



HEP





What are the big fundamental physics questions in high-energy physics?



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ChatGPT

In the field of high-energy physics, which focuses on the study of fundamental particles and their interactions at extremely high energies, there are several key questions that scientists are actively investigating. Here are some of the major fundamental physics questions in high-energy physics:

1. What is the nature of the Higgs boson? The discovery of the Higgs boson at the Large Hadron Collider (LHC) in 2012 was a significant achievement. However, further studies are needed to precisely determine the properties and behavior of this particle. Understanding the Higgs boson and its role in the mechanism of mass generation is crucial for validating the Standard Model of particle physics and exploring physics beyond it.
2. Are there undiscovered particles or forces beyond the Standard Model? While the Standard Model successfully describes the known particles and three fundamental forces (electromagnetism, weak nuclear force, and strong nuclear force), it is believed to be an incomplete theory. High-energy experiments aim to discover new particles, such as supersymmetric particles or candidates for dark matter, and explore potential new forces that might exist beyond the current understanding.
3. What is the nature of neutrinos? Neutrinos are elusive particles with extremely weak interactions. They were long thought to be massless, but experiments have now confirmed that they have tiny but nonzero masses. Understanding the origin of neutrino masses, their mixing properties, and their role in particle physics and cosmology are active areas of research.
4. What is the mechanism behind the generation of matter-antimatter asymmetry? The universe appears to be predominantly composed of matter, with very little antimatter. However, the Standard Model does not explain why this imbalance exists. Investigating processes that violate the conservation of baryon number (the quantity of matter minus antimatter) and understanding the mechanism responsible for the observed matter-antimatter asymmetry is an important question in high-energy physics.
5. Can the fundamental forces be unified? The Standard Model treats the electromagnetic, weak nuclear, and strong nuclear forces as separate entities. However, unifying these forces into a single framework, such as through grand unified theories or string theory, is an ongoing pursuit. Experimental evidence and theoretical developments that point toward a unified description of the forces would have profound implications for our understanding of the fundamental nature of the universe.

These are just a few examples of the big fundamental physics questions in high-energy physics. The field is dynamic and continually evolving, with new experiments, theoretical developments, and discoveries shaping our understanding of the fundamental particles and forces that govern the universe at the smallest scales.

Standard Model of Elementary Particles

		three generations of matter (fermions)			interactions / force carriers (bosons)	
		I	II	III		
mass		$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
charge		$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin		$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
		u up	c charm	t top	g gluon	H higgs
	QUARKS	$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
		$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	
		$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
		d down	s strange	b bottom	γ photon	
		$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$	
		-1	-1	-1	0	
		$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
		e electron	μ muon	τ tau	Z Z boson	
	LEPTONS	$< 1.0 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.360 \text{ GeV}/c^2$	
		0	0	0	± 1	
		$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
		ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
						GAUGE BOSONS VECTOR BOSONS
						SCALAR BOSONS

Standard Model of Elementary Particles

		three generations of matter (elementary fermions)			three generations of antimatter (elementary antifermions)			interactions / force carriers (elementary bosons)	
		I	II	III	I	II	III		
QUARKS	mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
	charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	$-\frac{2}{3}$	$-\frac{2}{3}$	$-\frac{2}{3}$	0	0
	spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
		u up	c charm	t top	\bar{u} antiup	\bar{c} anticharm	\bar{t} antitop	g gluon	H higgs
		d down	s strange	b bottom	\bar{d} antidown	\bar{s} antistrange	\bar{b} antibottom	γ photon	
		e electron	μ muon	τ tau	e^+ positron	$\bar{\mu}$ antimuon	$\bar{\tau}$ antitau	Z Z ⁰ boson	
LEPTONS		$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$
		0	0	0	0	0	0	1	-1
		ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	$\bar{\nu}_e$ electron antineutrino	$\bar{\nu}_\mu$ muon antineutrino	$\bar{\nu}_\tau$ tau antineutrino	W⁺ W ⁺ boson	W⁻ W ⁻ boson

GAUGE BOSONS
VECTOR BOSONS

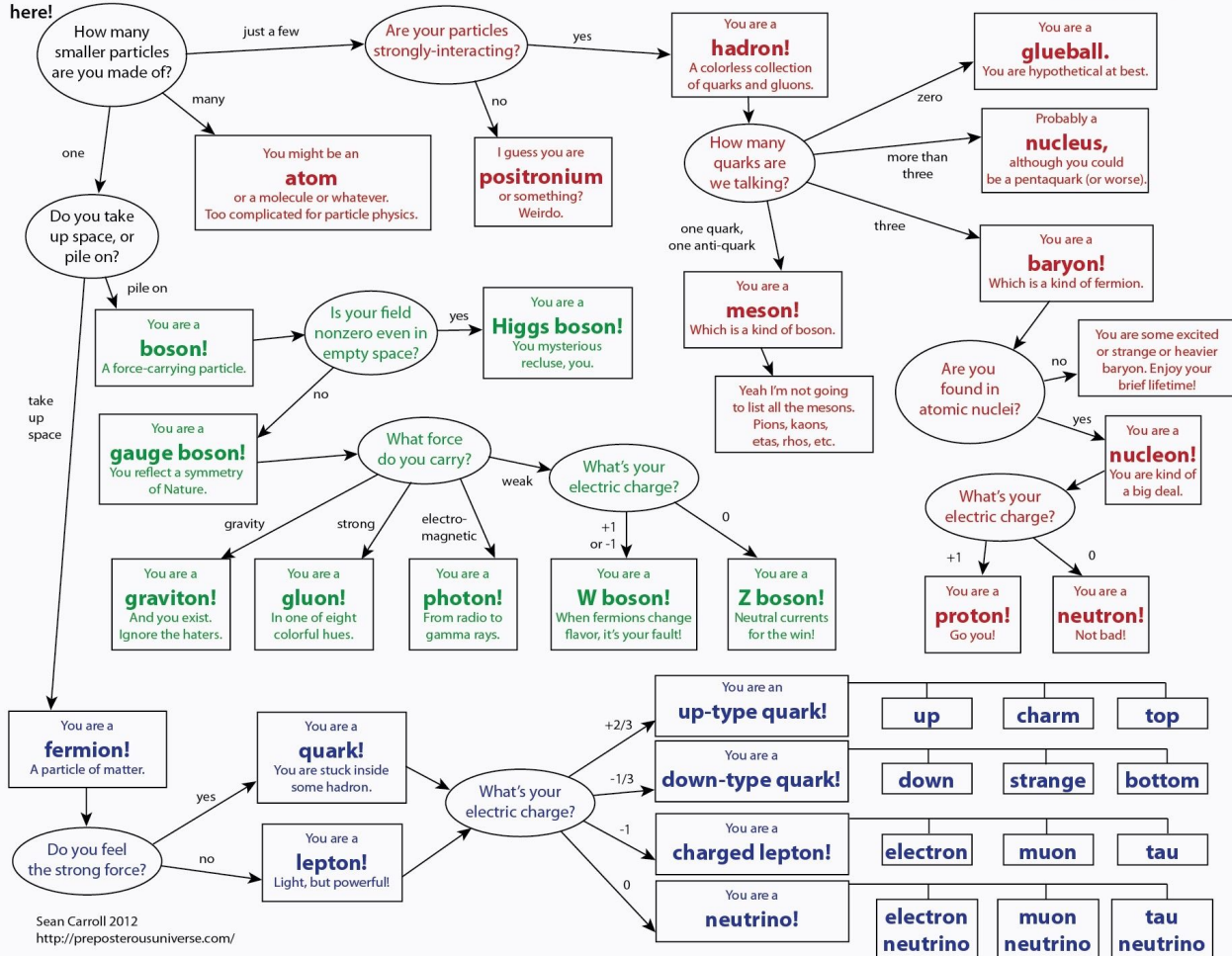
SCALAR BOSONS

What Particle Are You?

Color code:
 elementary fermions
 elementary bosons
 composite particles

(Standard Model particles only! Dark matter and other exotica not welcome.)

Start here!





High-energy physics:

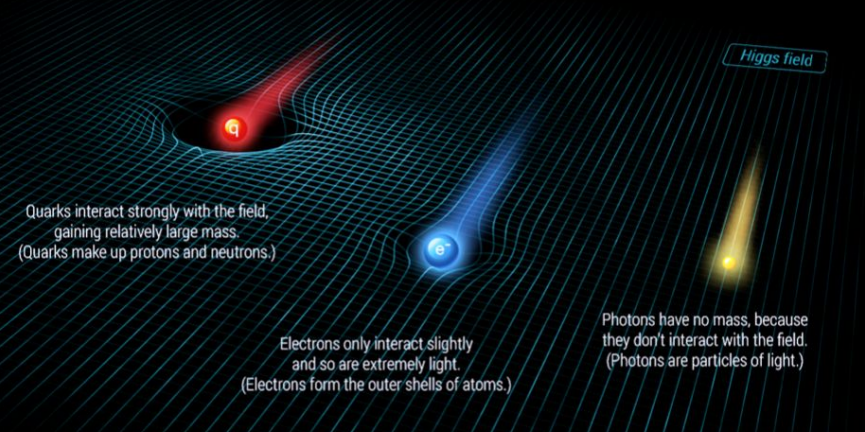
- a. The Report of DOE's Office of Science **Basic Research Needs** (BRN) for HEP Detector R&D that was published in 2019: <https://www.osti.gov/servlets/purl/1659761>; and
- b. The **European Committee for Future Accelerators** (ECFA) 2021 Detector R&D (DRD) Roadmap: <https://cds.cern.ch/record/2784893>.
- c. The 2021 **Snowmass** Study reports:
 - Energy Frontier: <https://arxiv.org/abs/2211.11084>
 - Instrumentation Frontier: <https://arxiv.org/abs/2209.14111>
 - Software & Computing: <https://arxiv.org/abs/2210.05822>

Higgs and the Energy Frontier

The Energy Frontier of Particle Physics encompasses the construction and operation of high energy particle colliders and particle detectors in order to study the fundamental laws of nature at the smallest distances and highest energies. Energy Frontier research has two primary goals: First, high energy colliders are the only tools scientists have to produce and directly study previously unknown particles and phenomena. Second, high energy colliders allow scientists to make precise measurements of the behavior of the known particles and phenomena; by observing small deviations between these precise measurements and

The Higgs Field

Existing everywhere, the Higgs field gives particles their mass.



Quarks interact strongly with the field,
gaining relatively large mass.
(Quarks make up protons and neutrons.)

Electrons only interact slightly
and so are extremely light.
(Electrons form the outer shells of atoms.)

Photons have no mass, because
they don't interact with the field.
(Photons are particles of light.)

Higgs field

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Neutrinos

Neutrinos are some of the most intriguing of the fundamental particles: although not exactly massless, they are anomalously light, and interact with matter only via the weak interaction gravity. These abundant particles pervade the universe over a huge range of energies. We are bathed in a relic neutrino glow from the Big Bang. Neutrinos emanate from astrophysical sources – stars (including our Sun), core-collapse supernovae, cosmic ray collisions, active cores of galaxies – as well as from radioactive nuclei in the Earth and nuclear reactors. We can also create neutrinos in accelerators, as focused beams or isotropic sources. Experiments over the past two decades using both natural and artificial neutrinos (see Figure 1) have elucidated some of the neutrinos' surprising properties, but many mysteries remain.



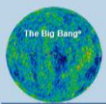
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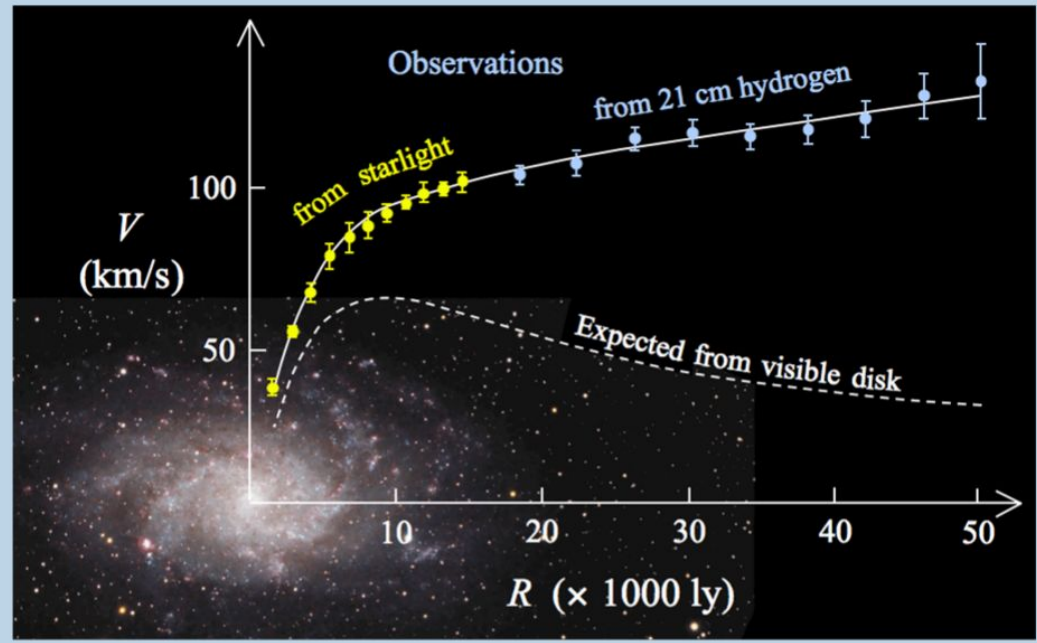


meV eV

Quarks interact strongly with each other, gaining relatively large amounts of energy. (Quarks make up protons and neutrons.)

Dark Matter

The composition of dark matter is one of the most mysterious puzzles in particle physics and astrophysics. These ghost-like particles make up approximately 85% of the matter in the universe, but only rarely interact with ordinary matter. As such, dark matter particles surround us and pass through our bodies essentially unimpeded. Scientists became aware of dark matter over 80 years ago by studying its gravitational effects on galaxies, and the evidence is now overwhelming that dark matter is a new kind of matter.

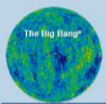


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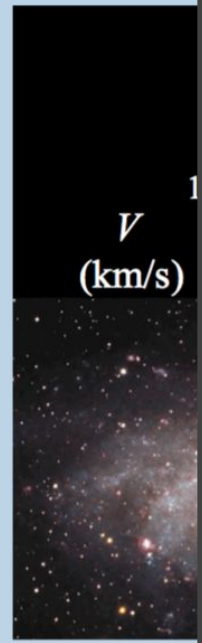


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Cosmic Acceleration: Dark Energy and Inflation

Cosmological surveys measure how the entire universe grows over time (see Figure I), and uniquely explore the fundamental physics underlying two eras of cosmic acceleration: an early acceleration epoch explained by the physics of inflation, and a period of late cosmic acceleration driven by Dark Energy. Neither are explained by our current standard model of particles and interactions, and cosmological surveys are the only measurements that can study them.

Over the past three decades, research into late (dark energy) and early (inflation) cosmic acceleration used a series of increasingly complex and sensitive cosmological surveys. The current generation of experiments are DESI and LSST, which study dark energy, and CMB-S4, which studies inflation. The combination of these three surveys will anchor our understanding of the universe at both early and late times, but still only provides access to a tiny fraction of the available Universe. The next generation of cosmic survey facilities aim to fully survey the evolution of the universe as it grows from these early instants into what we observe today. These new facilities include: a facility for an optical/infrared spectroscopic galaxy survey, and facilities for line intensity mapping surveys (LIM), one focused on the 21-cm line and one at mm-wavelengths.

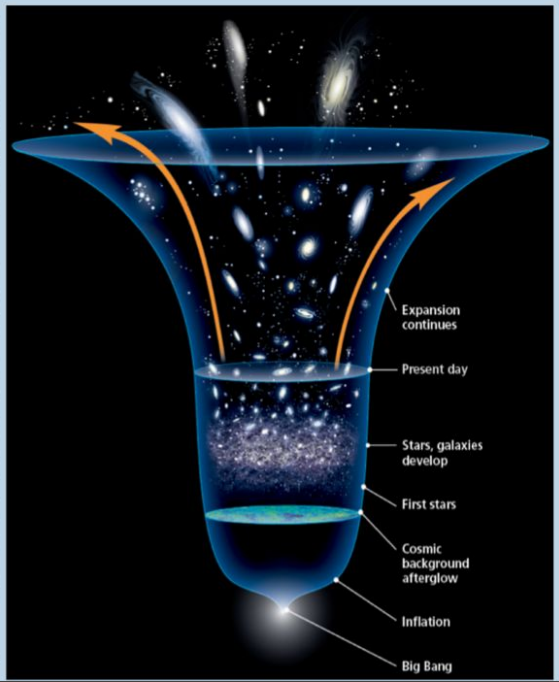


Figure II shows the sensitivity of each type of

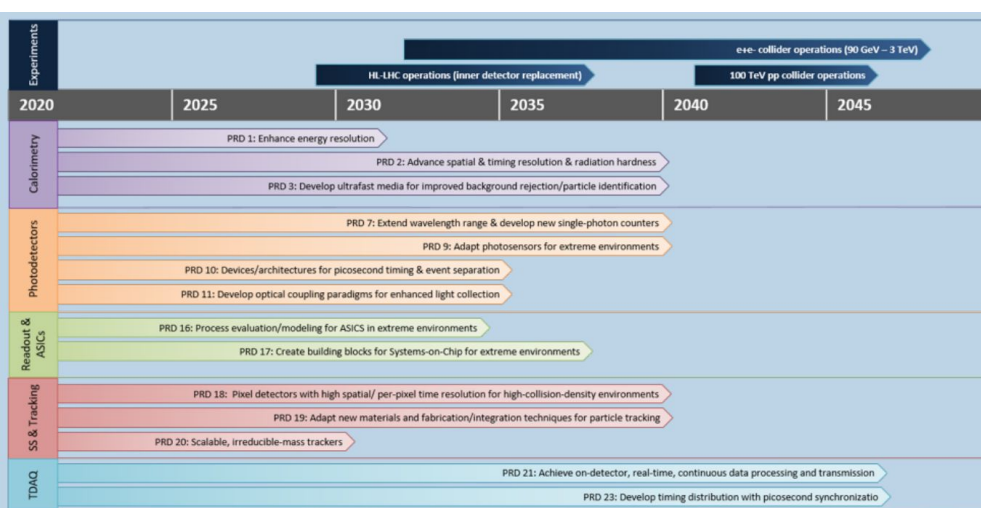
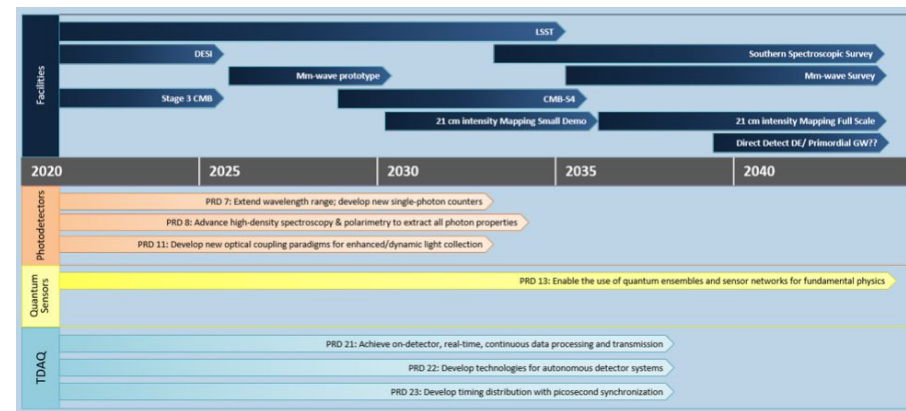
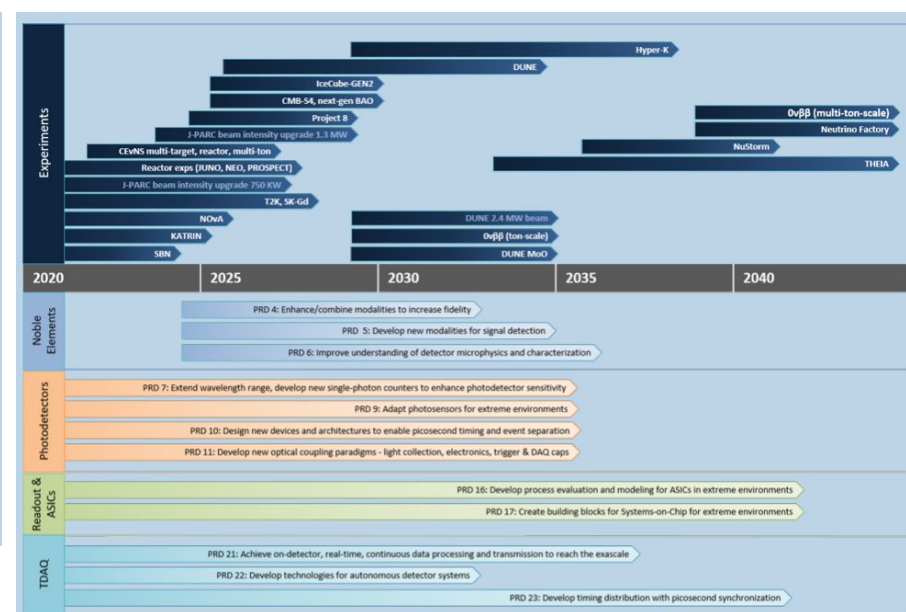
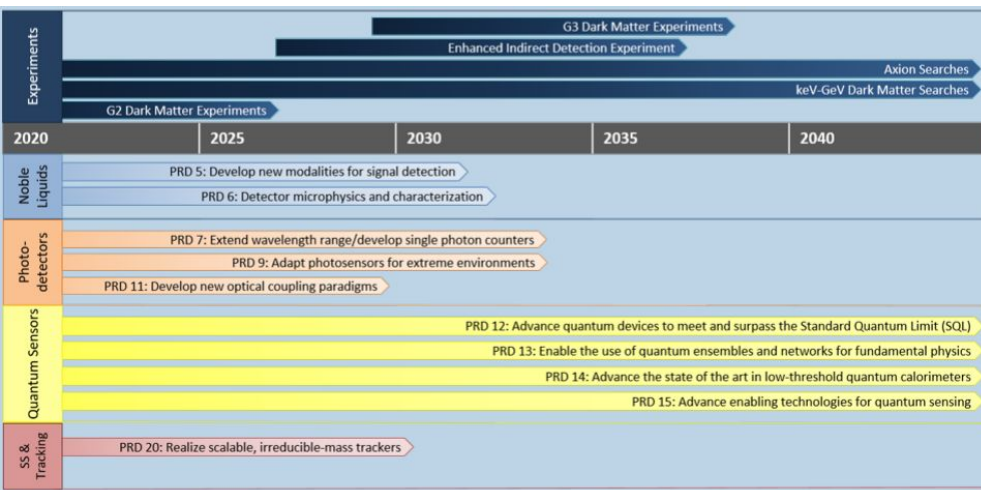
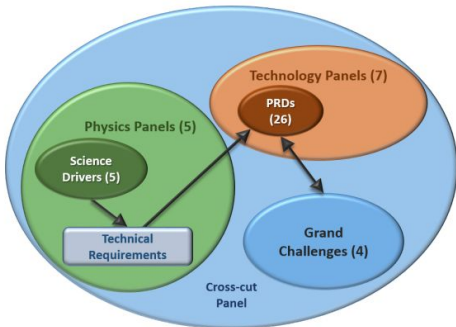


Figure IV: Higgs and Energy Frontier Timeline



In this report we summarize the need for new technologies in terms of four Grand Challenges. The technologies envisioned to address them are described in the body of the report. The Grand Challenges are:

1. **Advancing HEP detectors to new regimes of sensitivity**
2. **Using integration to enable scalability for HEP sensors**
3. **Building next-generation HEP detectors with novel materials and advanced techniques**
4. **Mastering extreme environments and data rates in HEP experiments**



Thrust 6: Develop analog and multiplexing blocks for 4 K environments and below

A wide range of QIS systems and high sensitivity detectors operate at cryogenic temperatures, ranging from a few milli-Kelvin to LHe (4 K) temperatures. Some of the components of these systems need to be superconducting, but others can be resistive. In most existing systems, the resistive component control is often performed by warm electronics through interconnect cables. In many cases a large number of interconnect cables are required, increasing heat loss and adding complexity and cost. Developing semiconductor devices capable of operating at these temperatures would allow a large reduction in system cabling and heat leaks. Useful device types include analog switches, digital logic, and amplifiers from low frequency to RF up-converters.

Thrust 8: Develop precision clock and timing circuits (PLL, DLL, Timing Discriminators, Delay Lines, Picosecond TDCs)

Timing information is an essential tool in background reduction techniques in HEP experiments. Future experiments will require 4D or 5D detectors capable of time resolution in the picosecond range. Circuit blocks for precision timing generation such as Phase-Locked Loops (PLL), Delay-Locked Loops (DLL), Timing Discriminators and Time to Digital Converters (TDCs) that operate with low power in extreme environments need to be developed in suitable technologies. To synchronize operation precision clock distribution strategies need to be investigated and optimized for precision timing SoCs.

	PRD: Priority Research Direction	Grand Challenge
Calorimetry	PRD 1: Enhance calorimetry energy resolution for precision electroweak mass and missing-energy measurements	1
	PRD 2: Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments	1,4
	PRD 3: Develop ultrafast media to improve background rejection in calorimeters and particle identification detectors	1,3,4
Nobles	PRD 4: Enhance and combine existing modalities to increase signal-to-noise and reconstruction fidelity	1,2
	PRD 5: Develop new modalities for signal detection	1
Photodetectors	PRD 6: Improve the understanding of detector microphysics and characterization	1
	PRD 7: Extend wavelength range and develop new single-photon counters to enhance photodetector sensitivity	1,3
	PRD 8: Advance high-density spectroscopy and polarimetry to extract all photon properties	2,3
	PRD 9: Adapt photosensors for extreme environments	2,4
	PRD 10: Design new devices and architectures to enable picosecond timing and event separation	1,2,4
	PRD 11: Develop new optical coupling paradigms for enhanced or dynamic light collection	1,2,3
	PRD 12: Advance quantum devices to meet and surpass the Standard Quantum Limit	1,3
	PRD 13: Enable the use of quantum ensembles and sensor networks for fundamental physics	1,2
	PRD 14: Advance the state of the art in low-threshold quantum calorimeters	1,3
Quantum	PRD 15: Advance enabling technologies for quantum sensing	1,2,3
	PRD 16: Develop process evaluation and modeling for ASICs in extreme environments	3,4
ASIC	PRD 17: Create building blocks for Systems-on-Chip for extreme environments	1,4
SolidState	PRD 18: Develop high spatial resolution pixel detectors with precise high per-pixel time resolution to resolve individual interactions in high-collision-density environments	1,4
	PRD 19: Adapt new materials and fabrication/integration techniques for particle tracking	2,3
	PRD 20: Realize scalable, irreducible-mass trackers	2,3
TDAQ	PRD 21: Achieve on-detector, real-time, continuous data processing and transmission to reach the exascale	2,4
	PRD 22: Develop technologies for autonomous detector systems	2
	PRD 23: Develop timing distribution with picosecond synchronization	1
Xcut	PRD 24: Manipulate detector media to enhance physics reach	1,3
	PRD 25: Advance material purification and assay methods to increase sensitivity	1,2,3,4
	PRD 26: Addressing challenges in scaling technologies	2,3