



HL-LHC and Future Perspectives

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PHENO26 Conference



1.4 QUADRILLION eV

particle
collider

**What are the constituents
of the universe?**

**How do they interact with
each other?**



**Understanding nature at
its most fundamental has
required flying in hot
air balloons and
instrumenting the
mountains...**

In 1912 Victor Hess reached an altitude of 5000 meters and discovered cosmic rays



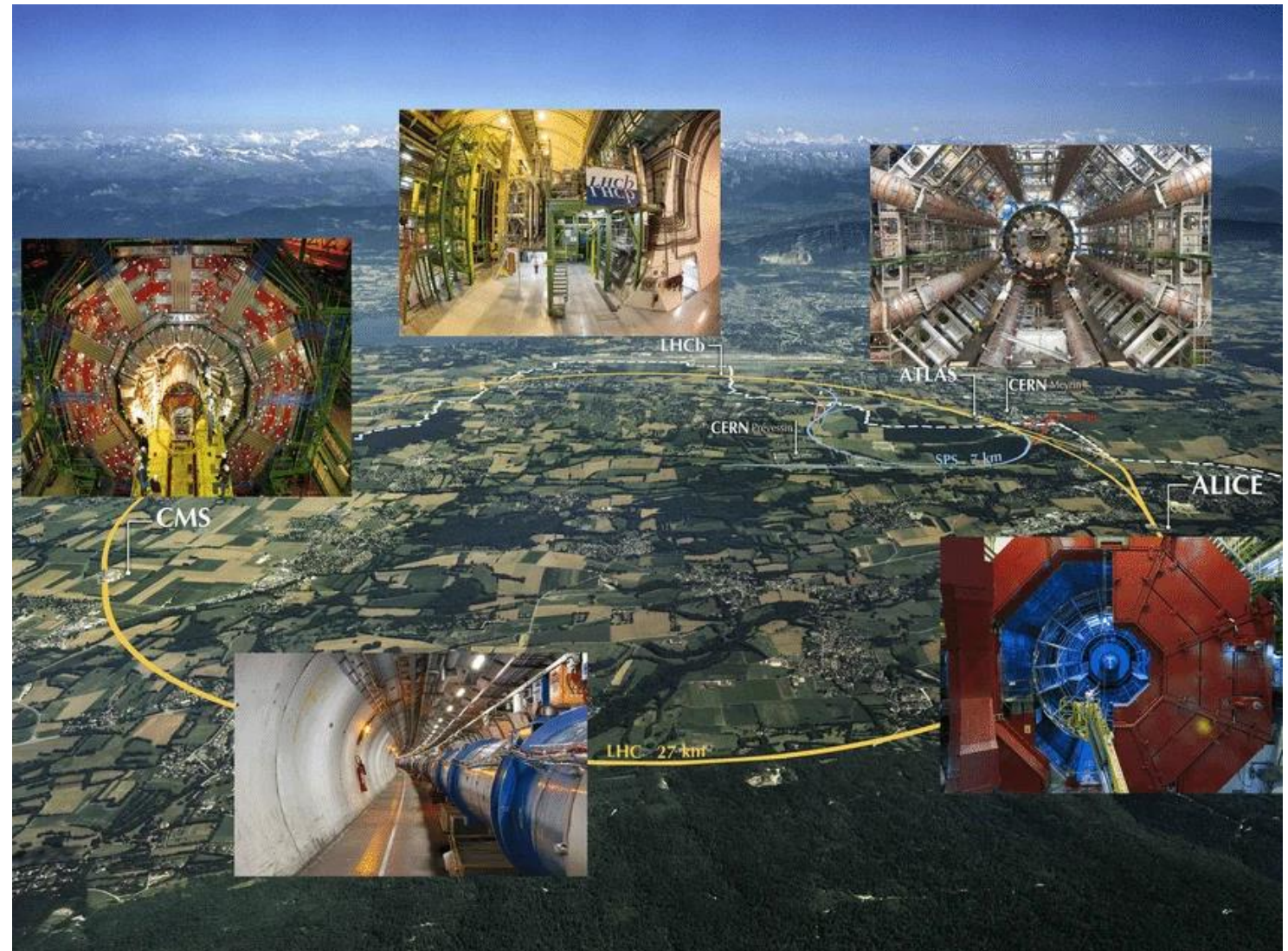
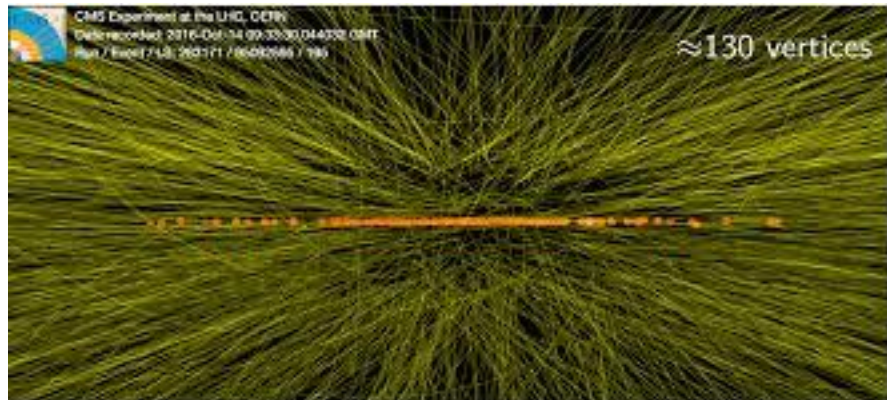
In 1938 Pierre Auger discovered extensive cosmic ray showers through detectors in the Alps



What are the constituents of the universe?

How do they interact with each other?

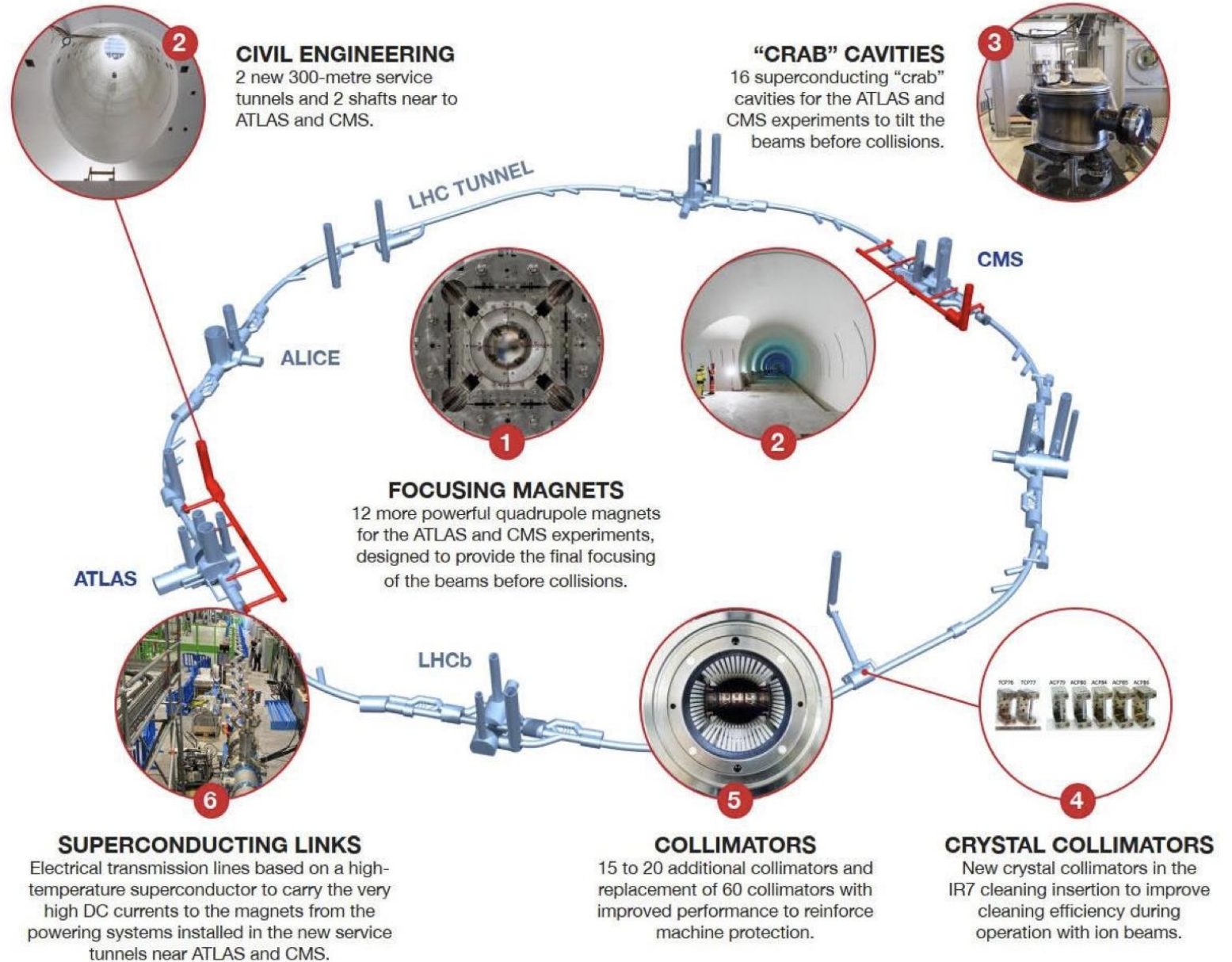
We are still going to extremes...



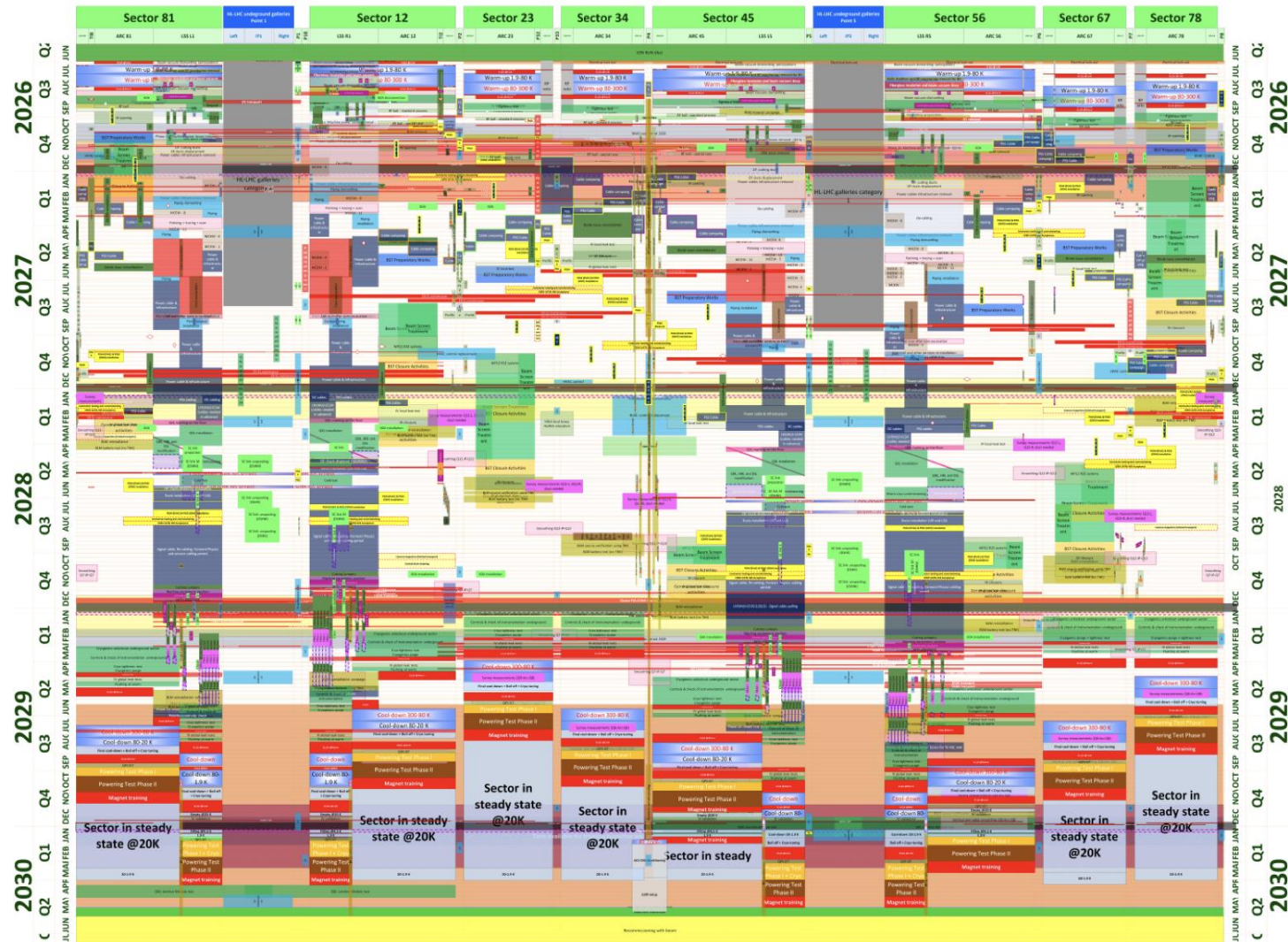
HL-LHC

main planned upgrades on the machine side

- 1 new inner triplets**
reach smaller β^ (down to ~ 10 cm)*
- 2 new service tunnels in IP1 and 5**
to house HL-LHC equipment
- 3 crab cavities**
compensate crossing angle effect
- 4 crystal collimators**
improve heavy-ions cleaning
- 5 new collimators**
lower impedance, better cleaning
- 6 new SC links**
to power the new triplets



While the collider teams are working hard...



Long Shutdown 3 Planning (Chamonix, 2026)

ATLAS Detector Upgrades

Upgraded Trigger and Data Acquisition (TDAQ)

1 MHz hardware trigger, 10 kHz High-level trigger with 150 kHz full-scan tracking

TDAQ TDR: <https://cds.cern.ch/record/2285584>

New and upgraded Forward and Luminosity detectors

New muon chambers & electronics

Inner barrel region with new RPC and sMDT detectors; inner endcap regions with new triplet TGC

Muon TDR: <https://cds.cern.ch/record/2285580>

High Granularity Timing Detector (HGTD)

Fast timing (~ 50 ps) with Low-Gain Avalanche Detectors in $2.4 < |\eta| < 4$ for pileup rejection

HGTD TDR:

<https://cds.cern.ch/record/2719855>

Upgrade of calorimeter electronics

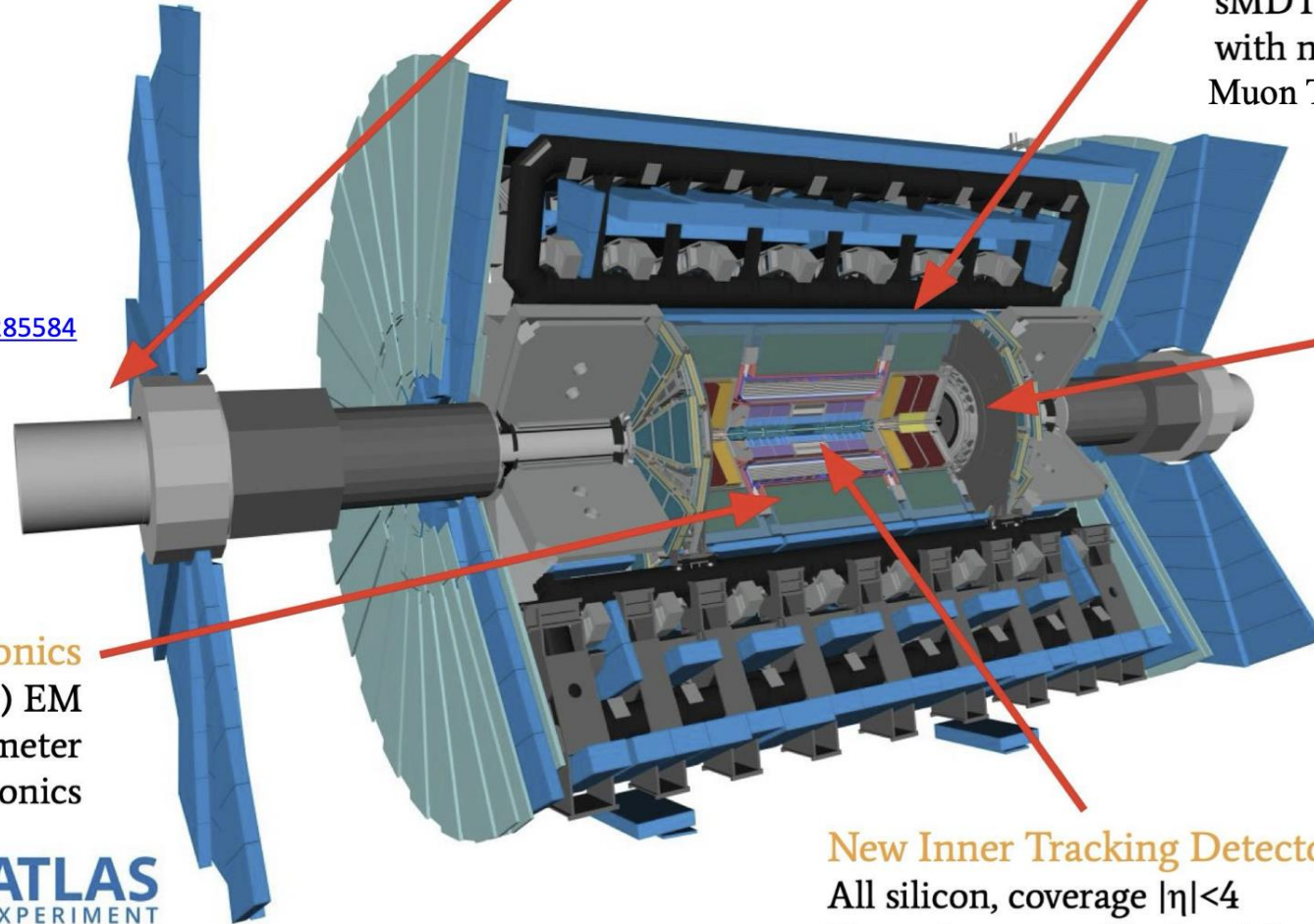
Upgrade of Liquid-Argon (LAr) EM and hadronic Tile calorimeter electronics

New Inner Tracking Detector (ITk)

All silicon, coverage $|\eta| < 4$

Two subsystems: Pixel and Strip

$50 \times 50 \mu\text{m}^2$ pixels for pileup rejection



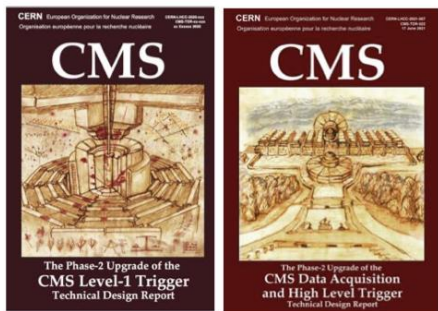
LAr TDR: <https://cds.cern.ch/record/2285582>

Tile TDR: <https://cds.cern.ch/record/2285583>

ITk Pixel TDR: <https://cds.cern.ch/record/2285585>

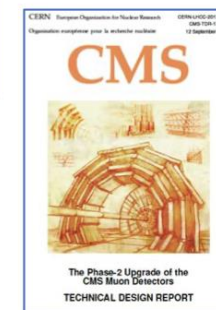
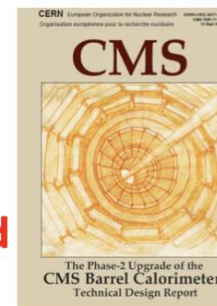
ITk Strips TDR: <https://cds.cern.ch/record/2257755>

CMS phase II detector upgrade

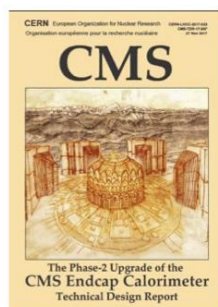


L1-Trigger HLT/DAQ
P5 – SCX5 & underground
New cooling (2-3 MW)
New power distr.

Barrel Calorimeters
P5 - SX5 & underground
New water cooling (9 C)
New power distr.

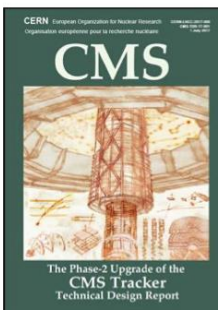


Muon systems
904 & underground
New gas distribution

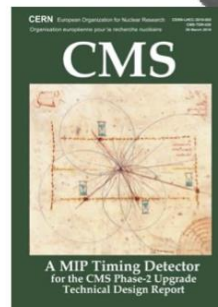


Calorimeter Endcap (HGCAL)
186, P5 - SX5, SXA5, underground

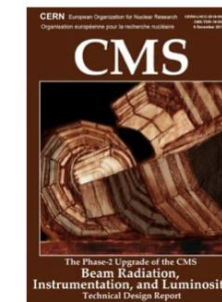
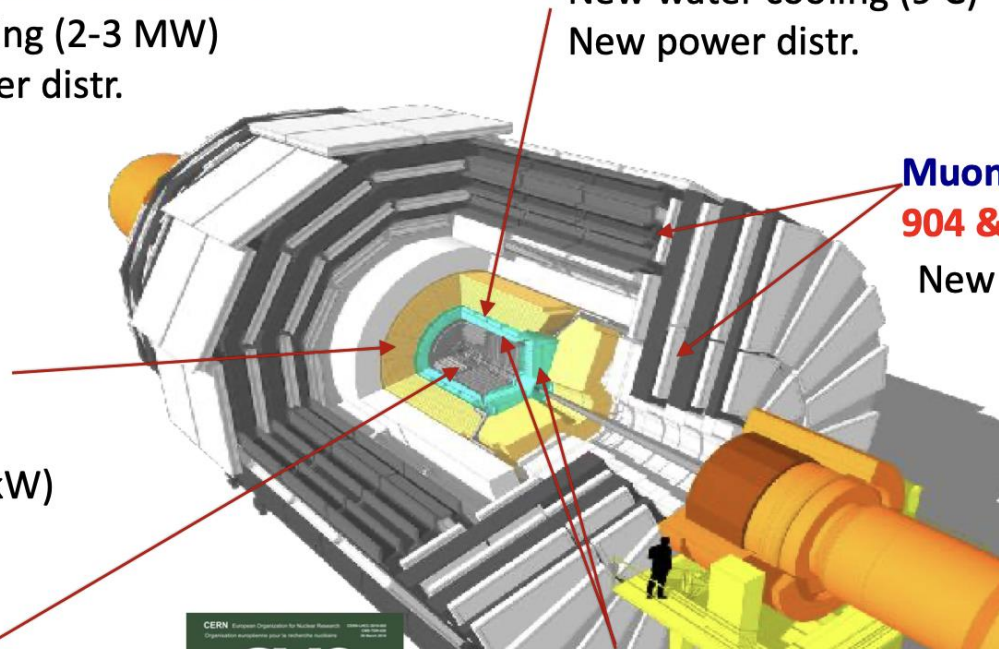
New CO₂ cooling (250 kW)
New power distr.
New hypoxic air



Tracker
186, P5 SX5, underground
New CO₂ cooling (150 kW)
New power distr.
Consolidated hypoxic air



MIP Timing Detector
186, P5 SXA5, SX5, underground
New CO₂ cooling (110 kW)
New power distr.



Beam Radiation Instr. and Luminosity
186, P5 SX5 & underground

The experiments will face challenges, as will the collider!

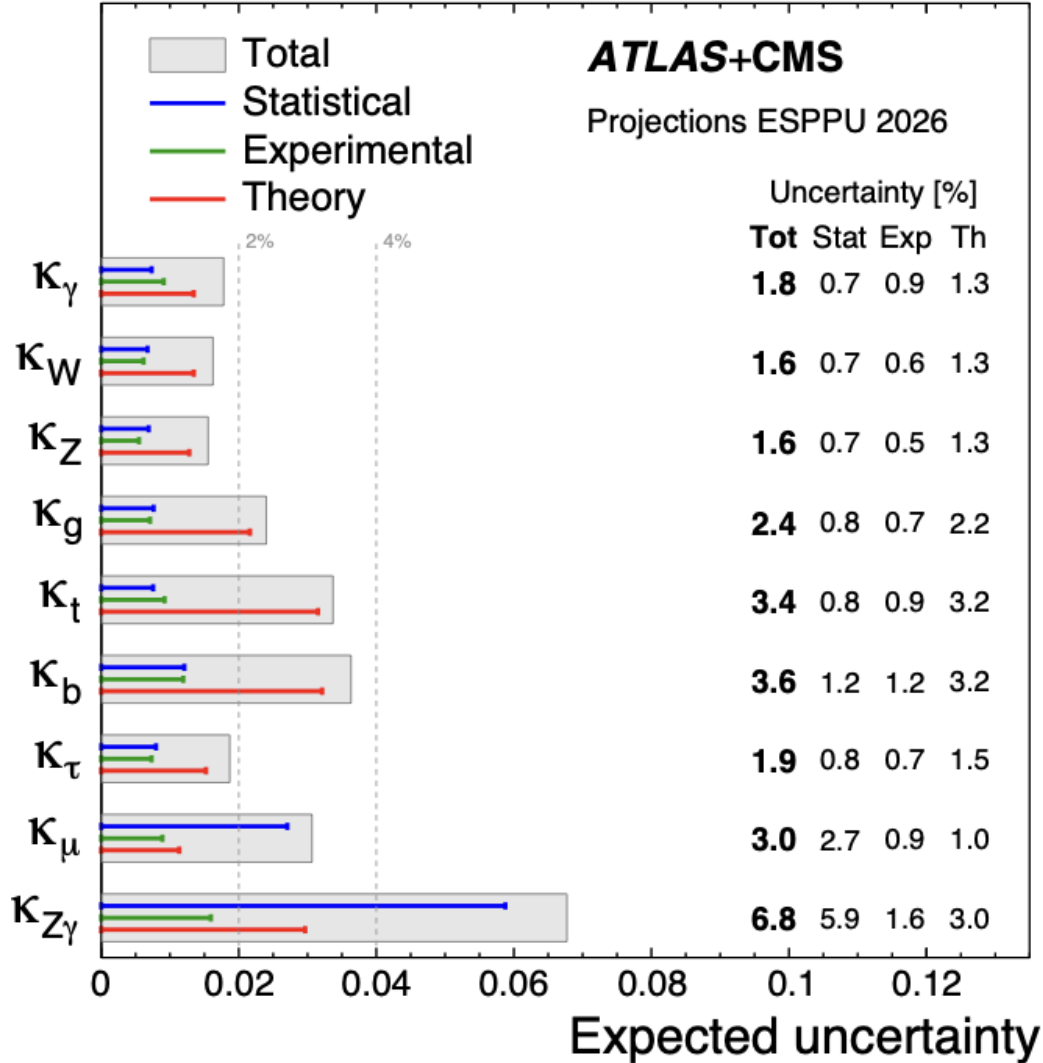
	# loaded bunches	Beam Intensity (10^{11})	Beam Heating Power (P/P_{2025})
run 2	2450	1.2	0.53
run 3	2450	1.65	1
HL-LHC	2750	2.3	2.18

(Some) HL-LHC Physics Goals

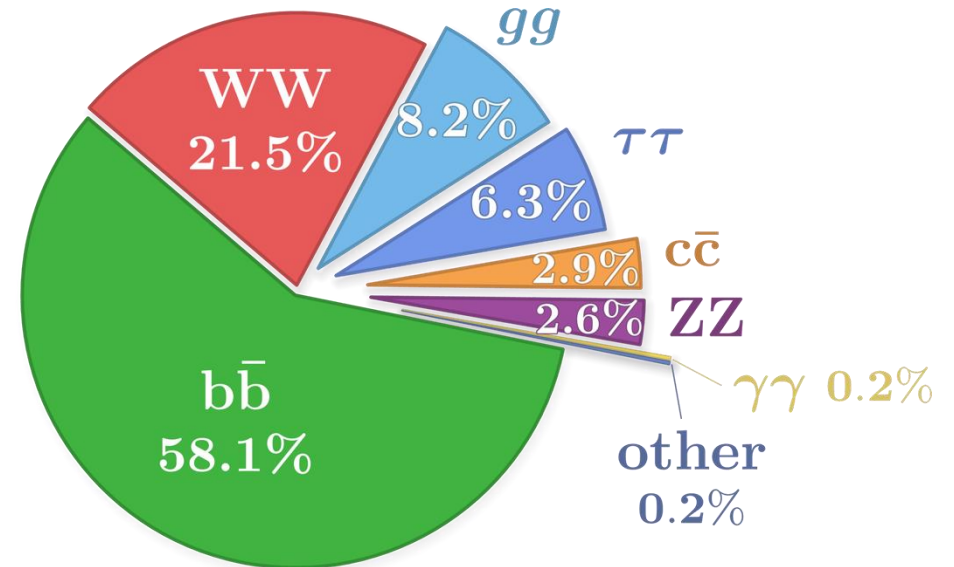
- **Studies of Higgs boson properties**
 - In particular, Higgs self coupling measurements are sensitive to modifications of the Higgs potential
- **Improve Standard Model precision measurements**
 - With $\sim 10x$ the data, new analysis techniques and upgraded systems, we can reach new precision and access rare decays
- **Searches for beyond the Standard Model (BSM) physics**
 - Dark matter, new sources of CP violation, other exotic new particles – we have so many questions!
 - We benefit from advanced machine learning, including anomaly detection
- **Studies of QCD matter at high density and temperature**
 - Understanding the quark-gluon plasma (QGP) and thermalization
- **Flavor physics of heavy quarks and leptons**

Higgs boson coupling measurements

$\sqrt{s} = 14 \text{ TeV}$, S2, 3 ab^{-1} per experiment



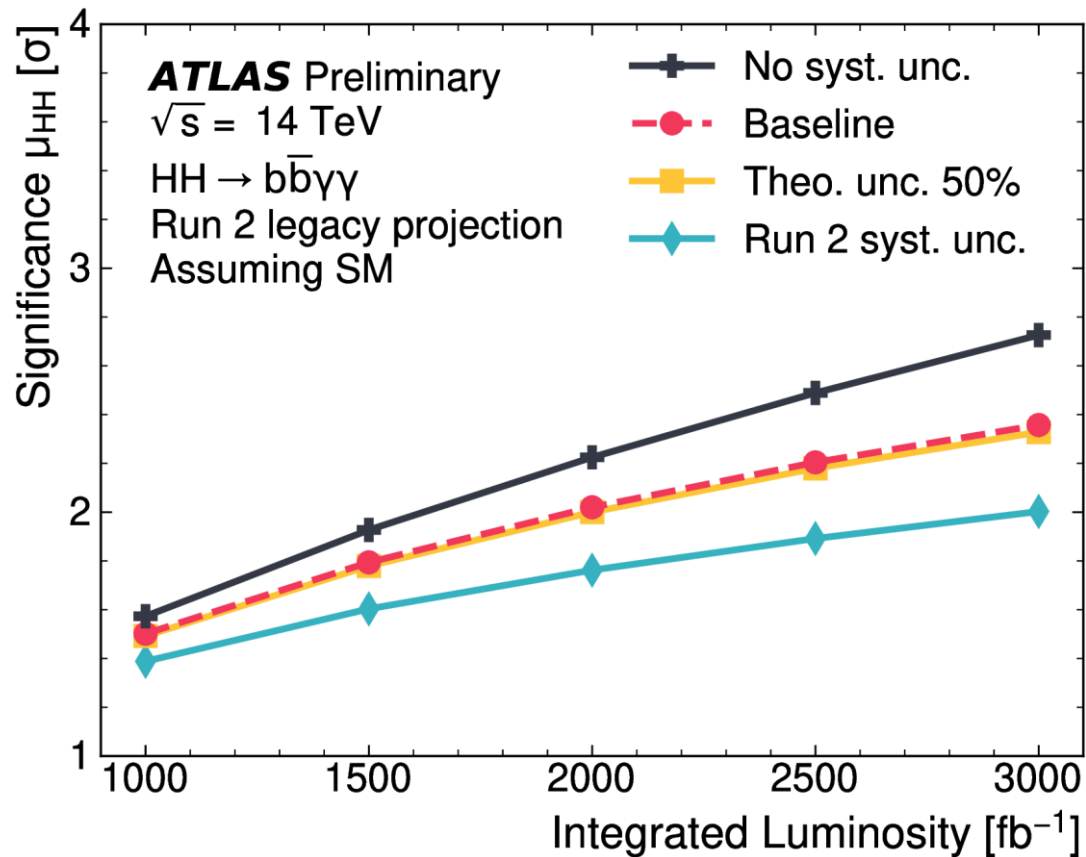
Note the dominance of **theory uncertainties** for many coupling measurements.



Updated ATLAS HH Sensitivity Projections

self-interaction strength measurements are needed
to verify the EW symmetry breaking mechanism of SM

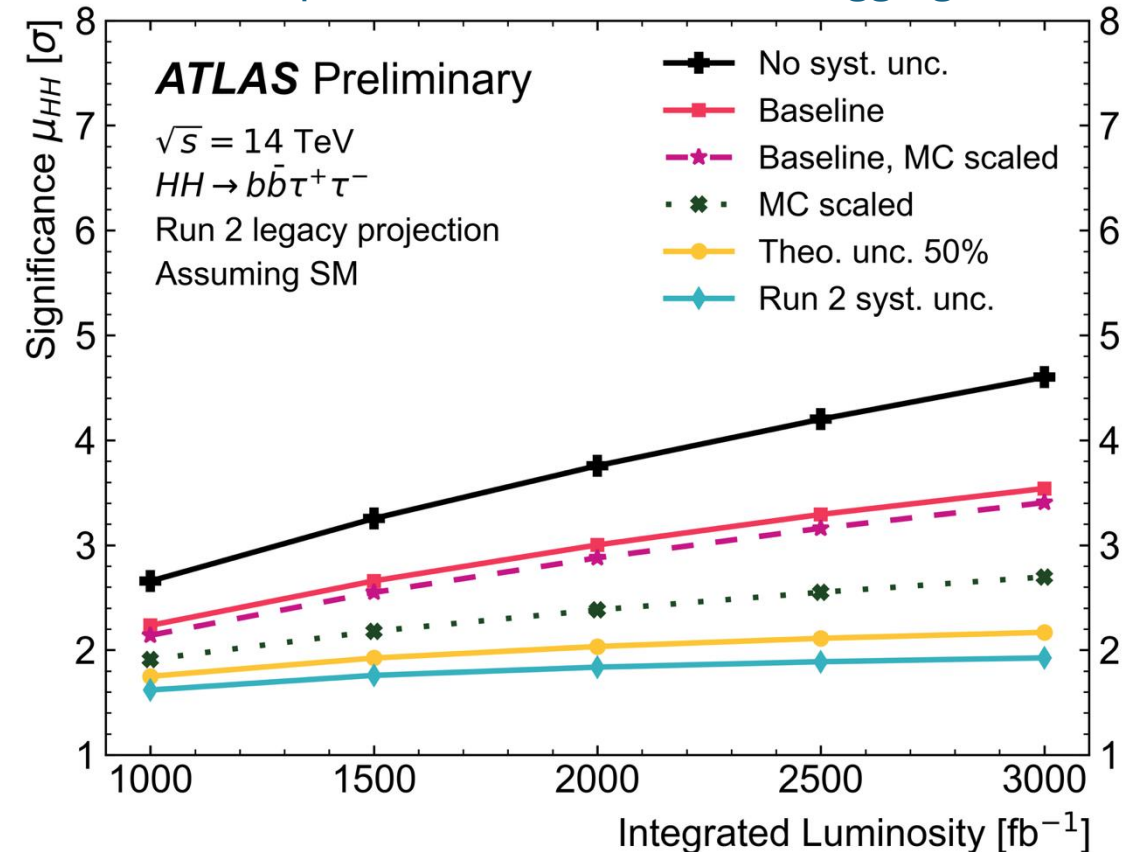
$$HH \rightarrow b\bar{b}\gamma\gamma$$



[ATL-PHYS-PUB-2025-001](#)

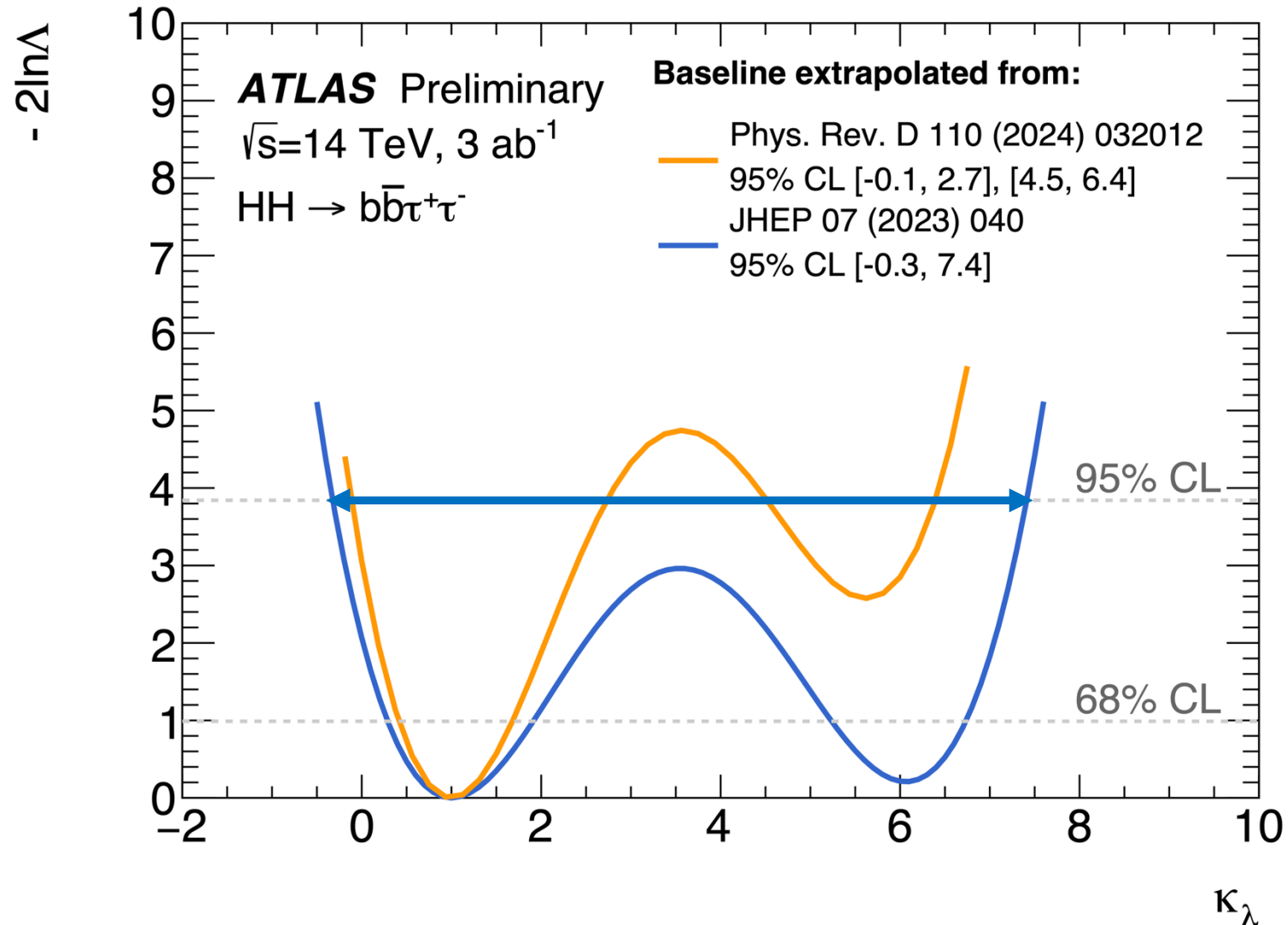
$$HH \rightarrow b\bar{b}\tau^+\tau^-$$

Before taking into account full expected
improvements in b and tau tagging...

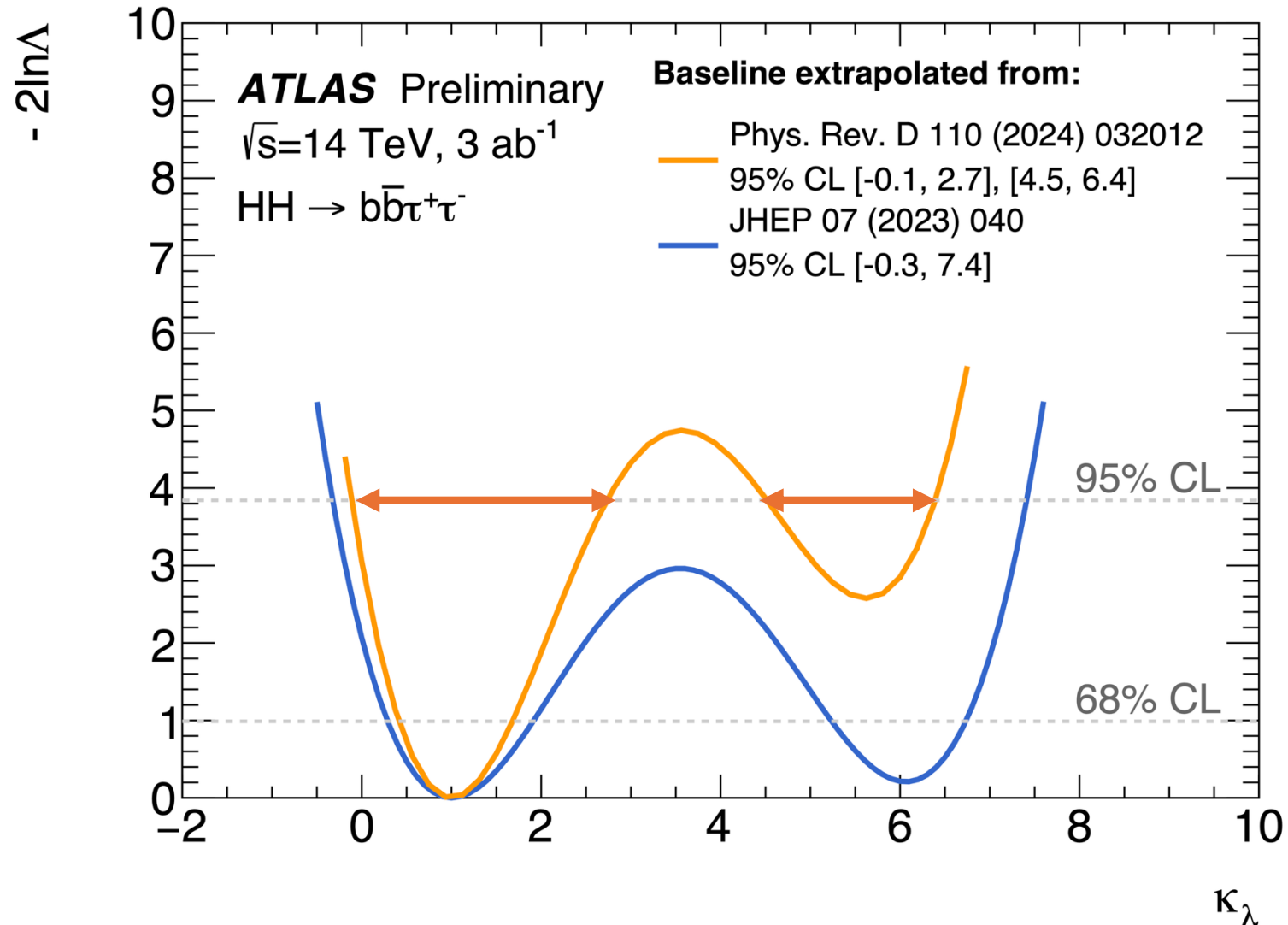


[ATL-PHYS-PUB-2024-016](#)

Zooming in: Improvements from previous extrapolations

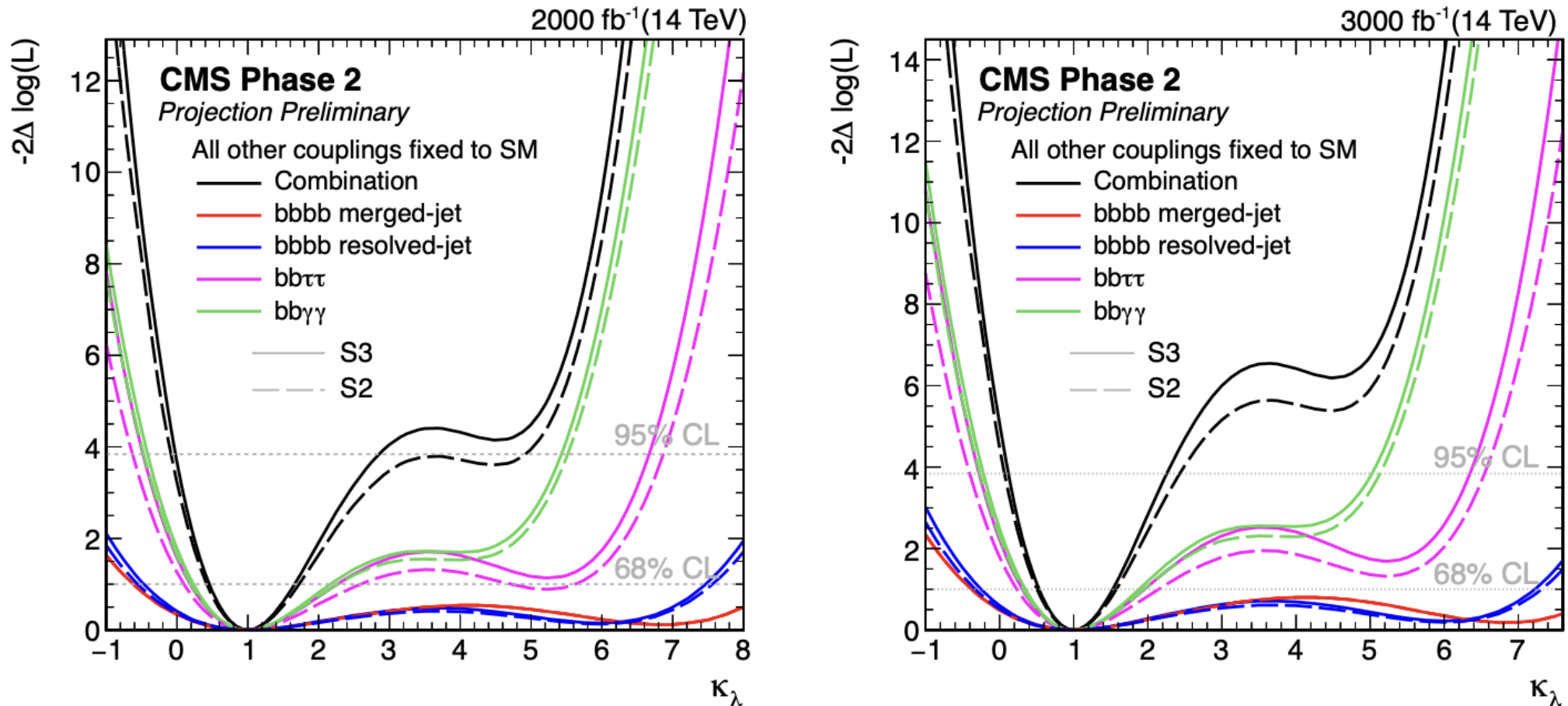


Zooming in: Improvements from previous extrapolations

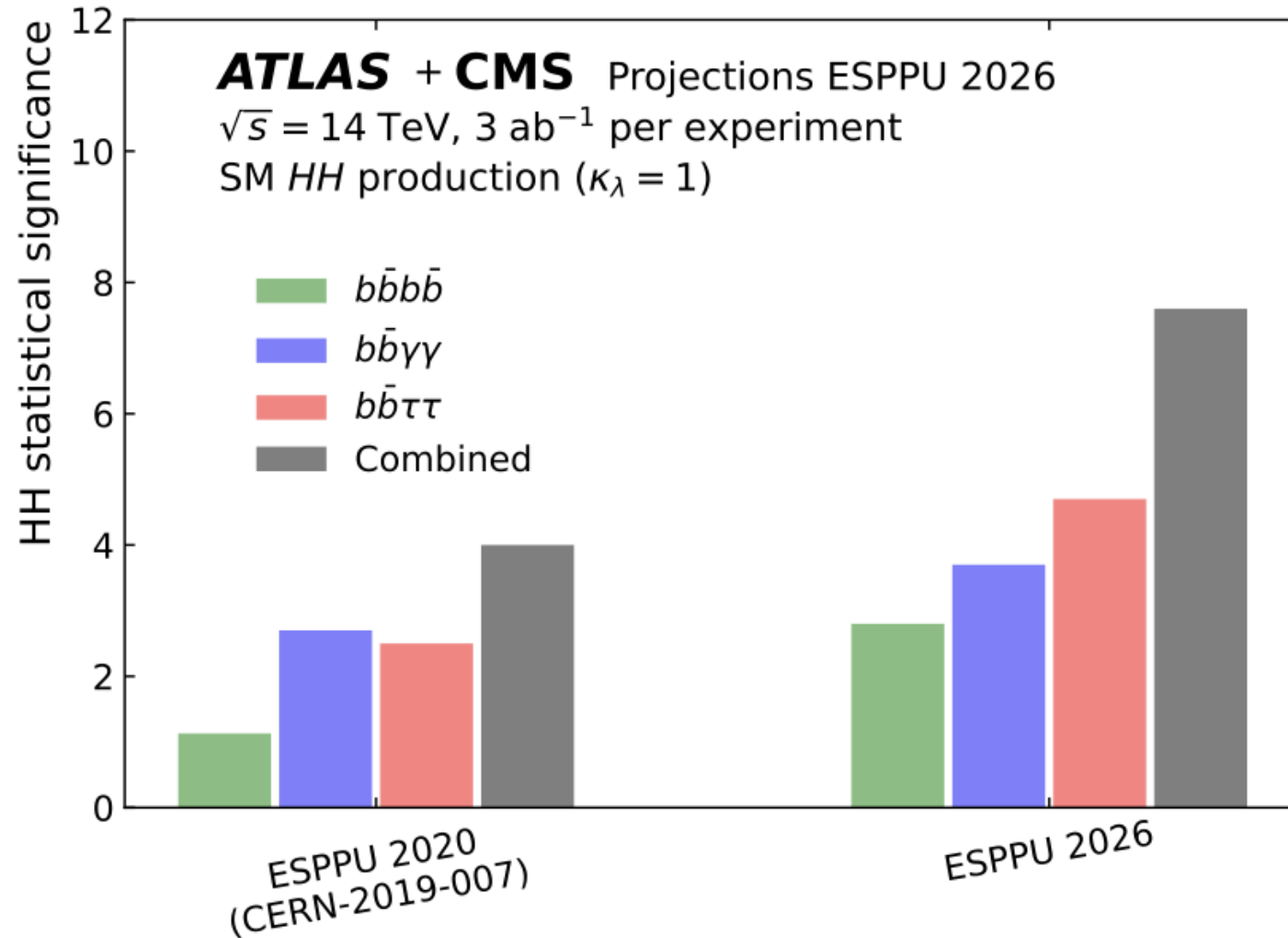


Combining three HH channels at CMS

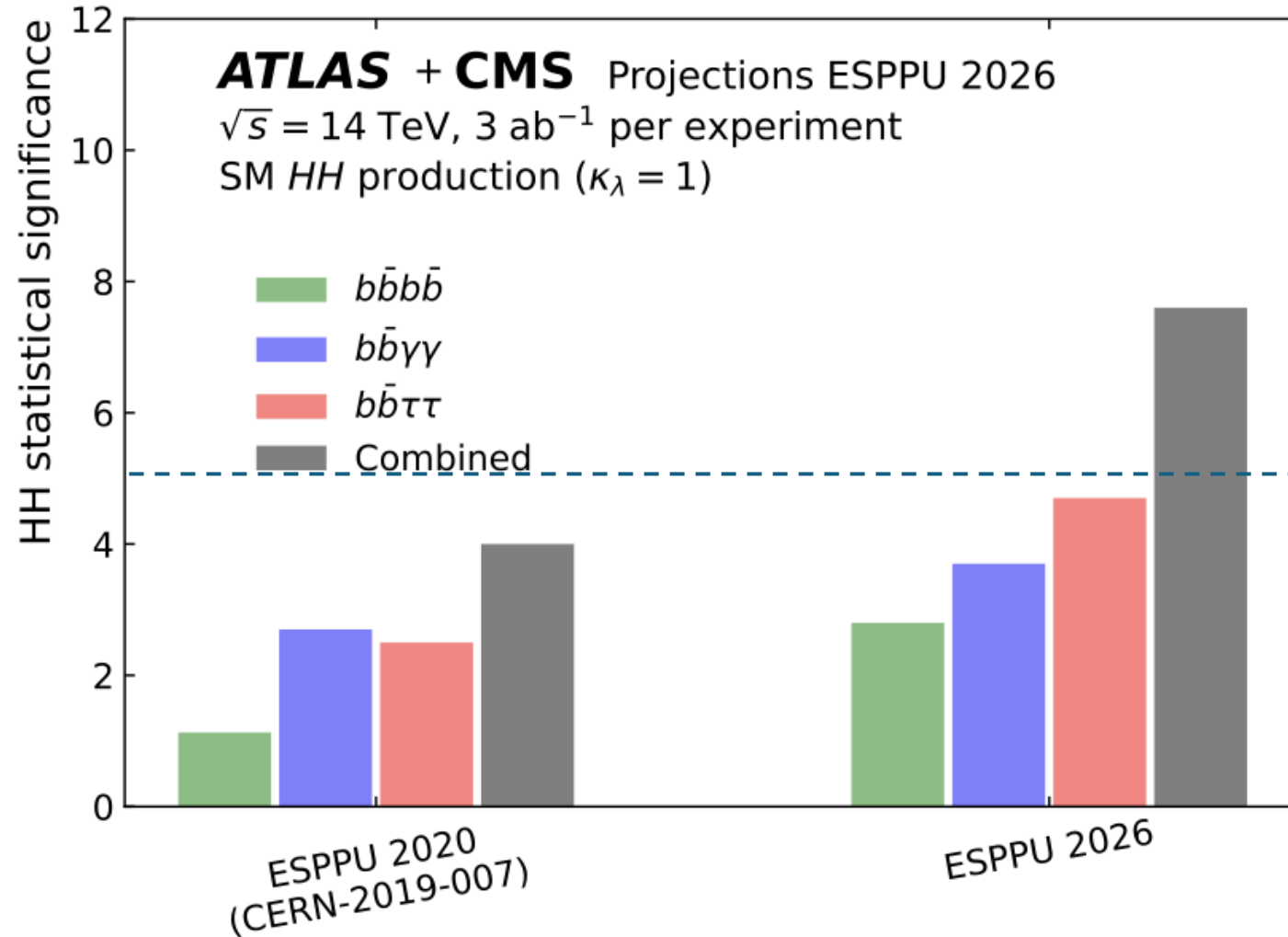
These are likely conservative projections, not taking into account improvements in analysis or due to the detector upgrades for the HL=LHC.



Innovations are driving improvements...



Innovations are driving improvements...

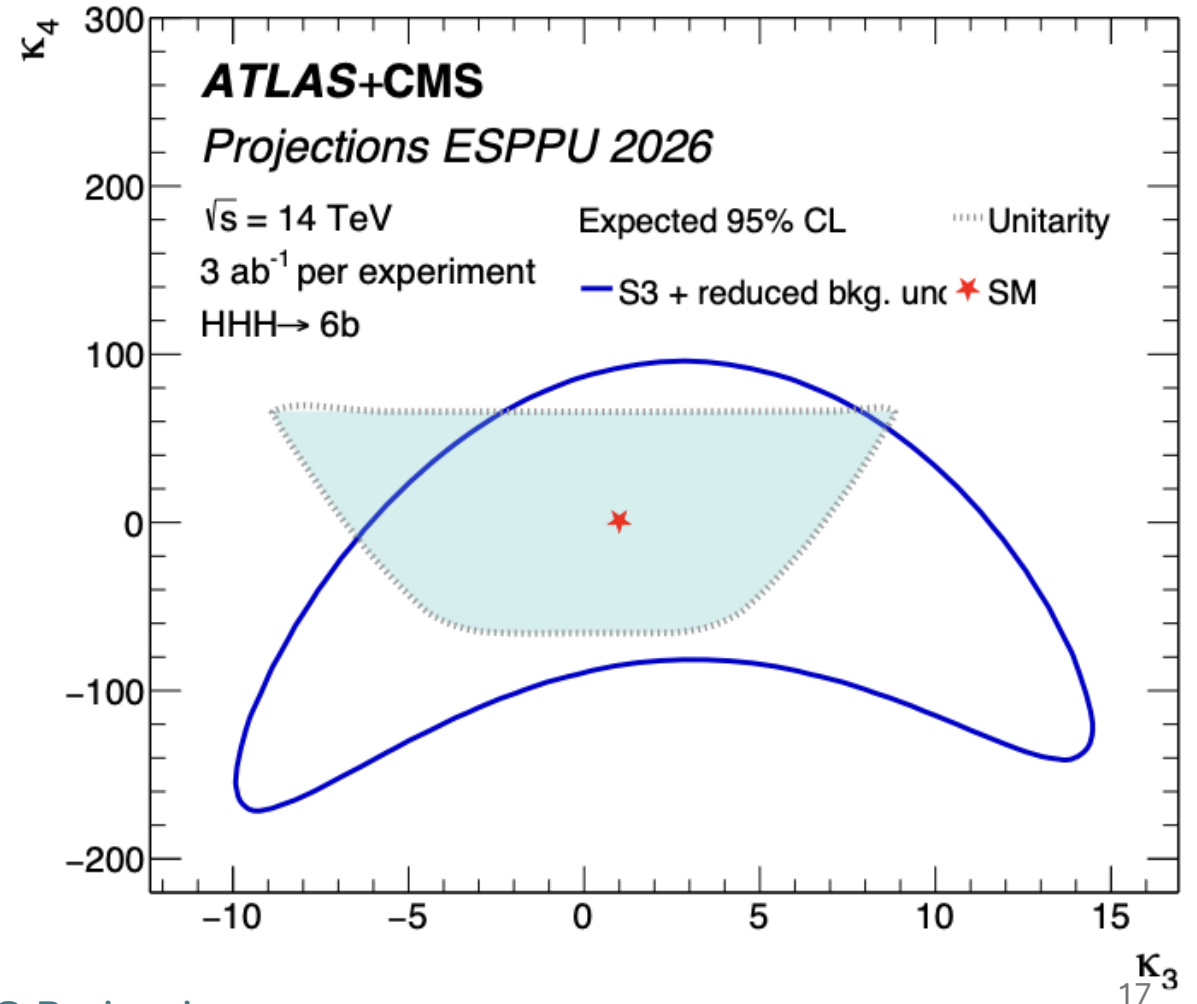
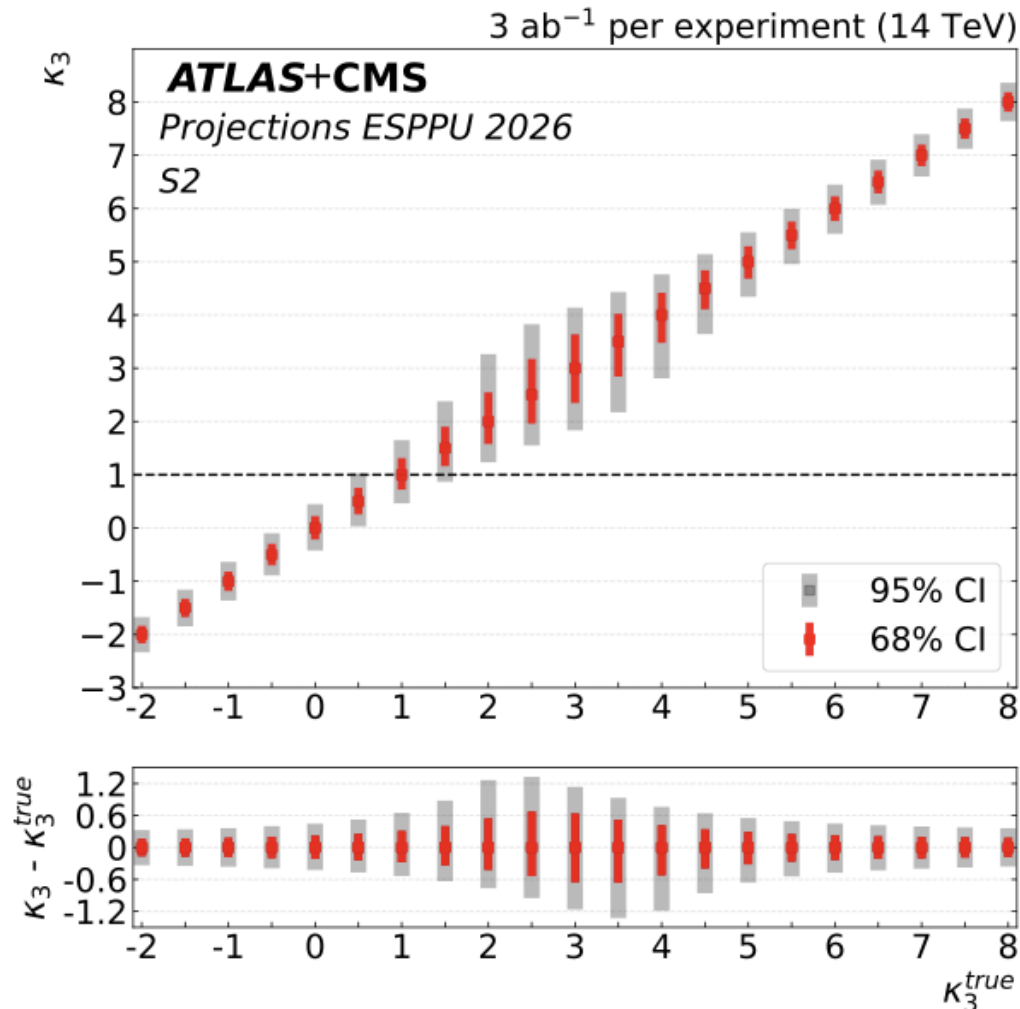


While we used to think that it would require ATLAS & CMS combinations to reach 5σ for HH measurements (assuming SM behavior), improvements to current analyses have been dramatic!

From trigger/DAQ to calibrations to analysis techniques, the data stretches further.

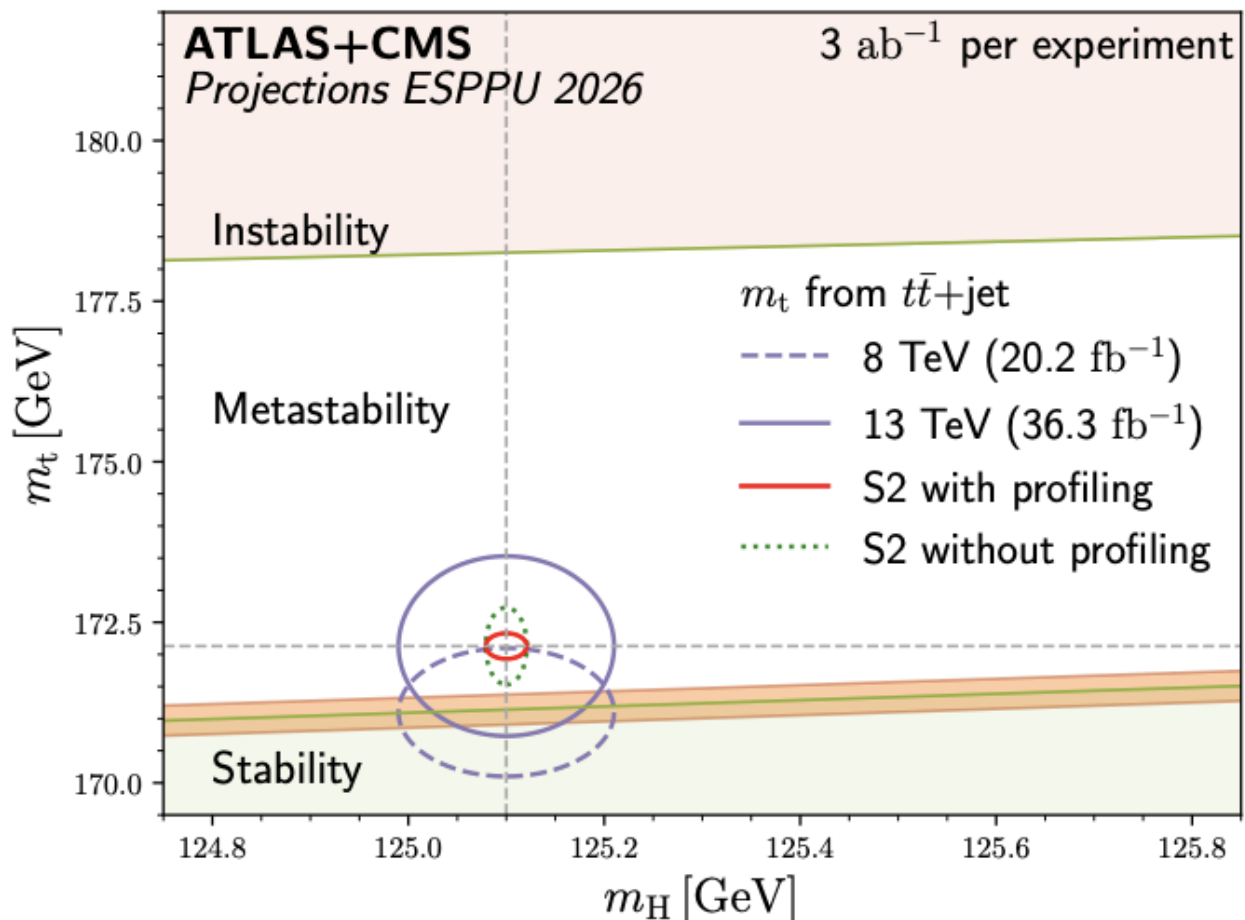
HHH Production and quartic Higgs couplings

Trilinear and quartic Higgs self couplings give insight into shape of Higgs potential and nature of electroweak phase transition. We will be able to explore bounds from perturbative unitarity.



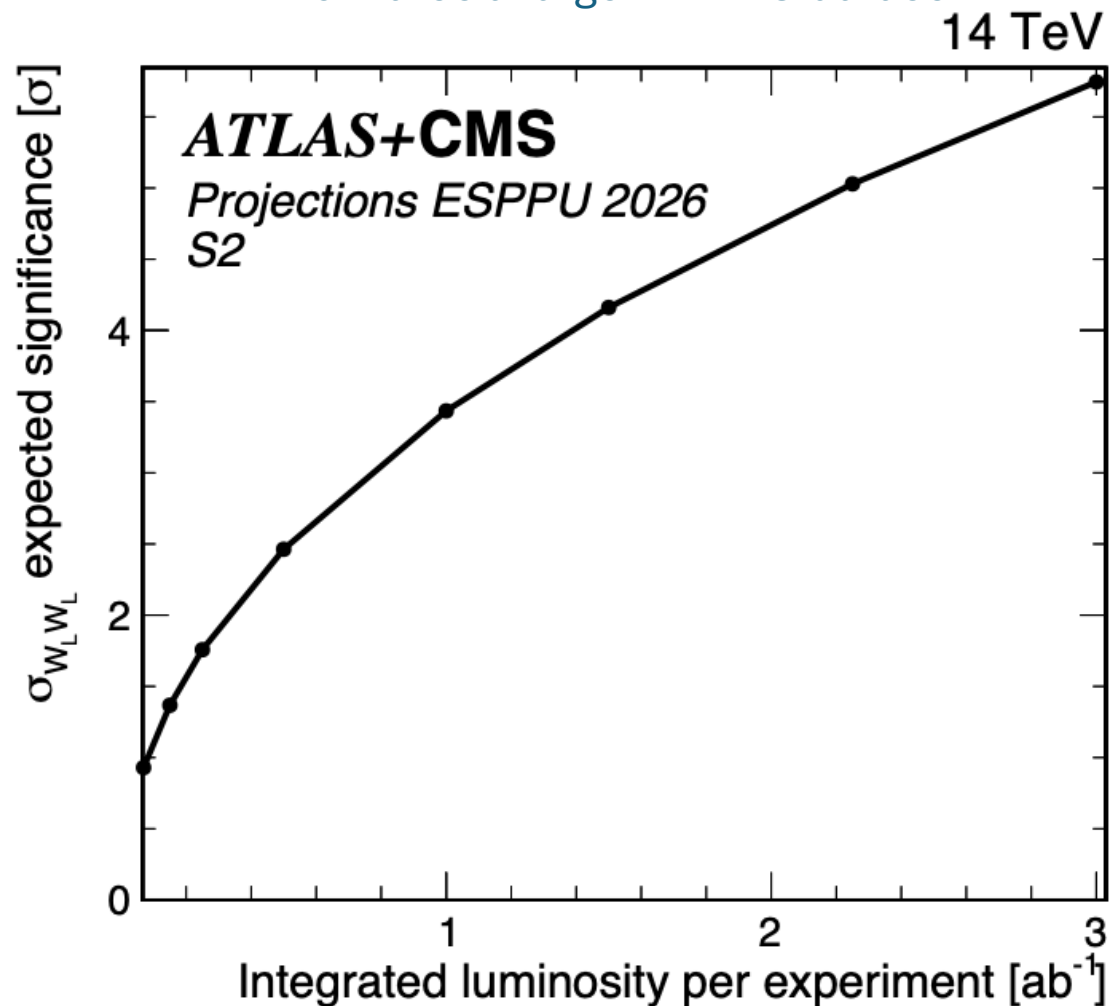
m_t and m_H

This precision enables order 10^{-3} probes of BSM effects on electroweak observables



WW Scattering

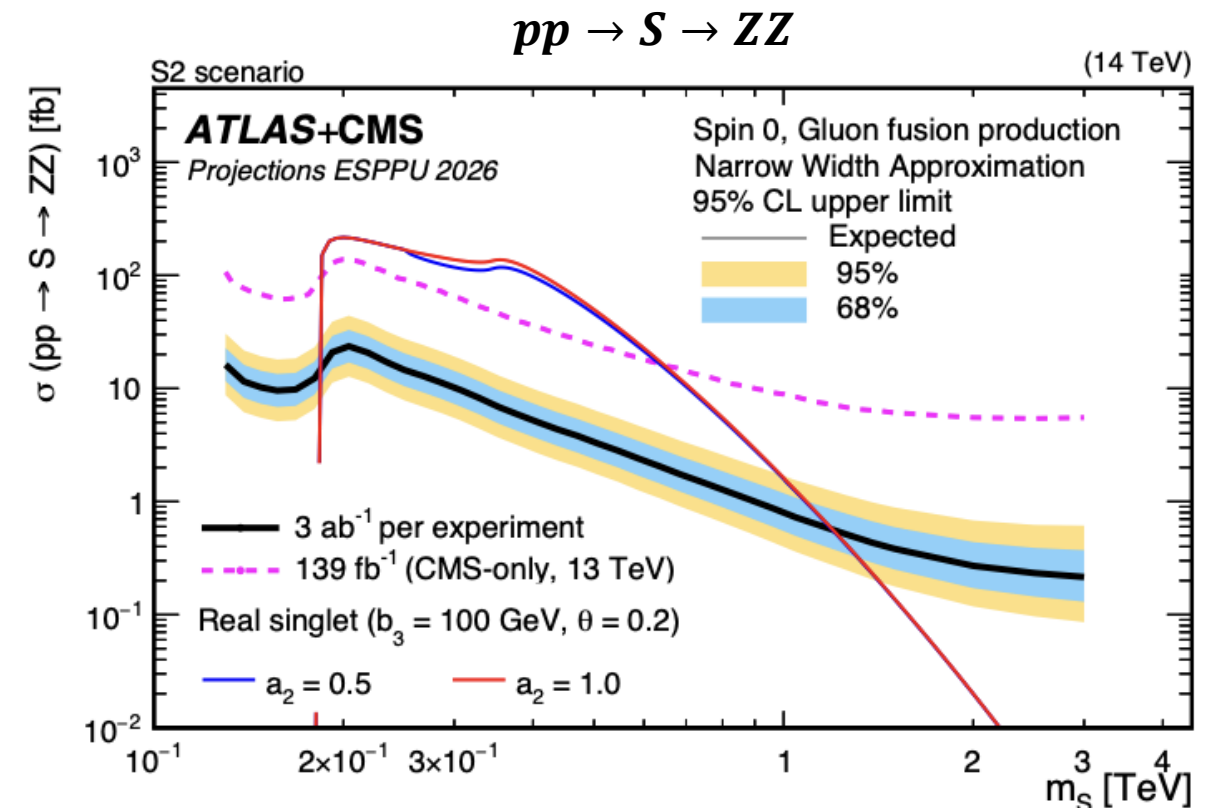
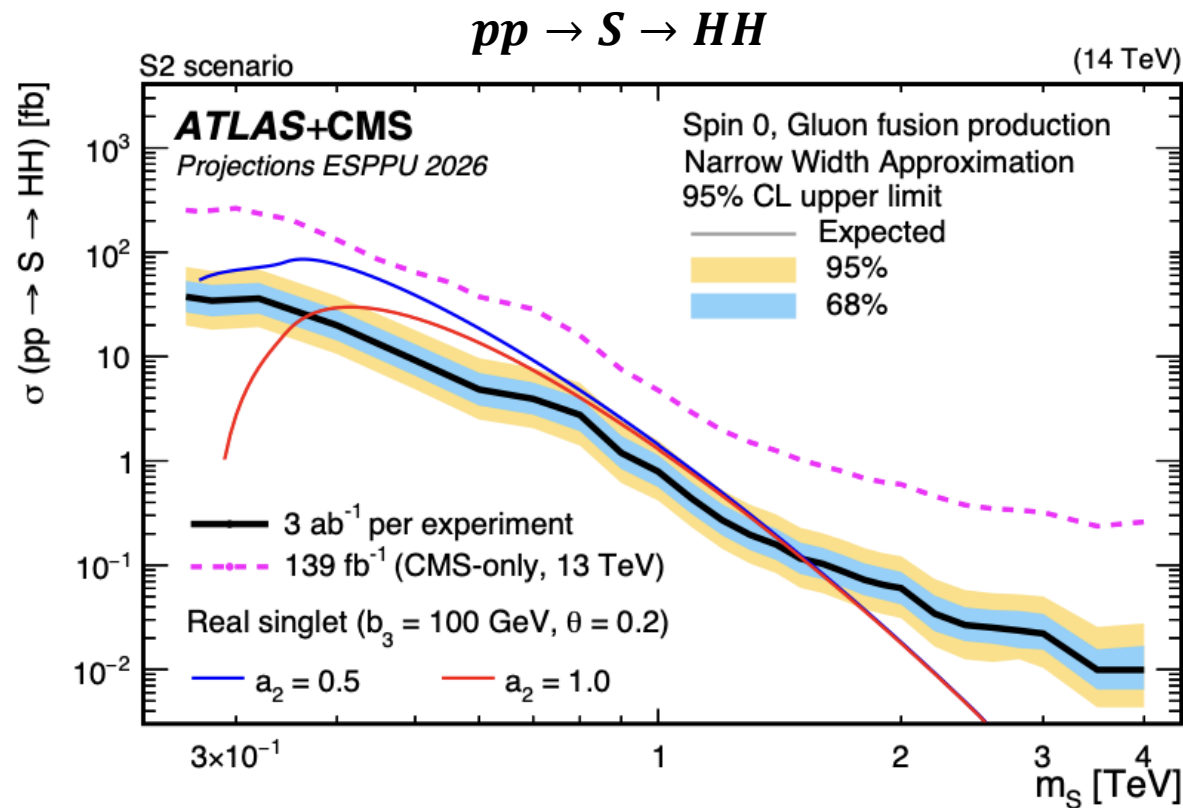
Access to longitudinal WW scattering motivates a large HL-LHC dataset



Searches for a Heavy Scalar

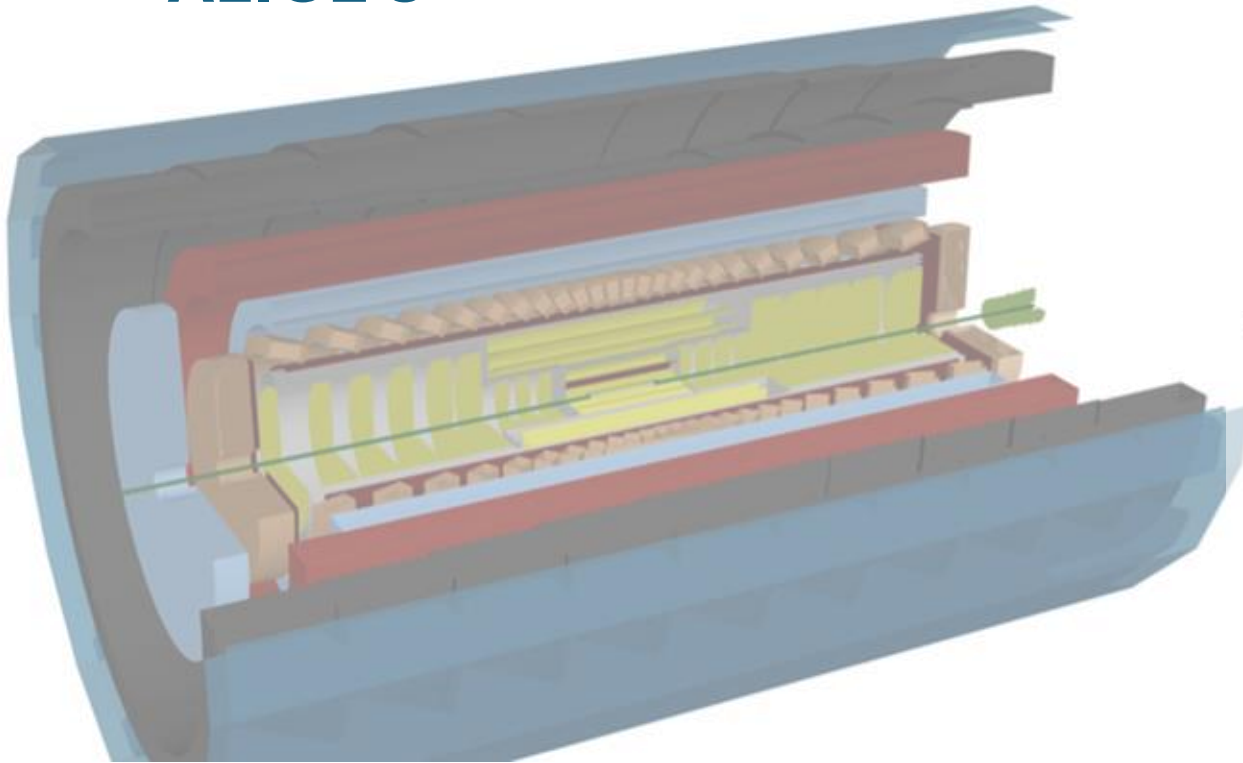
Consider a model with a heavy scalar, S , extending the Higgs sector.

Extrapolations based on CMS Run 2 searches for various coupling assumptions (a) and S masses.

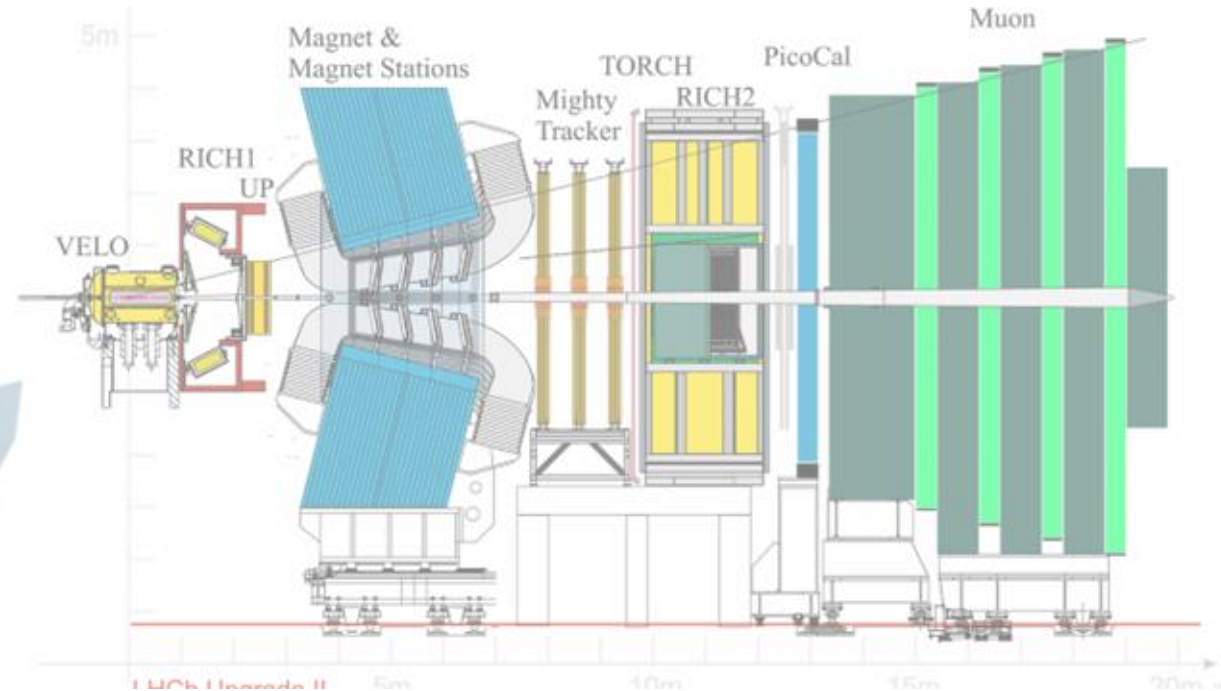


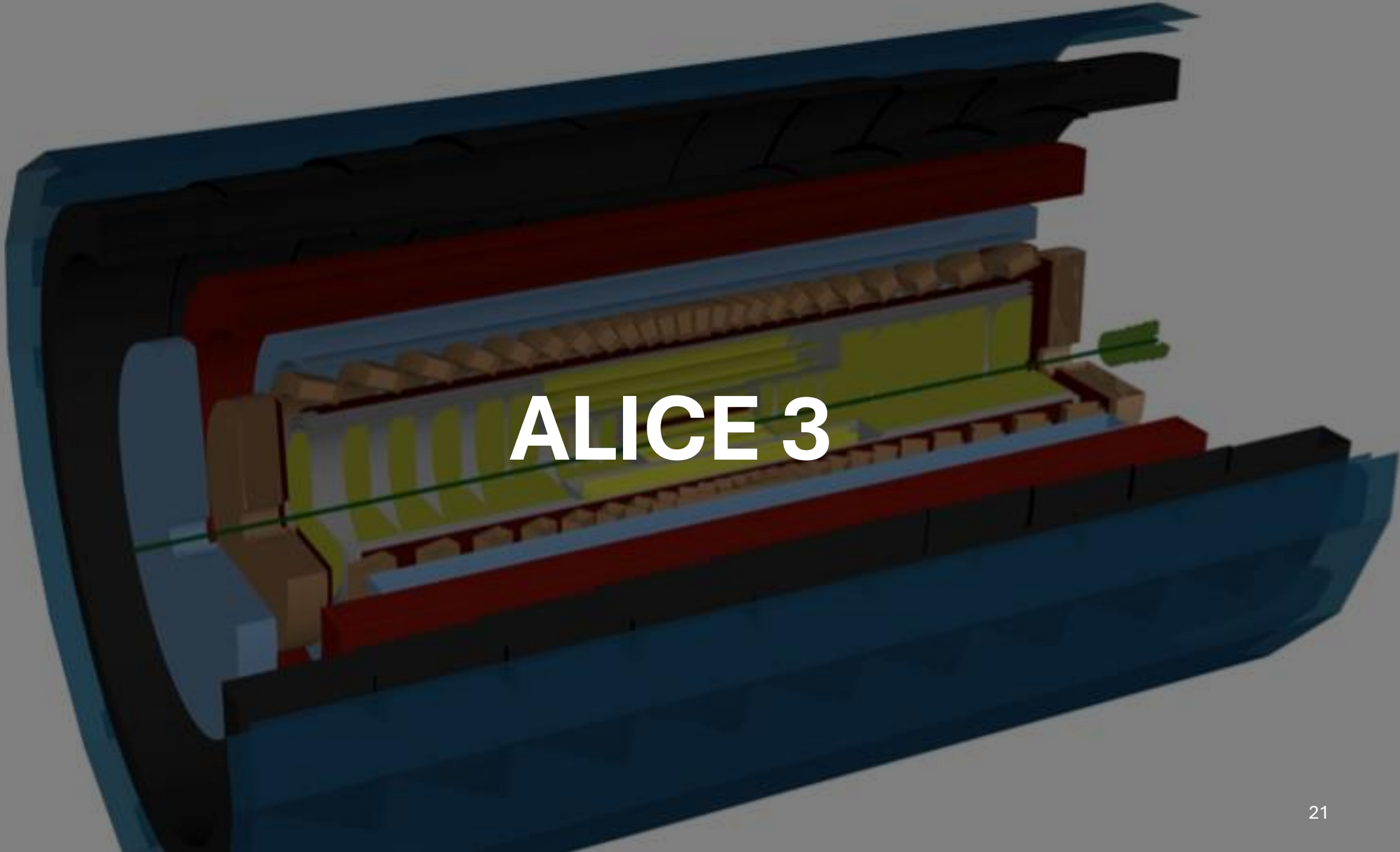
Proposed upgrades for Run 5

ALICE 3



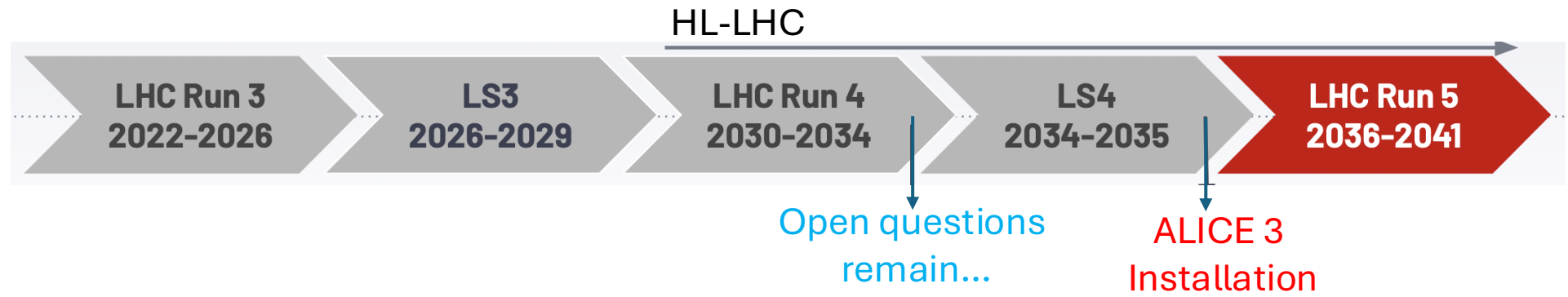
LHCb Upgrade II



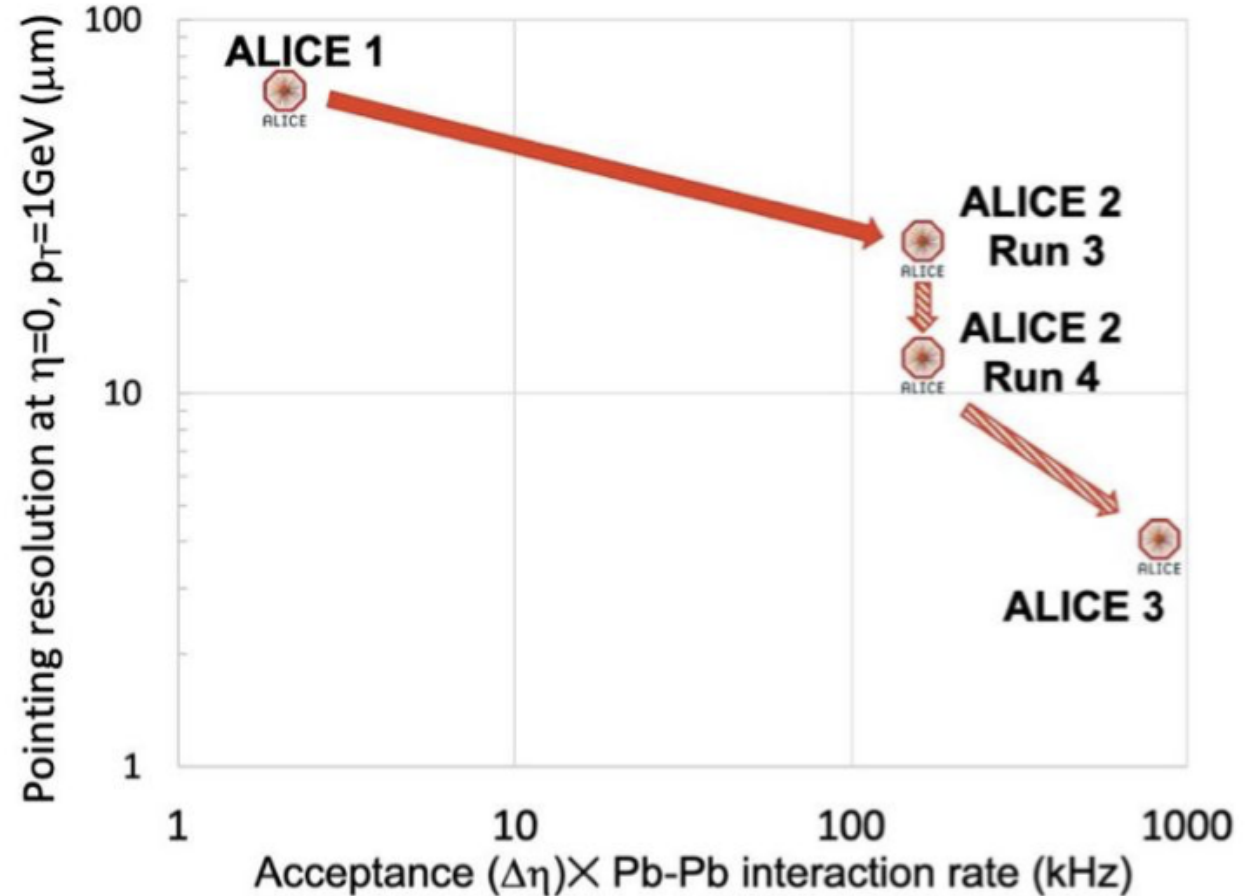


ALICE 3

ALICE 3

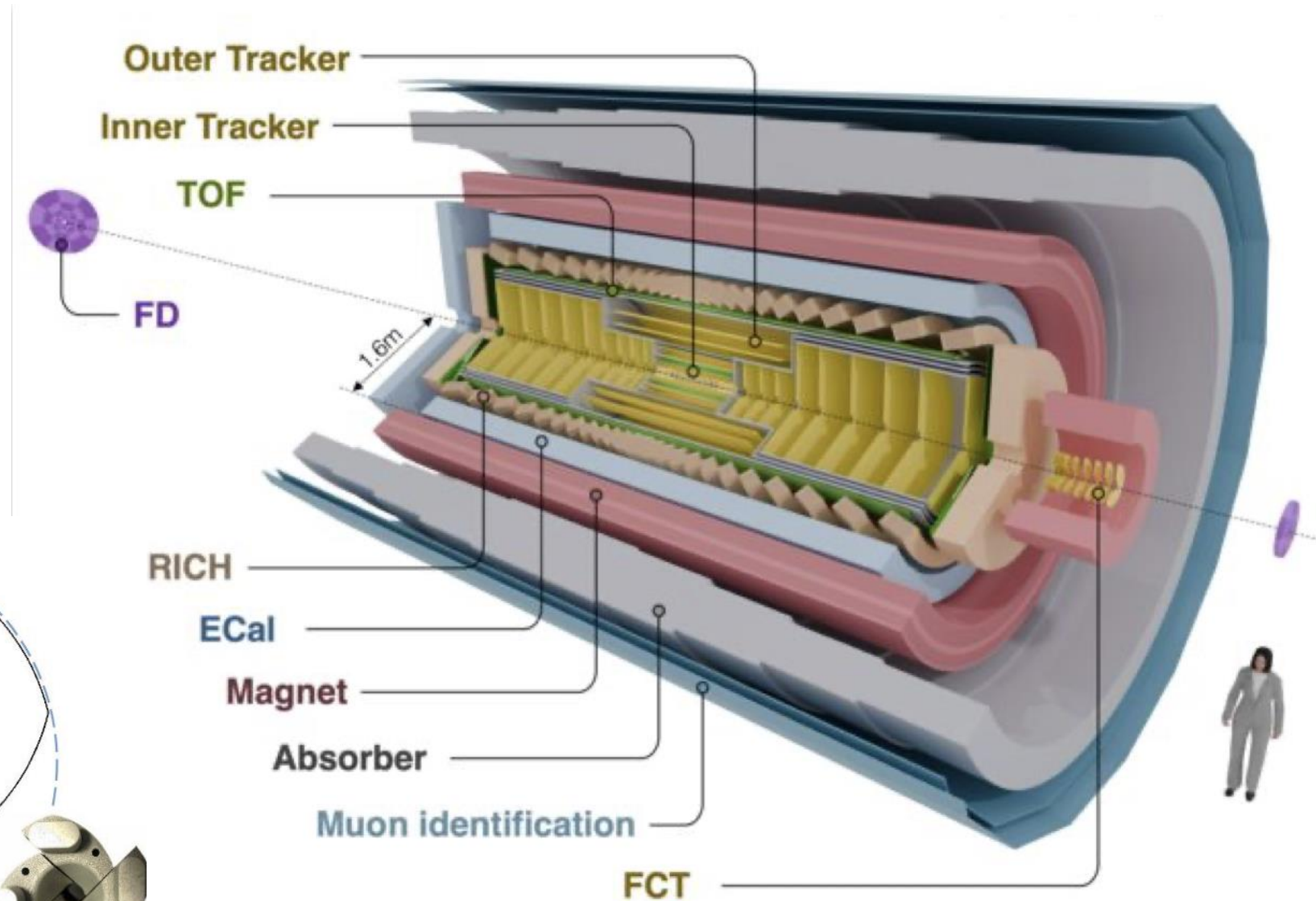
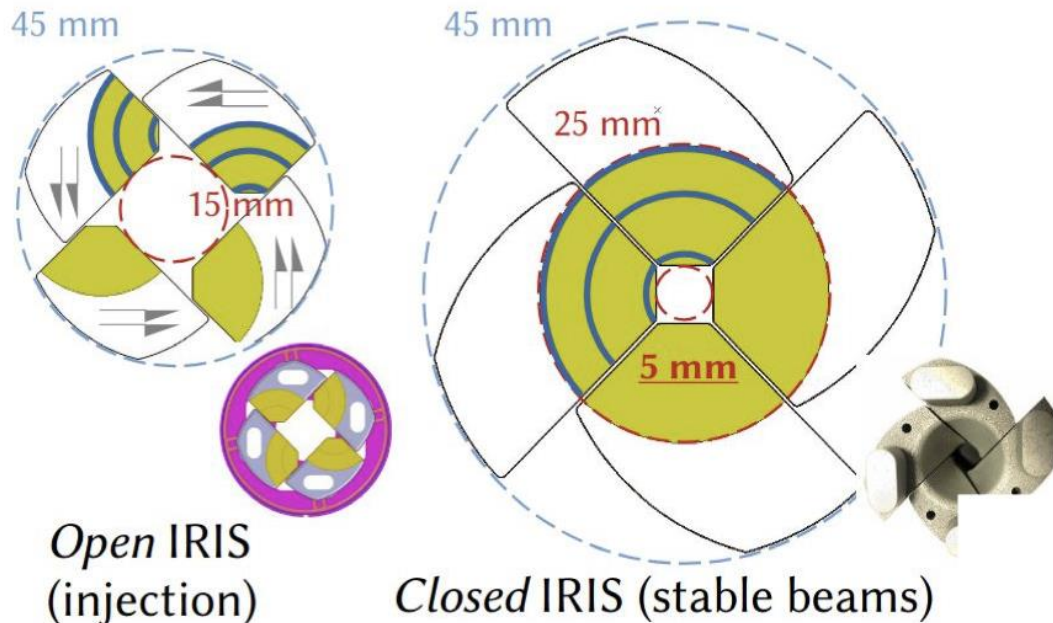


Understanding the thermalization of heavy quarks in the QGP
Accessing the **QGP temperature evolution** with thermal radiation
Characterizing the **cross-over to the QGP phase**
Exploiting a new laboratory for **hadronic physics**



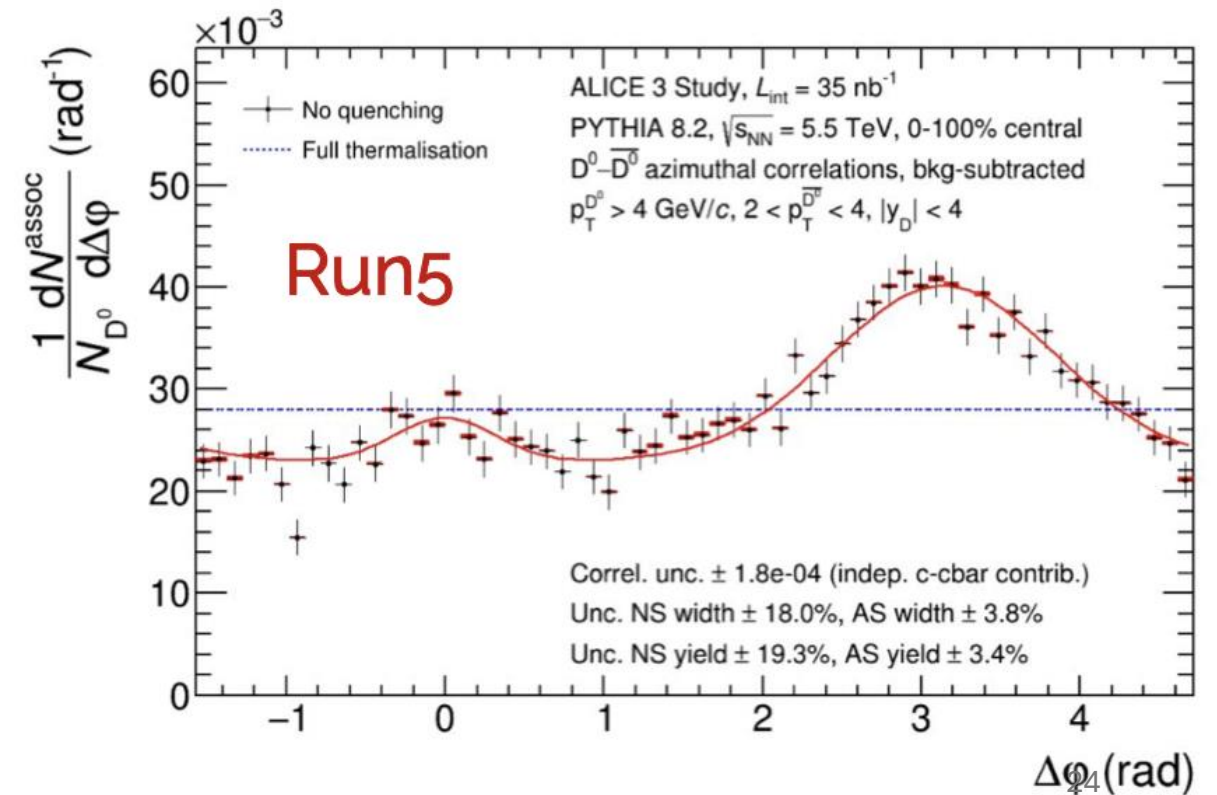
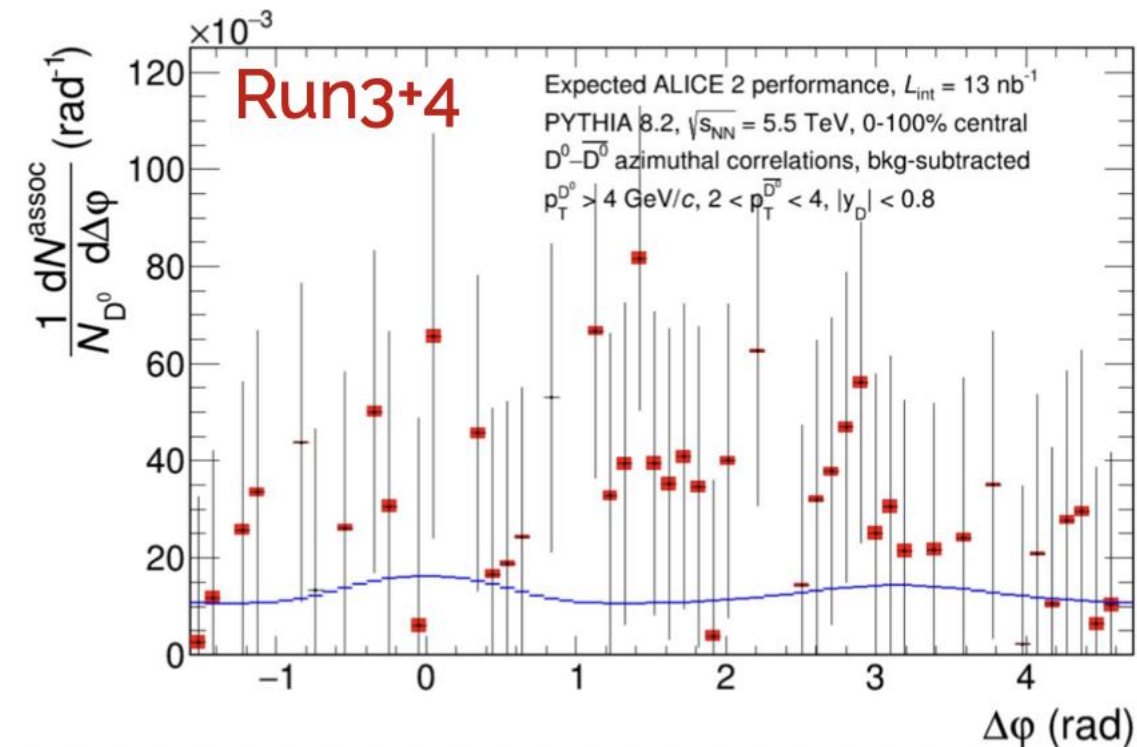
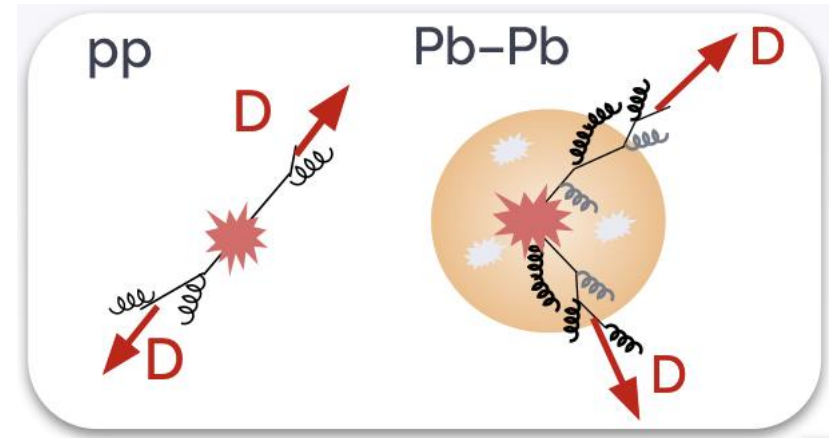
Detector Design

- Compact, ultra-light, high-resolution tracking
- Exceptional Particle ID
- Large acceptance (angular and momentum)

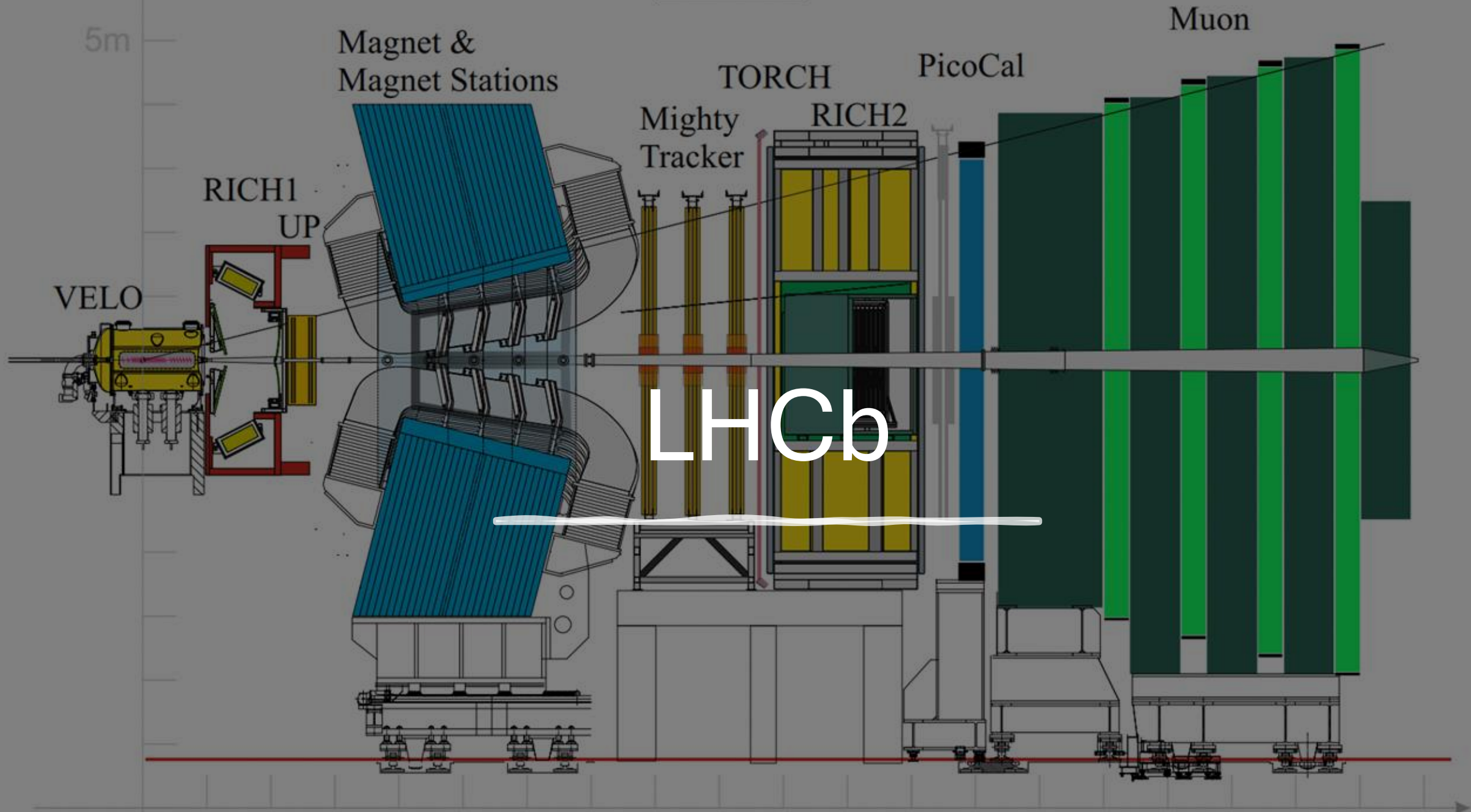


$D\bar{D}$ Angular Correlations

Sensitivity to charm energy loss and the degree of thermalization in the medium



Side View



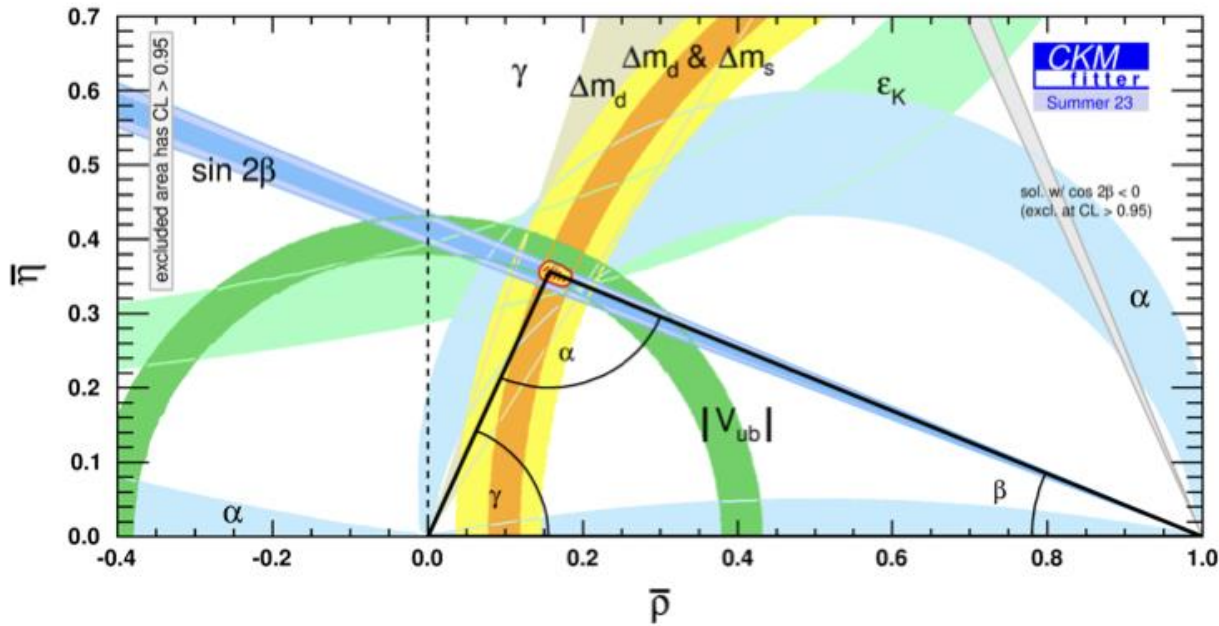
LHCb

LHCb Upgrade II

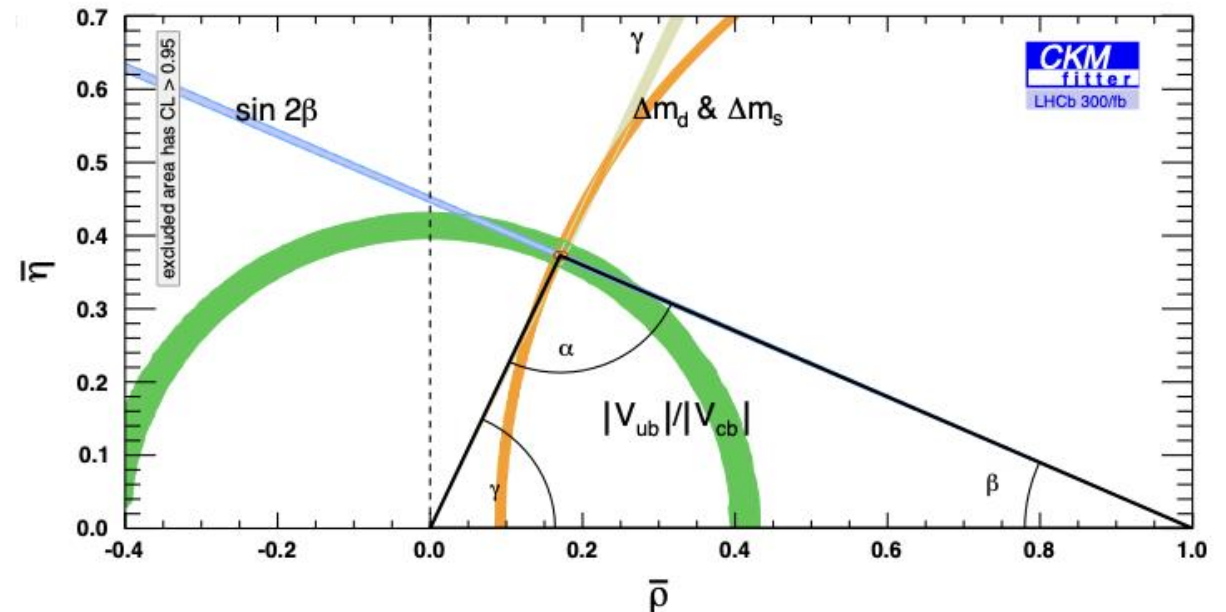


Run 3			LS3			Run 4					LS4		Run 5				
2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041
TDR phase			Construction phase					Installation		Exploitation							

SM Benchmarks: mapping out the CKM unitarity triangle



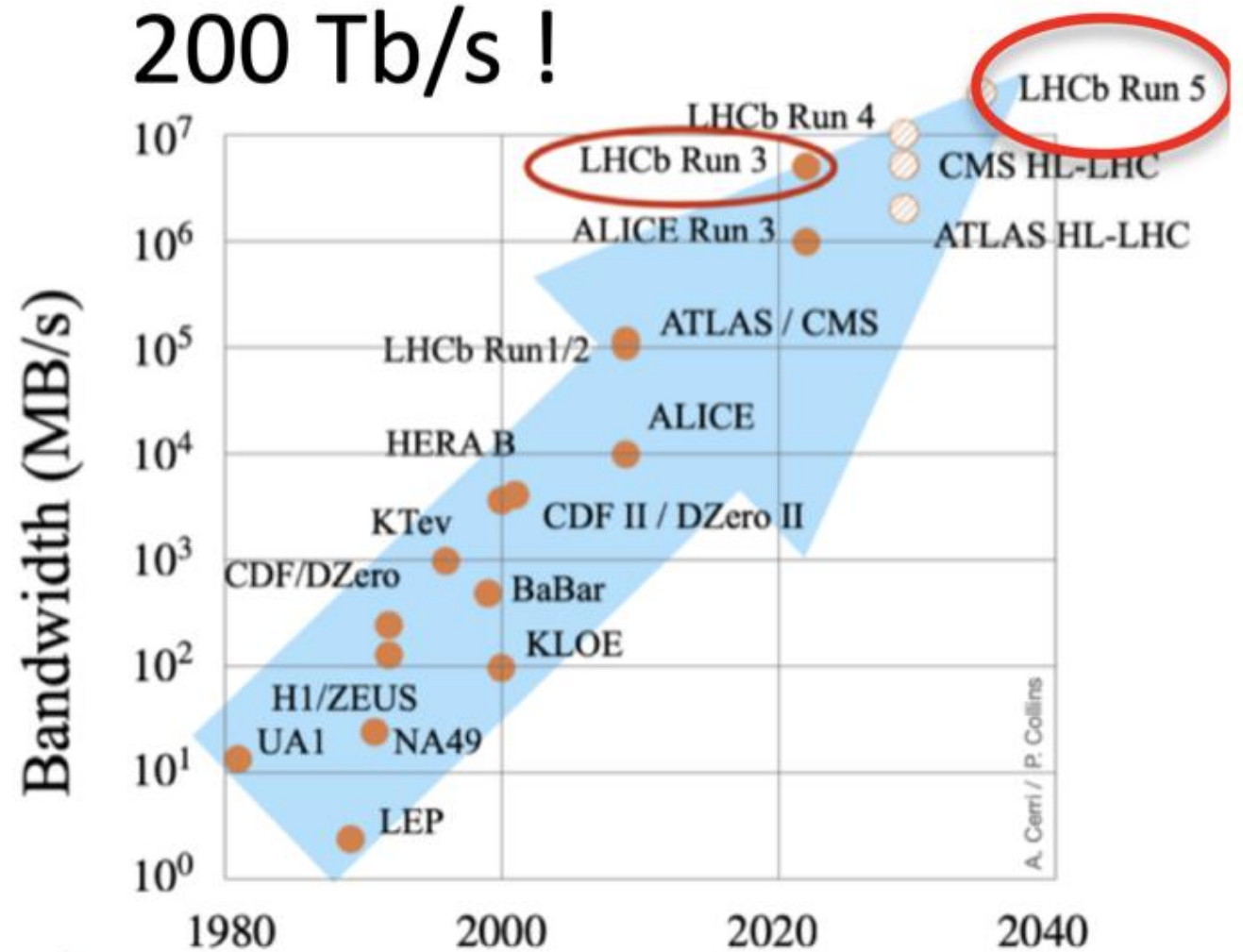
Physics Case (2019)



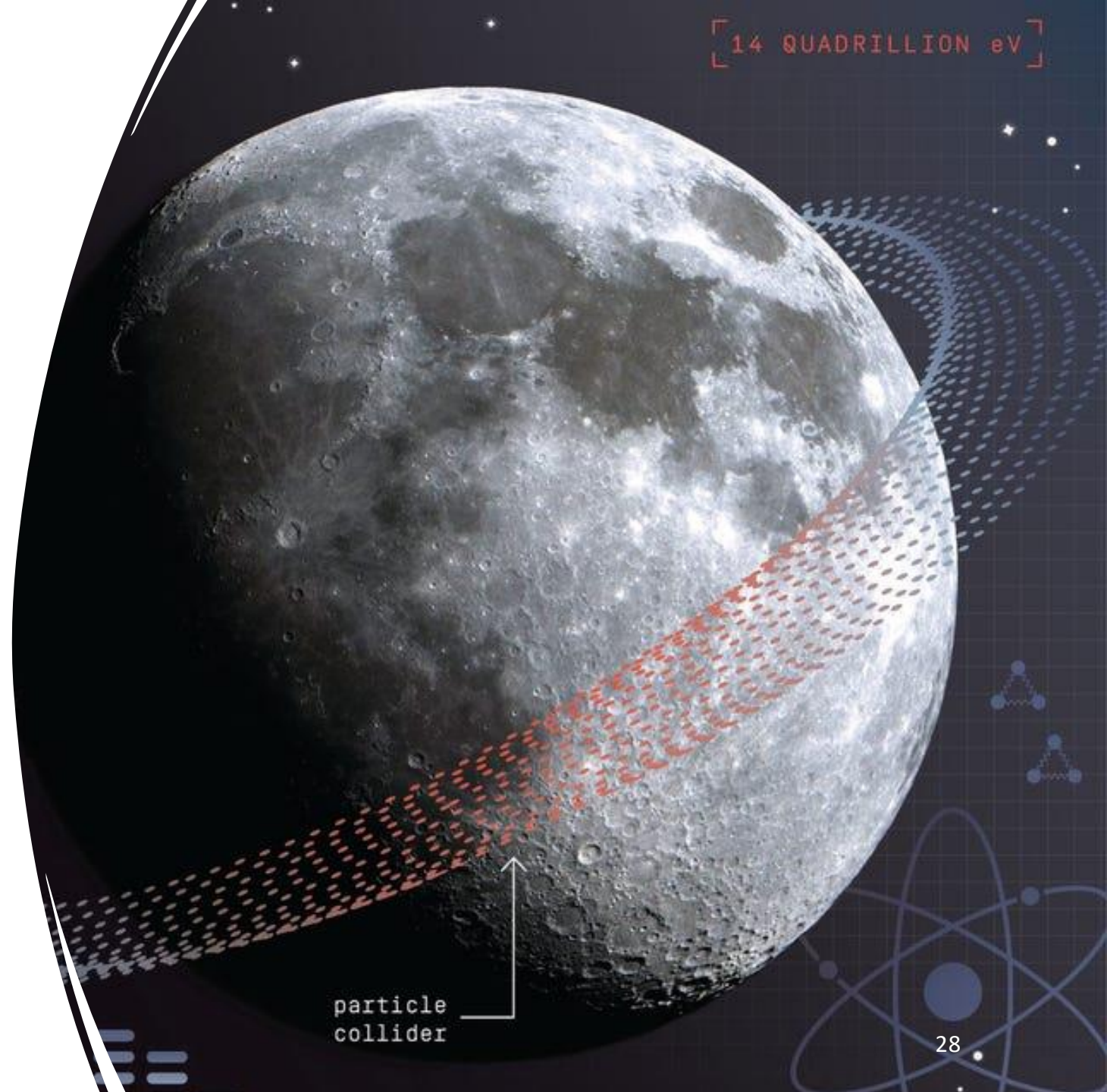
LHCb Upgrade II Scoping Document (2025)

Physics Program

- Establishing precision SM benchmarks
- New physics in CP violation
 - New Physics in charm
 - New Physics in rare decays
- Hadron Spectroscopy
- Dark sector and feebly interacting particles

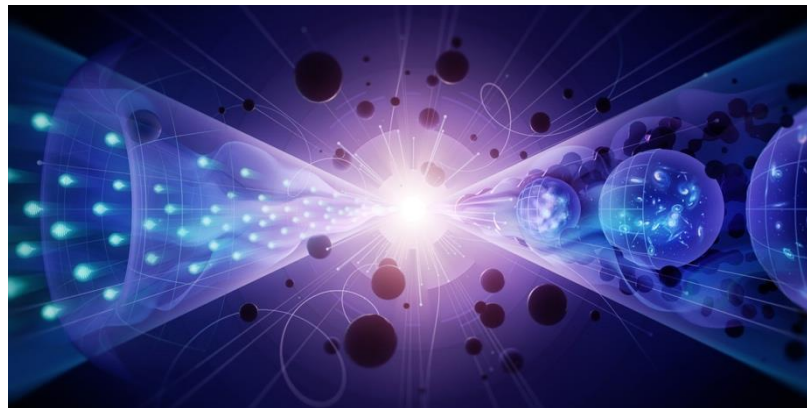


Future Colliders



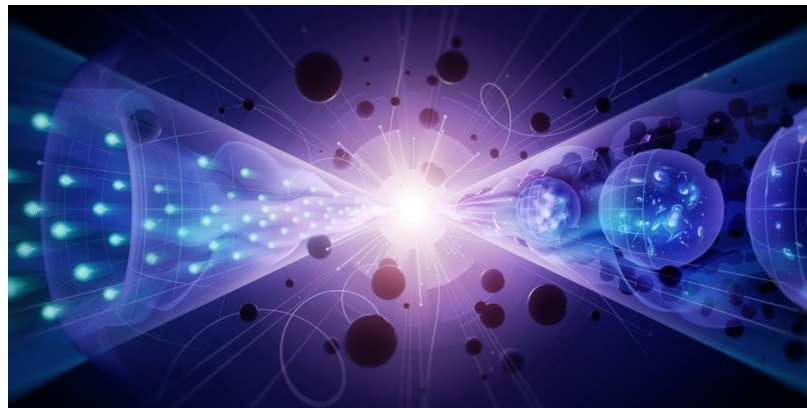
P5 Recommendation 2

An offshore Higgs factory: The current designs of FCC-ee and ILC meet our scientific requirements. The US should actively engage in feasibility and design studies. Once a specific project is deemed feasible and well-defined, the US should aim for a contribution at funding levels commensurate to that of the US involvement in the LHC and HL-LHC, while maintaining a healthy US onshore program in particle physics.



P5 Recommendation 4

A realistic path toward a 10 TeV pCM collider: Support vigorous R&D toward a cost-effective 10 TeV pCM collider based on proton, muon, or possible wakefield technologies, including an evaluation of options for US siting of such a machine, with a goal of being ready to build major test facilities and demonstrator facilities within the next 10 years.



European Strategy for Particle Physics



The electron–positron Future Circular Collider (FCC-ee) is recommended as the preferred option for the next flagship collider at CERN.

The FCC-ee would deliver the world’s broadest high-precision particle physics programme, ... Its technical feasibility is demonstrated... its scope and cost are well defined, plausible funding scenarios have been developed and its schedule enables first beams within five to seven years after the end of HL-LHC operations.

The FCC-ee would also pave the way towards a hadron collider reusing the tunnel and much of the infrastructure, providing direct discovery reach well beyond the 10 TeV parton energy scale, in line with the community’s ambition for exploration at the highest achievable energy.

Machine Comparison from the European Strategy Deliberation Document



Machine	Precision Physics	BSM physics	Physics vs CEPC	Technical readiness	Constr. cost (BCHF)	Time scale	Path to ≥ 10 TeV
FCC-ee	22	23			15.3	2046-2060	
Descoped FCC-ee	15	17			12.9	2046-2055	
LCF550	15	17			14.8	2045-2065	
CLIC1500	14	18			14.6	2045-2066	
LCF250	10	16			9.4	2045-2053	
CLIC380	10	16			7.5	2045-2054	
LEP3	15	17			4.1	2047-2062	
LHeC	8	7			2.1	2044-2051	



TOPIC: At CERN

Private donors pledge 860 million euros for CERN's Future Circular Collider

A consortium of private donors (individuals and philanthropic foundations) have agreed to support the proposed Future Circular Collider at CERN

—

18 December, 2025





SUISSE

FRANCE

Genève

Annecy

LHC

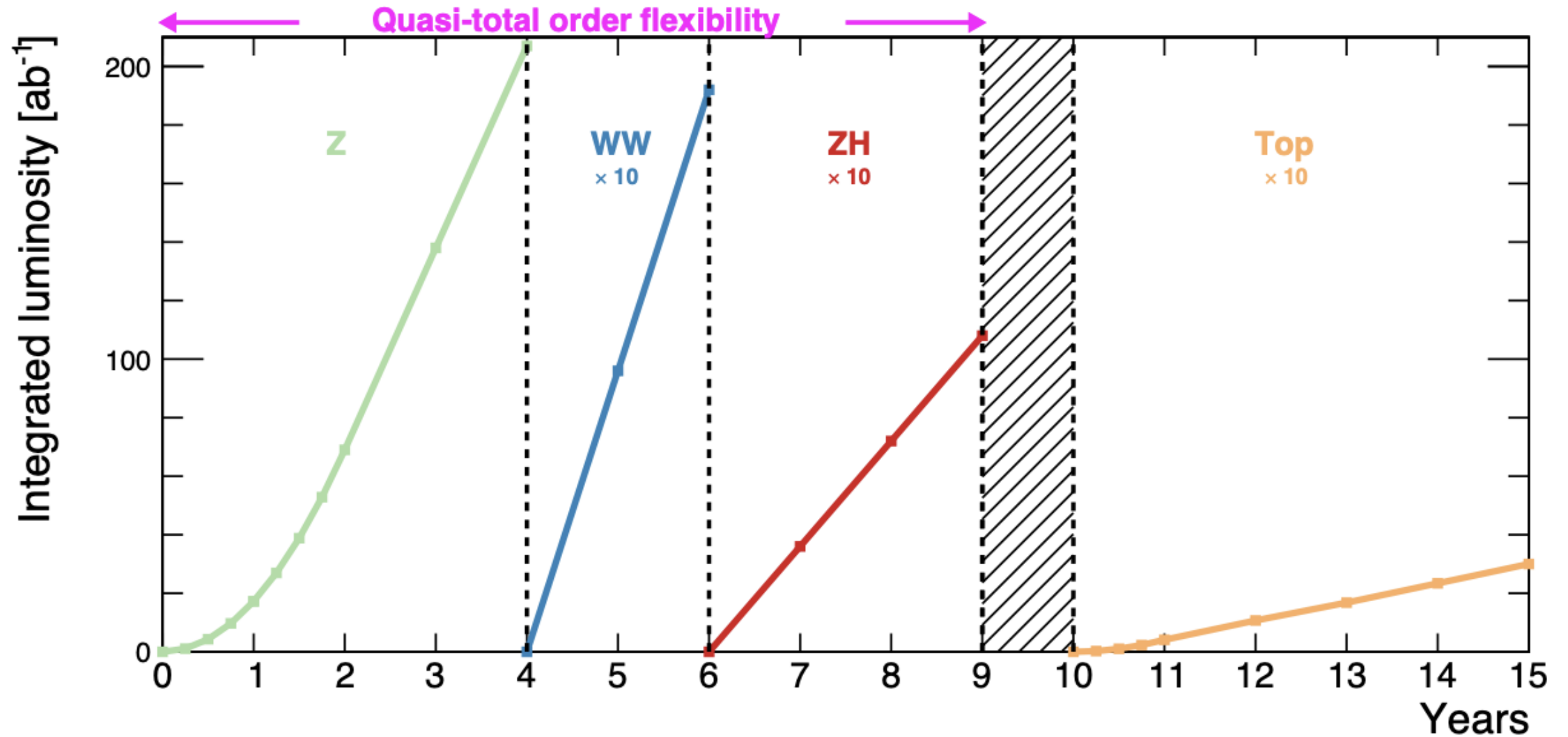
FCC

FCC-ee objectives include:

- **Measure the Higgs boson and other key particles with unmatched precision.**
- **Search for new particles, new forces and potential dark-matter candidates.**
- **Understand why matter dominates over antimatter in today's Universe.**
- **Explore entirely new phenomena through gains in precision and sensitivity.**



FCC-ee Feasibility Study: Example Program



FCC-ee Feasibility Study: Example Program

Z Production

$>5 \times 10^{11} Zs$

- Flavor physics
- QCD & hadronization
- Forbidden decays
- Z line shape
- Z invisible width
- Explore dark sector
- $\alpha_{QED}(m_Z), \alpha_s(m_Z)$
- ...

W⁺W⁻ Production

$>20 ab^{-1}$

- W mass / decay width
- # ν species
- α_s measurement
- ...

ZH Production

$>10 ab^{-1}$

- Per mil ZH coupling
- model-independent measurements of Higgs couplings from combination of its branching fractions and of the total ZH production cross section
- ...

$t\bar{t}$ Production

- Top quark mass
- ZH cross section dependence on \sqrt{s}
- Precision measurement of top electroweak couplings

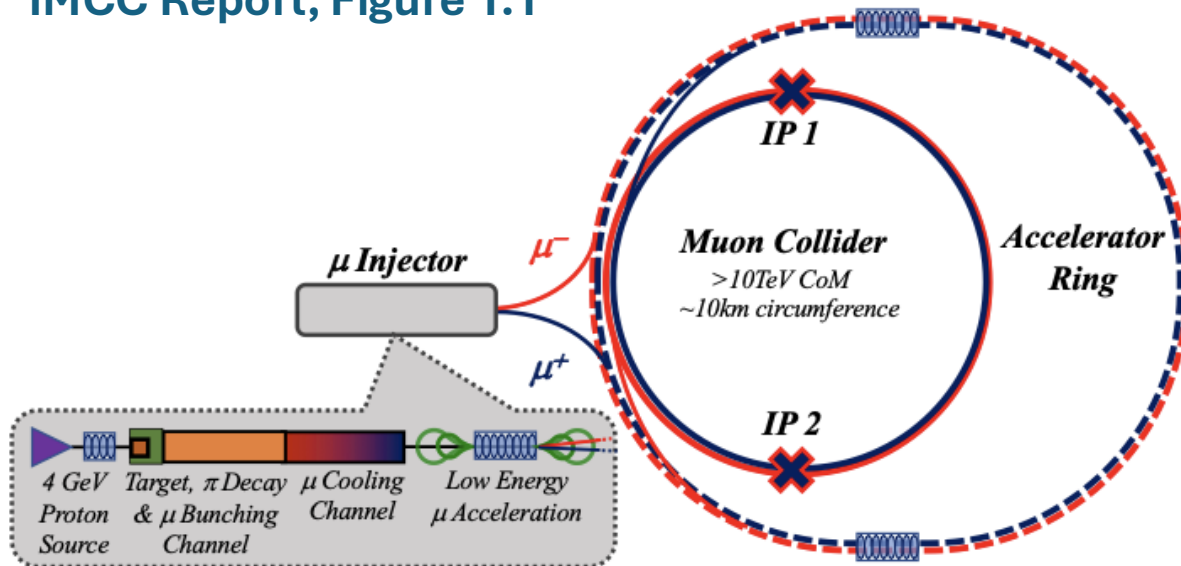
With four interaction points, there could be access to the Higgs coupling to electrons via the resonant production process $e^+e^- \rightarrow H @ \sqrt{s} = 125 GeV$

Substantial input from theory needed!

- Calculation of QED (mostly), EW, and QCD corrections to (differential) cross sections, needed to convert experimental measurements to so-called ‘pseudo-observables’: couplings, masses, partial widths, asymmetries, etc., without altering significantly the possible new-physics contributions in the original measurements. Appropriately accurate event generators are essential for the implementation of these effects in the experimental procedures.
- Calculation of the pseudo-observables with the precision required in the framework of the Standard Model so as to take full advantage of the experimental precision.
- Identification of the limiting issues, such as the questions related to the definition of parameters, in particular the treatment of quark masses and, more generally, QCD objects.
- Investigation of the sensitivity of the proposed (or new) experimental observables to the effect of new physics in a number of important, specific scenarios. This essential work must be done at an early stage, before the project is fully designed, since it potentially affects the priorities for detector concepts and for the running plan.

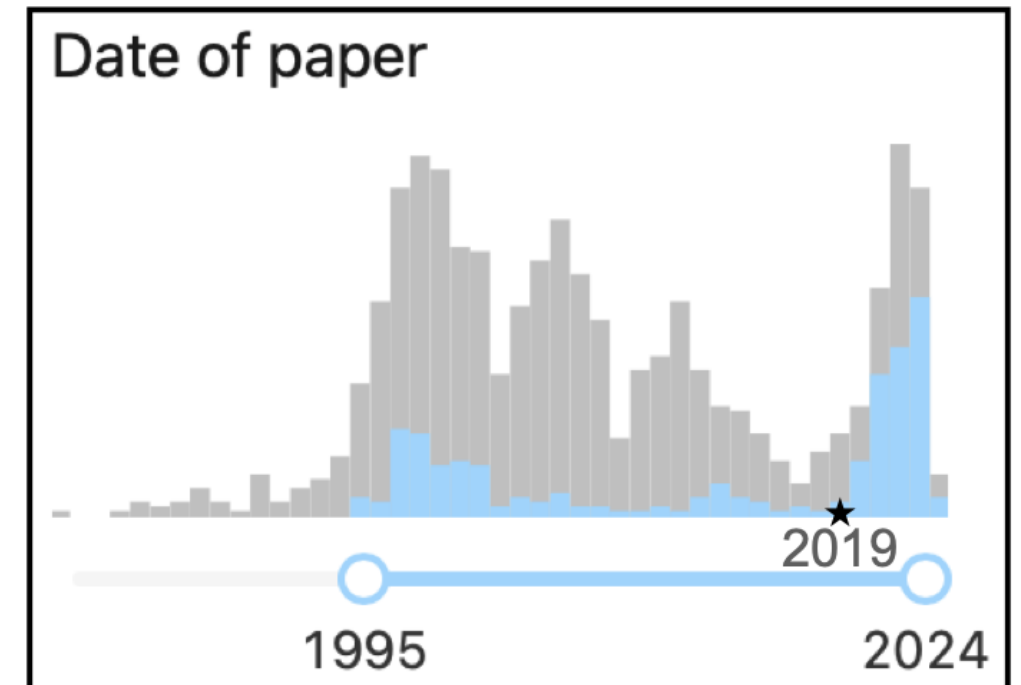
Muon Collider

IMCC Report, Figure 1.1



The muon collider offers a potential "small" footprint, and a landscape of technical challenges from the accelerators to the detectors to the analyses...

Muon collider papers used to be dominated by Accelerator studies, but [phenomenology/physics papers](#) have exploded...



IMCC Report, Figure 2.1

Muon Collider Physics

- **Direct Searches**

- Dark Matter, pair productions, resonances, VBF...

- **High-Rate Measurements**

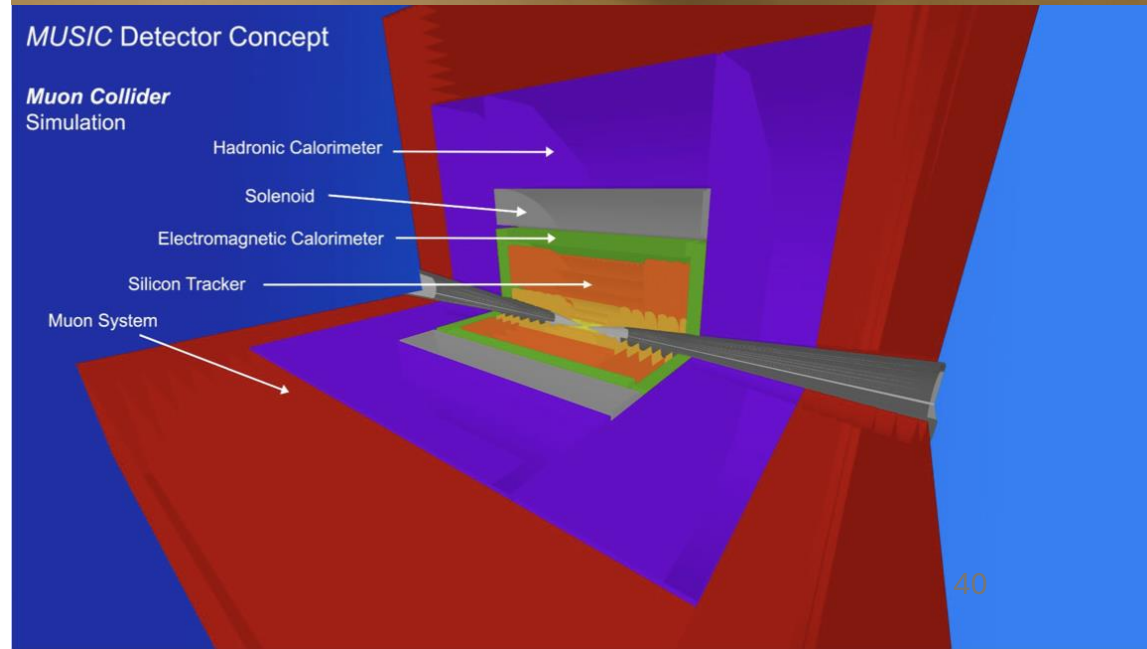
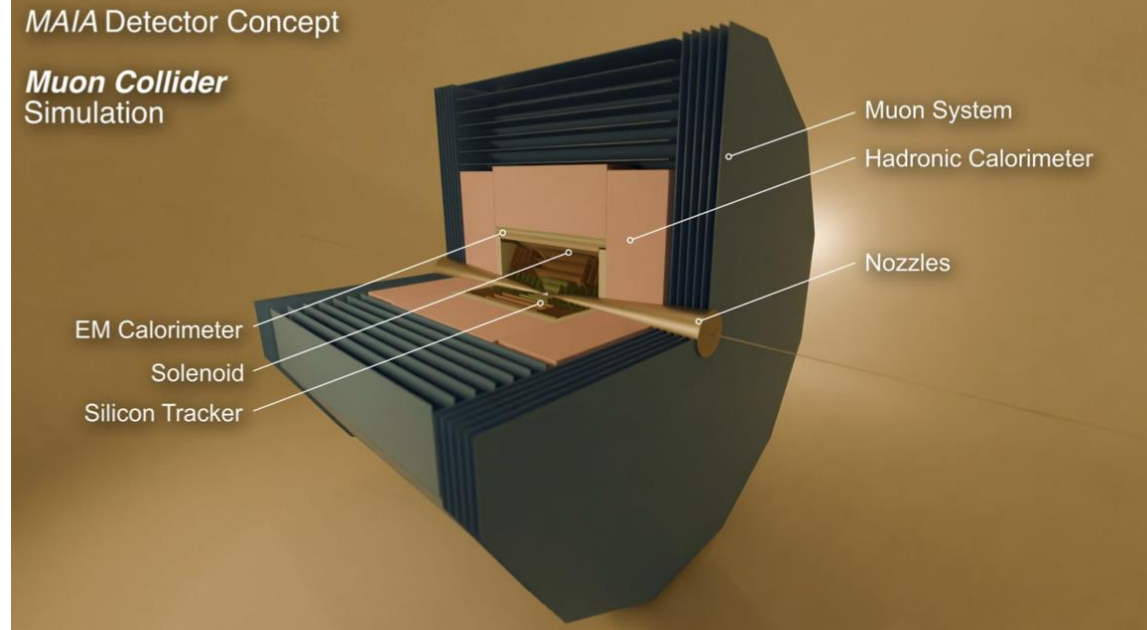
- Higgs self-coupling, rare and exotic Higgs decays, top quarks...

- **High-Energy Probes**

- di-boson, di-fermion, tri-boson, EFT, compositeness

- **Muon Physics**

- Lepton flavor universality, $b \rightarrow s\mu\mu$, muon $g-2$...



Looking ahead

- **The HL-LHC** brings an order of magnitude increase in data, with technological advances, an incredible playground for AI/ML, and real potential for **discovery** and **precision**.
- **Future Perspectives:**
 - There is unification behind the FCC-ee as the next machine. We will turn over every rock, probing the SM, searching for “forbidden” decays and measuring rare ones.
 - There is widespread agreement that a path toward 10 TeV pCM is needed
 - The FCC-ee provides the tunnel for an FCC-hh
 - Substantial excitement surrounding a muon collider from theorists, experimentalists, and accelerator physicists, needs small R&D investments to take the next steps



**Future discoveries will require energy, focus, determination, and compromise.
Our ability to keep taking the next step cannot be taken for granted.
It's all hands on deck!**