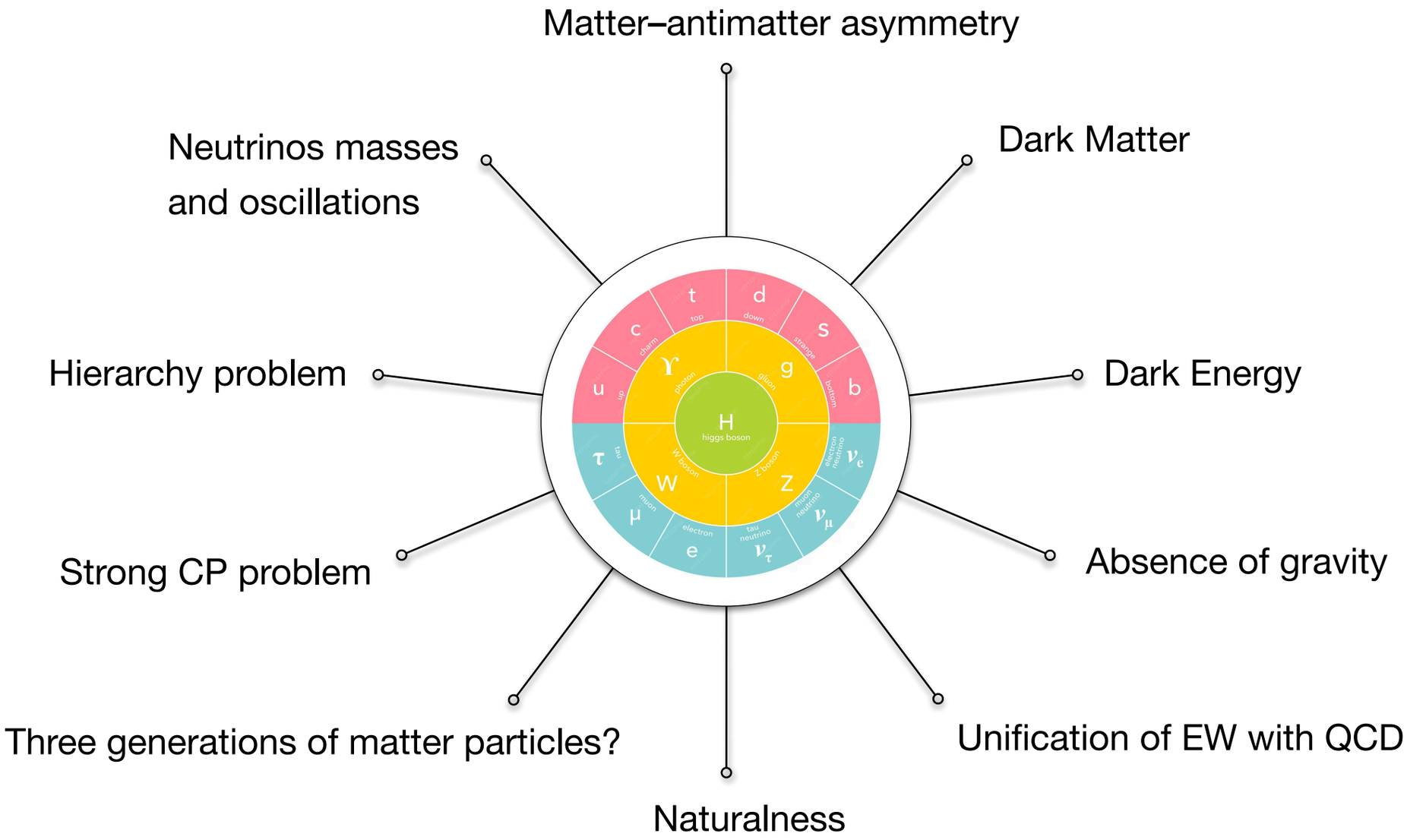
Status: February 2022



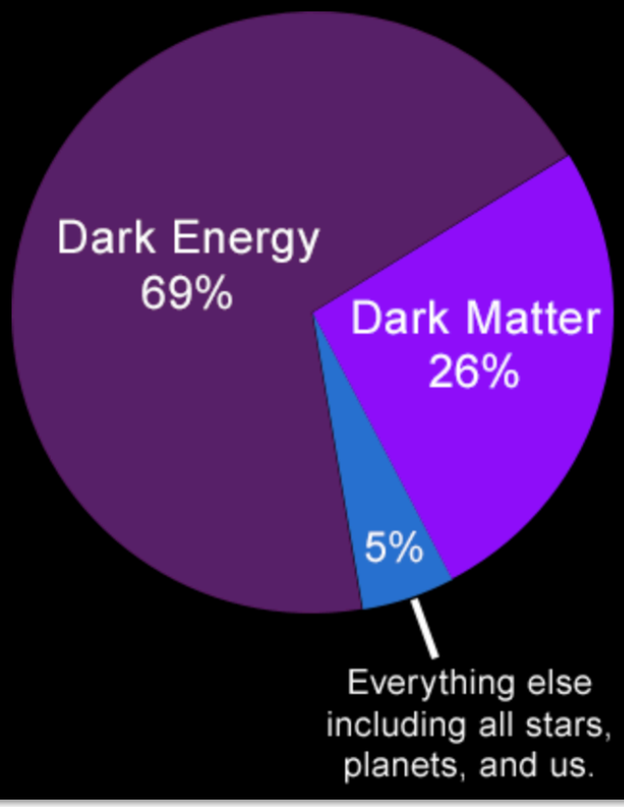
Measurements agree with SM predictions with remarkable precision!!!

Limitations of the Standard Model of Particle Physics

It is known that the SM has limitations which indicate that while the SM is a robust framework for understanding many aspects of particle physics, it is not a complete theory 😕😅



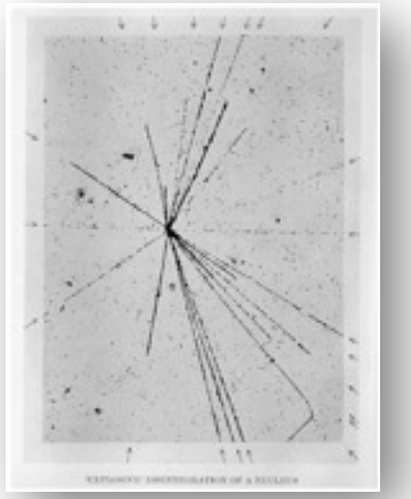
Limitations of the Standard Model of Particle Physics

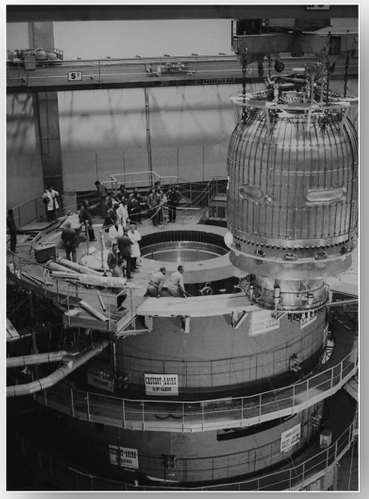


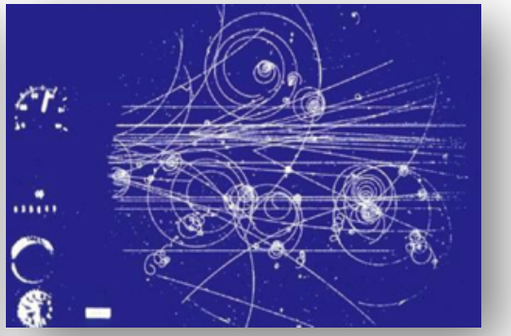
The Standard Model of particle physics is capable of explaining a significant portion of the universe 😎😅

Basis of Experimental High Energy Physics

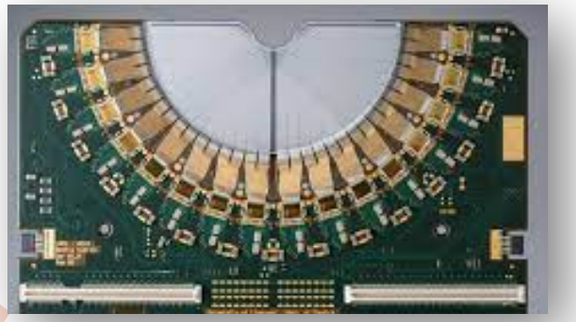
1. Technology of the detectors

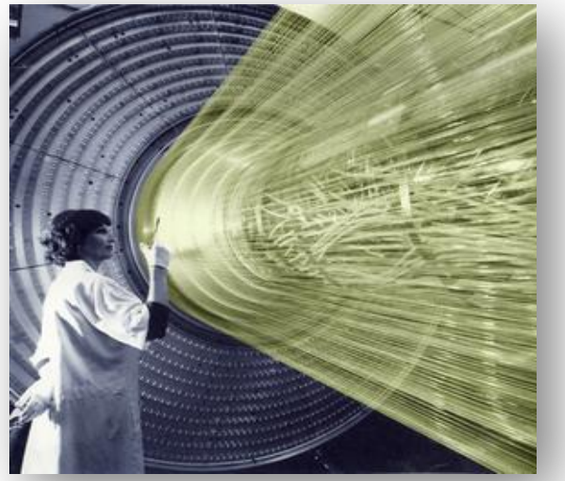


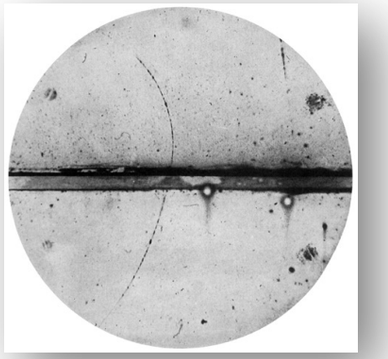




The micro-encapsulation allow to produced more are more compact and complex systems







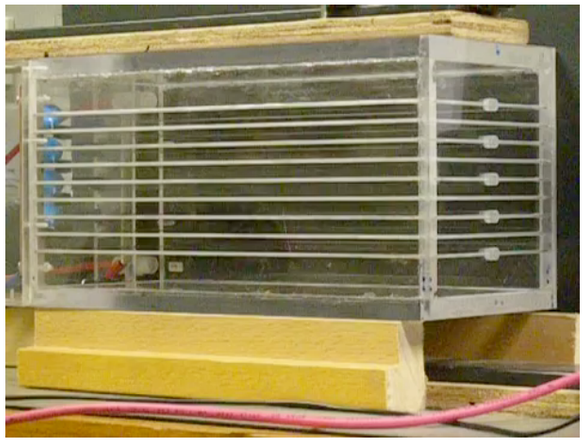
Semiconductors

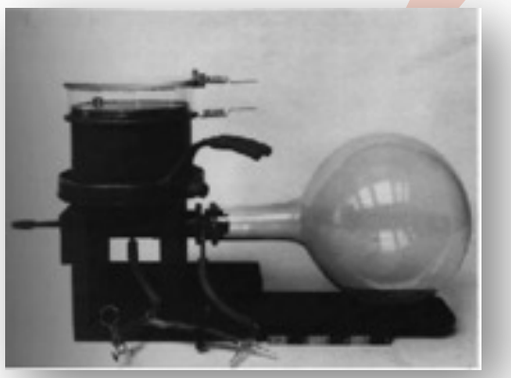
Bubble/Spark/
Wire chambers/TPC

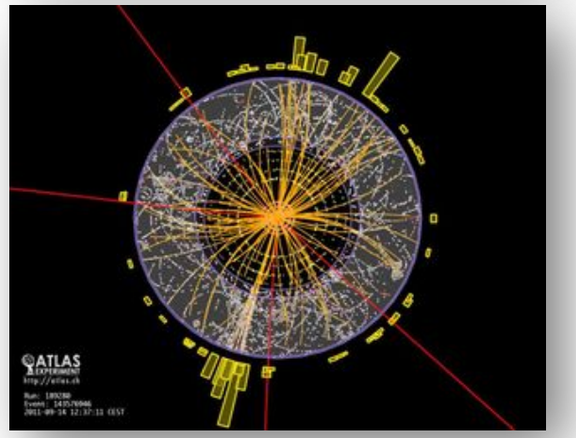
Scintillation
Counters

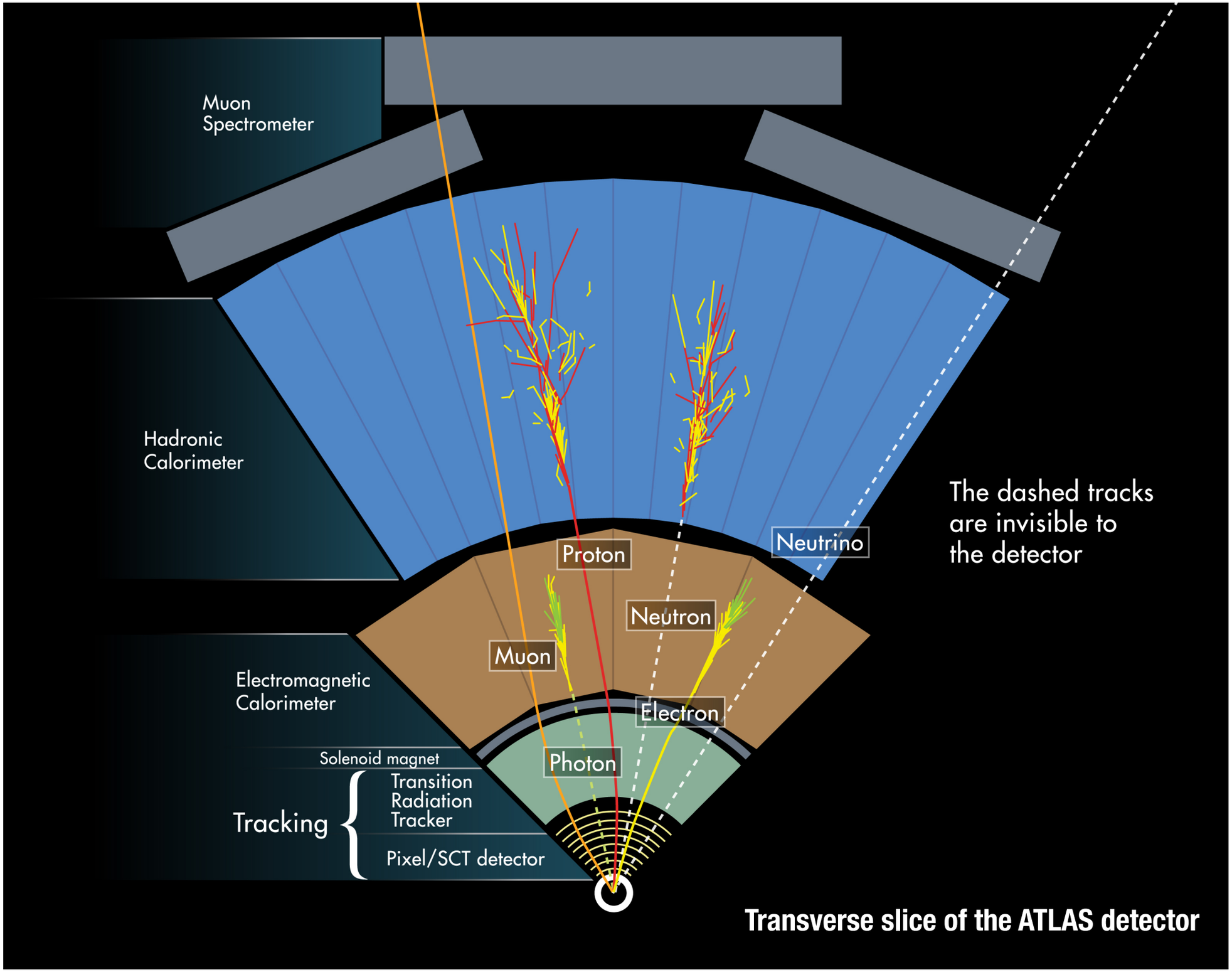
Films/Emulsions

Cloud chambers
Geigers counters



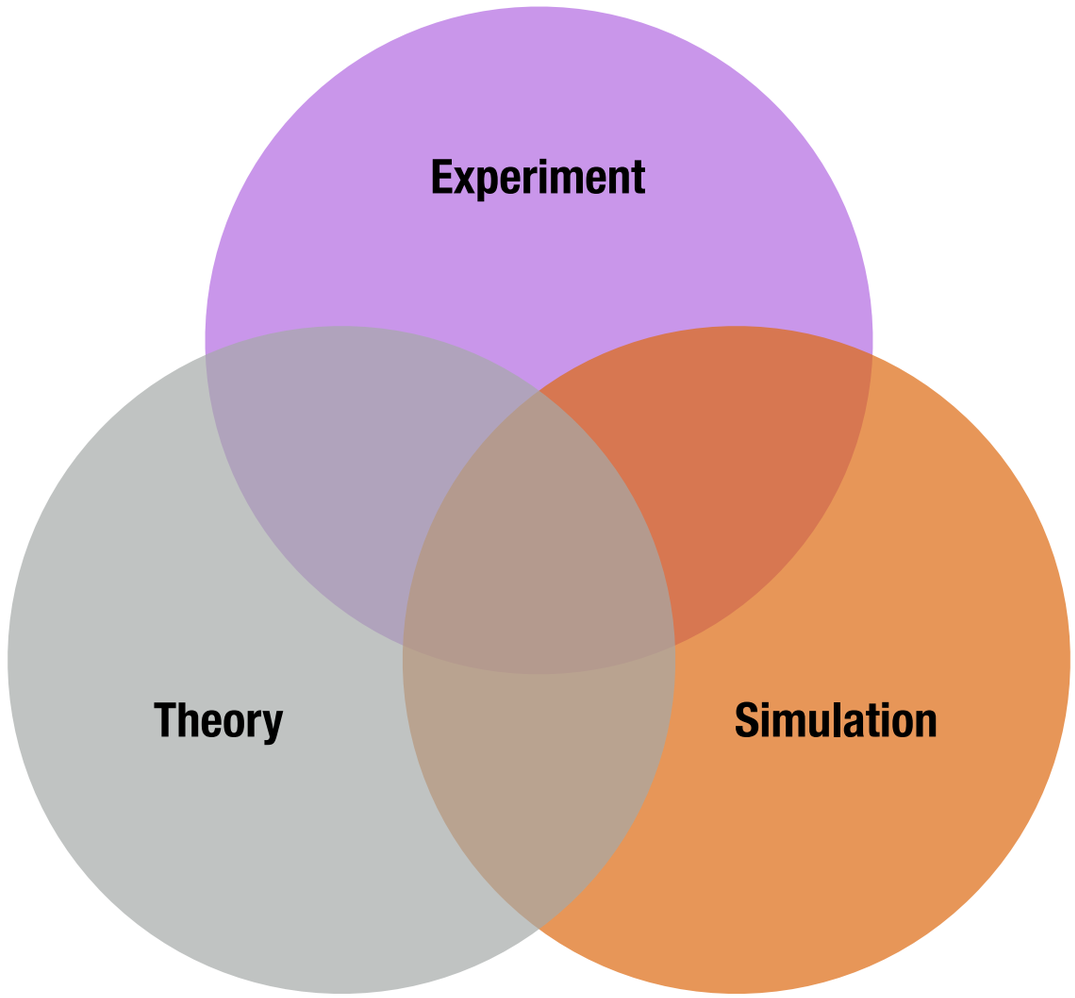




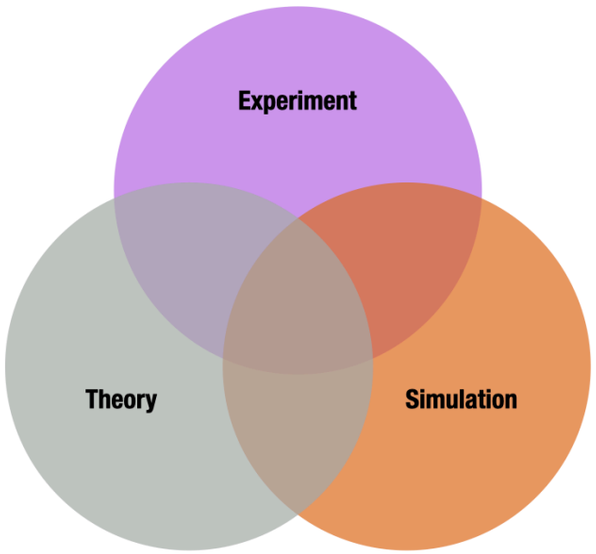


Transverse slice of the ATLAS detector

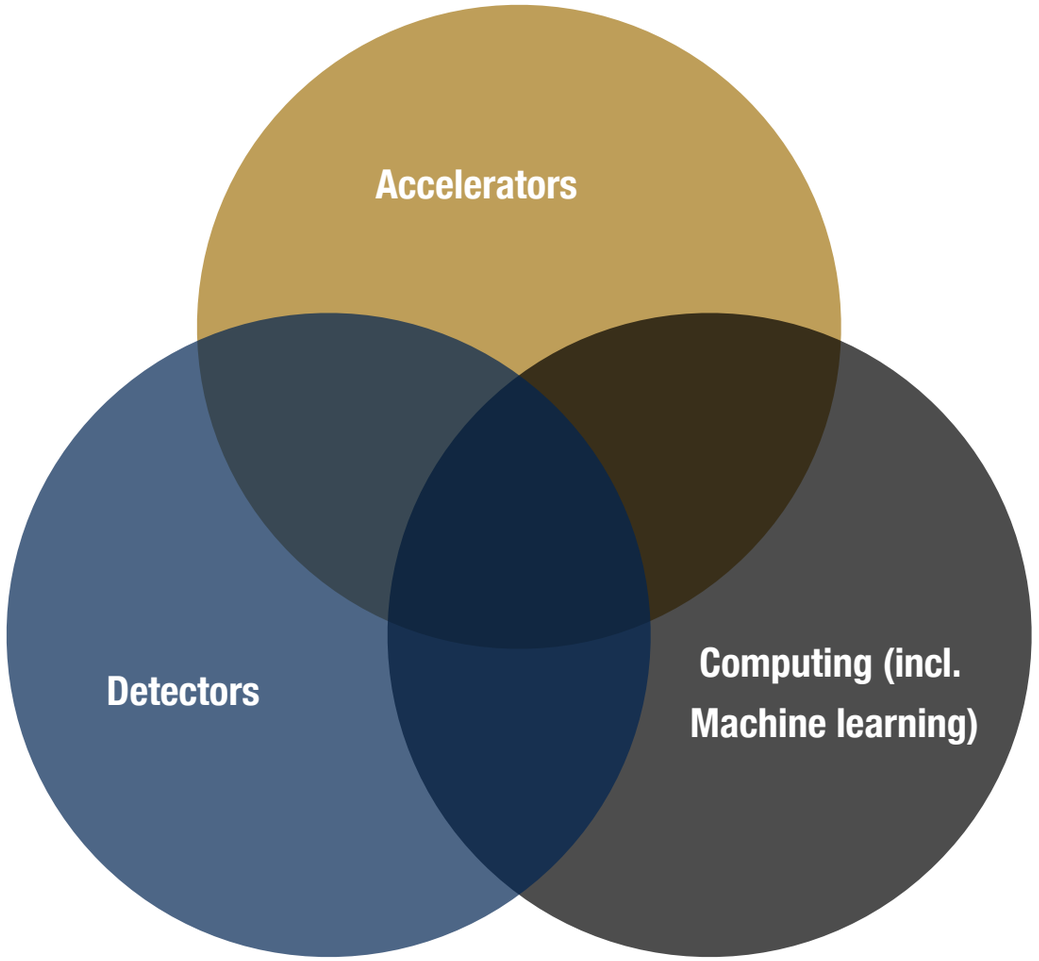
2. Requirements of Experimental High Energy Physics



2. Requirements of Experimental High Energy Physics



Enabled by advanced technologies



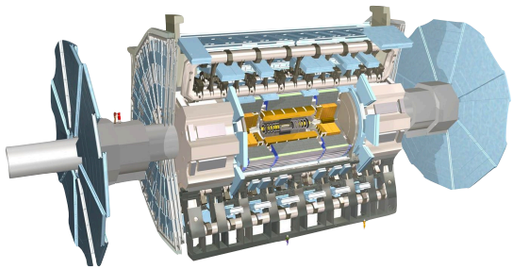
3. How experiments (analyses) are performed in Experimental High Energy Physics

Real data



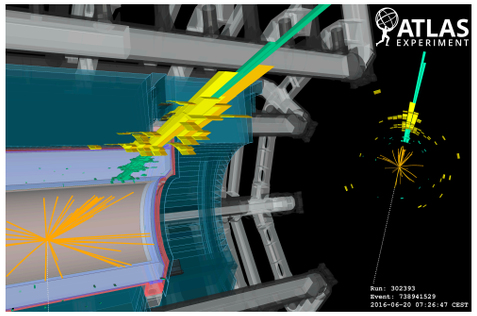
Data statistical uncertainty

Detector



Instrumental uncertainty

Reconstruction of physics objects

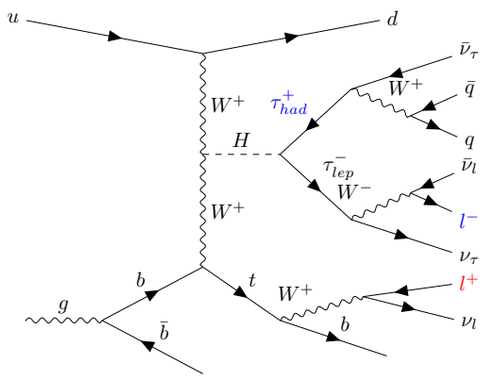


Experimental uncertainty

Data chain

Simulation chain

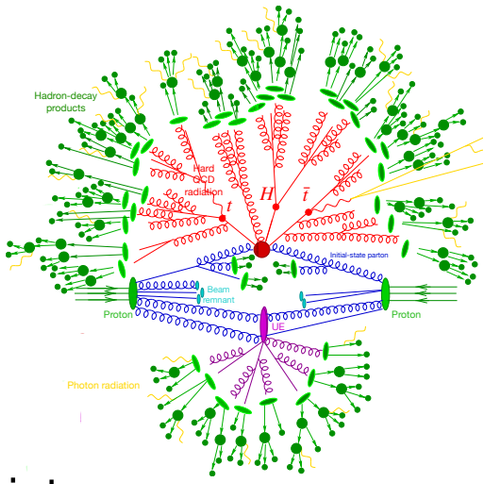
Simulation of the process



Monte Carlo statistical uncertainty

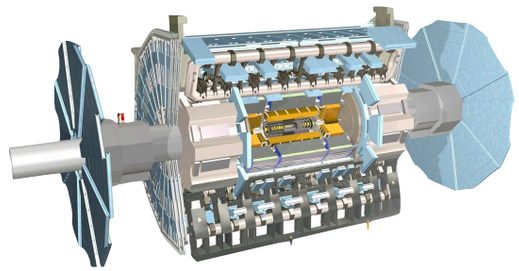
Theory/modelling uncertainty

Simulation of PS and hadronization



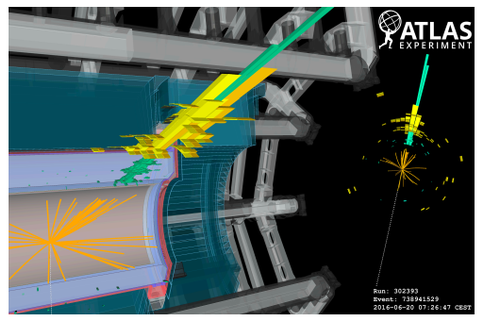
Theory/modelling uncertainty

Detector

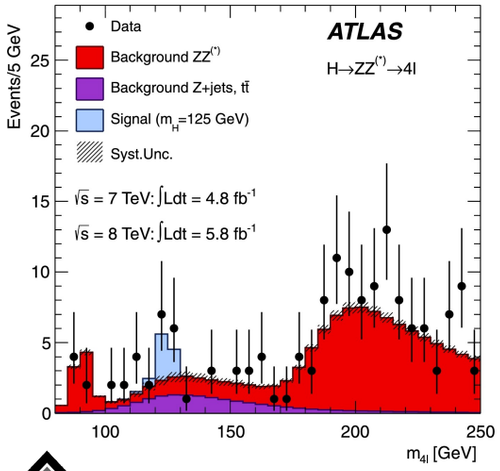


Detector modelling uncertainty

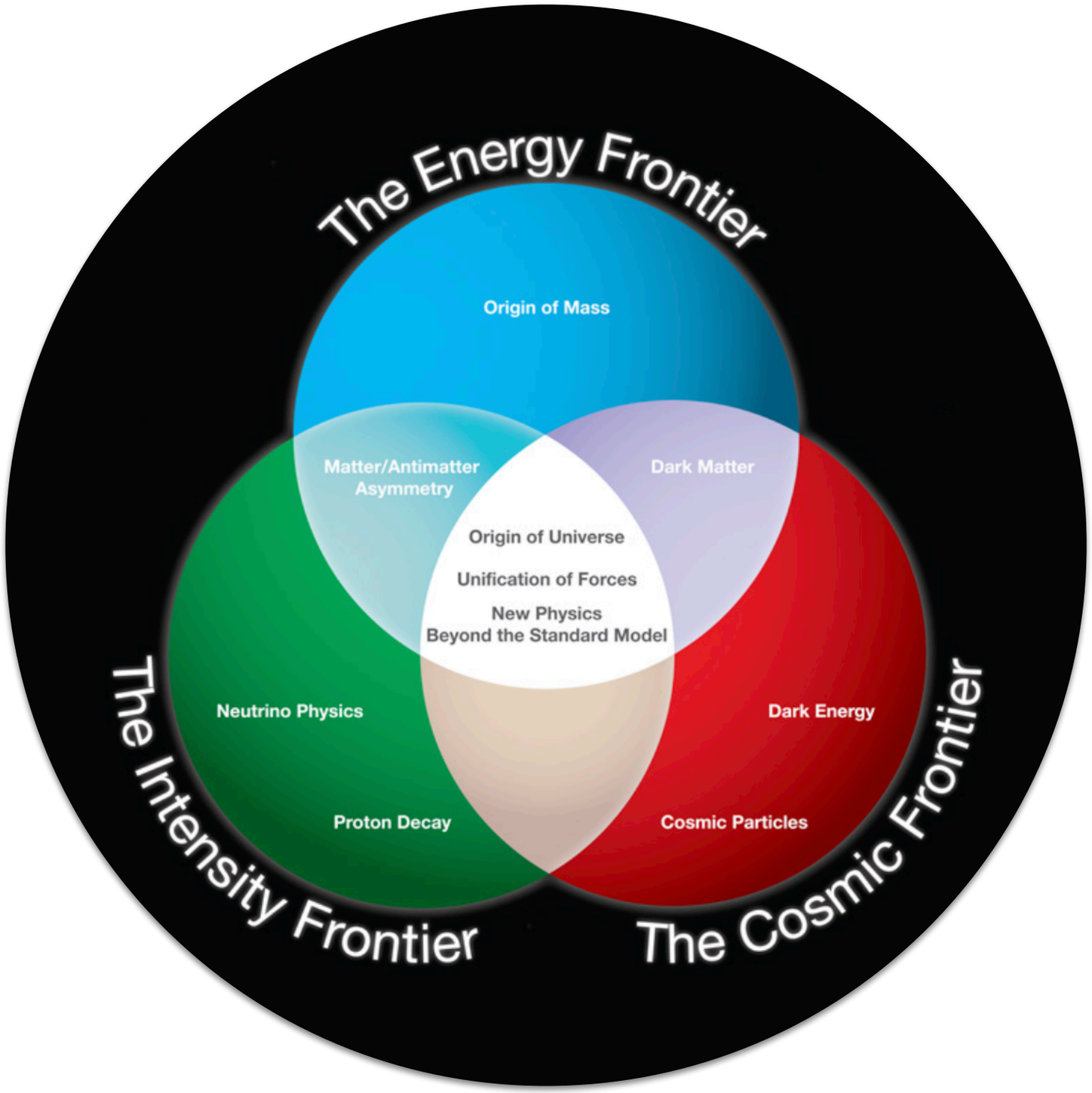
Reconstruction of physics objects



Experimental uncertainty



4. The Three Frontiers



Energy Frontier

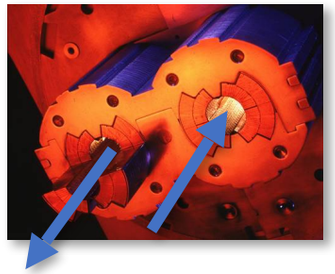
What is the Energy Frontier?

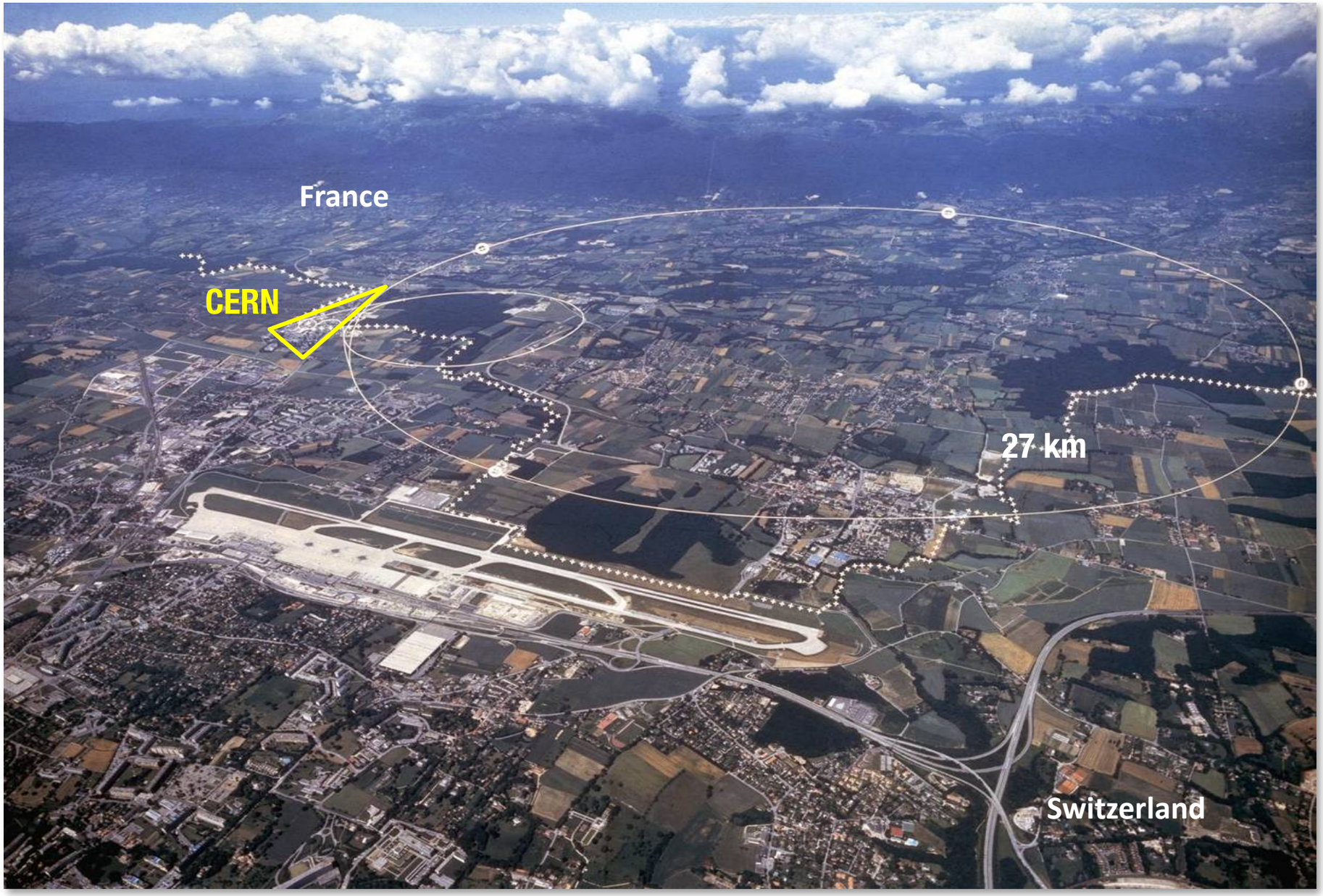
- Explore higher energy scales to discover new particles and phenomena that cannot be observed at lower energies
- Probe conditions similar to those just after the Big Bang
- Probe beyond the SM
- Investigate dark matter, extra dimensions, and new forces
- Based on high-energy colliders like the LHC

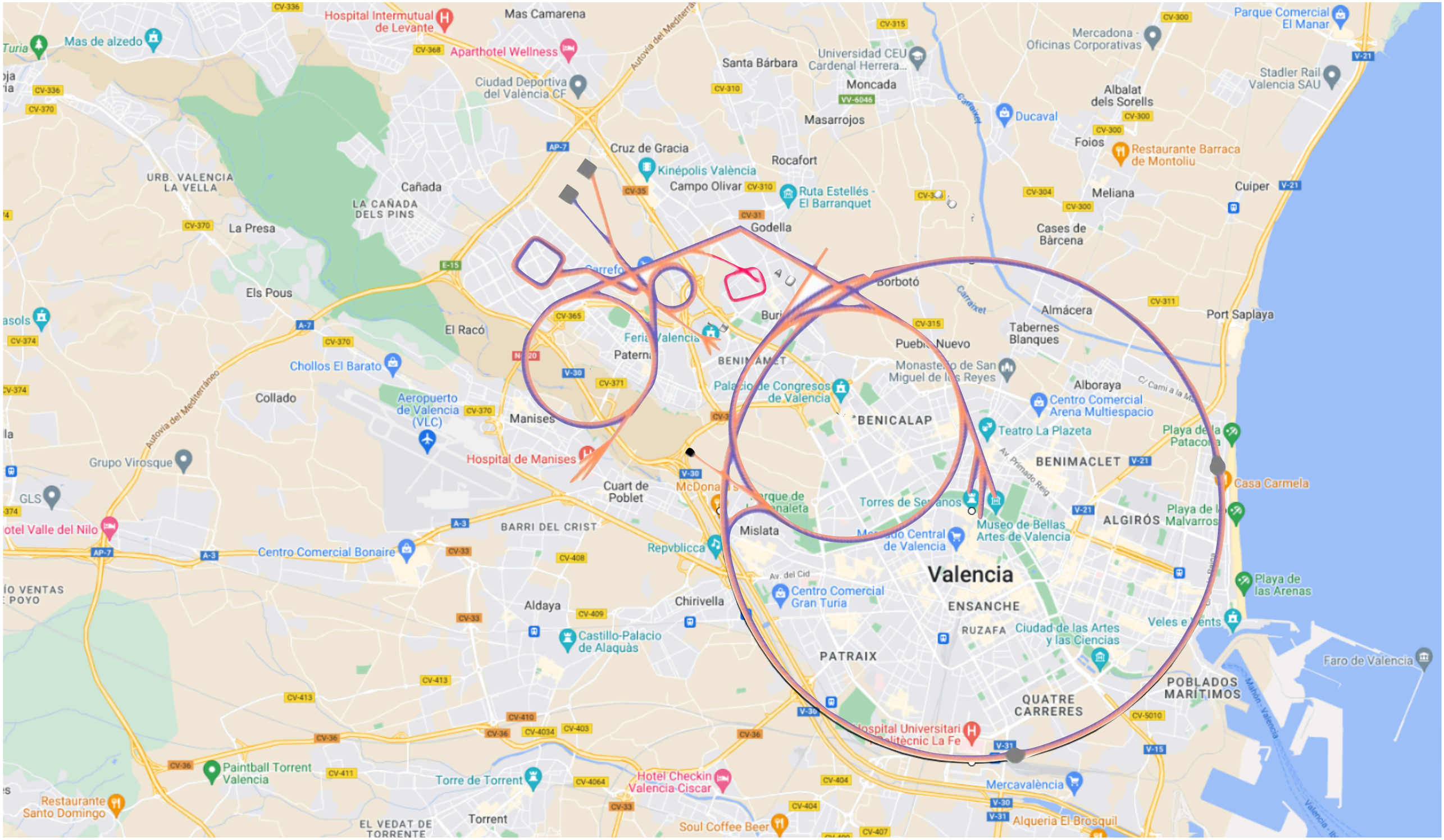
The Large Hadron Collider (LHC)

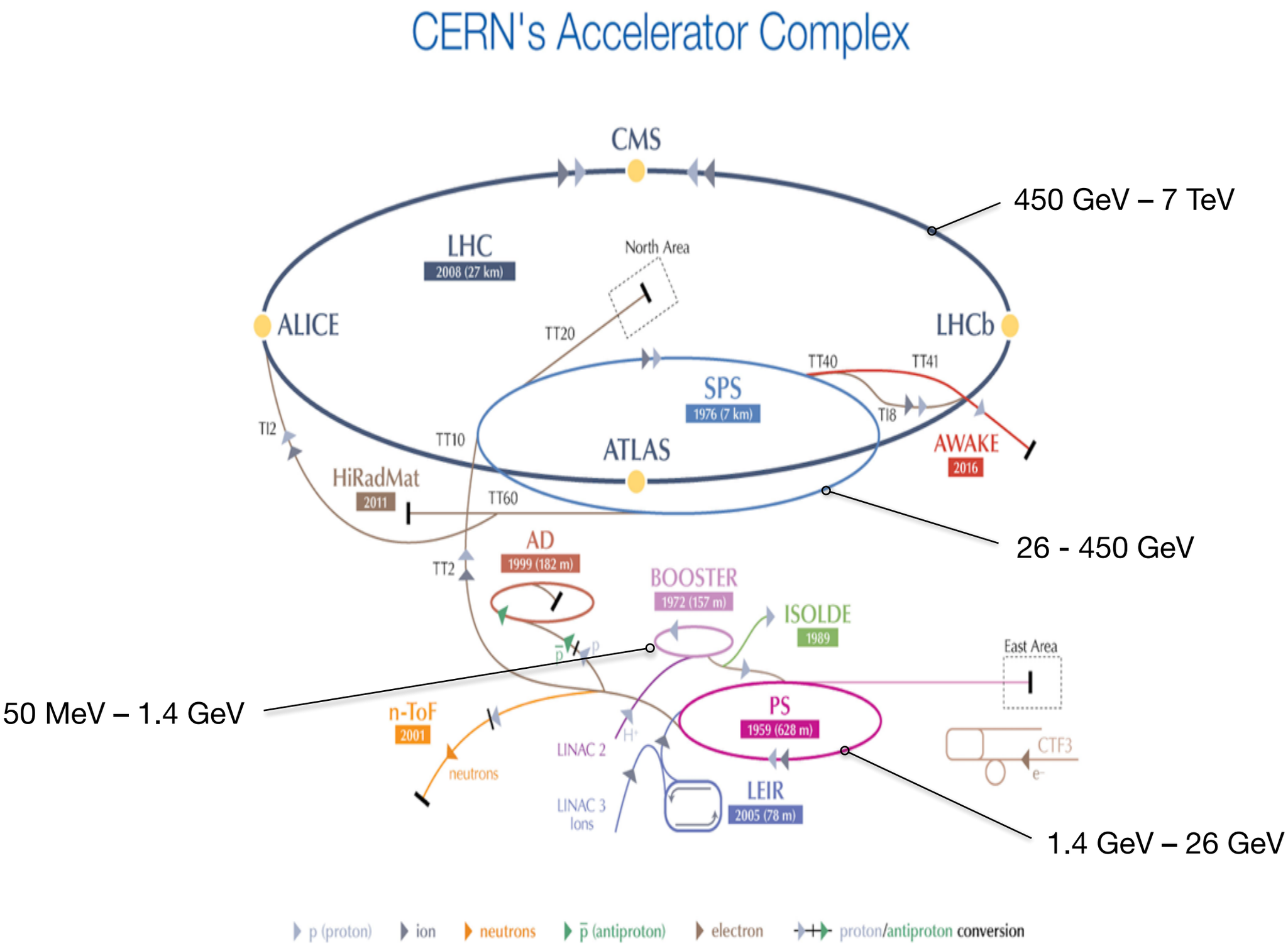
The Large Hadron Collider (LHC) is the most powerful particle accelerator in the world

- Located at CERN, 100 m underground
- 27 km collider where two beams go in opposite directions
- Collison rate: 40 MHz

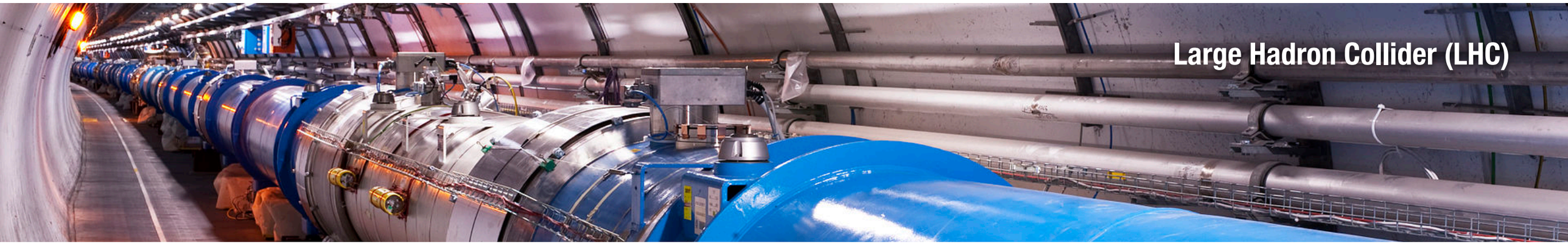





Hospital Intermutual de Levante
Mas Camarena
Mas de alzedo
Aparthotel Wellness
Ciudad Deportiva del València CF
Autovía del Mediterráneo
Santa Bárbara
Universidad CEU Cardenal Herrera...
Moncada
Masarrojos
Mercadona - Oficinas Corporativas
Parque Comercial El Manar
Stadler Rail Valencia SAU
Albalat dels Sorells
Ducaval
Foios
Restaurante Barraca de Montoliu
Cruz de Gracia
Kinépolis València
Rocafort
Campo Olivar
Ruta Estellés - El Barranquet
Meliana
Cuiper
Cases de Bàrcena
URB. VALENCIA LA VELLA
Cañada
LA CAÑADA DELS PINS
La Presa
Godella
Els Pous
Borbotó
Almácera
Port Saplaya
El Racó
Tabernes Blanques
Chollos El Barato
Collado
Aeropuerto de Valencia (VLC)
Manises
Palacio de Congresos de Valencia
BENICALAP
Monasterio de San Miguel de los Reyes
Alboraya
Centro Comercial Arena Multiespacio
Teatro La Plazeta
Playa de la Patacona
Hospital de Manises
Grupo Virosque
GLS
Cuart de Poblet
Torres de Serranos
Museo de Bellas Artes de Valencia
BENIMACLET
Casa Carmela
Playa de Malvarrosa
ALGIRÓS
Hotel Valle del Nilo
Centro Comercial Bonaire
BARRI DEL CRIST
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Valencia
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Centro Comercial Gran Turia
ENSANCHE
Playa de las Arenas
Castillo-Palacio de Alaquàs
RUZAFA
Ciudad de las Artes y las Ciencias
PATRAIX
Faro de Valencia
POBLADOS MARÍTIMOS
QUATRE CARRERES
Hospital Universitari i Politècnic La Fe
Paintball Torrent Valencia
Torre de Torrent
Hotel Checkin Valencia Ciscar
Mercavalència
Restaurante Santo Domingo
EL VEDAT DE TORRENTE
Torrent
Soul Coffee Beer
Alqueria El Brosquil


CERN's Accelerator Complex
CMS
LHC
2008 (27 km)
North Area
ALICE
LHCb
TT20
TT40
TT41
SPS
1976 (7 km)
TI8
TI2
TT10
ATLAS
AWAKE
2016
HiRadMat
2011
TT60
AD
1999 (182 m)
TT2
BOOSTER
1972 (157 m)
ISOLDE
1989
East Area
n-ToF
2001
PS
1959 (628 m)
CTF3
LINAC 2
neutrons
LINAC 3
Ions
LEIR
2005 (78 m)
450 GeV – 7 TeV
26 - 450 GeV
50 MeV – 1.4 GeV
1.4 GeV – 26 GeV
p (proton)
ion
neutrons
p̄ (antiproton)
electron
proton/antiproton conversion

The Large Hadron Collider (LHC)

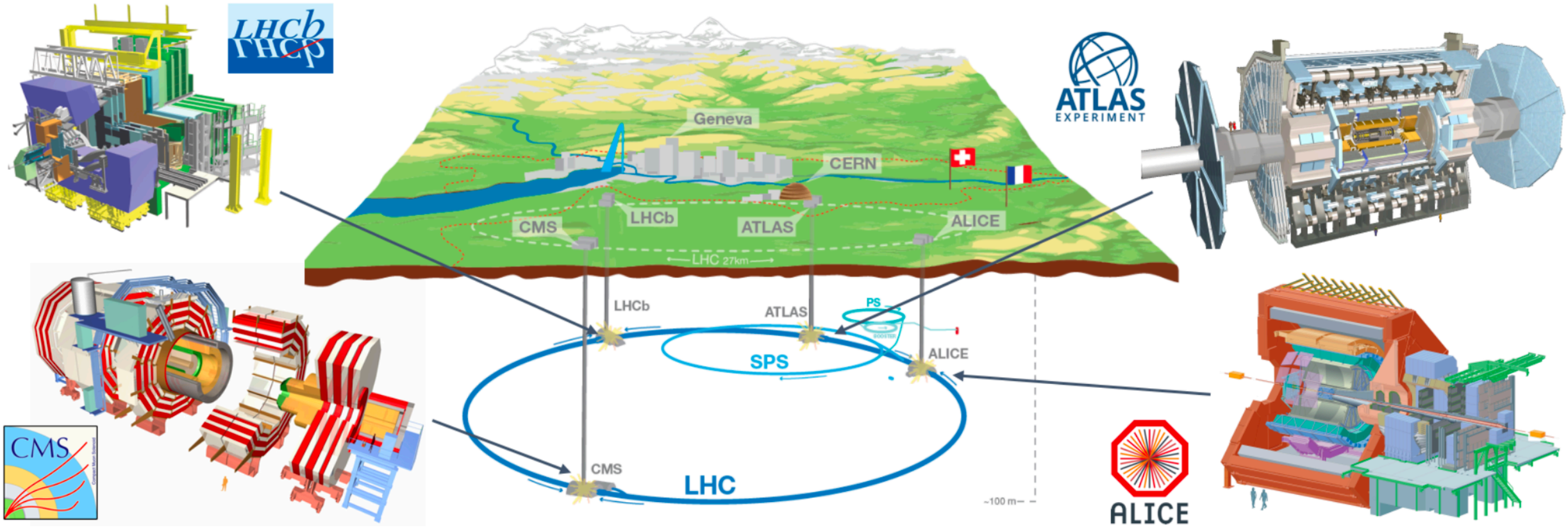


LHC uses about 9300 superconductor magnets — Largest technological challenge!

- 1232 dipols, 392 quadrupols, sextupols, etc
- Superfluid Helium at -271 ºC (1.9 K)

Parameter	Design	Run 1	Run 2	Run 3
Beam energy	7	3.5 - 4	6.5	6.8
Centre-of-mass energy ($\sqrt{s}$) [TeV]	14	7 - 8	13	13.6
Bunch spacing [ns]	25	50	25	25
Bunch Intensity [10^{11} ppb]	1.15	1.6	1.2	up to 1.8
Number of bunches (n_b)	2800	1400	2500	2800
Transverse emittance (ϵ) [µm]	3.5	2.2	2.2	2.5
Amplitude function at the interaction point (β^*)[cm]	55	80	30→25	30→25
Crossing angle [µrad]	285	-	300→260	300→260
Peak Luminosity [10^{34} $cm^2\,s^{-1}$]	1.0	0.8	2.0	2.0
Peak pileup	25	45	60	55
Nominal magnetic field (B) [T]	8.73	4.16 - 7.76	7.73	8.73
Injection energy [GeV]	450			
Circunference length [km]	26.7			
Radius [km]	4.24			
Number of dipole magnets	1232			
Length of dipole magnets [m]	14.3			
Number of quadripole magnets	395			
Total mass [tons]	27.5			

The Large Hadron Collider (LHC)



There are 4 main experiments placed in the LHC ring:

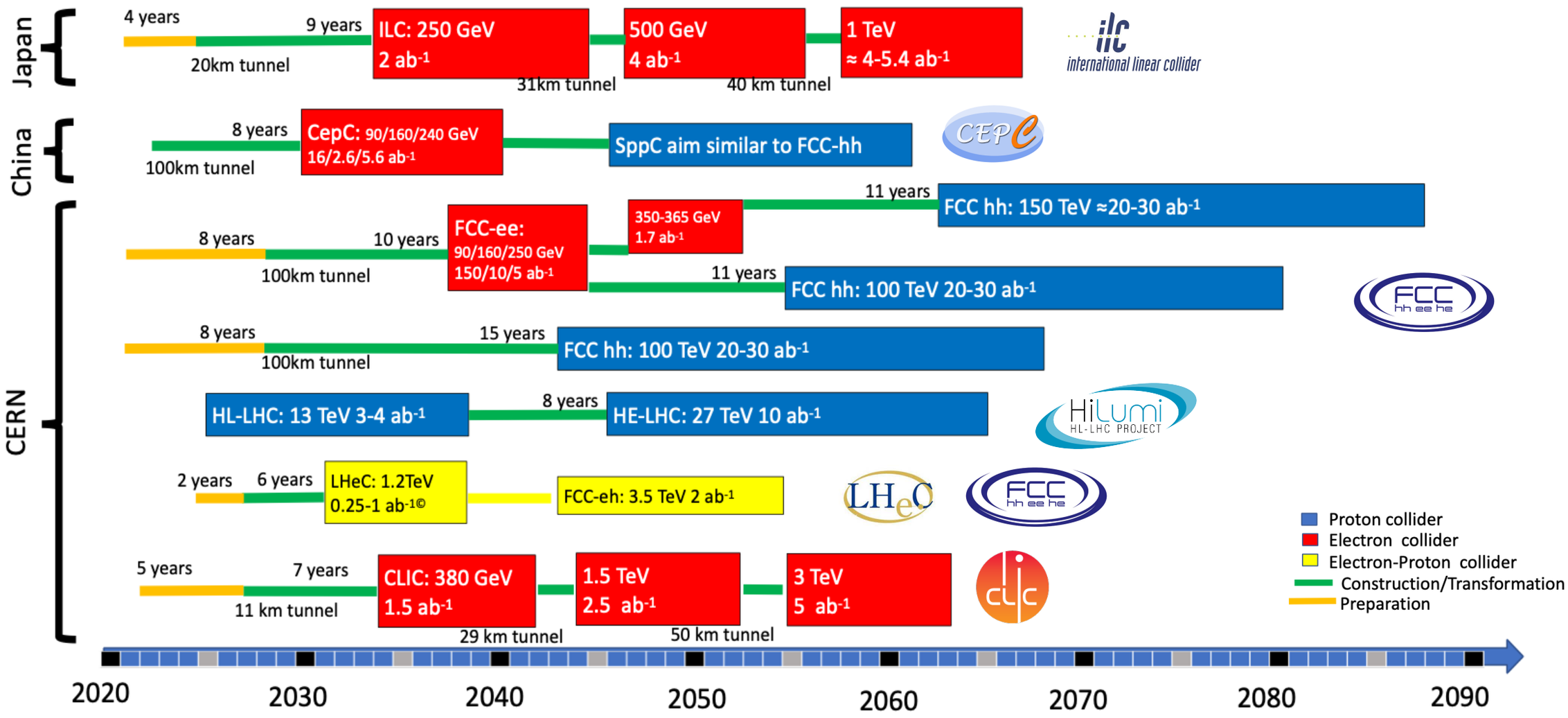
- LHCb: flavour physics of the SM
- ALICE: physics of strongly interacting matter at extreme energy densities (quark-gluon plasma)
- CMS and ATLAS: General-purpose detectors exploring a wide range of physics topics
- Some other smaller experiment : TOTEM, MoEDAL, LHCf, FASER and SND@LHC

- Higgs boson was observed in 2012, validating the last missing piece of the SM
- **Search for New Physics**: SUSY, dark matter, and other theories beyond the SM

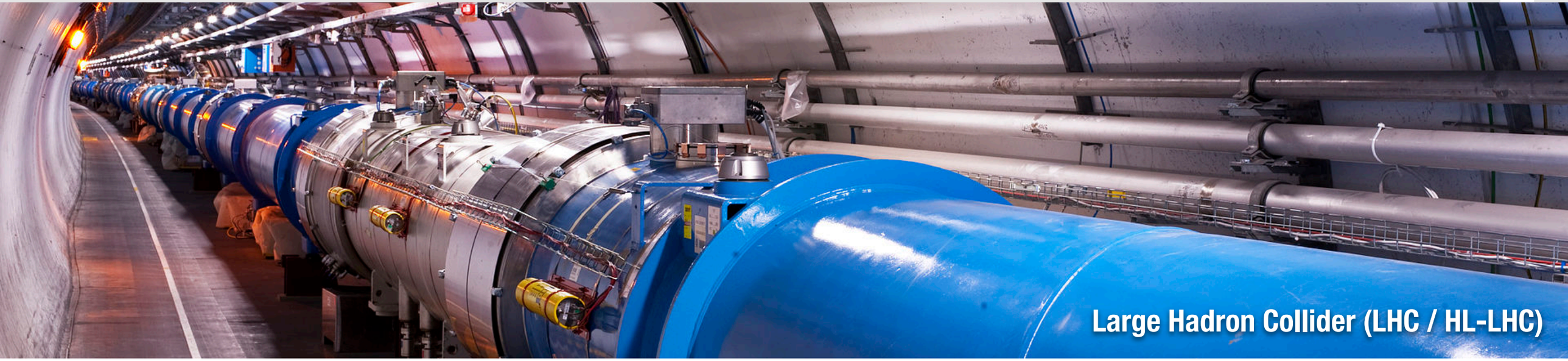
Current Challenges and future directions

European, America and Asian strategies seems to converge though there are many proposals:

1. **HL-LHC**
2. **Higgs factories (e^+e^- colliders):**
   - Large circular colliders: FCC-ee (CERN) and CepC (China)
   - Lineal colliders: ILC (Japan), CLIC (CERN), C^3 (US)
3. **Exploring the high energy frontier:**
   - *pp colliders*: FCC-hh (CERN), SppC (China)
   - *μμ colliders*: m-collaboration (CERN+US)

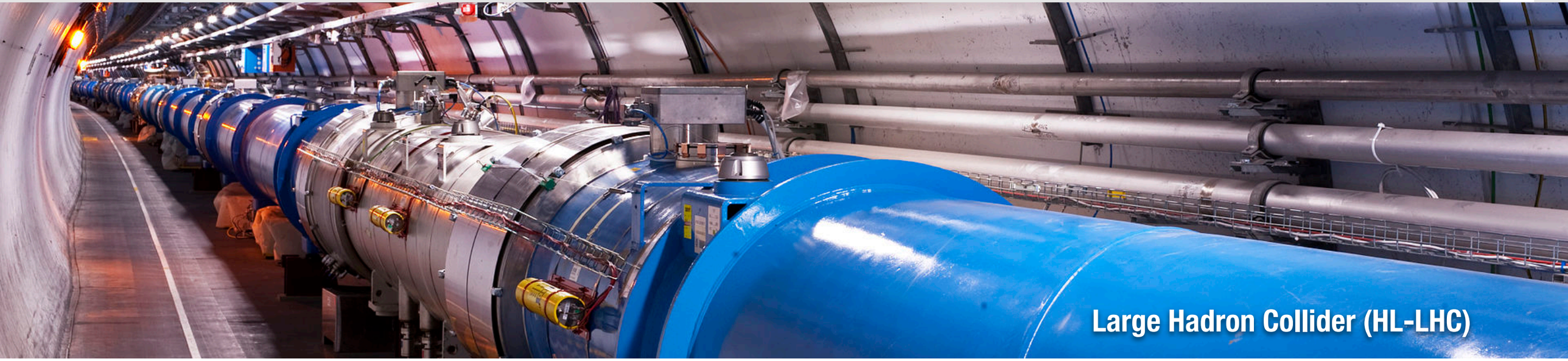


Current Challenges and future directions: HL-LHC



Parameter	Design	Run 1	Run 2	Run 3	HL-LHC
Beam energy	7	3.5 - 4	6.5	6.8	7
Centre-of-mass energy ($\sqrt{s}$) [TeV]	14	7 - 8	13	13.6	14
Bunch spacing [ns]	25	50	25	25	25
Bunch Intensity [10^{11} ppb]	1.15	1.6	1.2	up to 1.8	2.2
Number of bunches (n_b)	2800	1400	2500	2800	2800
Transverse emittance (ϵ) [µm]	3.5	2.2	2.2	2.5	2.5
Amplitude function at the interaction point (β^*)[cm]	55	80	30→25	30→25	donw to 15
Crossing angle [µrad]	285	-	300→260	300→260	TBD
Peak Luminosity [10^{34} cm^2 s^{-1}]	1.0	0.8	2.0	2.0	5.0
Peak pileup	25	45	60	55	150
Nominal magnetic field (B) [T]	8.73	4.16 - 7.76	7.73	8.73	11
Injection energy [GeV]	450				
Circunference length [km]	26.7				
Radius [km]	4.24				
Number of dipole magnets	1232				
Length of dipole magnets [m]	14.3				
Number of quadripole magnets	395				
Total mass [tons]	27.5				

Current Challenges and future directions: HL-LHC



Major interventions on more than 1.2 km of the LHC tunnel

- **Beam current and brightness** (number of protons in beam)
- **Luminosity levelling (interaction point)** → better to have a constant luminosity for a longer time

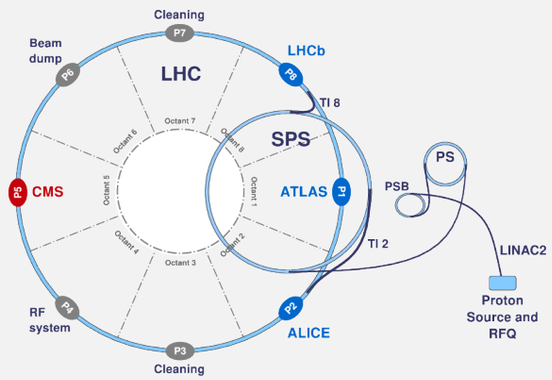
➡ New IR-quads Nb3Sn (inner triplets), New 11T Nb3Sn (short) dipoles, Collimation upgrade, Cryogenics upgrade, Crab Cavities, Cold powering, Machine protection, etc

Beam current and brightness

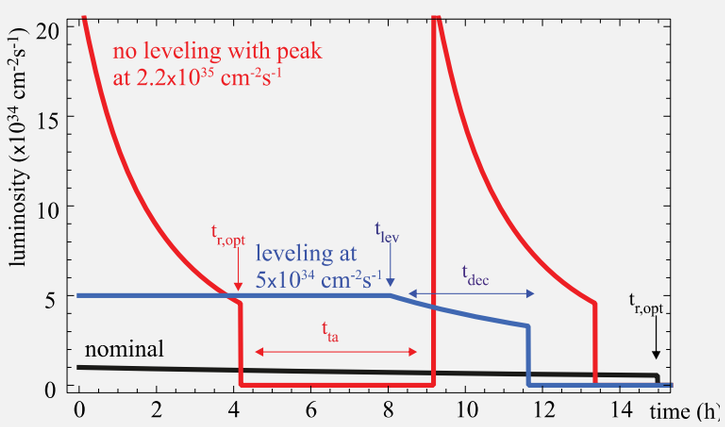
(number of protons in beam)

New/better injectors

LIU (LHC Injector Upgrade)



Luminosity leveling (interaction point)



Useful luminosity.
Reduce radiation damage on IP and keep pile-up under control.
For efficiency it is better to have a constant luminosity for a longer time.

Intensity Frontier

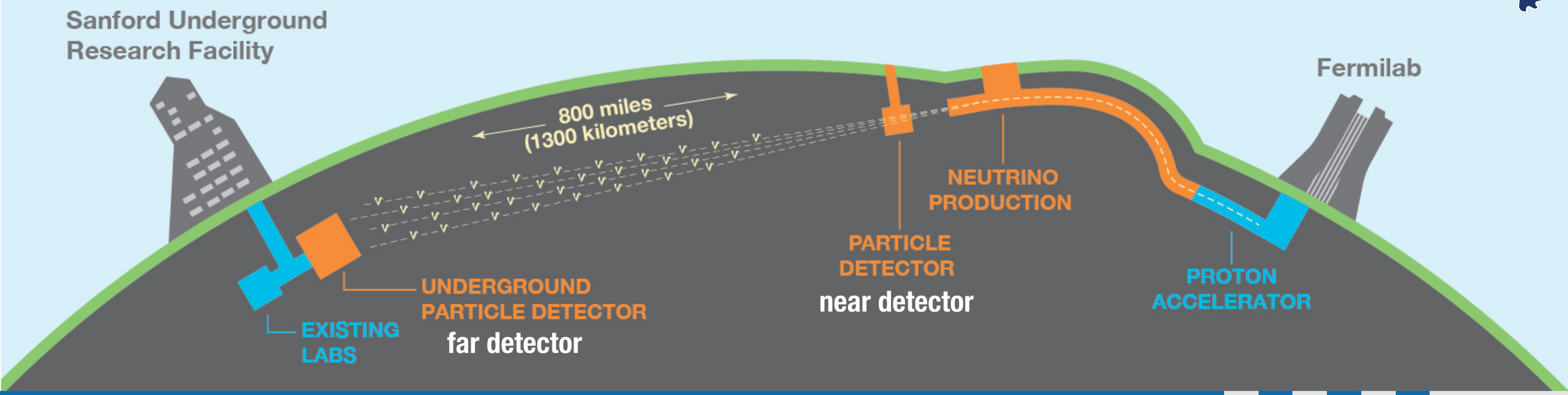
What is the Intensity Frontier?

- Focuses on studying rare processes and making precise measurements of known particles and forces
- Understand the properties of neutrinos and their oscillations
- Investigate CP violation to explain the matter-antimatter asymmetry in the universe
- Detect kaon and muon rare decays and subtle effects that might hint at new physics

Deep Underground Neutrino Experiment (DUNE)

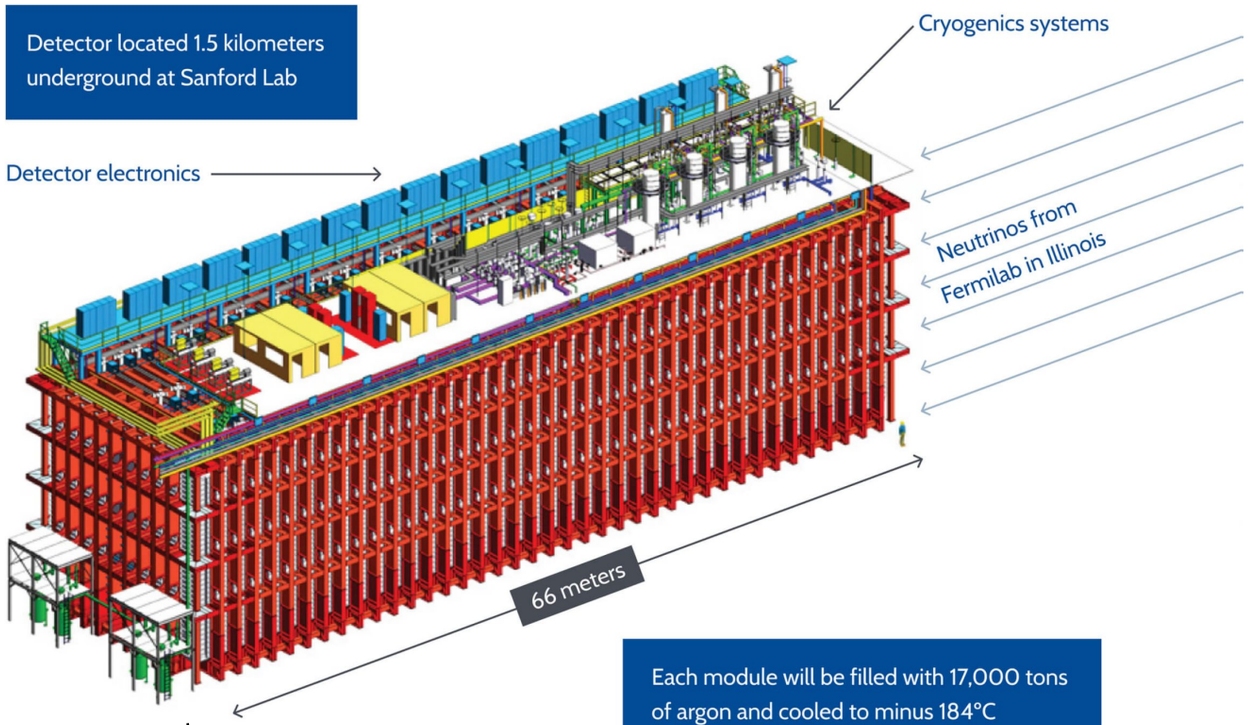
- Located in Fermilab (Illinois), with a detector at the Sanford Underground Research Facility (South Dakota)
- Study neutrino properties, especially neutrino oscillations
- Goals:
  - Determine the neutrino mass hierarchy
  - Investigate CP violation in the neutrino sector; could provide clues about the matter-antimatter asymmetry
- **Technology:**
  - a new MW-scale neutrino beamline (LBNF) - protons @ 60 – 120 GeV → ~10^{21} POT/yr
  - a high-resolution, high-rate near detector (NDLAr (~2032) → NDLAr+NDGAr (2040))
  - a far detector (FD) comprising four 17-kiloton liquid argon time-projection chamber (TPC) modules
  - Uses a LAr TPC for precise detection of neutrino interactions



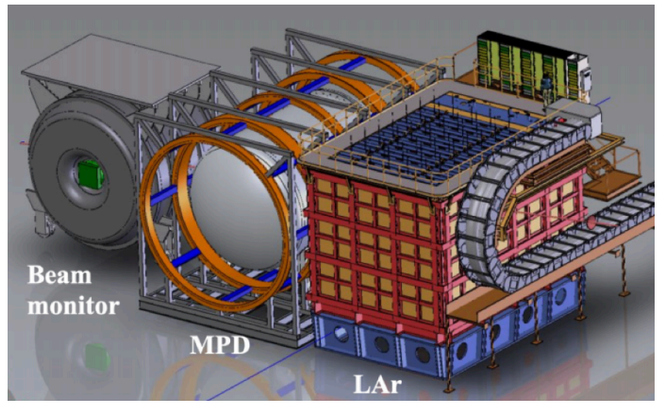


Deep Underground Neutrino Experiment (DUNE)

Detector located 1.5 kilometers underground at Sanford Lab



Each module will be filled with 17,000 tons of argon and cooled to minus 184°C

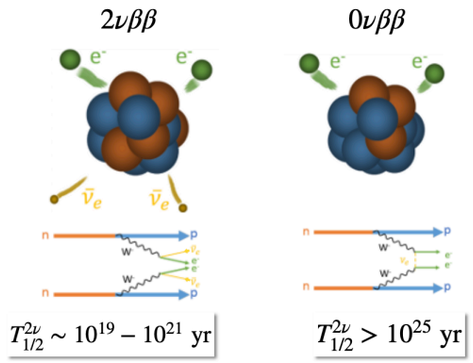


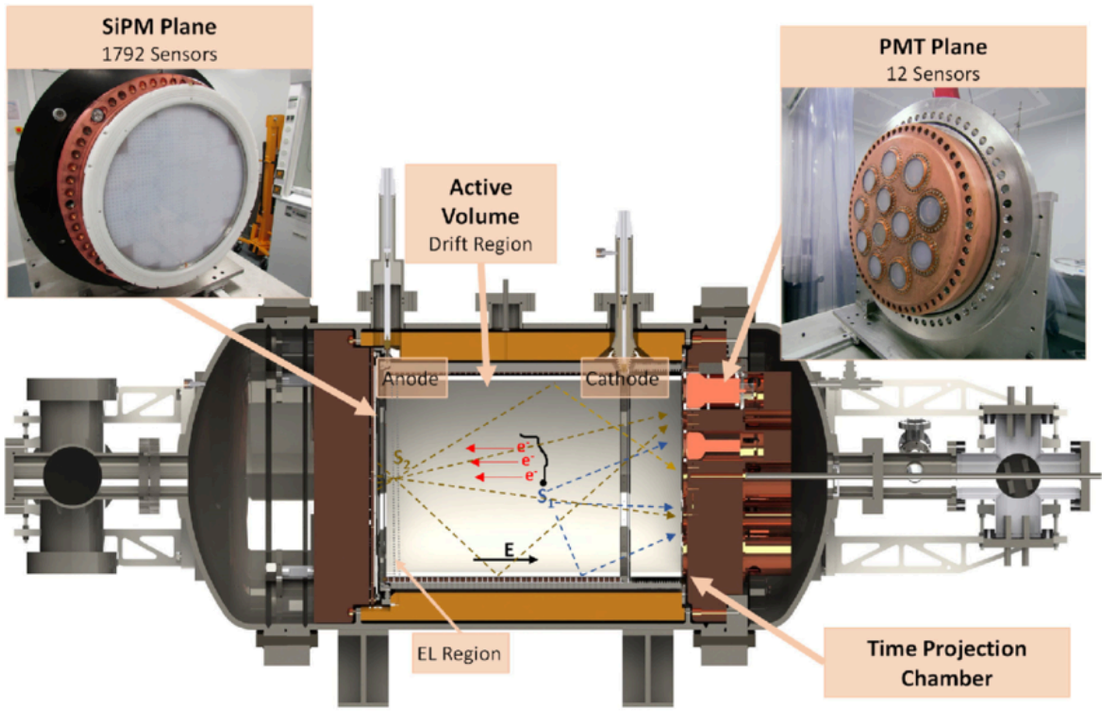


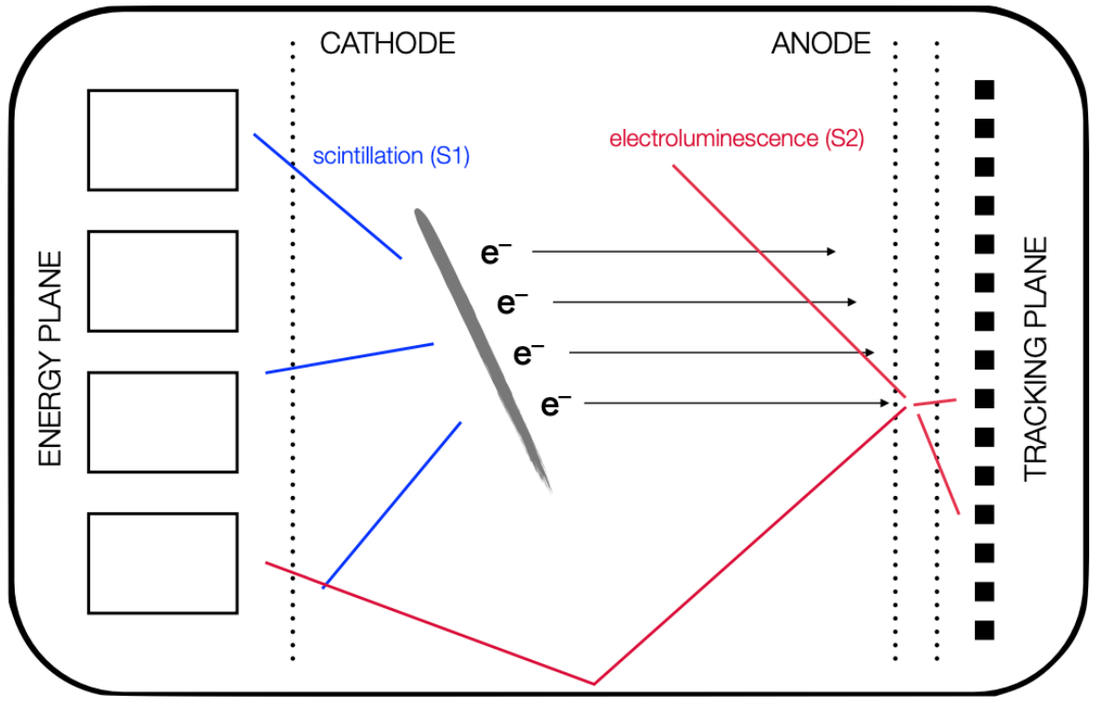
Neutrino Experiment with a Xenon TPC (NEXT)

Located in the Canfranc Underground Laboratory, Spain

- Search for neutrinoless double beta decay, which if observed, would show that neutrinos are Majorana particles (their own antiparticles).
- Would provide insights into the absolute mass of neutrinos
- Test the conservation of lepton number
- **Technology**: High-pressure Xe gas time-projection chamber (TPC), providing excellent energy resolution and background discrimination







Xe gas time projection chamber with electroluminescent amplification

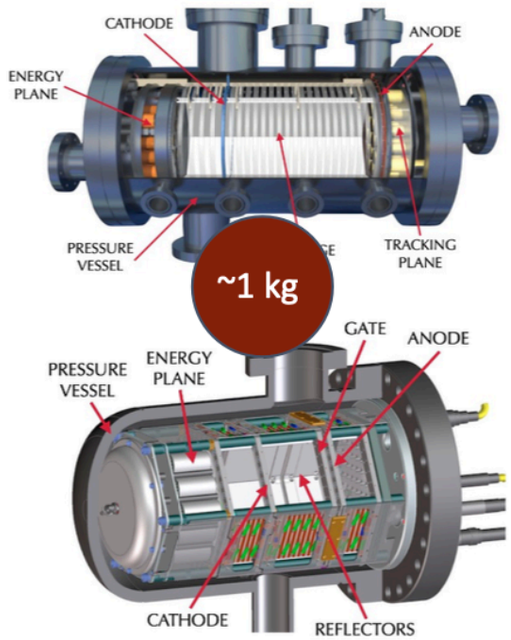
- Primary scintillation (S1) establishes the start-of-event time
- Secondary scintillation (S2) is used for calorimetry and tracking
- Specialised photosensor arrays for each measurement

Neutrino Experiment with a Xenon TPC (NEXT)

Prototypes

2008-2014

Demonstration of detector concept

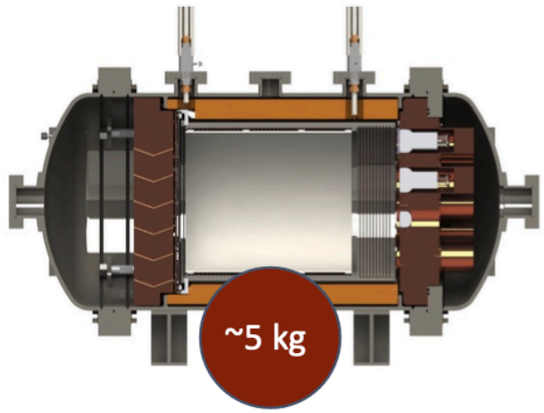


NEXT-White

2015-2021

Background model assessment

$2\nu\beta\beta$ measurement for ^{136}Xe

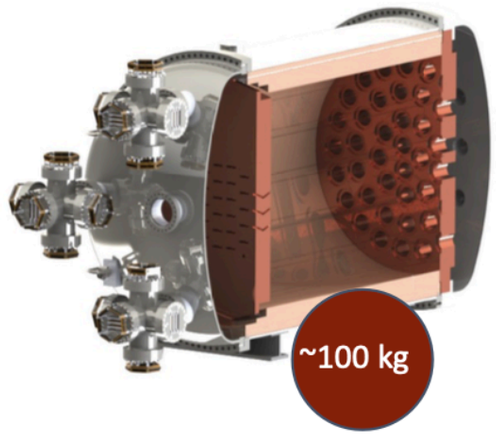


NEXT-100

2022-2025

Background model assessment

Neutrinoless double beta decay search in ^{136}Xe



NEXT-HD

2026?

Neutrinoless double beta decay search through inverted neutrino mass ordering

NEXT-BOLD

Barium tagging for background-free experiment

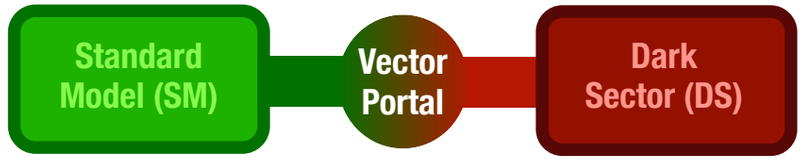


2009 2014 2015 2021 2022 2025 2026



NA64 Experiment

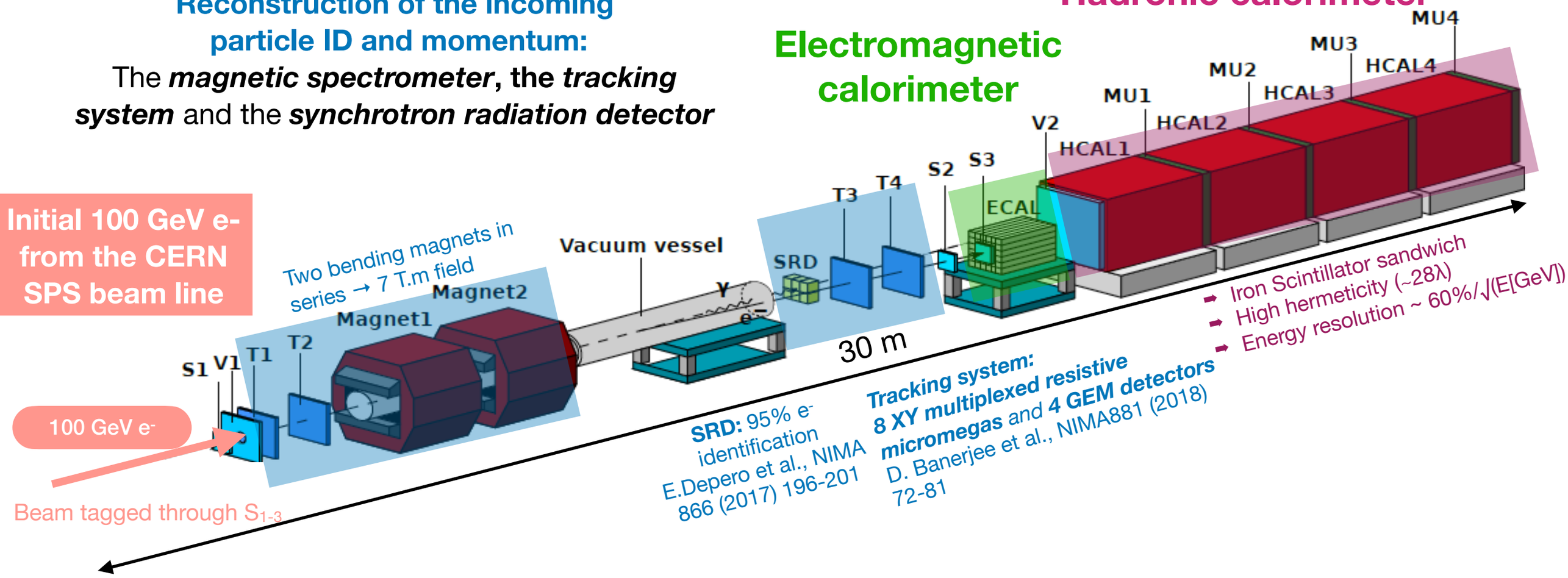
- Located in the North Area of the SPS at CERN
- Search for dark sector particles and other BSM physics, focusing on dark photons and light dark matter
- High-intensity electron beam from SPS directed at a fixed target
  - NA64e (5.1 x 10^{11} EOT), NA64μ (1.5 x 10^{11} MOT), NA64e+ (1.5 x 10^{10} e^+OT), NA64π (1.9 x 10^{10} πOT)



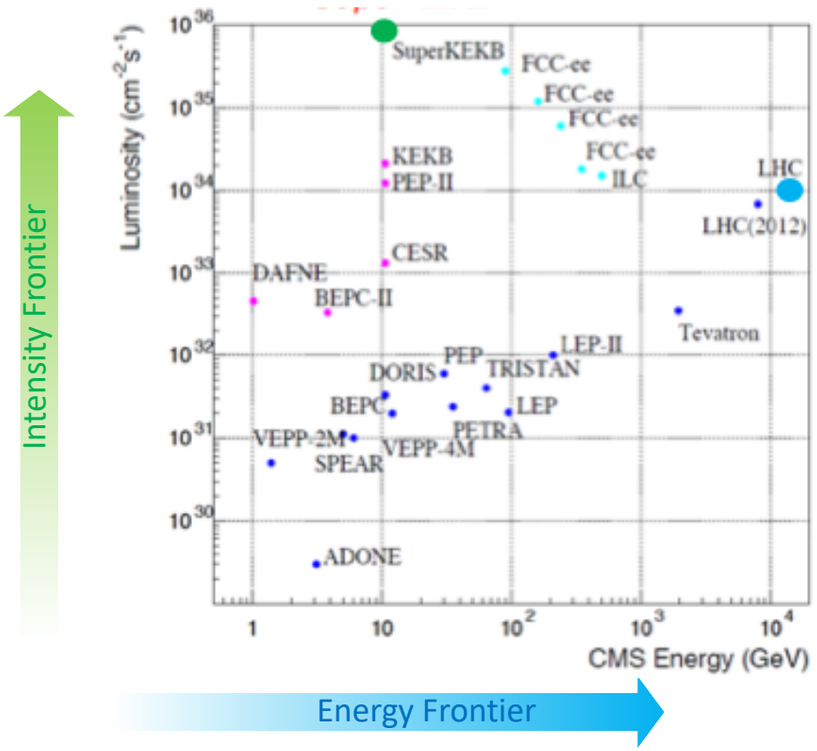
Reconstruction of the incoming particle ID and momentum:
The ***magnetic spectrometer***, the ***tracking system*** and the ***synchrotron radiation detector***

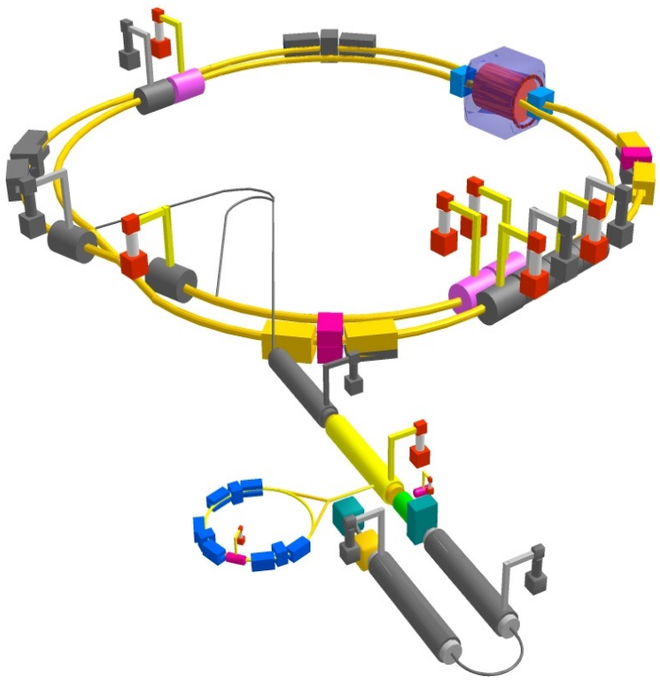
Electromagnetic calorimeter

Hadronic calorimeter



SuperKEKB and the Belle II Experiment





SuperKEKB is an advanced e^+e^- collider designed to achieve unprecedented luminosity (6×10^{35} cm^{-2} s^{-1})

- Nanobeam scheme
- Goals:
  - Study of CP Violation
  - Precision SM measurements, specially flavour physics
  - Search for New Physics

The SuperKEKB Accelerator

Mt. Tsukuba

SuperKEKB ring (HER+LER)

Belle II detector

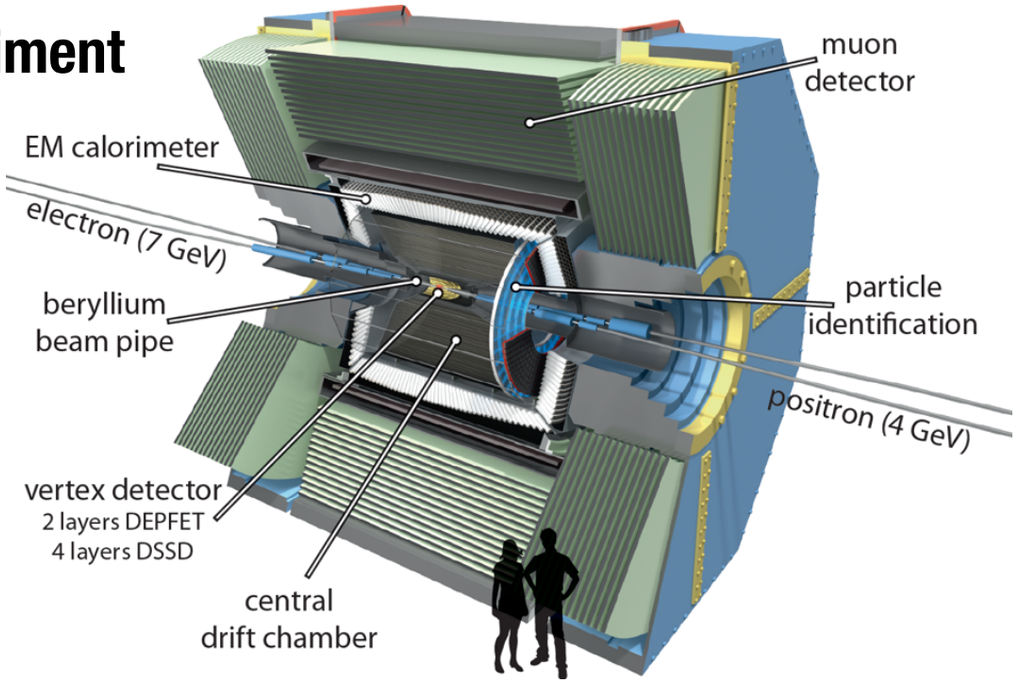
Linac



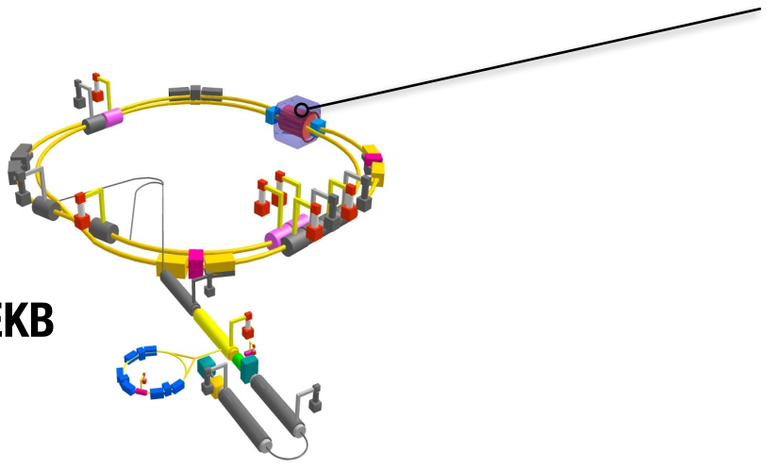
KEK - Tsukuba

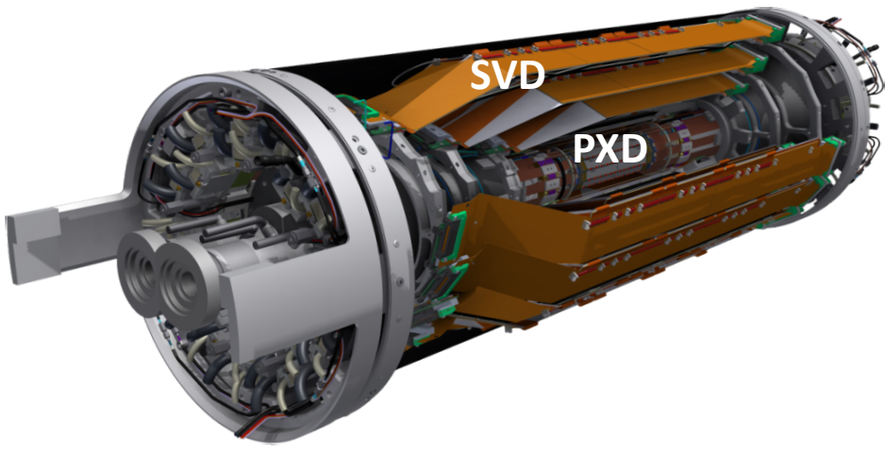
39

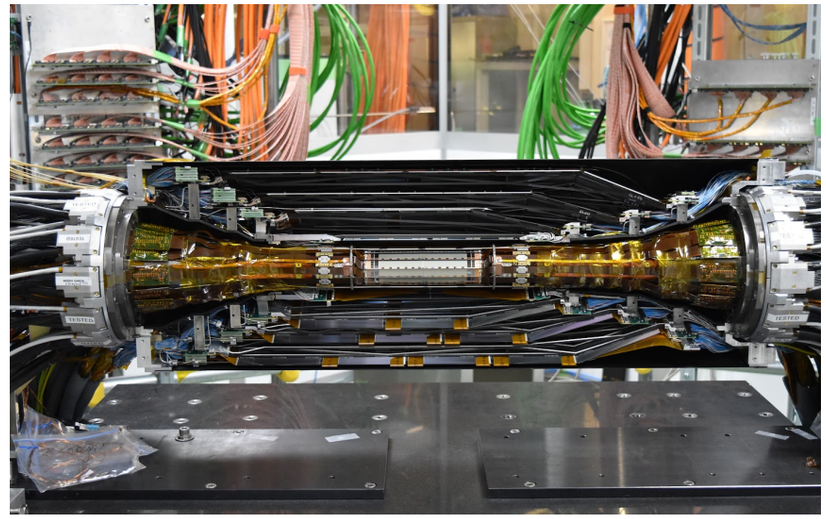
Belle II Experiment



SuperKEKB







Vertex detector

- PXD: 2 layers DEPFET
- SVD: 4 layers of Double-sided Silicon Strip Detectors (DSSD) detectors

These innermost layers have to cope with high background occupancy, high radiation and must have minimal material to reduce multiple scattering

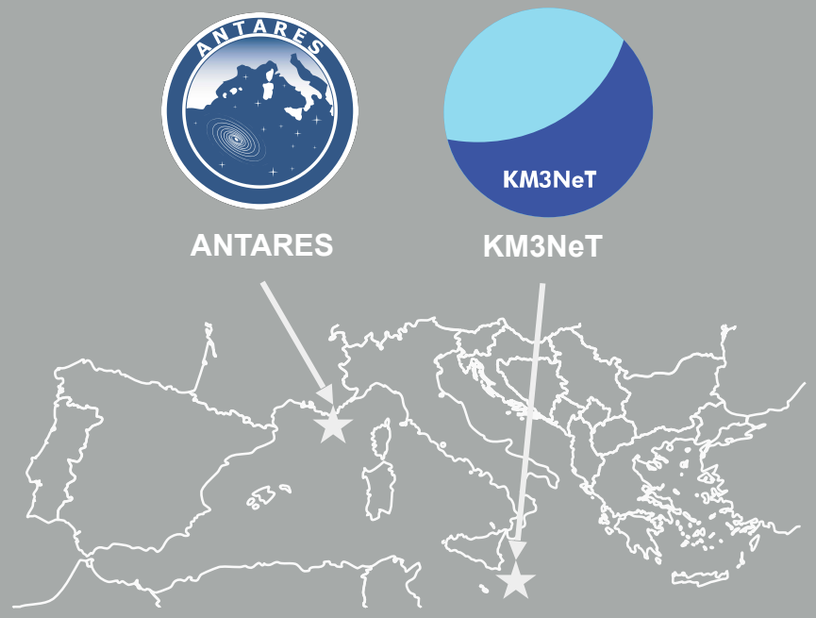
Cosmic Frontier

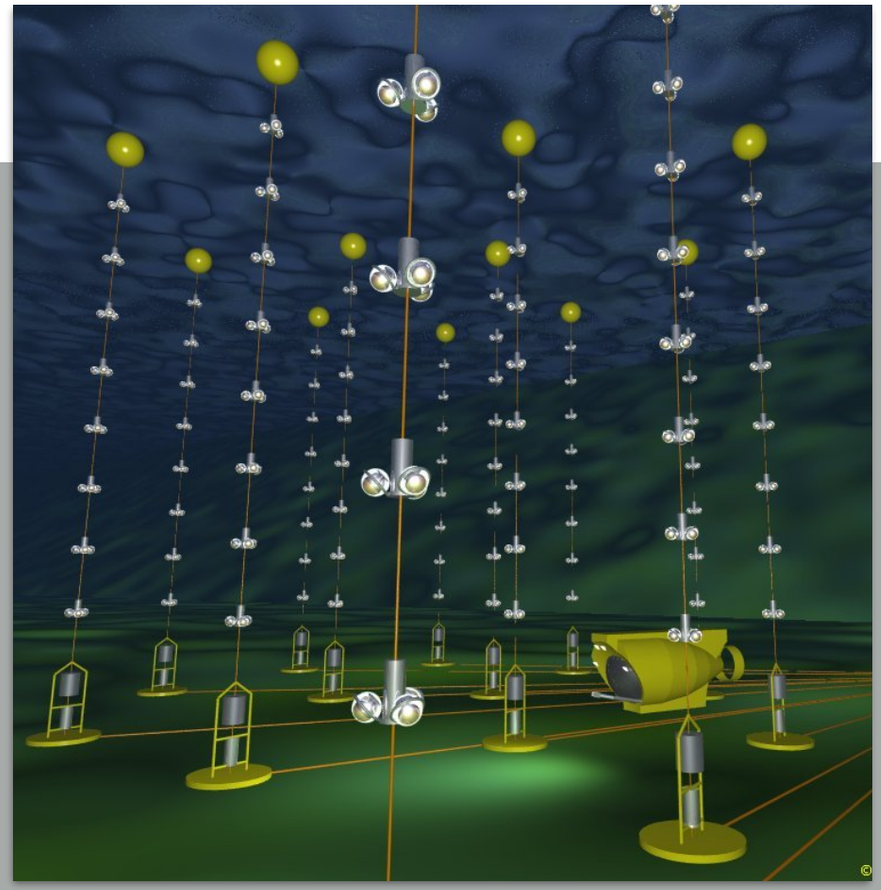
What is the Cosmic Frontier?

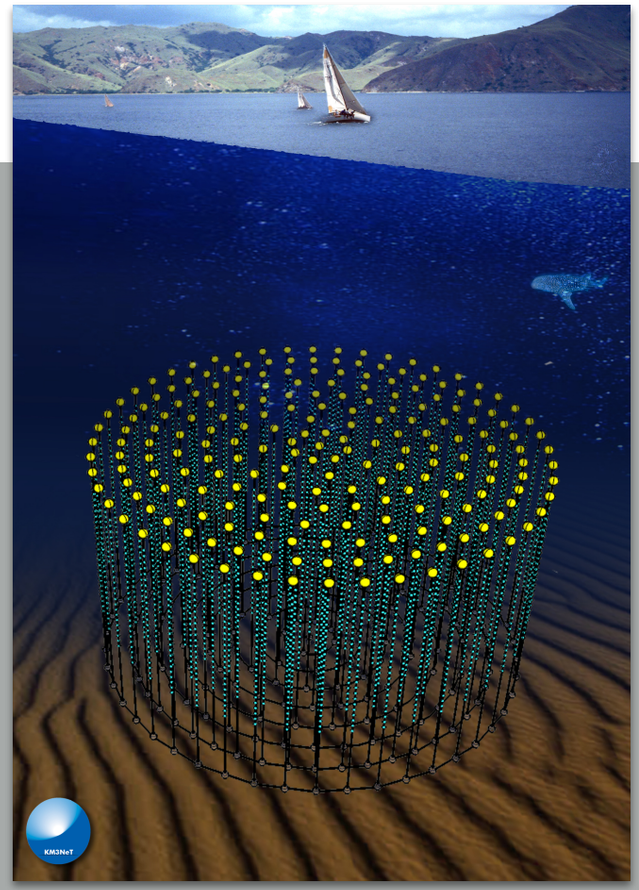
- Exploration and study of the universe on its largest scales using particles and phenomena from space
- Focuses on fundamental questions about the universe, such as the nature of dark matter, dark energy, cosmic rays, and the origins of the universe itself

Antares and KM3Net

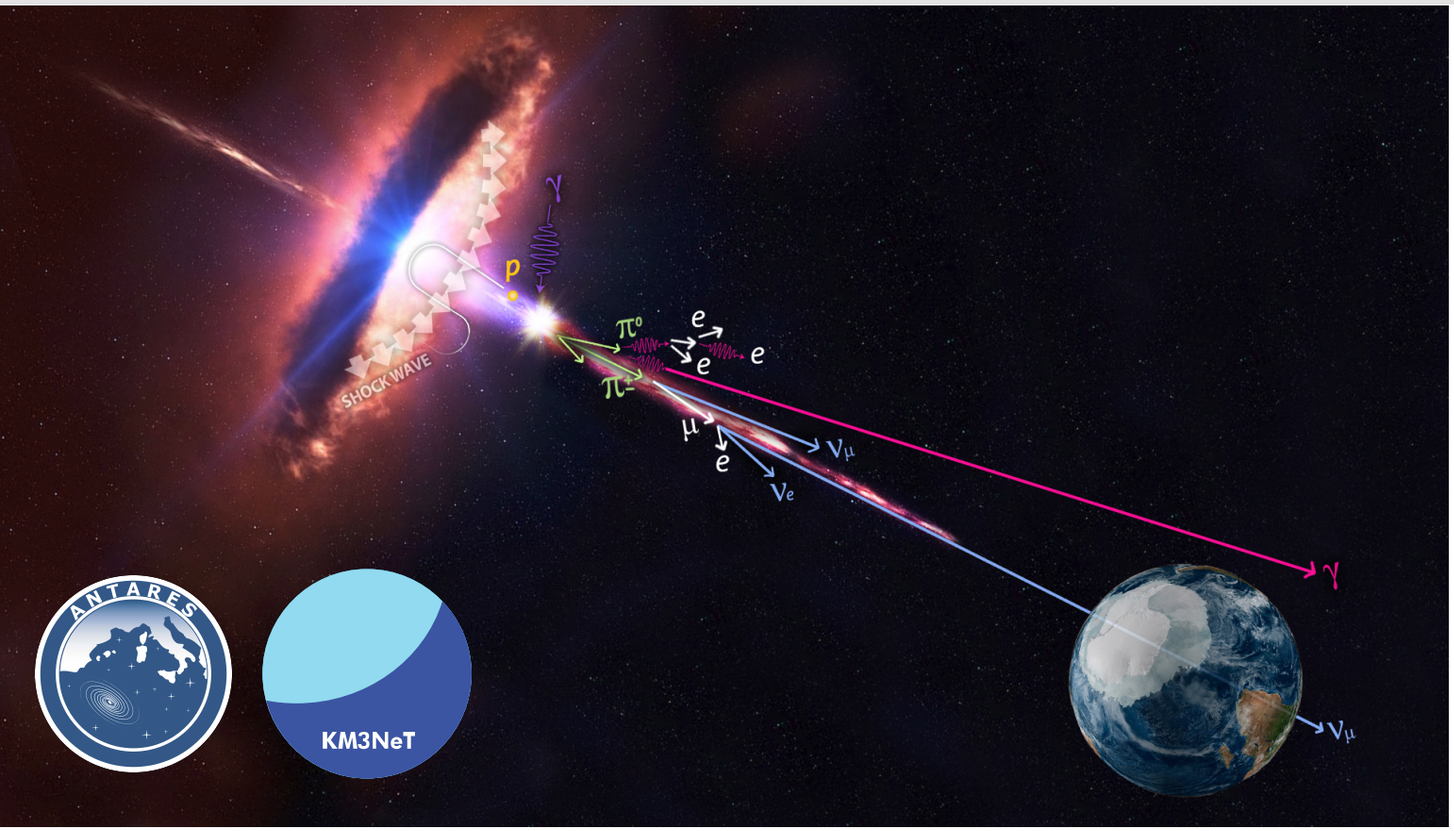
- Antares: An underwater neutrino telescope located in the Mediterranean Sea (decommissioned)
- KM3Net: A next-generation neutrino telescope being constructed in the Mediterranean, designed to be much larger and more sensitive
- Detect high-energy neutrinos from cosmic sources such as supernovae, gamma-ray bursts, and active galactic nuclei
- **Technology:** Arrays of photomultiplier tubes embedded in the deep sea, detecting Cherenkov light produced by neutrino interactions







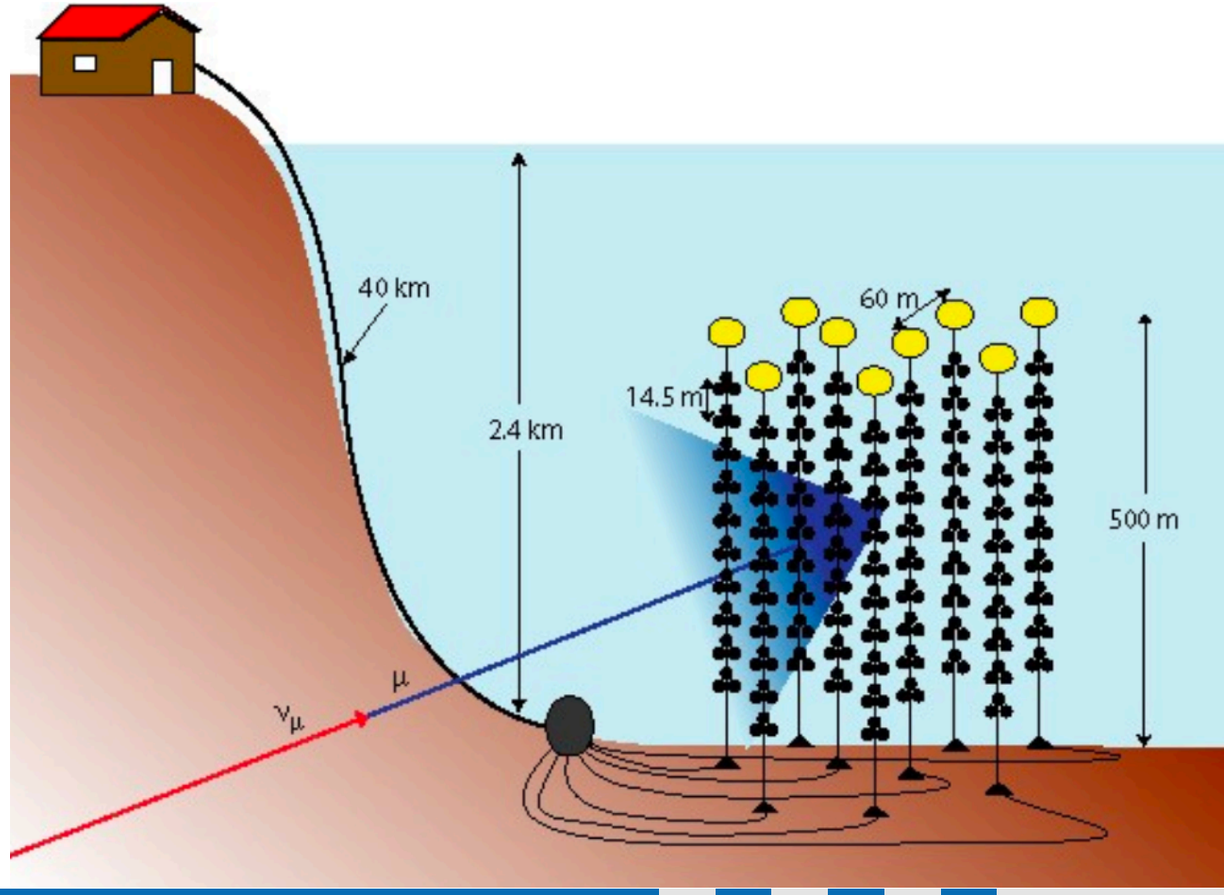
Antares and KM3Net



These detectors observe upward-going neutrinos from most of the sky due to the Earth's rotation

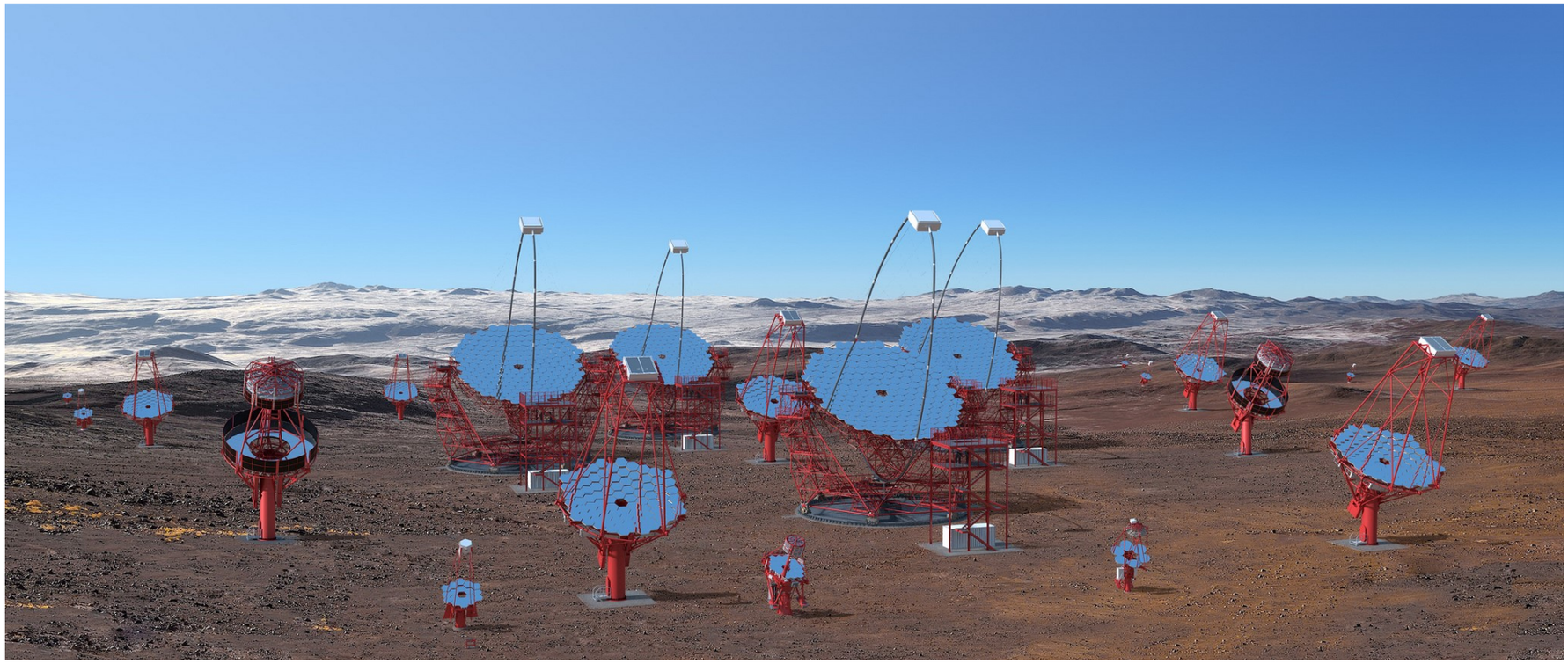
Arrays of large-area photomultiplier tubes (PMTs) enclosed in pressure-resistant glass spheres to form optical modules

- Antares used 900 PMTs
- KM3NeT utilizes a total of approximately 2070 PMTs across both ARCA (Astroparticle Research with Cosmics in the Abyss) and ORCA (Oscillation Research with Cosmics in the Abyss) detectors

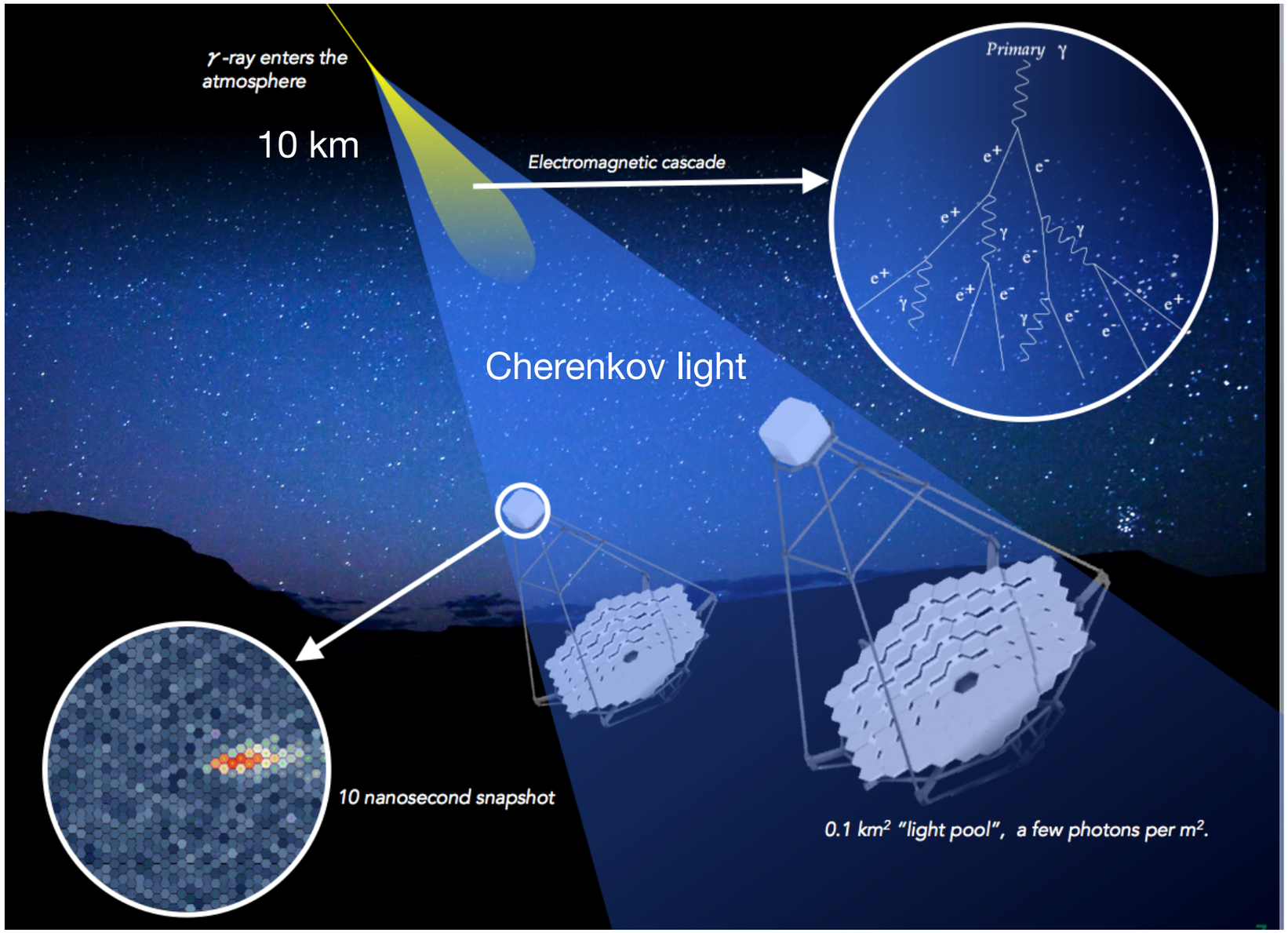


The Cherenkov Telescope Array (CTA) observatory

- Located Northern Hemisphere (La Palma, Spain) and the Southern Hemisphere (Chile)
- Detect high-energy gamma rays with energies from 20 GeV to 300 TeV to study extreme environments like black holes, neutron stars, and supernova remnants
- Goals:
  - Understand particle acceleration mechanisms
  - Mapping the Gamma-Ray Sky
  - Explore dark matter and fundamental physics through gamma-ray observations
- **Technology:** large array of imaging atmospheric Cherenkov telescopes (IACTs) to detect very high-energy gamma rays by observing the Cherenkov light produced when gamma rays interact with the Earth's atmosphere



Cherenkov Telescope Array (CTA)



Segmented mirror to reflect the Cherenkov light to a high-speed camera (PMTs and SiPMs) that records the image of the shower

High Altitude Water Cherenkov (HAWC)

The HAWC (High-Altitude Water Cherenkov) observatory

- Located at an altitude of 4.100 m on the Sierra Negra volcano near Puebla, Mexico
- Study gamma rays and cosmic rays with energies from 100 GeV to 100 TeV
- Goals:
  - Investigate and understand the galactic/extragalactic sources of high-energy cosmic rays
  - Mapping the High-Energy Sky (TeV scale)
  - Monitor transient events like Gamma-Ray Bursts
  - Dark Matter Searches
- **Technology:** array of water Cherenkov (300) detectors spread over a large area to detect secondary particles produced by cosmic rays and gamma rays interacting with the atmosphere





High Altitude Water Cherenkov (HAWC)

HAWC Observatory

HAWC operates day and night, providing a large field of view for the observation of the highest energy gamma rays.



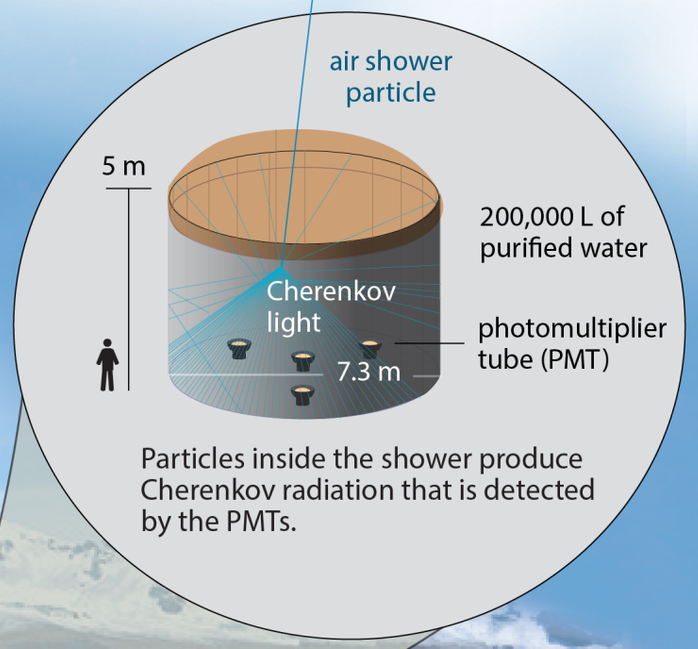
HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

Pico de Orizaba
(5,626 m)

HAWC is located at 4,100 m above sea level, covering an area of 20,000 m^2.

Water Cherenkov tank

HAWC comprises an array of 300 tanks that record the particles created in gamma-ray and cosmic-ray showers.

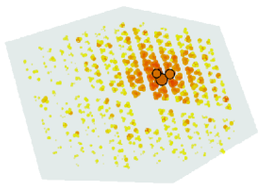


Particles inside the shower produce Cherenkov radiation that is detected by the PMTs.

Gamma rays vs cosmic rays

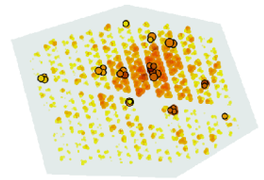
HAWC selects gamma rays from among a much more abundant background of cosmic rays.

gamma-ray shower



"hot" spots concentrate around the core

cosmic-ray shower



"hot" spots are more dispersed

Emerging proposals for extending current experiments

Emerging experiments and current proposals

The SM, while highly successful, is known to be incomplete

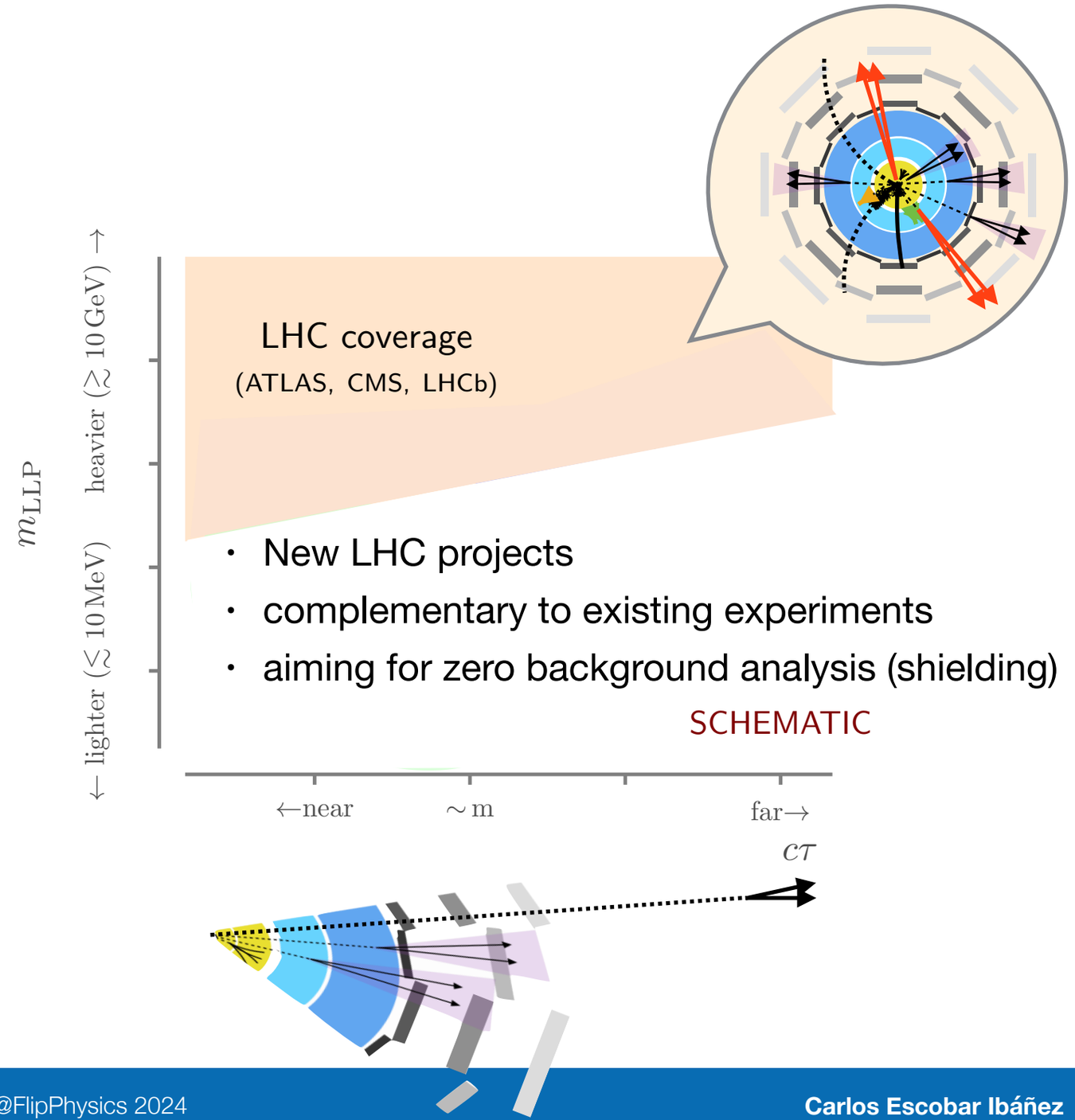
- It cannot explain several phenomena such as dark matter, neutrino masses, matter-antimatter asymmetry, etc
- We need to push the boundaries of our understanding of particle physics
- Many BSM theories, such as SUSY, hidden valleys, and extra dimensions, predict the existence of long-lived particles (LLPs)

- Indeed, several experiments and collaborations are actively searching for LLPs:

- **ATLAS and CMS (LHC, CERN)** employ various techniques to identify unusual signatures such as displaced vertices, disappearing tracks, and delayed photons, which are indicative of LLPs.
- **LHCb (LHC, CERN)** has excellent vertex resolution capabilities, making it well-suited to detect particles that decay at significant distances from the interaction point.
- **MoEDAL (Monopole and Exotics Detector at the LHC)** is specifically designed to search for highly ionizing particles and other exotic states, including LLPs. It uses passive detectors and has unique sensitivity to long-lived, heavy, and stable charged particles.
- **Belle II (SuperKEKB accelerator, Japan)** has a program for searching for LLPs that might be produced in B-meson decays or other processes.
- **NA62 (CERN)** also looks for LLPs produced in kaon decays that can travel a significant distance before decaying.
- **DUNE (US)** has a large detector volume and underground location making it sensitive to certain types of LLPs, especially those produced in cosmic rays or from neutrino interactions.

Emerging experiments and current proposals

- Many of the theories involving LLPs give no specifications on lifetimes
- We need new experiments that complement existing ones like the LHC
- LLPs with very long lifetimes could decay after traversing the main LHC detectors (O(10m))
  - Need of dedicated experiments far away from the IP!
- Can we profit from our existing experiments and “easily” extend them?

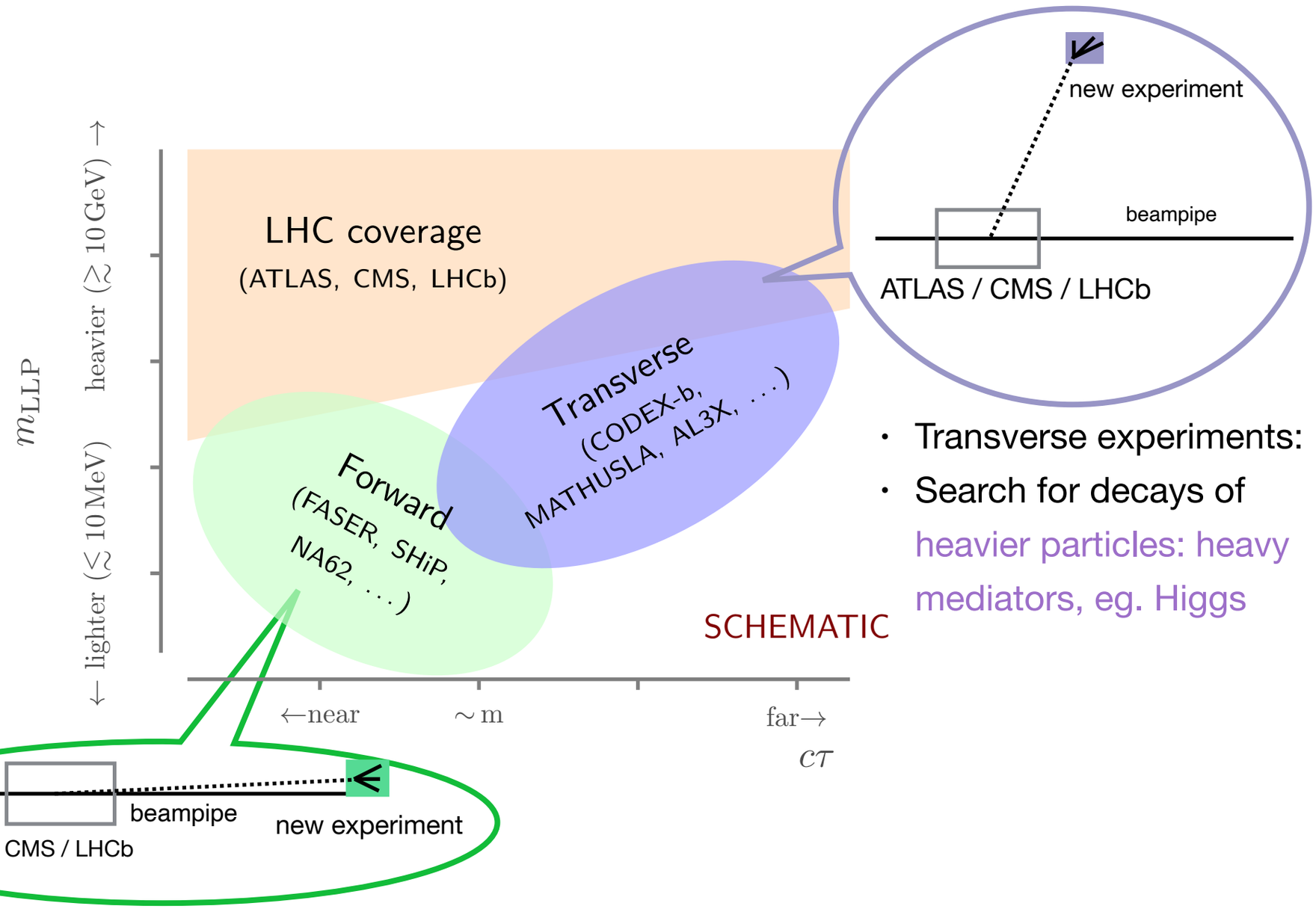


- Trigger constraints
- lots of SM background
- limited by size

- New LHC projects
- complementary to existing experiments
- aiming for zero background analysis (shielding)

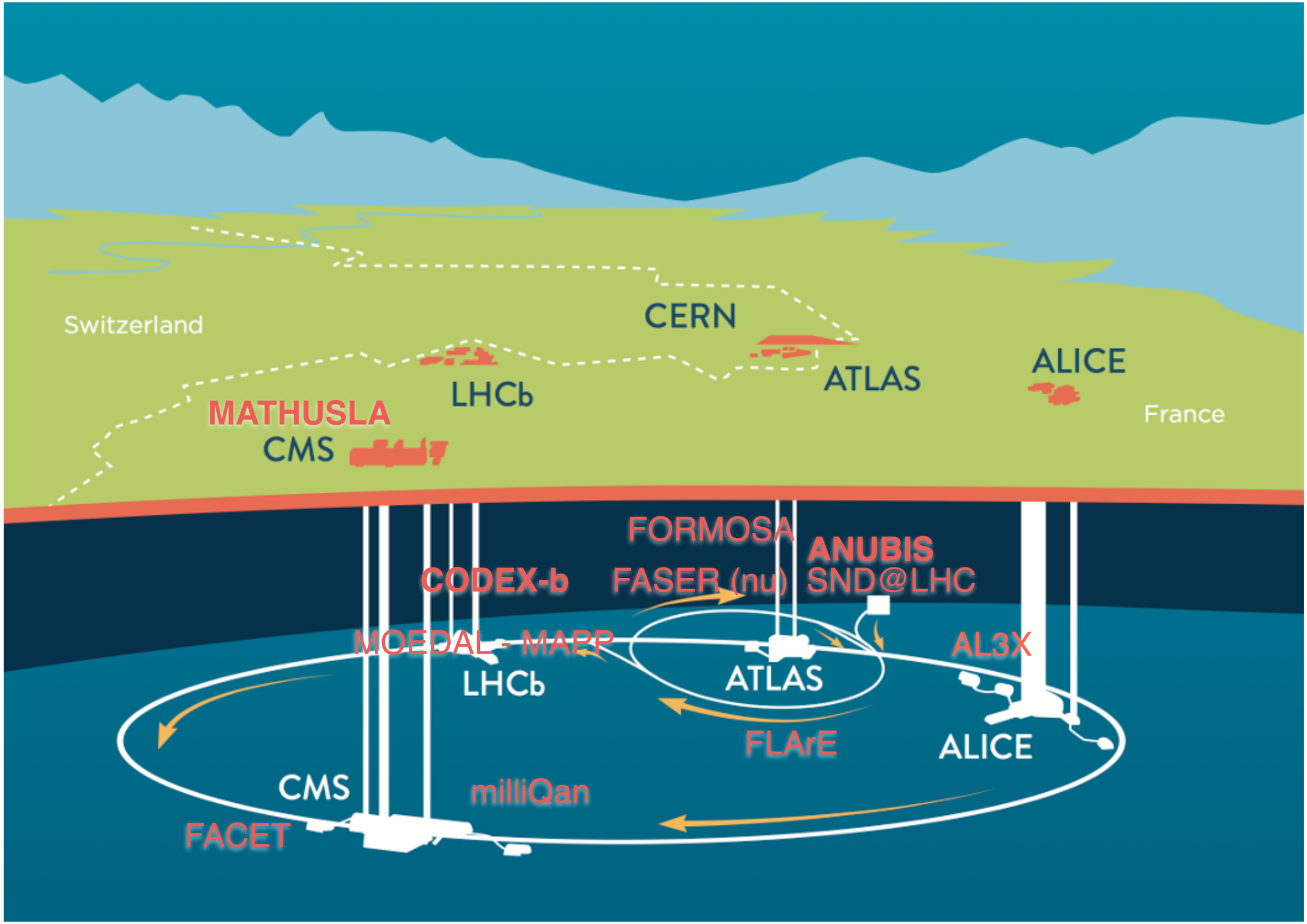
Emerging experiments and current proposals

- Forward experiments:
- Search for very weakly coupled to light particles: light mediators, ALPs



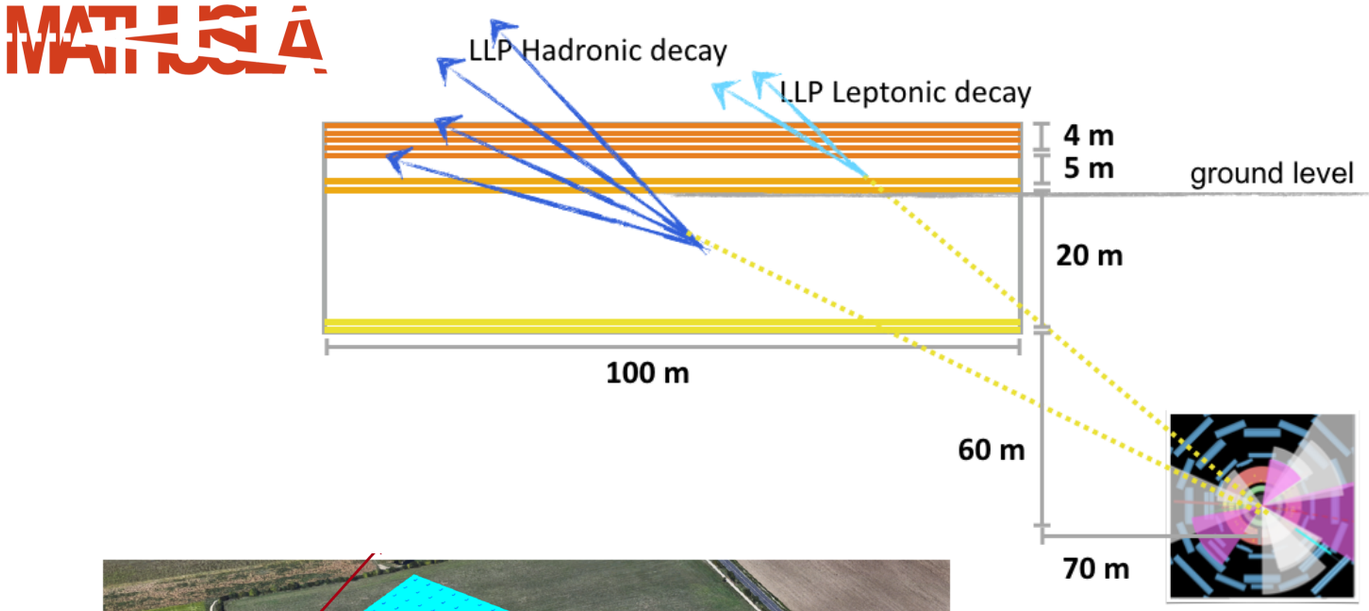
- Transverse experiments:
- Search for decays of heavier particles: heavy mediators, eg. Higgs

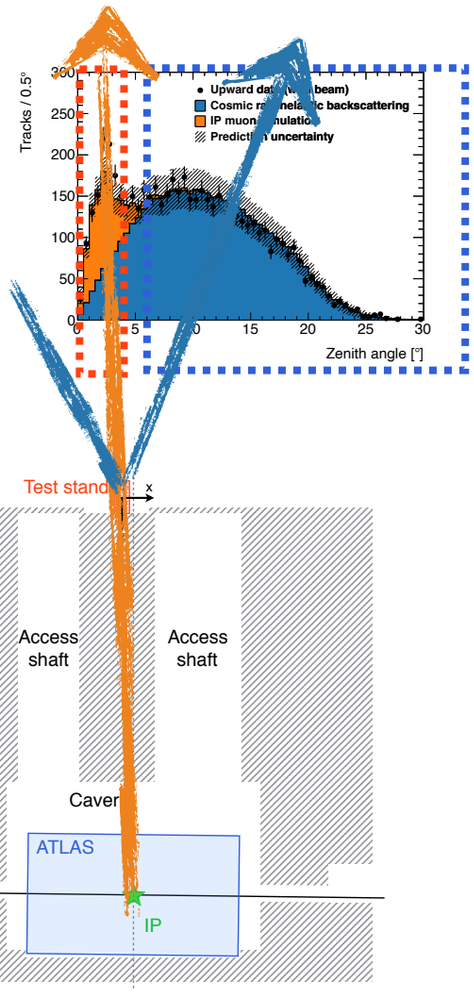
Emerging experiments and current proposals

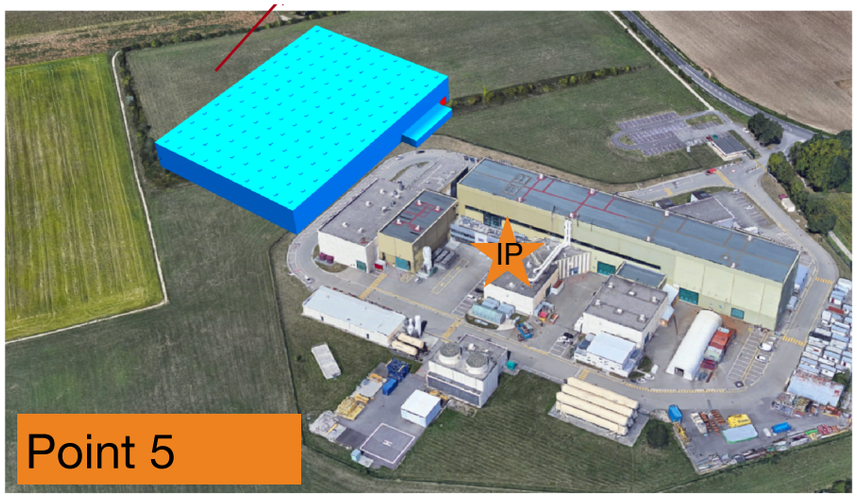


MATHUSLA (Massive Timing Hodoscope for Ultra Stable Neutral Particles)

- Purpose: Designed to detect LLPs with lifetime up to 10^8 m that could escape detection in the LHC's main detectors
- Location: Proposed to be constructed on the surface above the CMS detectors during HL-LHC: rock shielding
  - Aiming for zero background analysis
- Technology: Uses a large array of detectors to track particles over long distances and times
- Goals: Search for new particles predicted by theories beyond the SM, such as those associated with hidden sectors or dark matter







- Test stand with 2018 confirmed background hypothesis and gives confidence in projected physics reach

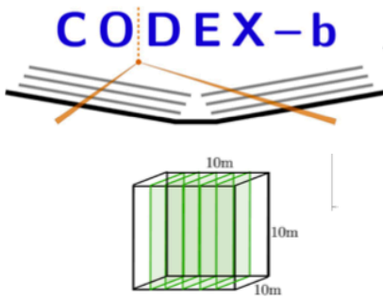
CODEX-b (Compact Detector for Exotics at LHCb)

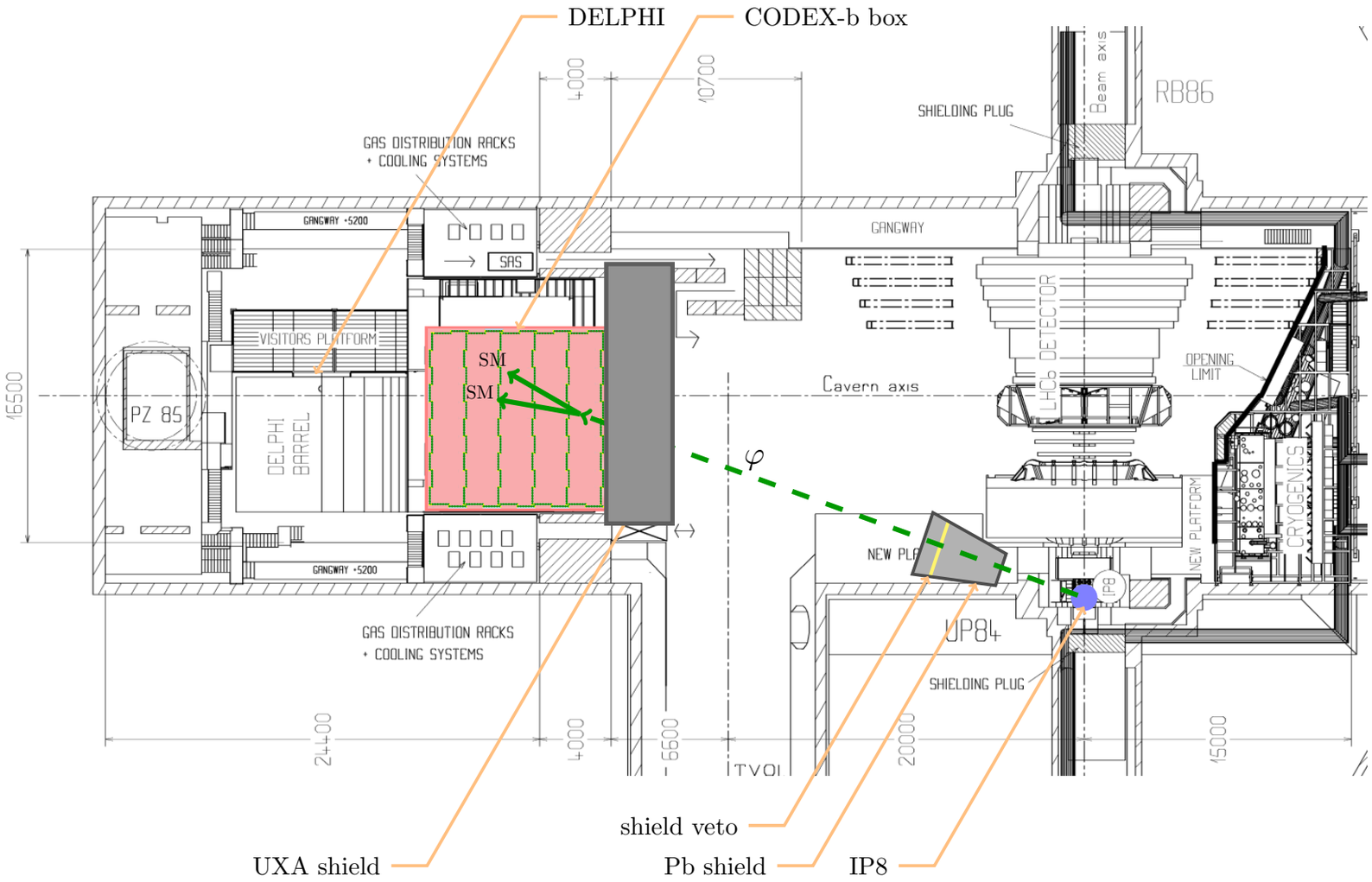
Purpose: Aims to detect low-mass, LLPs that might be missed by the LHCb detector

Location: Proposed to be located in the LHCb cavern at CERN

Technology: Utilizes precise tracking detectors to identify exotic particles and LLP decay vertex

Goals: Explore new physics scenarios including hidden valley models and other extensions of the SM

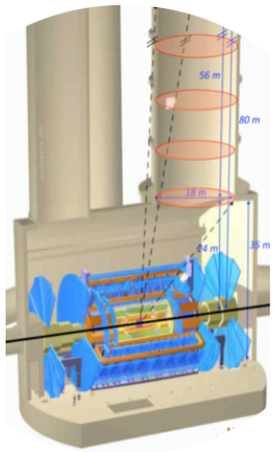




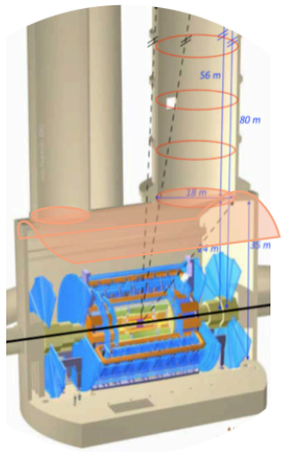
ANUBIS (An Underground Belayed In-Shaft)

- Purpose: Designed to detect LLPs with LLPs with decay lengths > 10 m and masses > 1 GeV that could escape detection in the LHC's main detectors
- Location: Proposed to be constructed in the ATLAS access shaft (56m) and/or part of the cavern for HL-LHC
- Technology: Uses a RPC chambers to track particles over long distances and times (to reject cosmic rays)
- Goals: Search for new particles predicted by theories beyond the SM, such as those associated with hidden sectors or dark matter

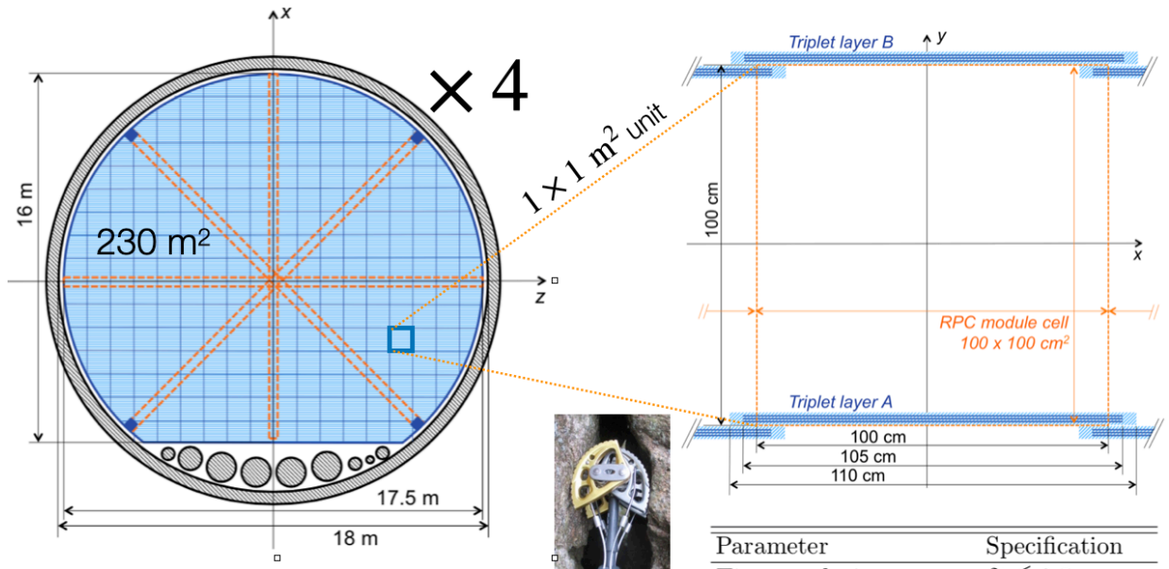
ANUBIS



Shaft configuration



Ceiling configuration

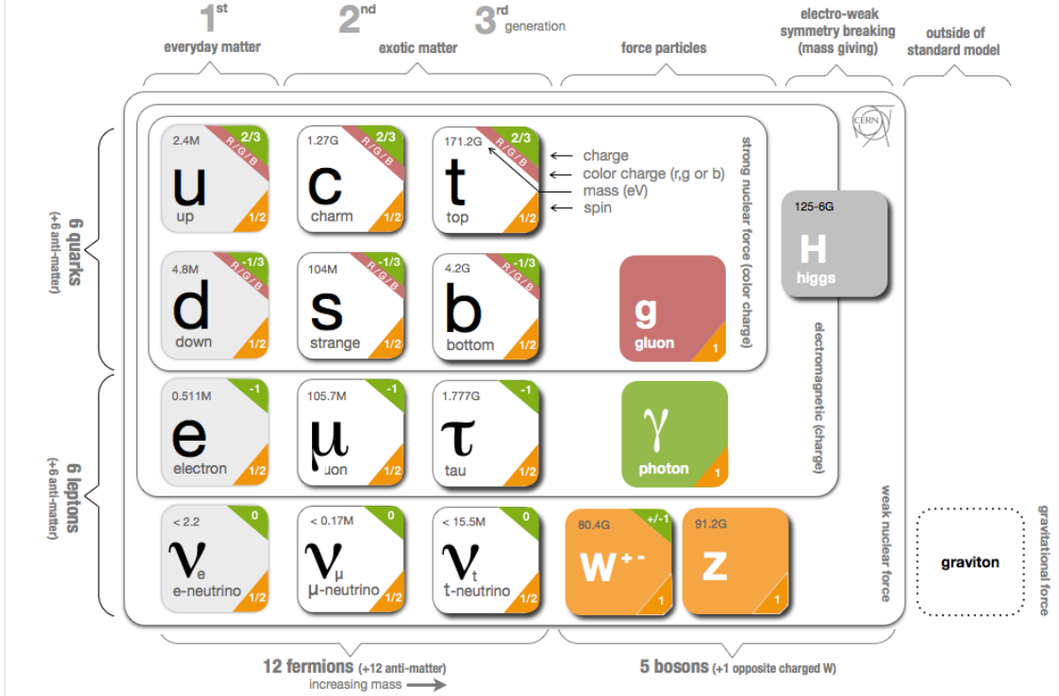


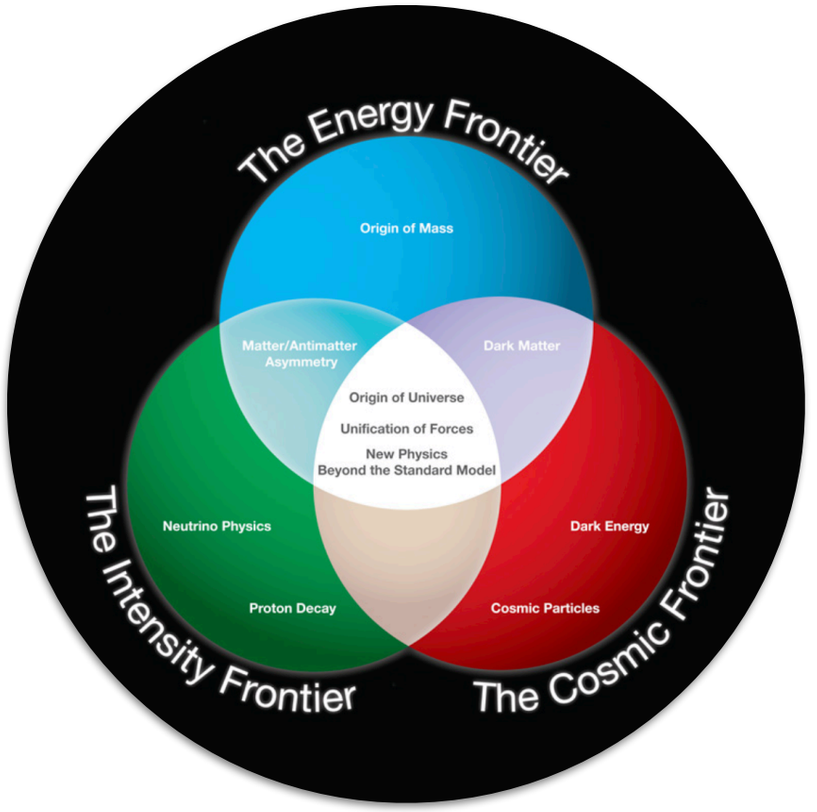
Tracking stations affixed with cams: extract tracking stations to surface quickly & easily in an emergency

Parameter	Specification
Time resolution	$\delta t \lesssim 0.5$ ns
Angular resolution	$\delta\alpha \lesssim 0.01$ rad
Spatial resolution	$\delta x, \delta z \lesssim 0.5$ cm
Per-layer hit efficiency	$\varepsilon \gtrsim 98\%$

Summary and conclusions

- High Energy Physics continues to probing the fundamental nature of the universe
- The Standard Model (SM) of Particle Physics is a well-established theoretical framework that describes the fundamental particles and their interactions but it has limitations which indicate that is not a complete theory
- Importance of the three Frontiers: Energy, intensity, cosmic frontiers provide complementary insights
- Ongoing and future experiments promise exciting discoveries



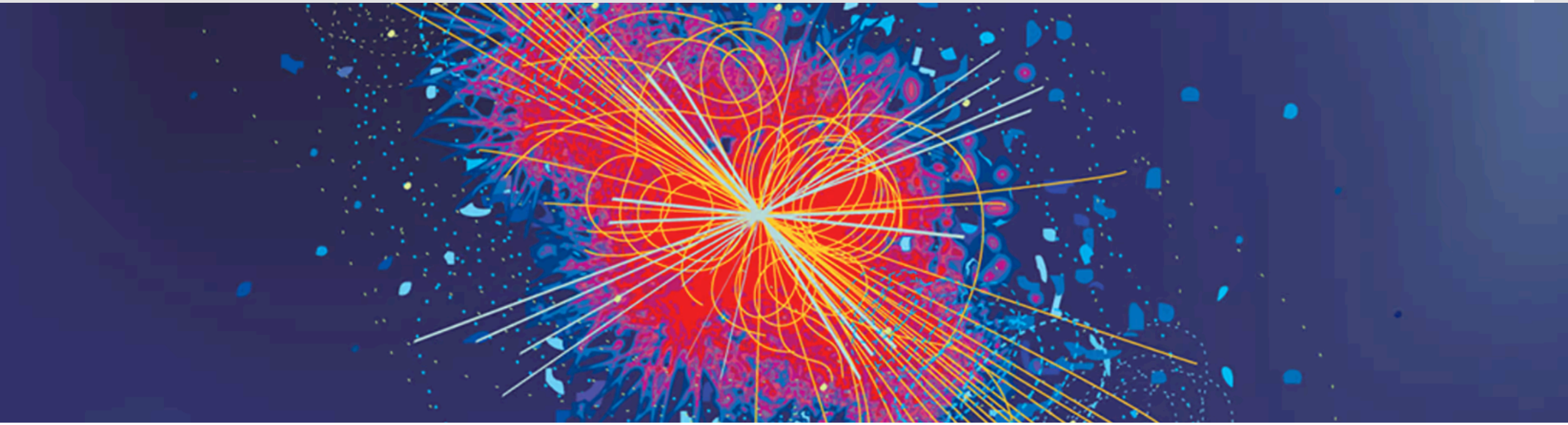


Summary and conclusions



BACKUP

Introduction to High Energy Physics



What is High Energy Physics?

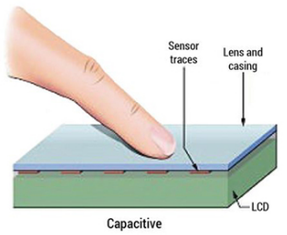
High Energy Physics (HEP) explores what the world is made of and how it works at the smallest and largest scales, seeking new discoveries from the tiniest particles to the outer reaches of space

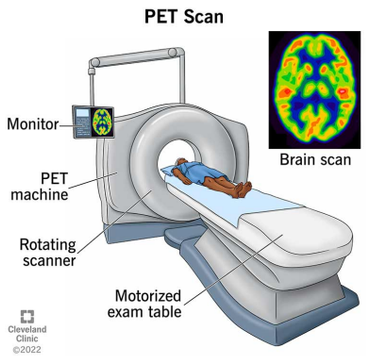
- Inspired by some of the biggest questions about our universe:
  - What is it made of? What forces govern it? How did become the way it is today?
- Aims to understand the fundamental particles and their interactions providing insight into the basic structure of the universe and its origins

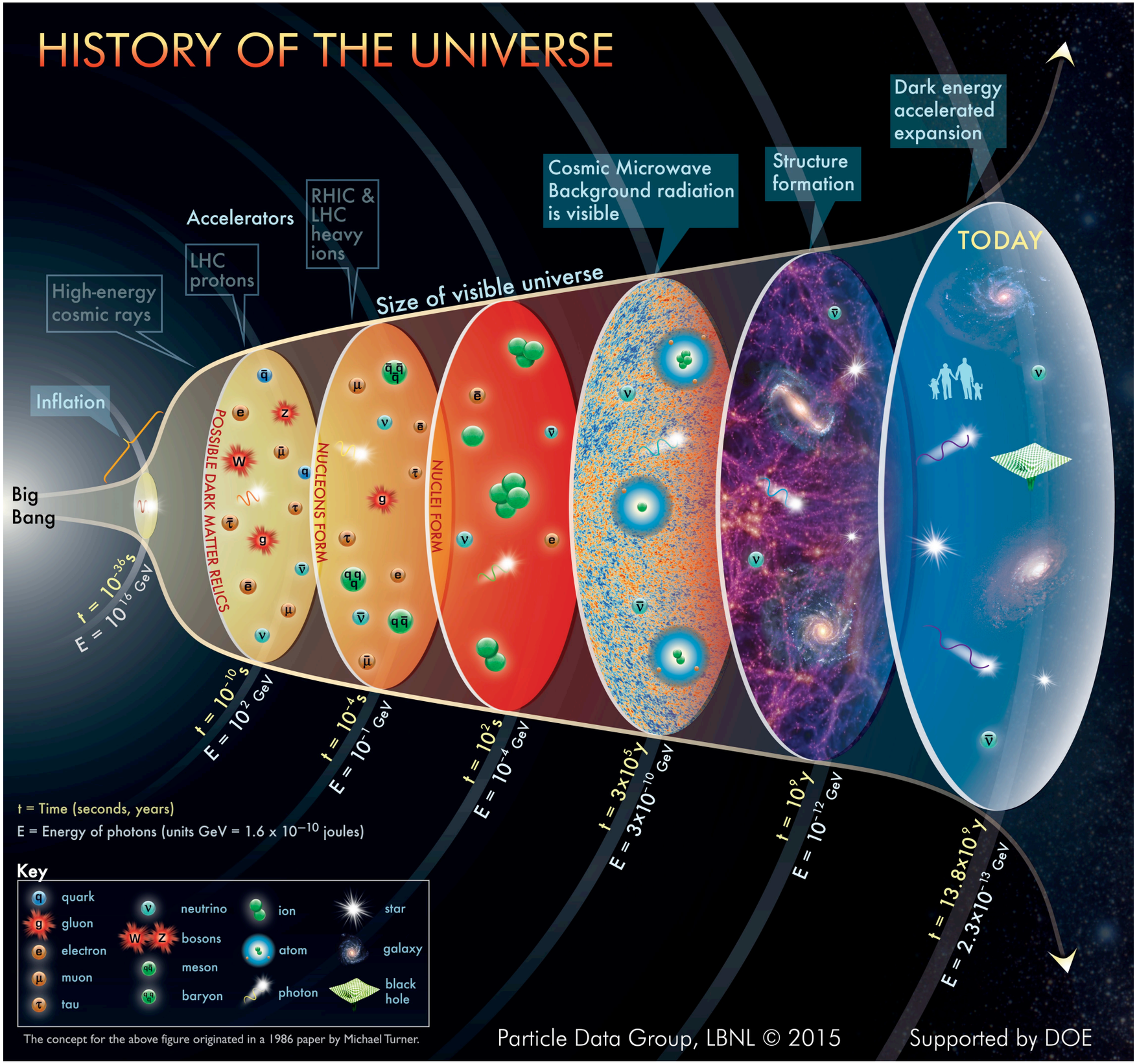
Connected to real-world applications

Innovative and disruptive technological advancements in HEP have led to innovations such as the world wide web (www), capacitive touch screens, medical imaging techniques like PET scans, and advancements in superconducting technologies





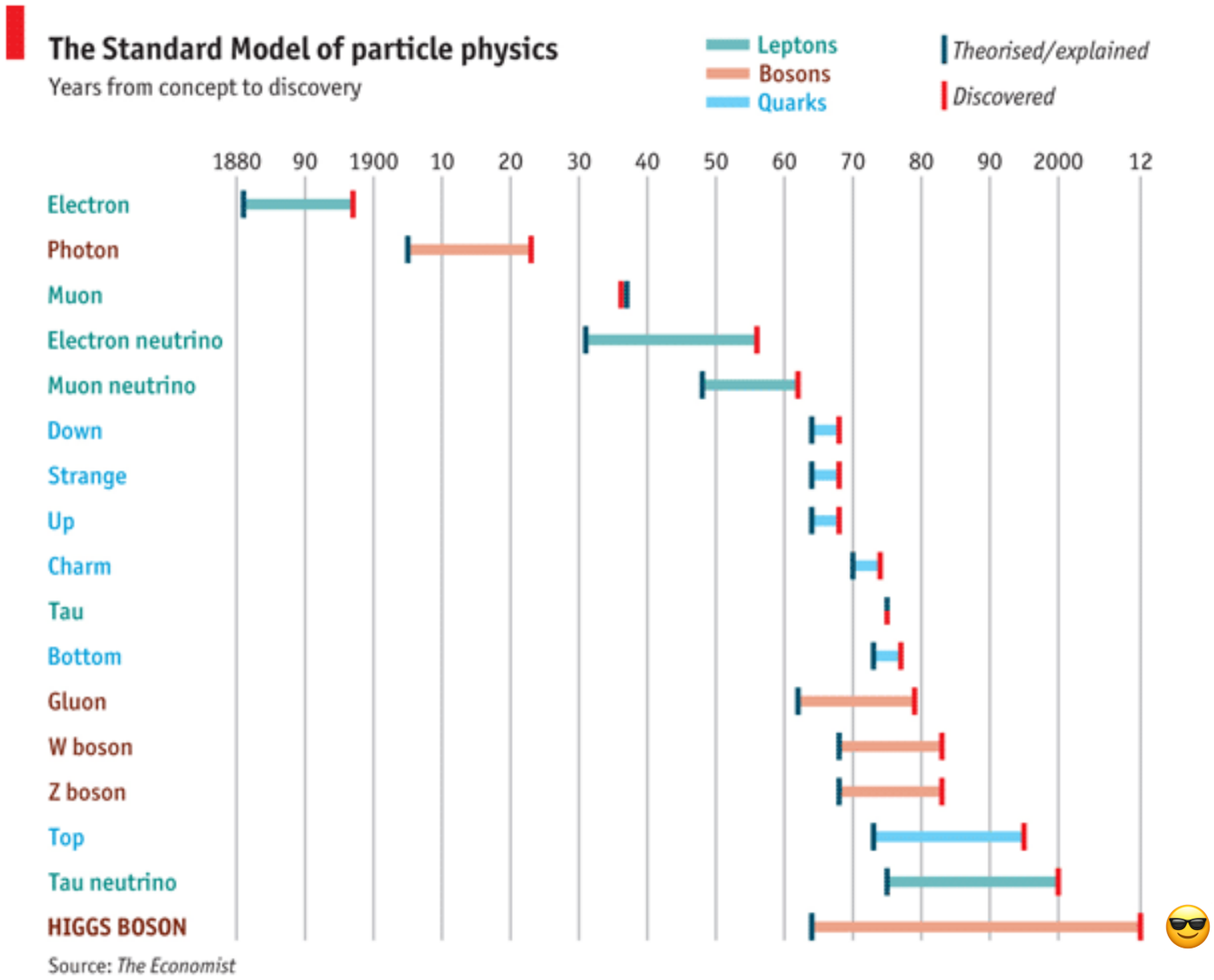



HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^-10 joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE

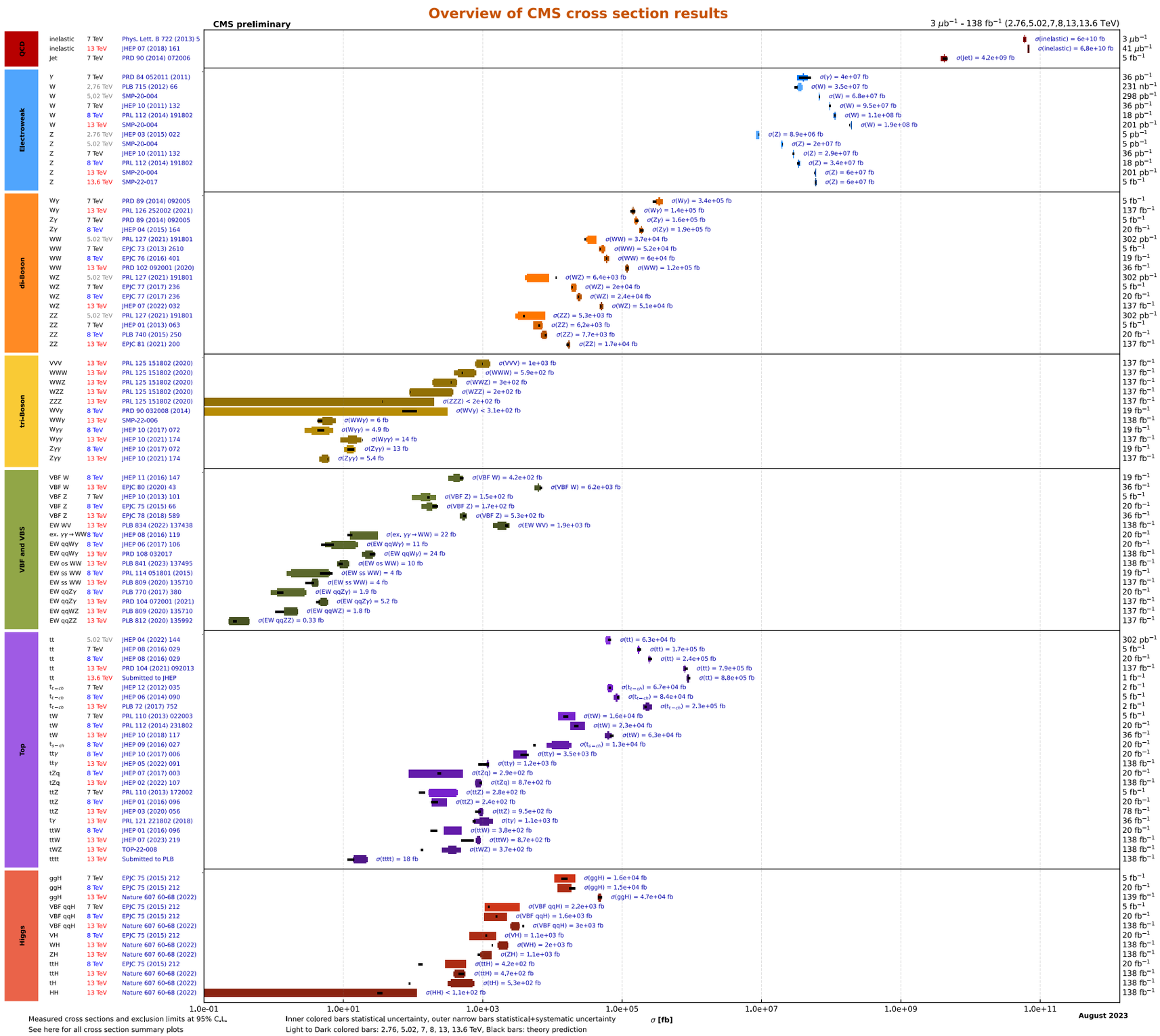
Which comes first: theory or experiment?

The Standard Model (SM) of Particle Physics is a well-established theoretical framework that describes the fundamental particles and their interactions and allow to predict them

- Particles were (almost always) predicted by theory
- Some of the experimental discoveries took a while (limited by technology)



Measurements at the LHC

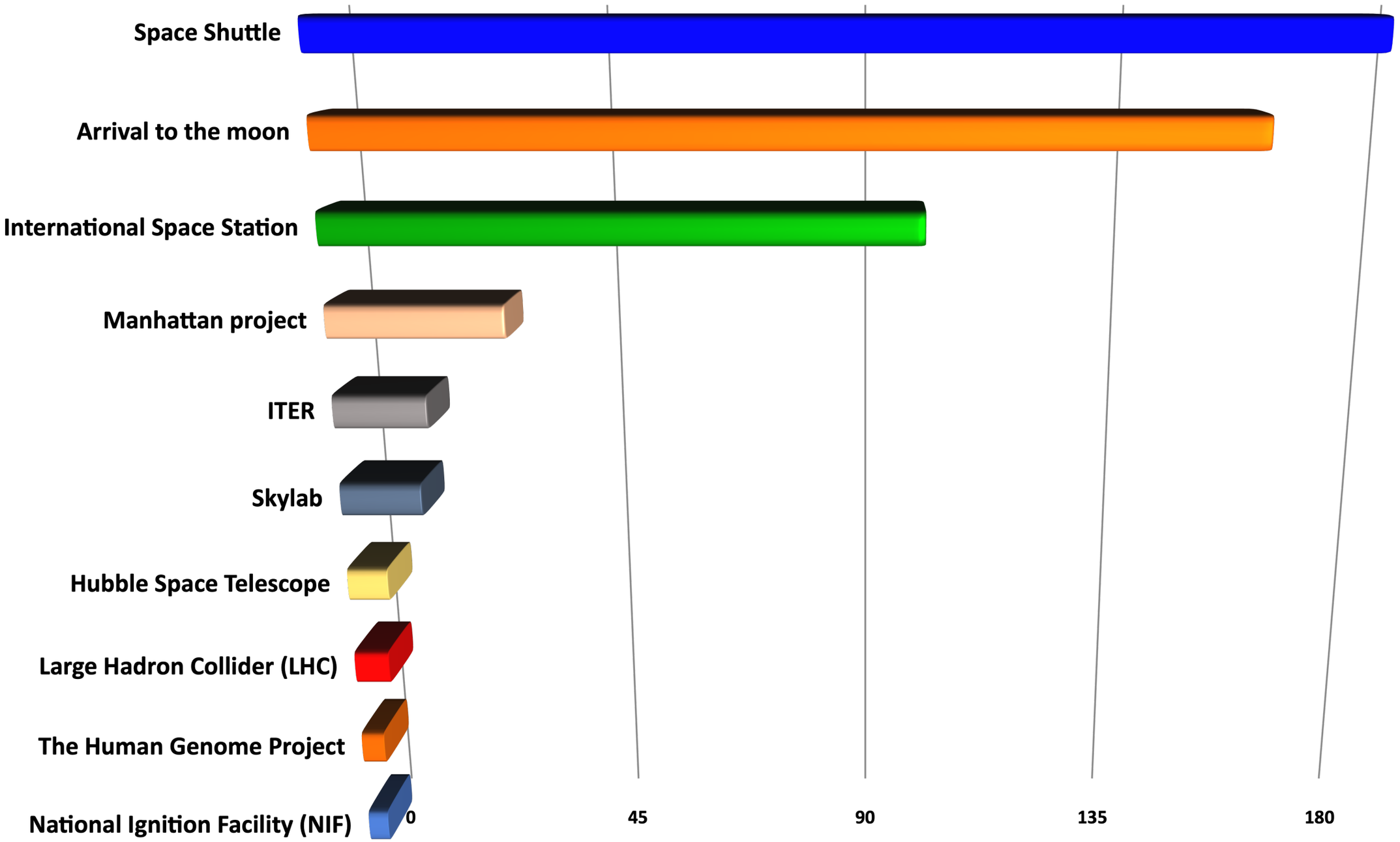


Measurements agree with SM predictions with remarkable precision!!!

	Collision point	Distance from IP	Fiducial volume	Use main experiment?	Shielding cosmics	Shielding collision	Technology
MATHUSLA	CMS	~90 m	25m x 100m x 100m	Under study	NO	YES	Scintillators (+ 1 RPC)
ANUBIS	ATLAS	~25 m	~56m x $(9m)^2$	YES	Partial	NO	RPC (scintillators
CODEX-b	LHCb	~35 m	10m x 10m x 10m	Under study	YES	YES	RPC
AL3X	ALICE	~4.25 m	~12m x $(2.5m)^2$	NO	YES	YES	Gas TPC

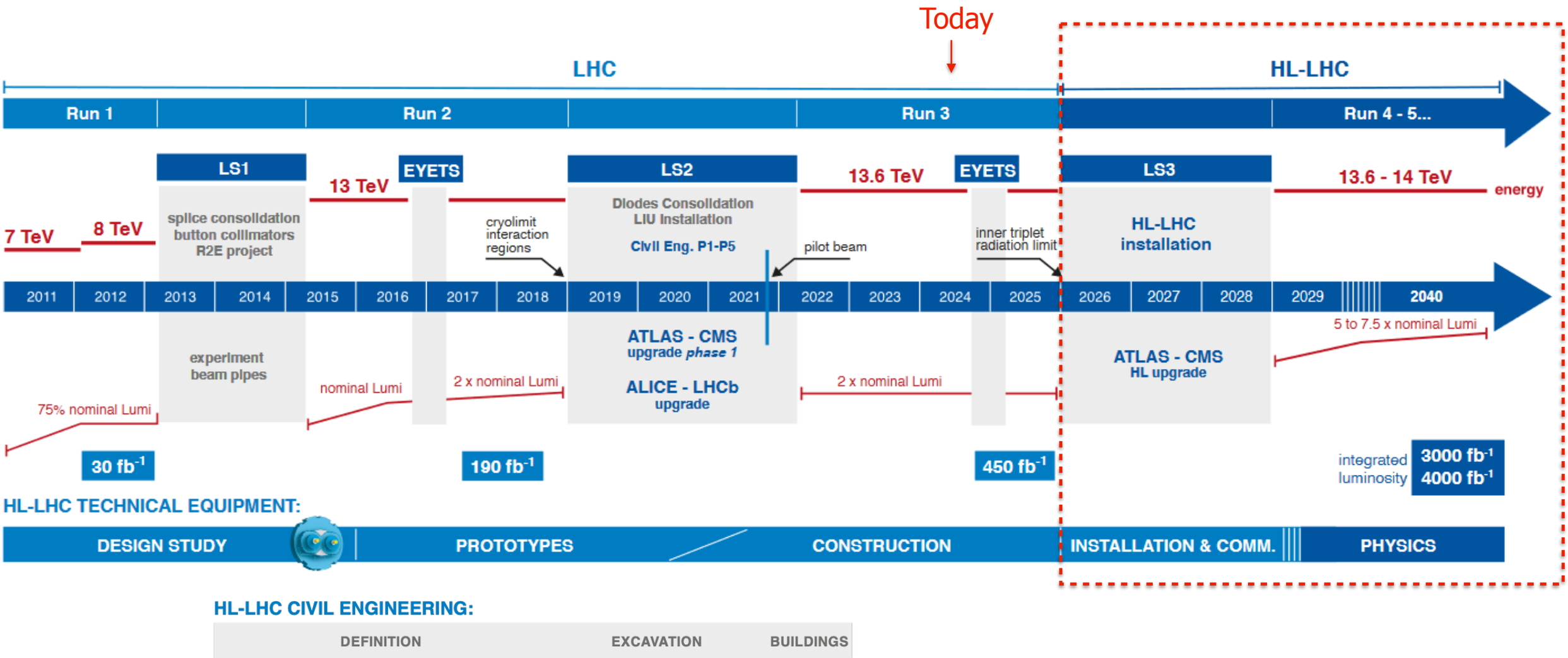
- For a given decay volume,
- More solid angle if closer to the IP
- Number of decays higher if closer to the IP
- LHC collision backgrounds more important if closer to the IP (depending on shielding)

Cost of the latest projects



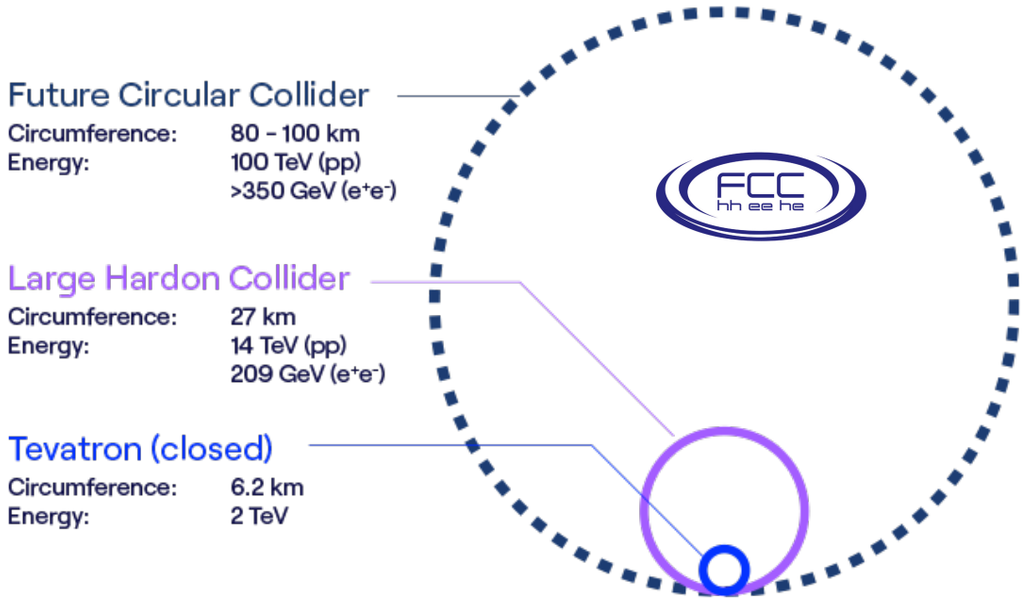
LHC and HL-LHC schedule

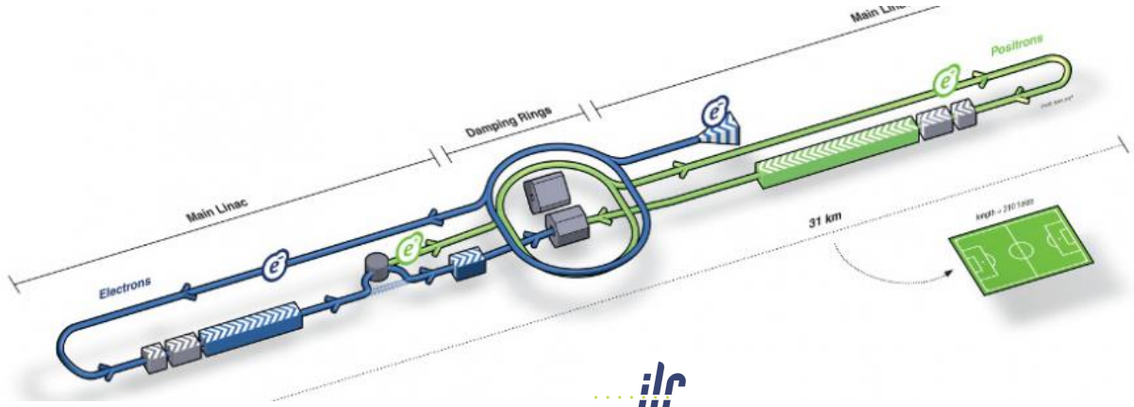
- HL-LHC **installation phase** currently scheduled to start in **2026**
- HL-LHC **physics phase** currently scheduled to start in **2029**



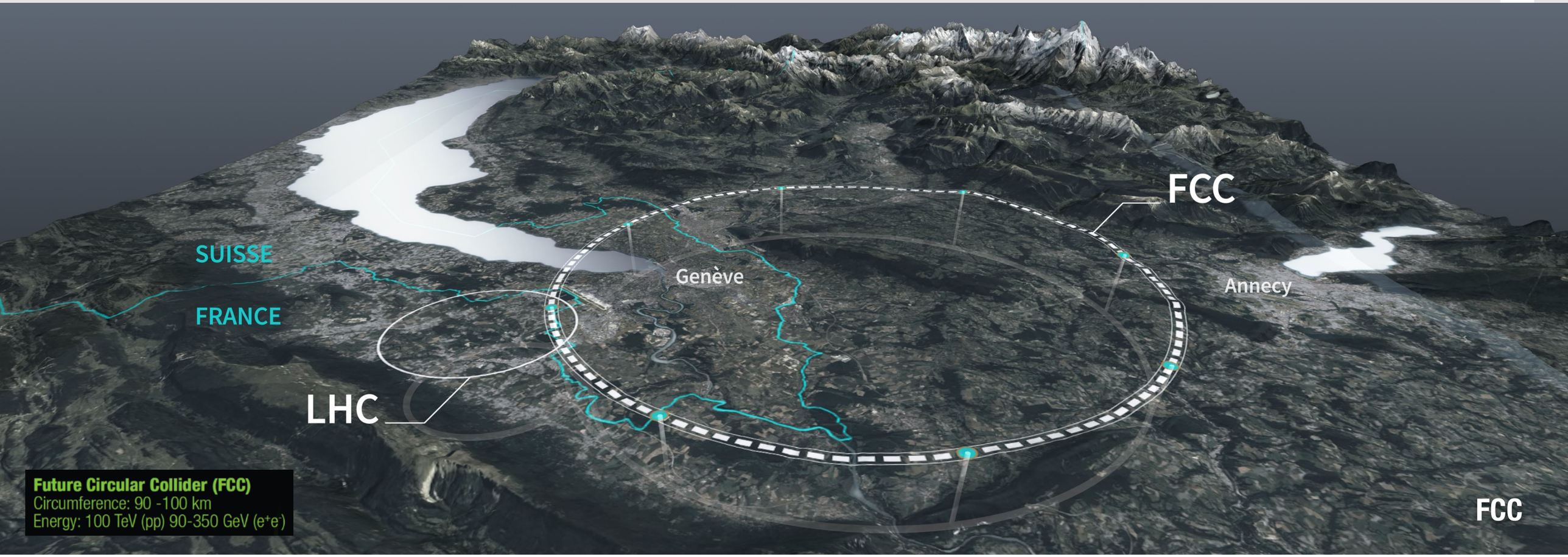
Circular or lineal colliders?

- Both accelerators can do excellent (Higgs) physics and they can reach the threshold to produced $t\bar{t}$
- Circular colliders can reach larger luminosities at the Large Electron-Positron (LEP) energies (~100 GeV)
- Future updates of linear colliders would access di-Higgs, $t\bar{t}H$, and “energy-growth” in new physics





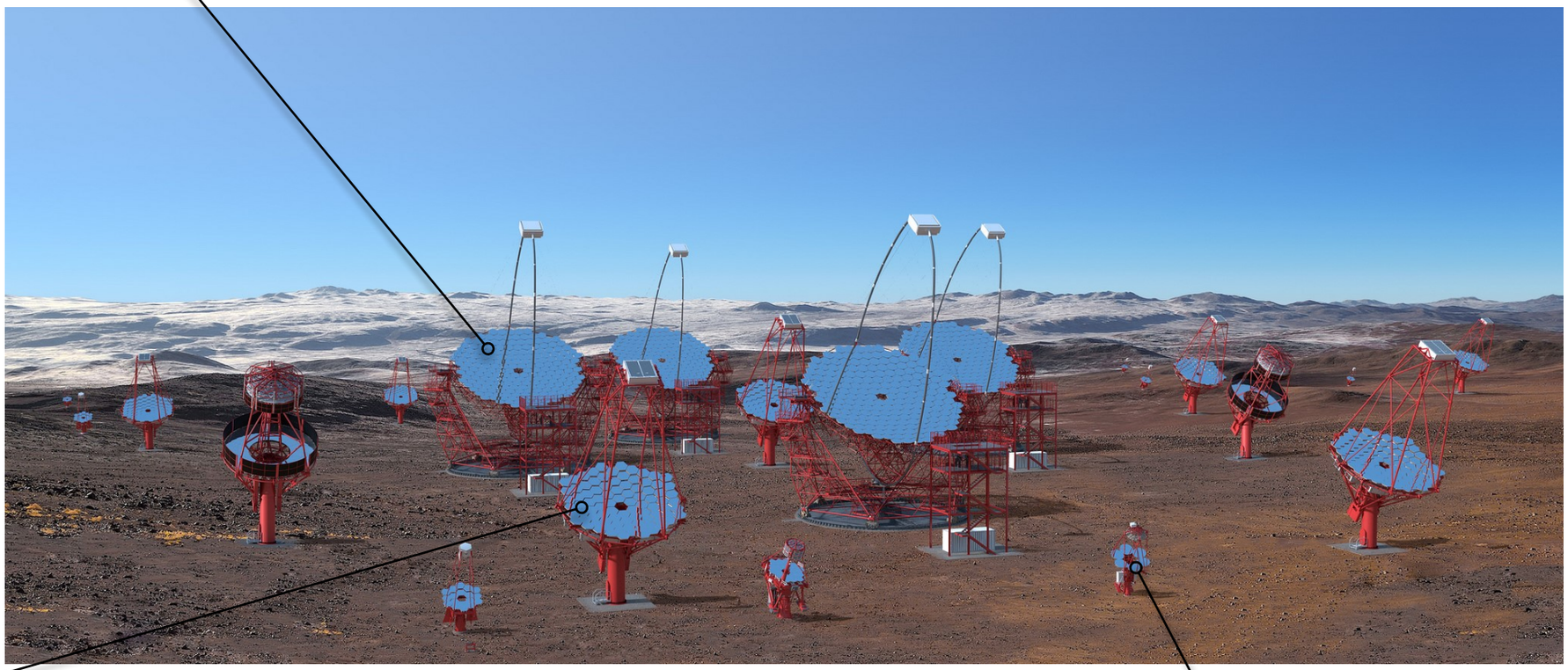
Current Challenges and future directions: FCC



Future Circular Collider (FCC): 100 km tunnel in Geneva

- FCC-ee:
  - $\sqrt{s} = 90 - 350$ GeV
  - Potencial: improve from 20 up to 50 times SM measurements, Higgs width, DM as invisible decays of H, BSM through loops
  - Possibility to explore energy scales of ~10 TeV
- FCC-hh:
  - $\sqrt{s} = 100$ TeV → 16 T magnets needed
  - Potencial: Heavy resonances up to m ≈ 40TeV, stops up to m ≈ 10TeV, Higgs self-coupling, rare decays, EWK, top-quark physics in extreme regimes

The 8 large-sized telescopes, with a mirror diameter of 23 m and a camera built of photomultiplier tubes, are optimized for the measurement of the low energy gamma rays



The core energy will be measured by the 40 medium-sized telescopes which consist of a mirror with diameter of 12 m and a field of view of 7-8 degrees. The camera will also consist of PMTs

The array will be complemented with 70 small-sized telescopes, with a field of view of about 9 degrees and a 4 m diameter mirror, which are sensitive to the highest energy gamma rays. These ones will be spread out over several square km in the southern hemisphere array