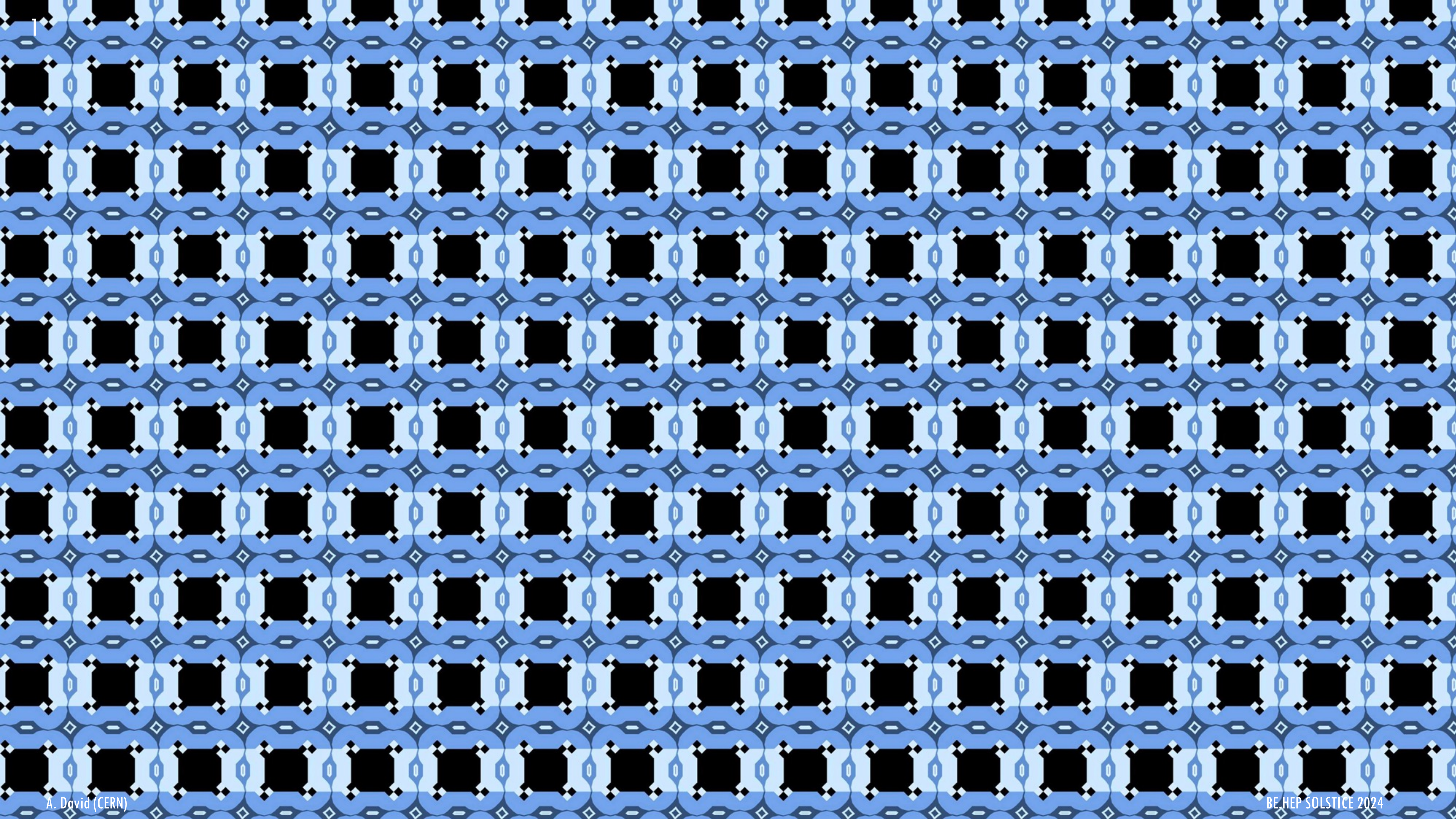
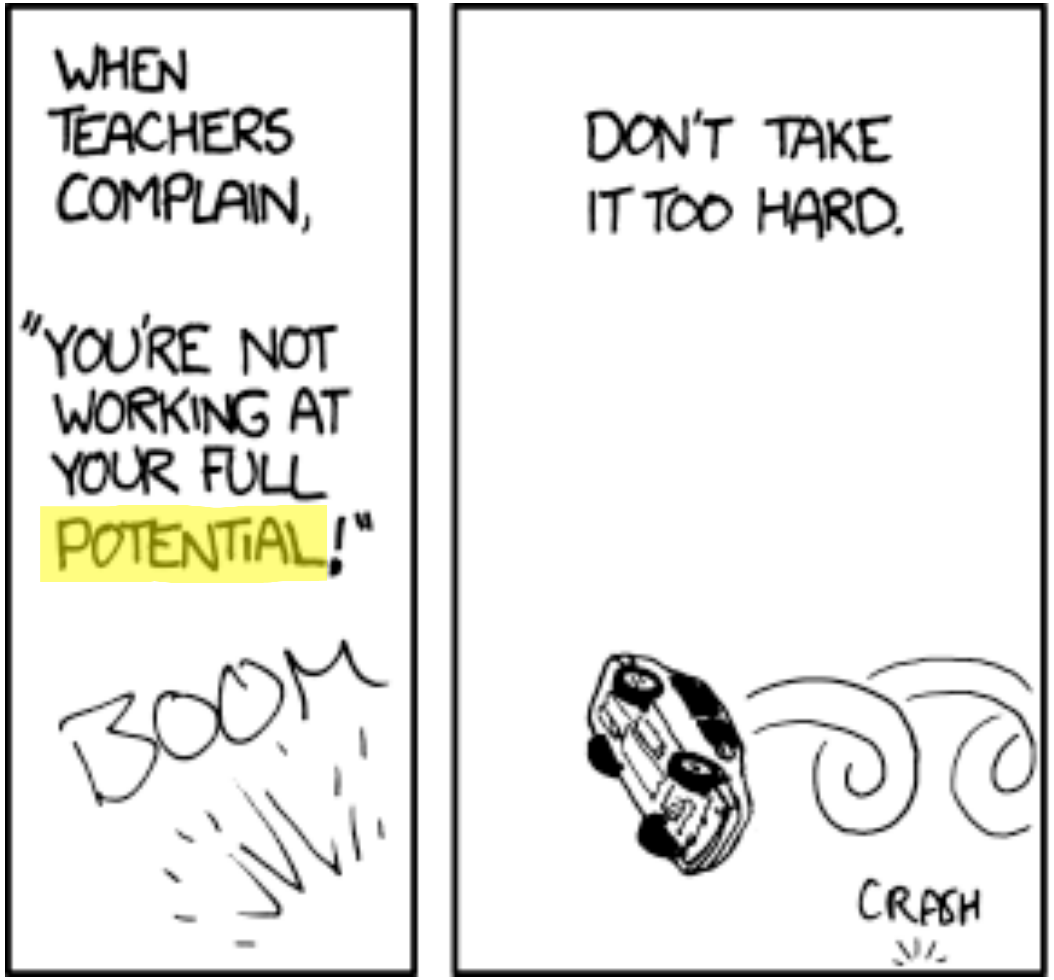


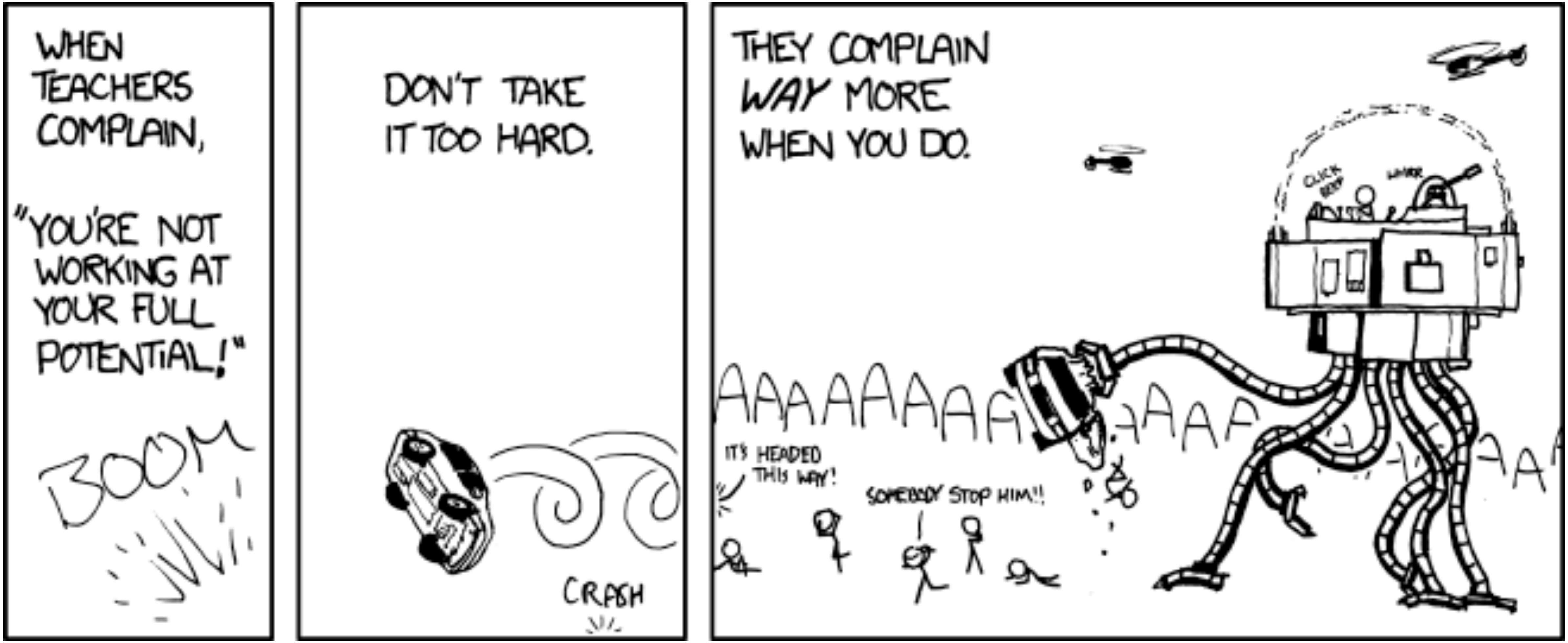
https://xkcd.com/987

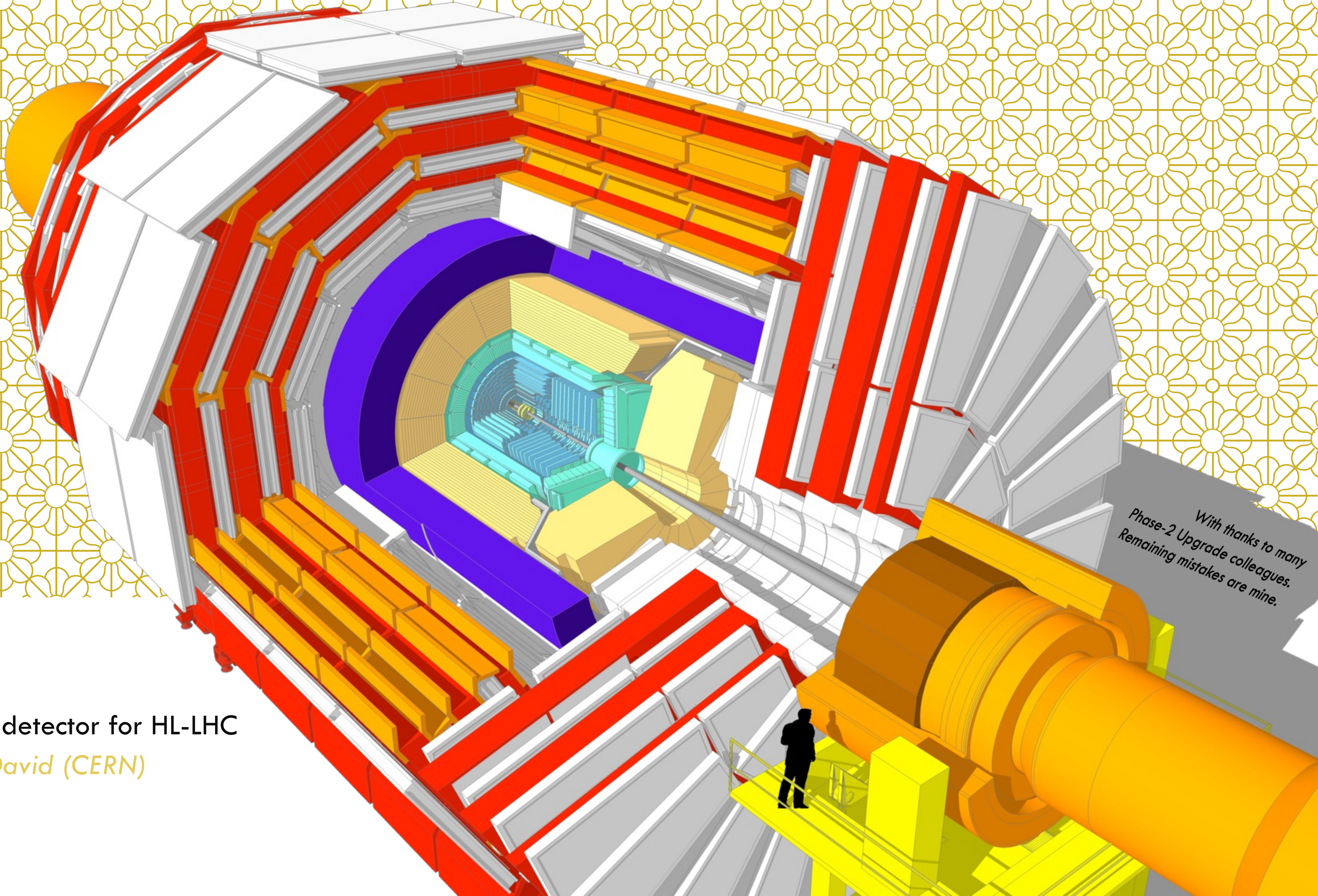
THE POTENTIAL OF...



https://xkcd.com/987

THE POTENTIAL OF WORKING AT YOUR FULL POTENTIAL





With thanks to many Phase-2 Upgrade colleagues.
Remaining mistakes are mine.

CMS 2

The detector for HL-LHC

A. David (CERN)

December 19, 2024

30 years CMS

1992	2002	2012	2022	2032	2042

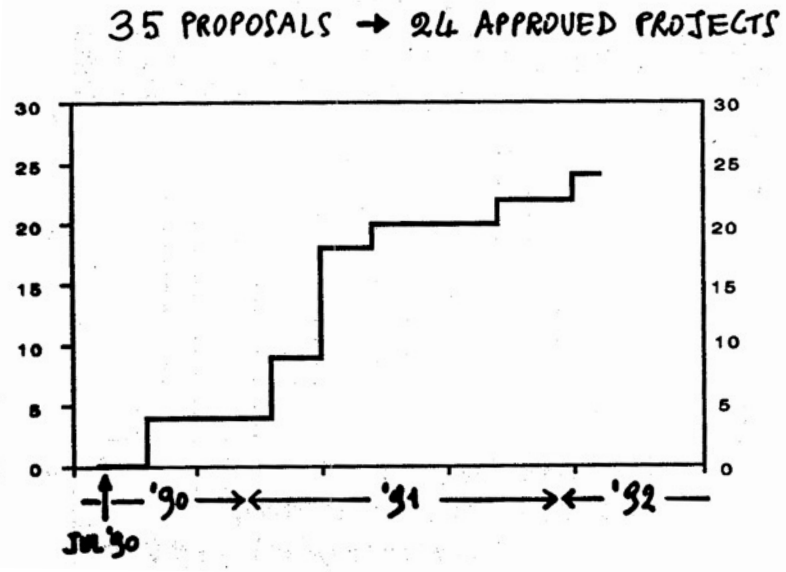
1992	2002	2012	2022	2032	2042

https://cds.cern.ch/record/236265
http://cds.cern.ch/record/247472
https://cds.cern.ch/record/1133994

NO DETECTORS, NO PHYSICS INSIGHTS

DRDC

- With the LHC becoming a real project, the CERN management suggested at the beginning of 1990, to establish a Detector Research and Development Committee (DRDC). It was considered too early to move already then to the EOI stage, on the other hand it was clear that a significant amount of detector R&D had to be done and that it should be done in the most cost effective way. The DRDC was therefore asked to evaluate (peer review) R&D proposals, with the main emphasis on detector system development, stimulating collaboration and avoiding duplication of efforts.



https://commission.europa.eu/topics/strengthening-european-competitiveness/eu-competitiveness-looking-ahead_en

NO DETECTORS, NO PHYSICS INSIGHTS

The CERN success story

A notable example of the remarkable returns from the joint collaboration of European countries is the creation of the European Organization for Nuclear Research (CERN) in 1954. CERN started with an initial coalition of 12 European countries. Today, it comprises 23 European Member States, along with 11 non-European Associate Member States and 4 Observers (the EU, UNESCO, Japan, and the US). CERN made it possible to set up and sustain investment in high-energy physics research that any single European country would have regarded as unsustainable over such a prolonged period of time. The pooling of country-specific resources allowed single countries to share the considerable risks and uncertainty inherent to fundamental innovative research. Its collaborative effort has yielded remarkable successes, including two most notable discoveries: the invention of the World Wide Web, invented at CERN 35 years after its inception, and the discovery of the Higgs Boson particle, announced on 4 July 2012. CERN scientific leadership spans various domains, including superconductivity, magnets, vacuum, radio frequency, precision mechanics, electronics, instrumentation, software, computing and Artificial Intelligence. CERN's technologies have generated significant societal benefits, including advancements in cancer therapy, medical imaging, autonomous driving with artificial intelligence, and environmental applications of superconducting cables.

The Large Hadron Collider has propelled CERN to global leadership in particle physics – a mantle that has shifted from the US to Europe – and it stands as CERN's flagship facility. One of CERN's most promising current projects, with significant scientific potential, is the construction of the Future Circular Collider (FCC): a 90-km ring designed initially for an electron collider and later for a hadron collider. Chinese authorities are also considering constructing a similar accelerator in China, recognising its scientific potential and its role in advancing cutting-edge technologies. If China were to win this race and its circular collider were to start working before CERN's, Europe would risk losing its leadership in particle physics, potentially jeopardising CERN's future.

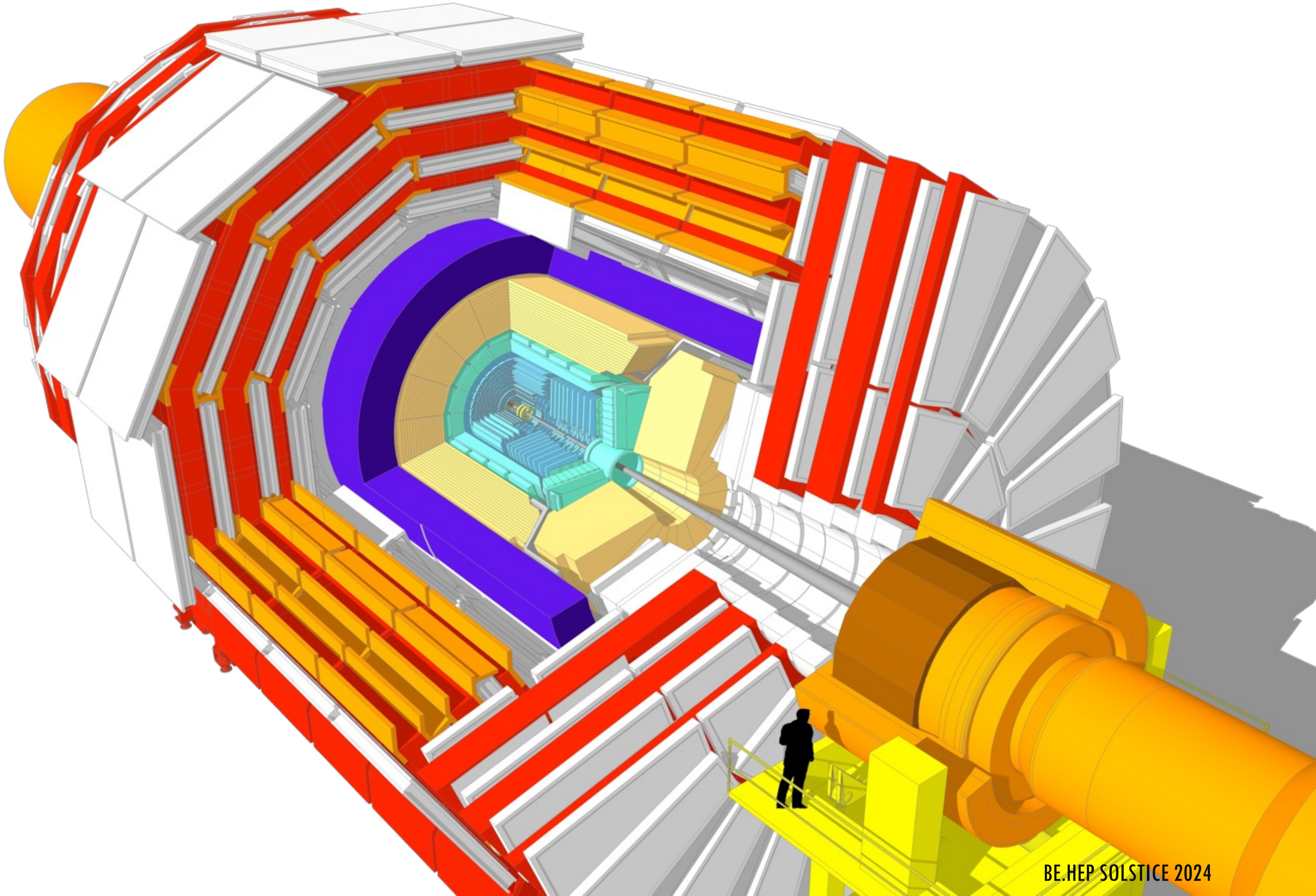
HL-LHC: BEYOND PRESENT DETECTOR ABILITY

Pile-up target of 200,
for 10 years:

- Cannot resolve vertex density.
- Cannot sustain radiation levels.

Reined in through:

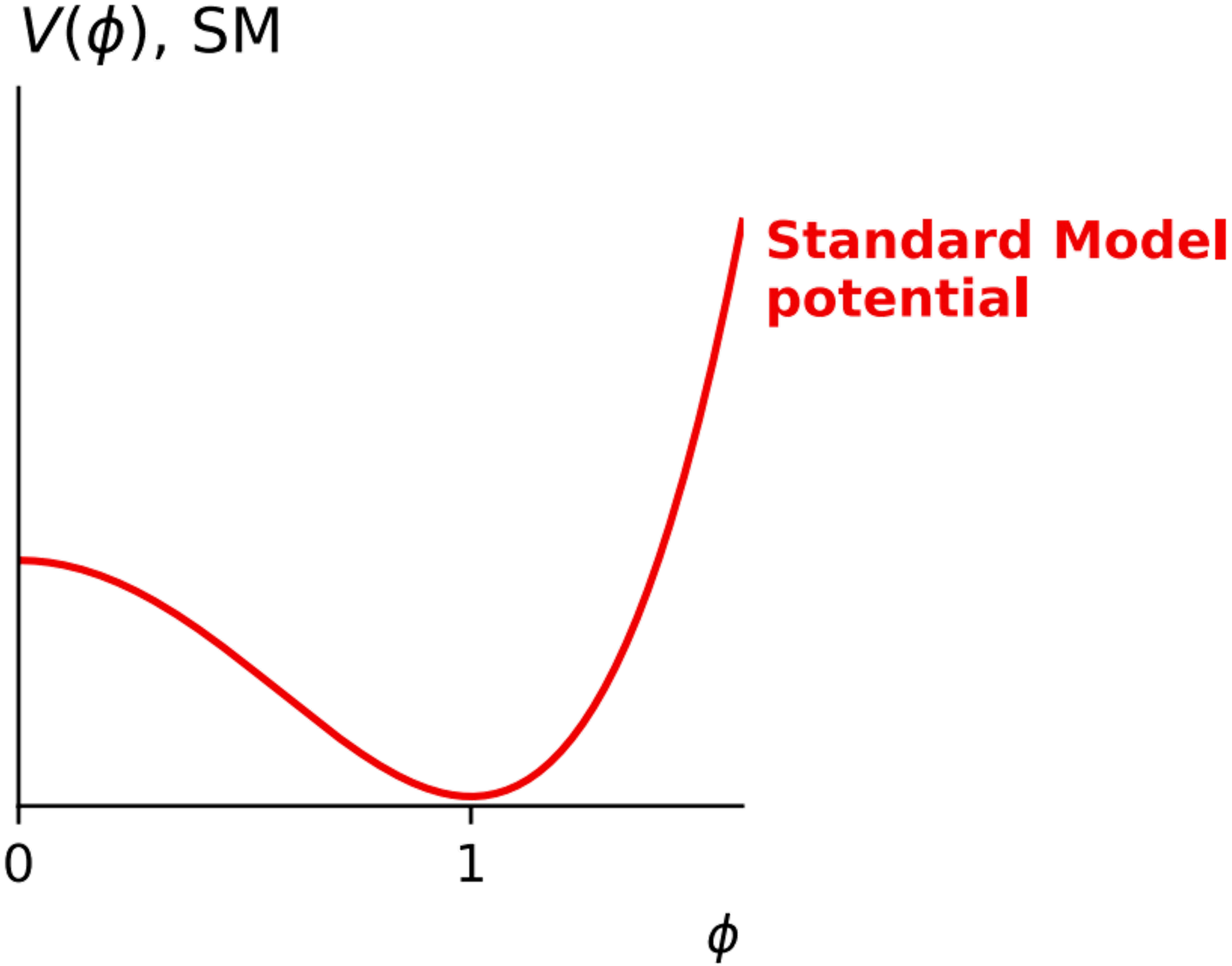
- **Higher radiation tolerance.**
- Better **3D granularity.**
- **O(50 ps)** timing precision (3D → 4D).
- **More information at trigger level.**
- **Computing that can make use of** all this additional information.



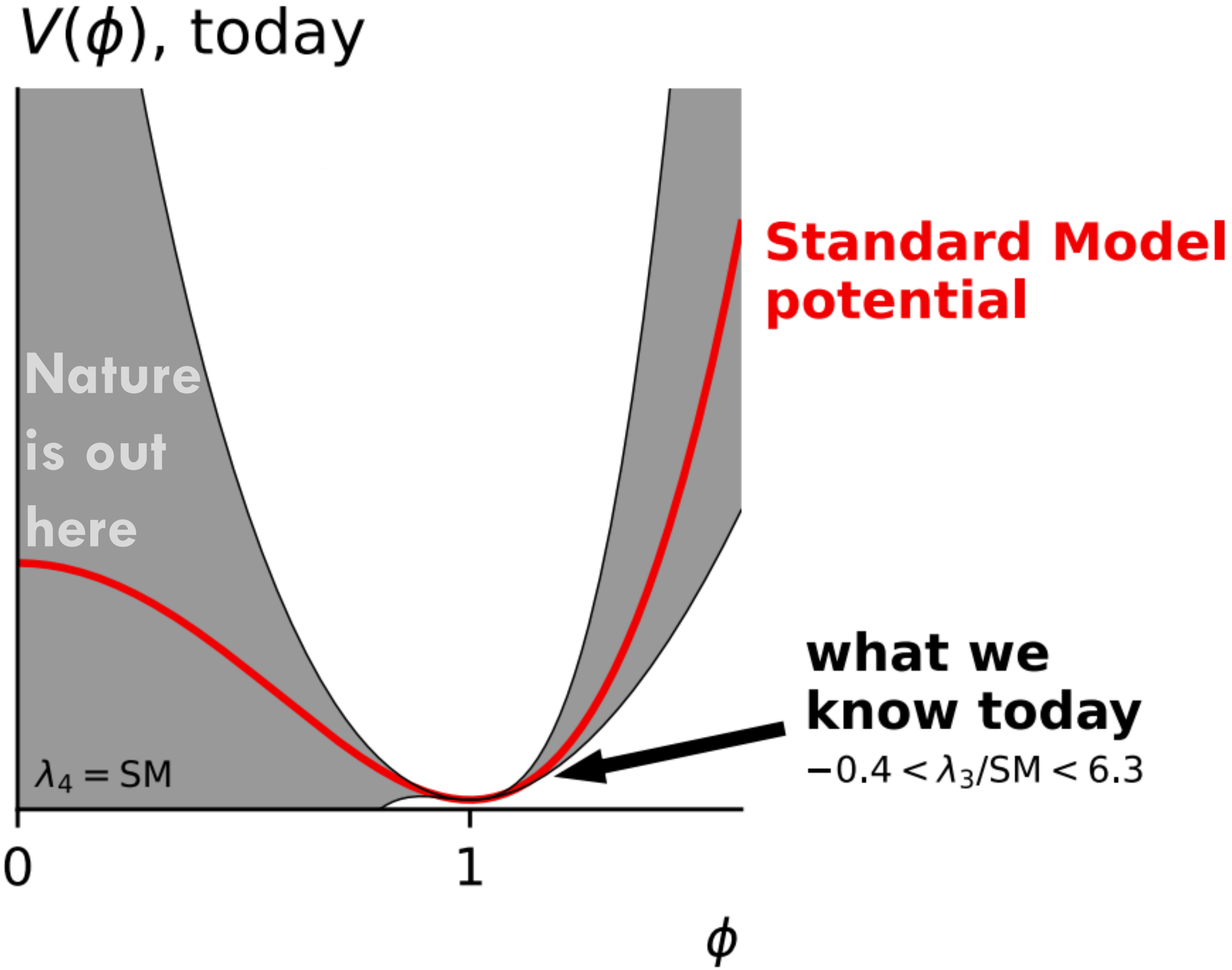
A POTENTIAL WHY

$$V_{\rm SM}(h) = \frac{m_h^2}{2}\, h^2 + \frac{m_h^2}{2v} h^3 + \frac{m_h^2}{8v^2} h^4$$

THE SHAPE ACCORDING TO **SOME THEORY**



THE SHAPE OF THINGS IN NATURE AFTER A DECADE



Caveats:
This is a cartoon. E.g. realistic BSM models do not just modify the potential, but may bring extra scalars.
Even if we take the picture seriously, we may want to consider impact of limited constraints on λ_4.

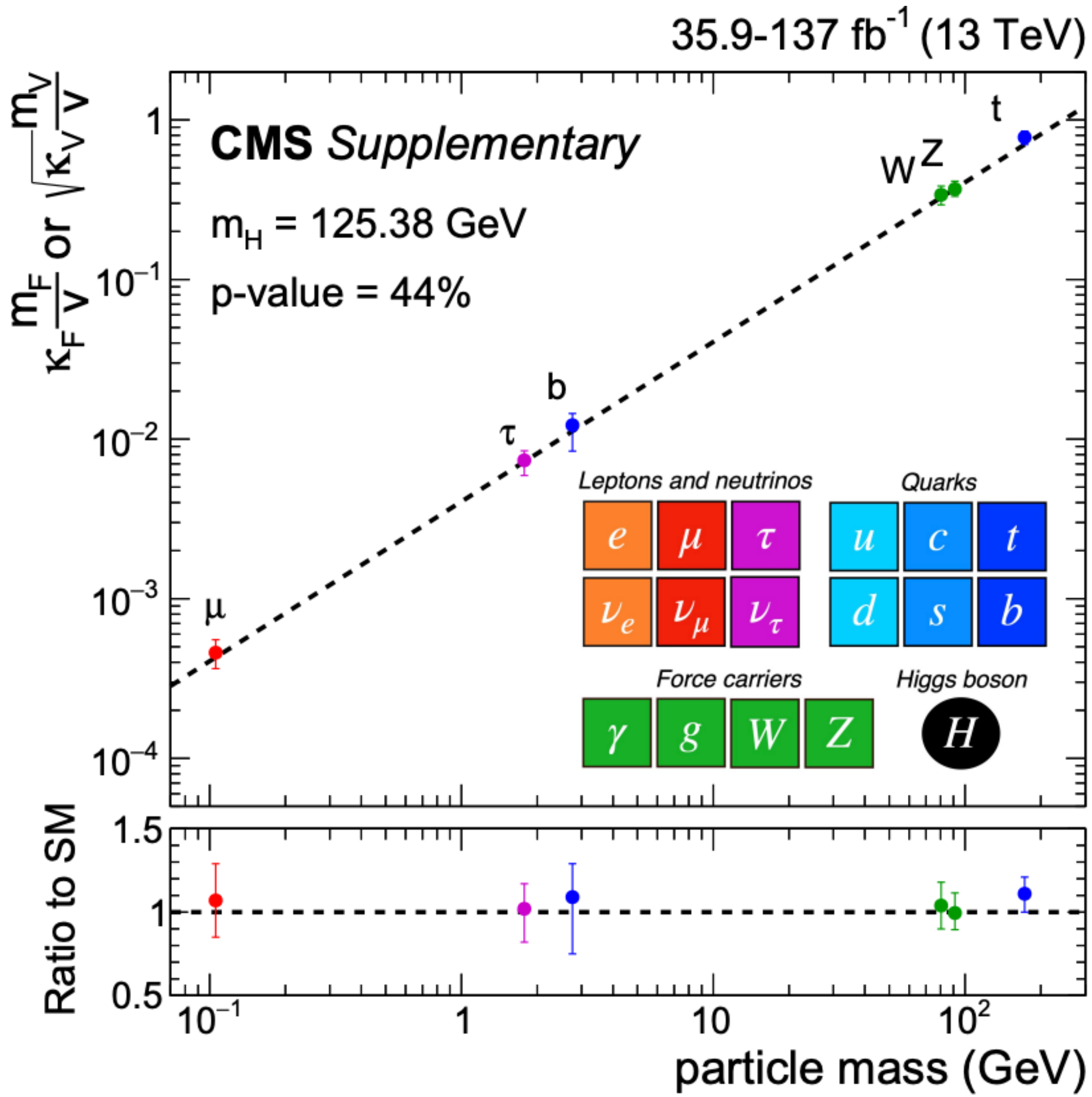
$$V_{\mathrm{SM}}(h) = \frac{m_h^2}{2} h^2 + \frac{m_h^2}{2v} h^3 + \frac{m_h^2}{8v^2} h^4$$

Since 2012

https://inspirehep.net/literature/2721493

$$V_{\mathrm{SM}}(h) = \frac{m_h^2}{2} h^2 +$$

Since 2012



$$V_{\mathrm{SM}}(h) = \frac{m_h^2}{2} h^2 + \frac{m_h^2}{2v} h^3 + \frac{m_h^2}{8v^2} h^4$$

Since 2012

Beyond 2042

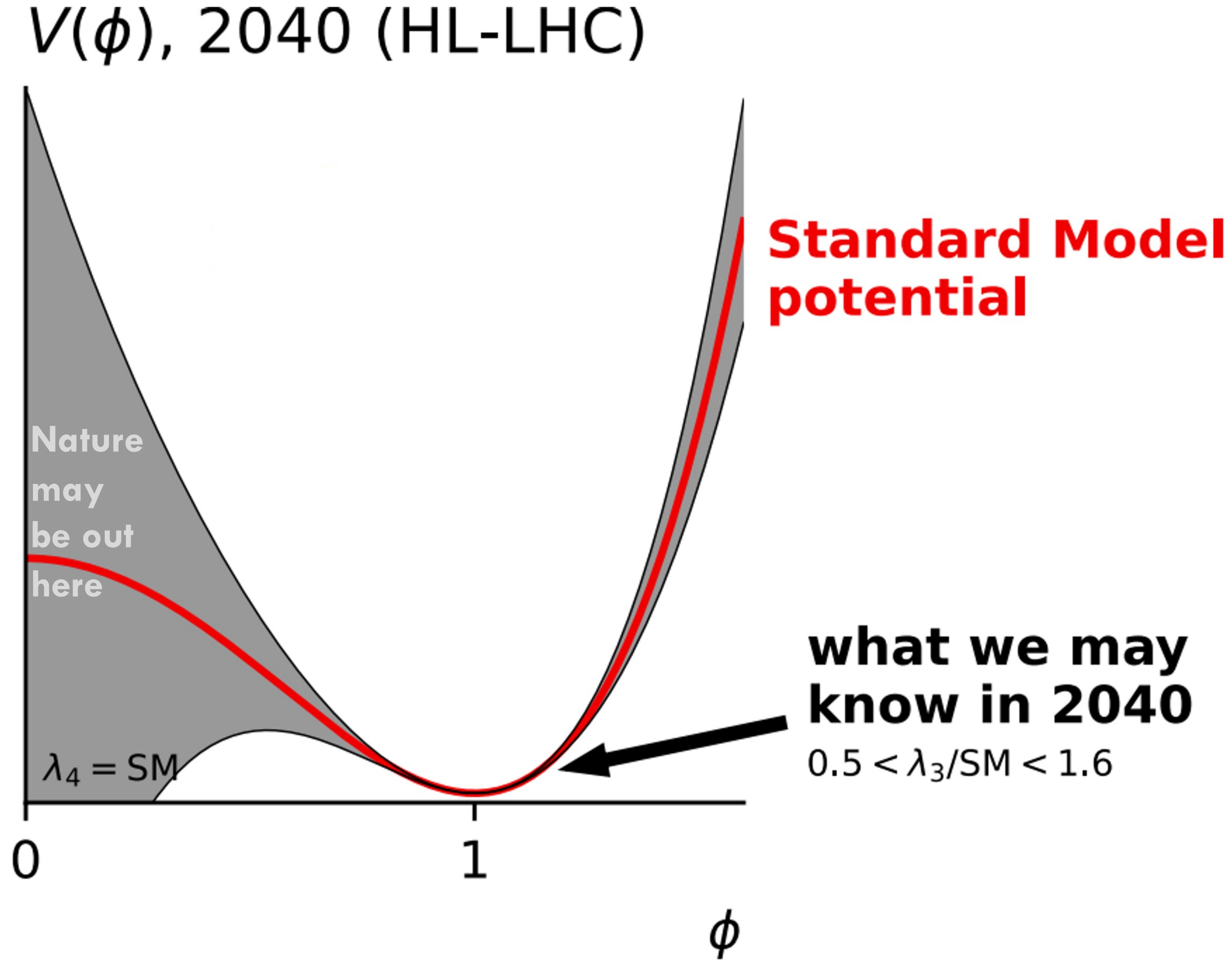
$$V_{\rm SM}(h) = \frac{m_h^2}{2} h^2 + \frac{m_h^2}{2v} h^3 + \frac{m_h^2}{8v^2} h^4$$

Since 2012

The detector for HL-LHC

Beyond 2042

SHAPING THINGS TO COME



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Since 2012

The detector for HL-LHC

Beyond 2042

$$V_{\mathrm{SM}}(h) = \frac{m_h^2}{2}h^2 + \frac{m_h^2}{2v}h^3 + \frac{m_h^2}{8v^2}h^4$$

Since
2012

The detector
for HL-LHC that can handle anything
Nature may have in store !

Beyond

https://inspirehep.net/literature/585092

22 YEARS AGO

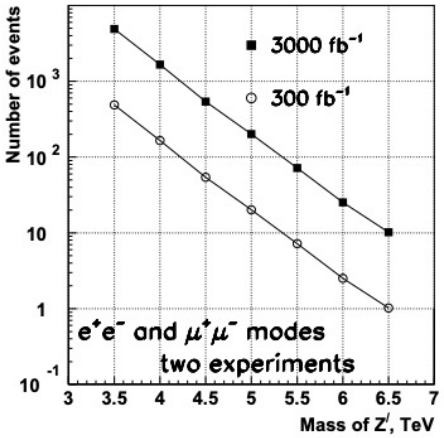
CERN-TH/2002-078
hep-ph/0204087
April 1, 2002

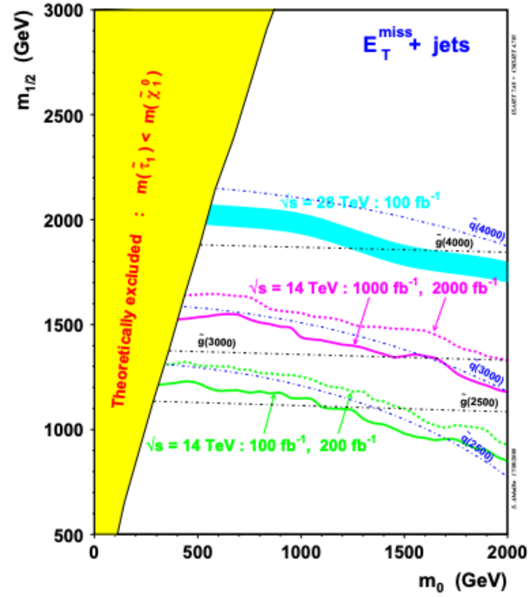
PHYSICS POTENTIAL AND EXPERIMENTAL CHALLENGES OF THE LHC LUMINOSITY UPGRADE

Conveners: F. Gianotti [1], M.L. Mangano [2], T. Virdee [1,3]

Table 8: Expected numbers of signal and background events after all cuts for the $gg \to HH \to 4W \to \ell^+\ell'^+ 4j$ final state, for $\int \mathcal{L} = 6000\ \text{fb}^{-1}$.

m_H	Signal	$t\bar{t}$	$W^\pm Z$	$W^\pm W^+ W^-$	$t\bar{t}W^\pm$	$t\bar{t}t\bar{t}$	$S/\sqrt{B}$
170 GeV	350	90	60	2400	1600	30	5.4
200 GeV	220	90	60	1500	1600	30	3.8





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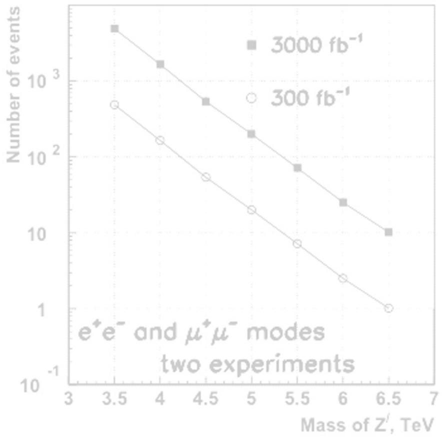

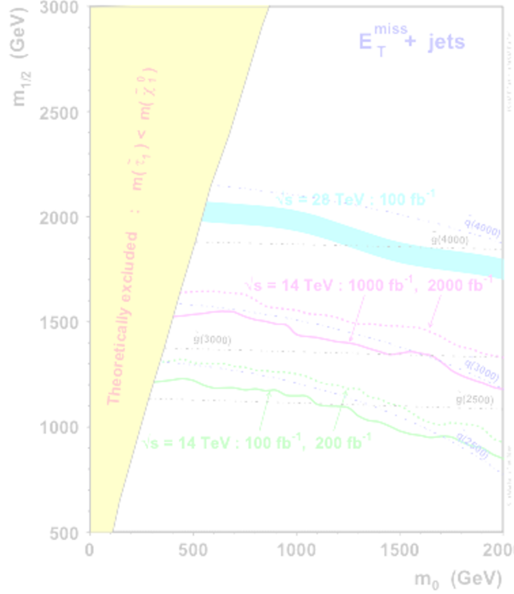

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PHYSICS POTENTIAL AND EXPERIMENTAL CHALLENGES OF THE LHC LUMINOSITY UPGRADE

Conveners: F. Gianotti [1], M.L. Mangano [2], T. Virdee [1,3]

Faster bunch crossing.
Running the actual electronics at 80MHz is impossible.

b) Trigger rates
The increased event size reduces the maximum allowed level-1 rate for fixed readout bandwidth. This suggests that one should perhaps try at least to avoid increasing level-1 rate beyond the maximum of 100 kHz presently envisaged in ATLAS and CMS. Such a strategy appears to be possible, as discussed later, but implies raising the transverse-momentum thresholds on candidate electrons, photons, muons,

Table 17: Hadron fluence and radiation dose in different radial layers of the CMS Tracker (barrel part) for an integrated luminosity of 2500 fb^{-1}.

Radius (cm)	Fluence of fast hadrons ($10^{14}cm^{-2}$)	Dose (kGy)	Charged Particle Flux ($cm^{-2}s^{-1}$)
4	160	4200	5×10^8
11	23	940	10^8
22	8	350	3×10^7
75	1.5	35	3.5×10^6
115	1	9.3	1.5×10^6

We conclude that the only viable solution is to completely rebuild the Inner Detector systems of ATLAS and CMS.

…among other omens.

https://indico.cern.ch/event/41587/contributions/1008853

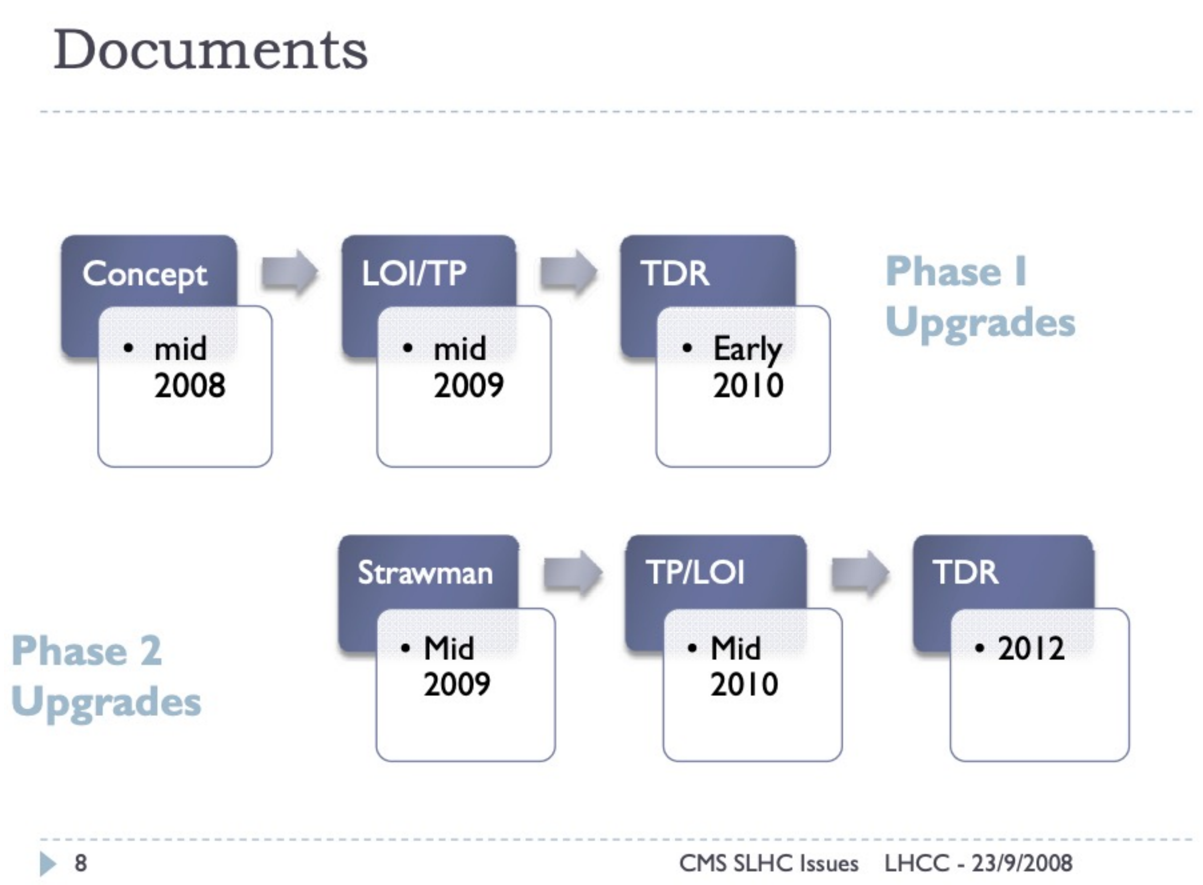
16 YEARS AGO IN CMS

2008

Upgrade Scope

System	Phase I	Phase 2
Pixel	New Pixel Detector (1 or 2 iterations?)	
Tracker	FEDs?	New Tracking System (incl Pixel)
HCAL	Electronics + PD replacement	HF/HE?
ECAL	TP (Off Detector Electronics) ?	EE?
Muons	ME4/2, ME1/1 ,RPC endcap, Minicrate spares, some CSC Electronics	Electronics replacement
Trigger	HCAL/RCT/GCT to μTCA	Complete replacement

7 CMS SLHC Issues LHCC - 23/9/2008



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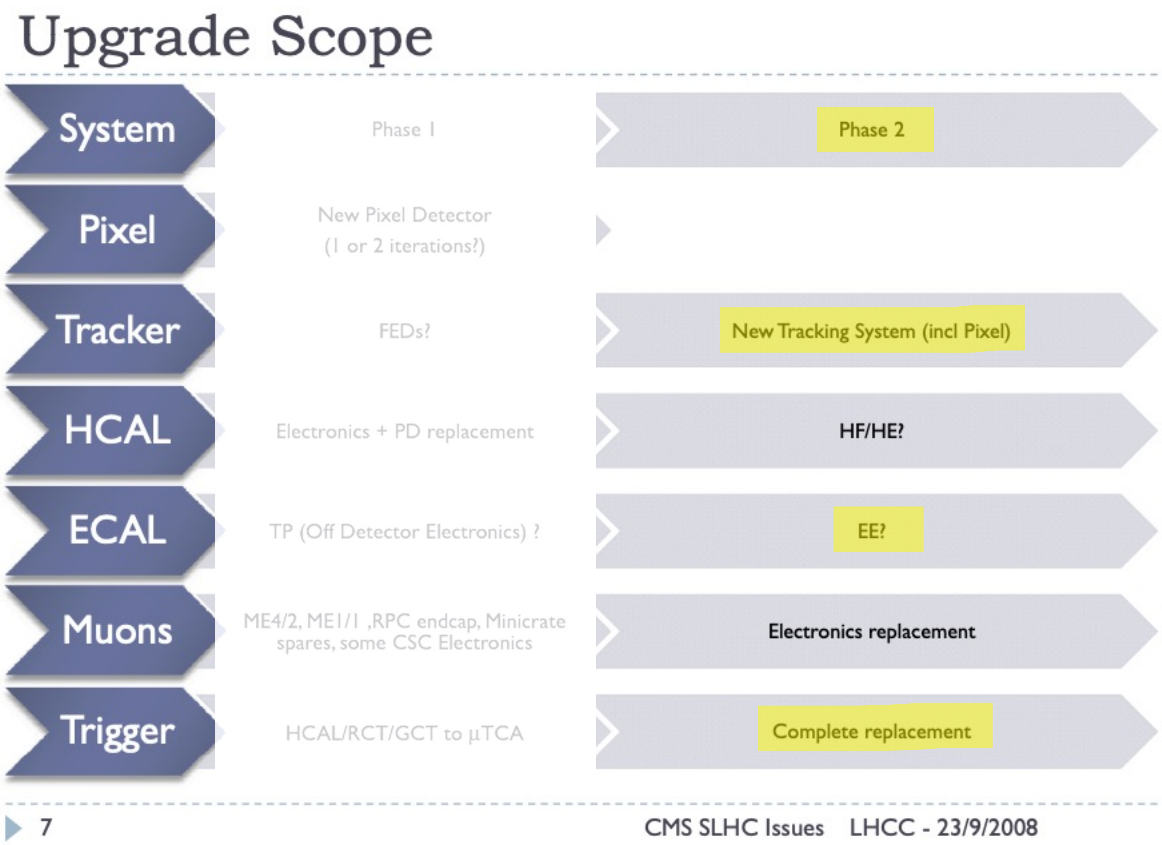
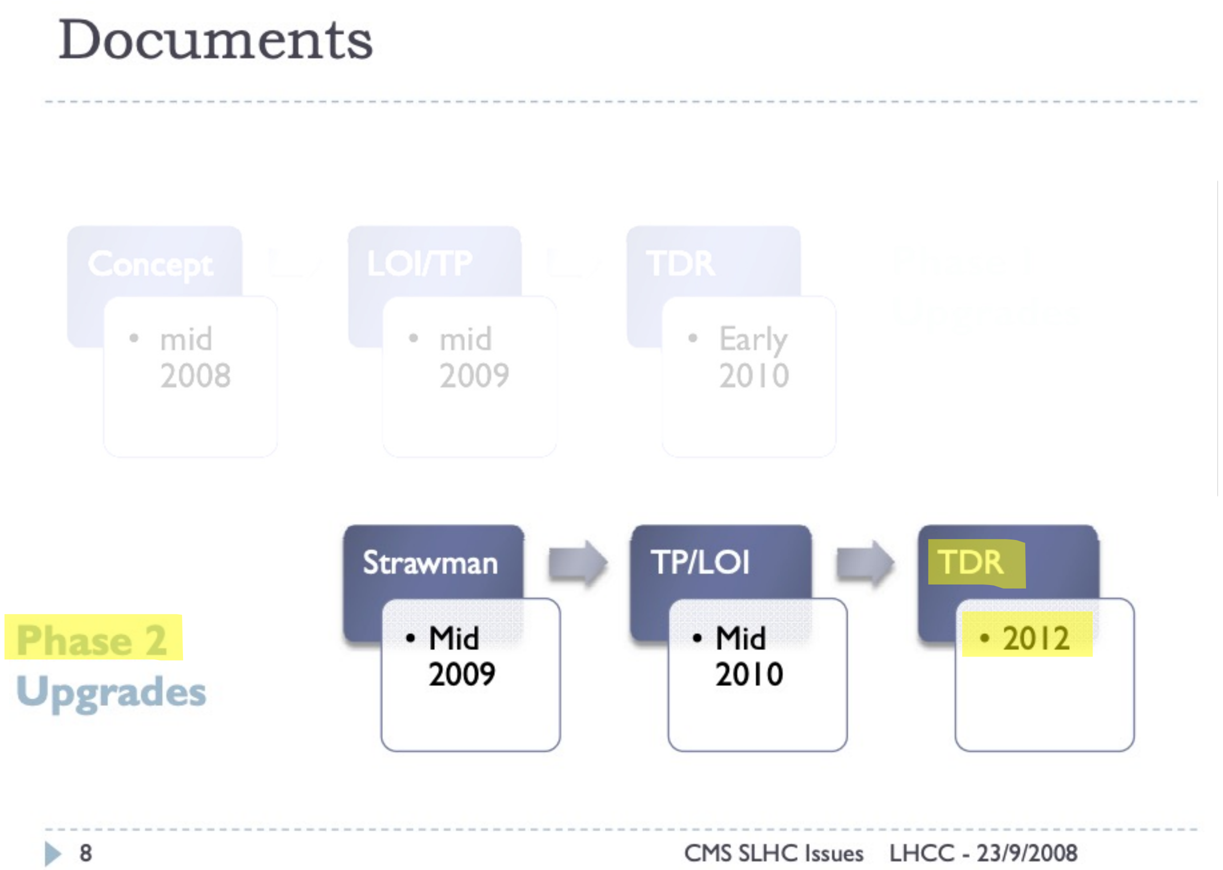
16 YEARS AGO IN CMS

2008





https://indico.cern.ch/event/73212/contributions/2084129

17 YEARS AGO IN CMS

2009

Possible strawman timescale for the Phase II Upgrade

2010 - Decide on Physics objectives and begin simulations, taking into account any data available.

2011 - Choose configuration. Begin design detector

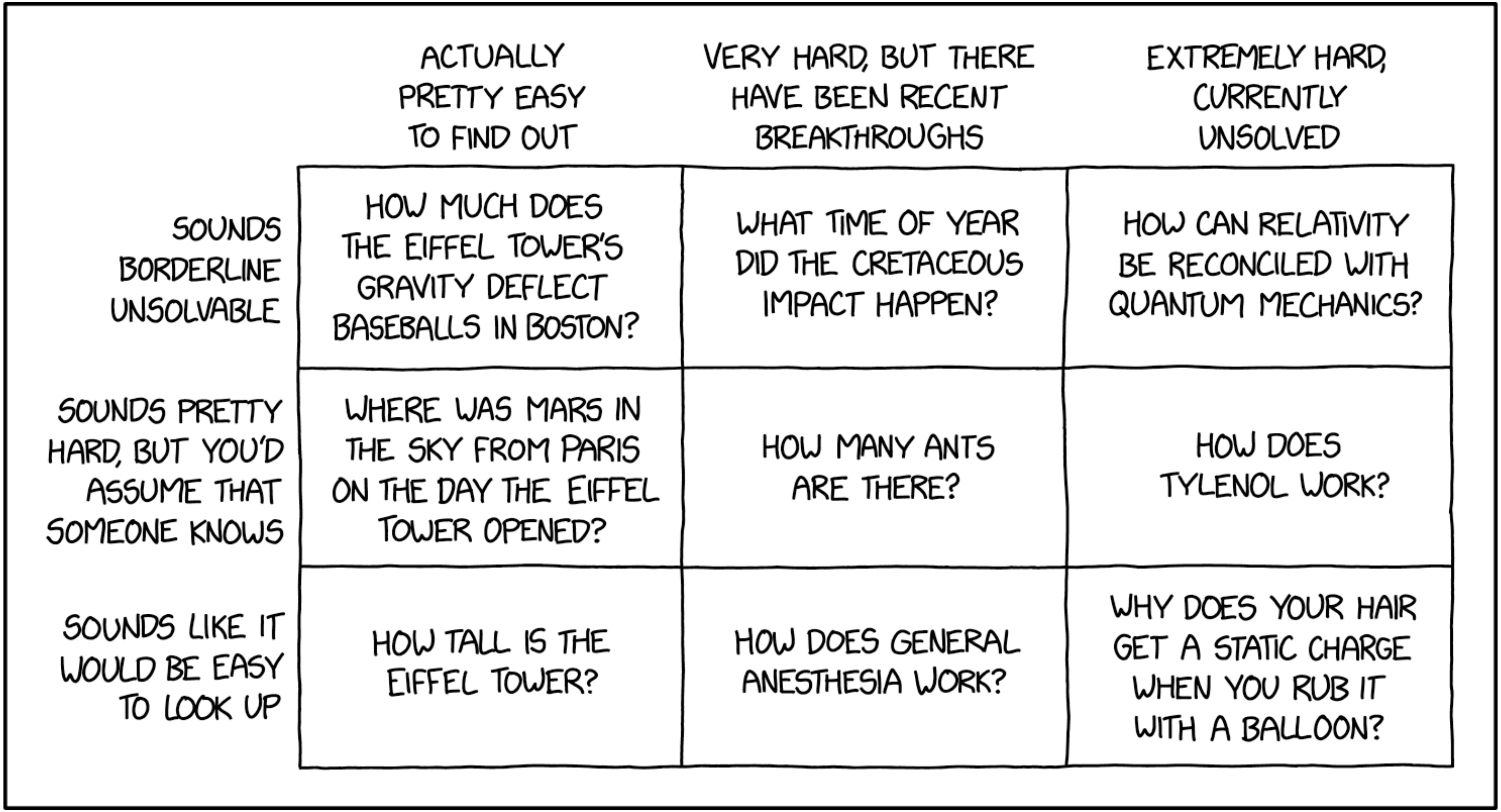
2011-12 - "Directed" R&D for rad hardness of components (in addition to any already performed prior to the design phase)

2013-2018 Five years to build two endcaps

IF 2018 is the goal for new endcaps, this schedule is tight

IN CMS FOR THE LAST 7 YEARS

https://xkcd.com/2682/



	ACTUALLY PRETTY EASY TO FIND OUT	VERY HARD, BUT THERE HAVE BEEN RECENT BREAKTHROUGHS	EXTREMELY HARD, CURRENTLY UNSOLVED
SOUNDS BORDERLINE UNSOLVABLE	HOW CAN I AVOID ARTIFICIAL NEURAL NETWORKS IN MY ANALYS?	WHY DO ASYMPTOTICS WORK FAR FROM THE LARGE N REGIME?	HOW CAN WE MAKE A TRACKING DETECTOR WITHOUT ANY MATTER?
SOUNDS PRETTY HARD, BUT YOU'D ASSUME THAT SOMEONE KNOWS	WHICH SOURCES OF SYSTEMATIC UNCERTAINTY AFFECT MY ANALYSIS?	HOW ARE WE IMPROVING THE LHC DETECTORS FOR PHASE 2?	WHEN WILL MACHINE LEARNING REPLACE PHYSICISTS?
SOUNDS LIKE IT WOULD BE EASY TO LOOK UP	WHY IS IT AN ERROR TO CALL UNCERTAINTIES "ERRORS"?	WHICH DETECTORS HAVE WIRELESS POWER AND WIRELESS READOUT?	HOW TO MAKE REVIEWER TWO HAPPY?

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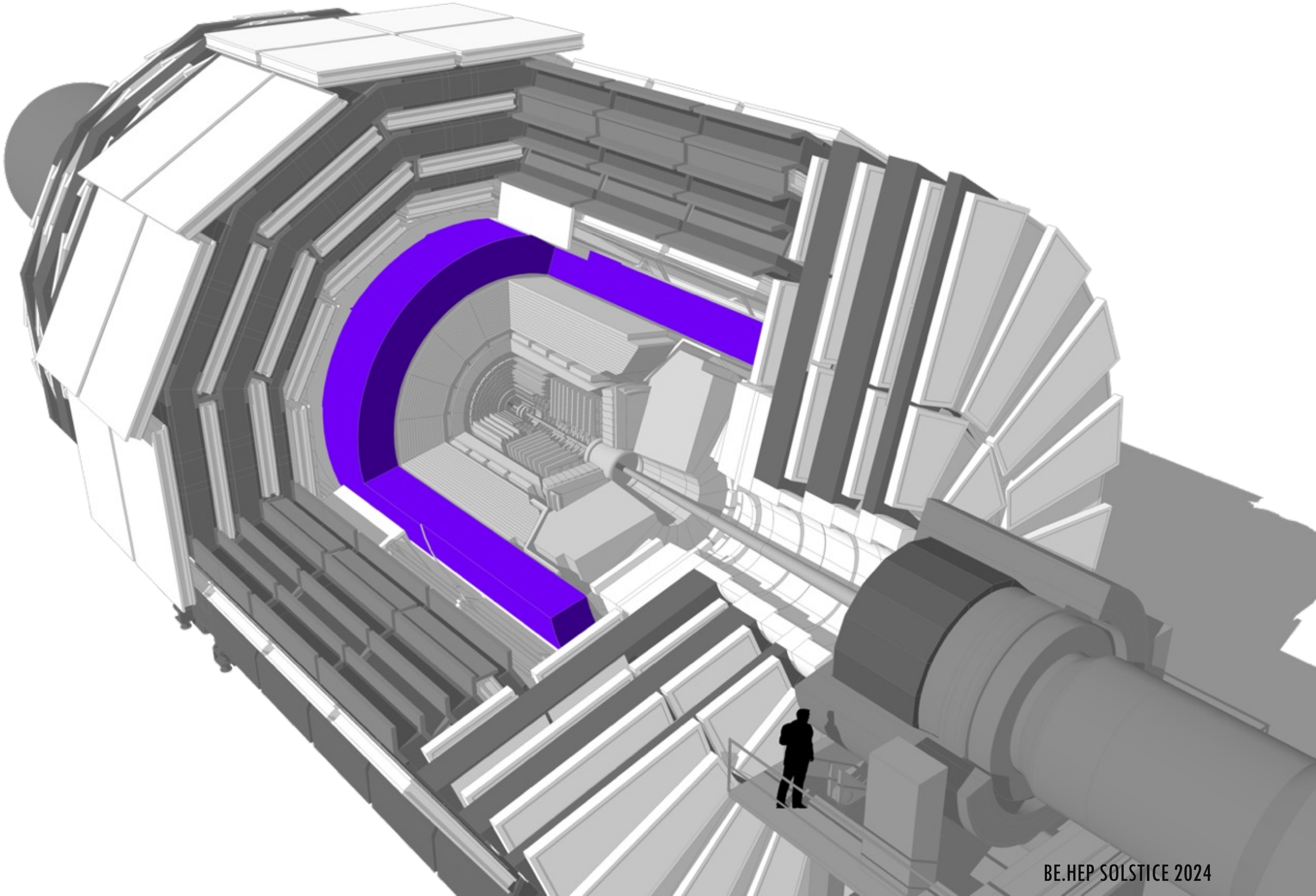
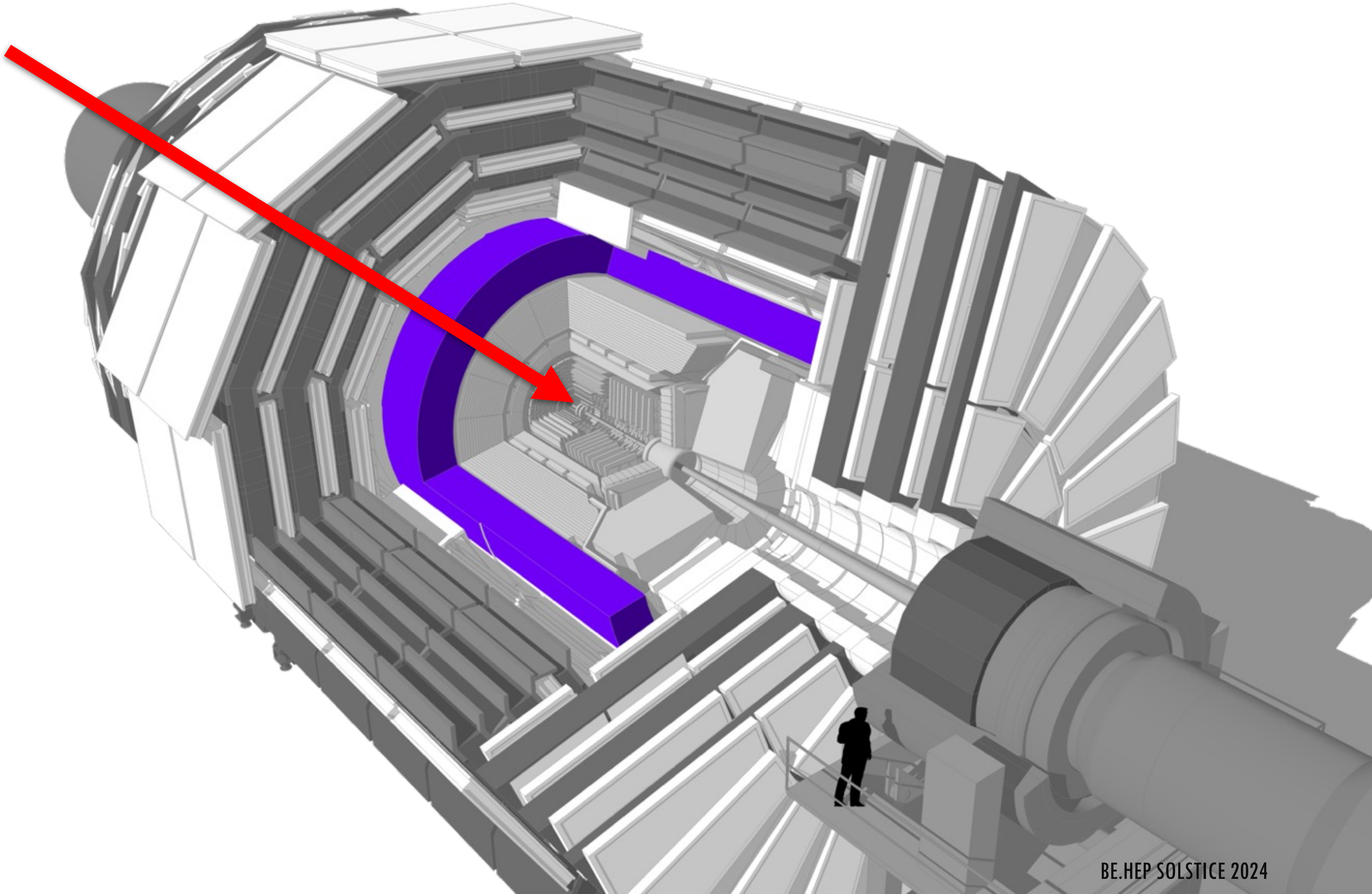
CMS PHASE-2 UPGRADES IN A NUTSHELL



CMS PHASE-2 UPGRADES IN A NUTSHELL

New tracker

- More granular and lighter.
- L1-trigger p_T information.
- Coverage extended to $\eta < 4$.



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New tracker

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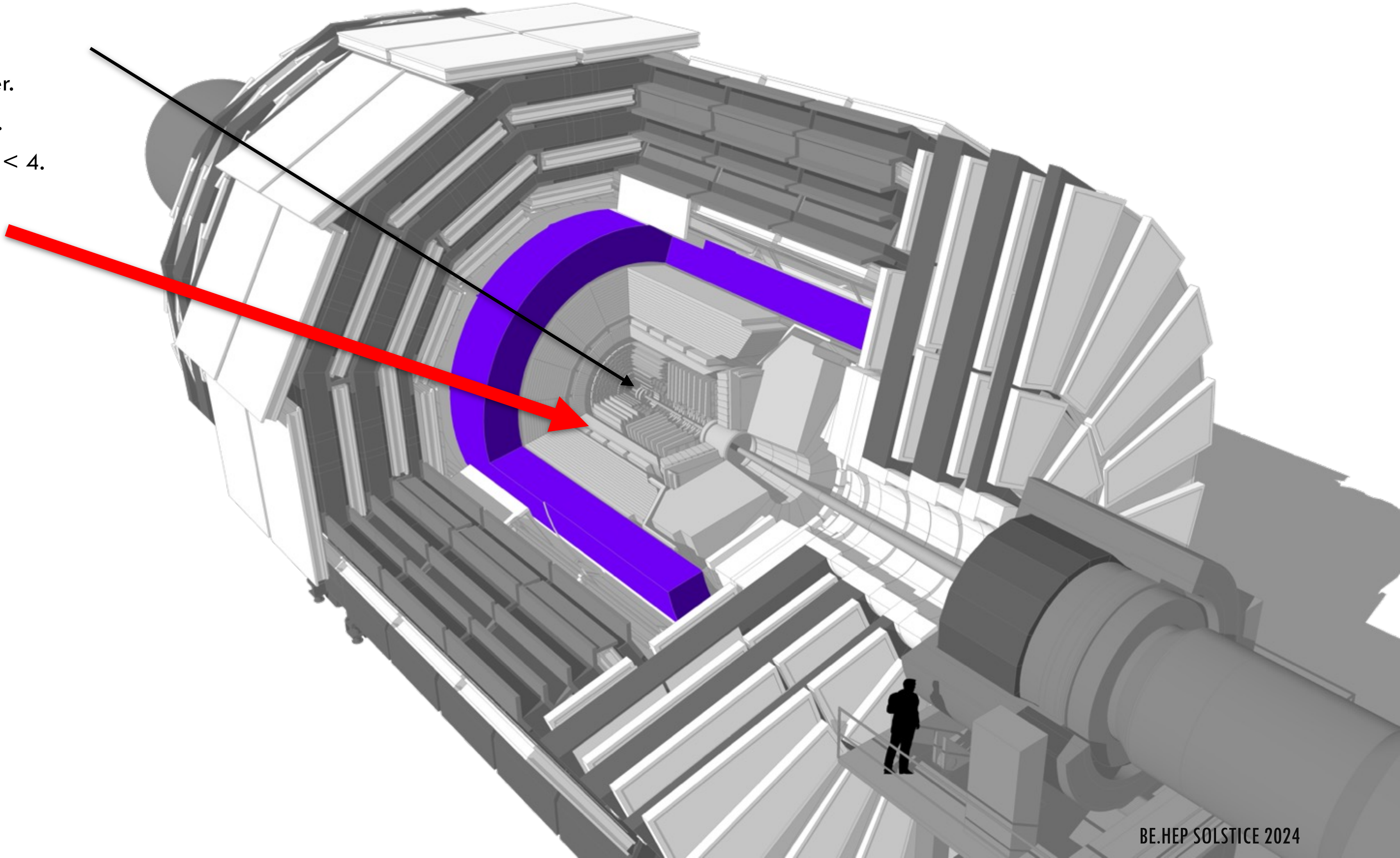
Barrel EM calorimeter

- New 160 MHz FE electronics.
- Full granularity L1 trigger.
- Lower running temperature (9C).



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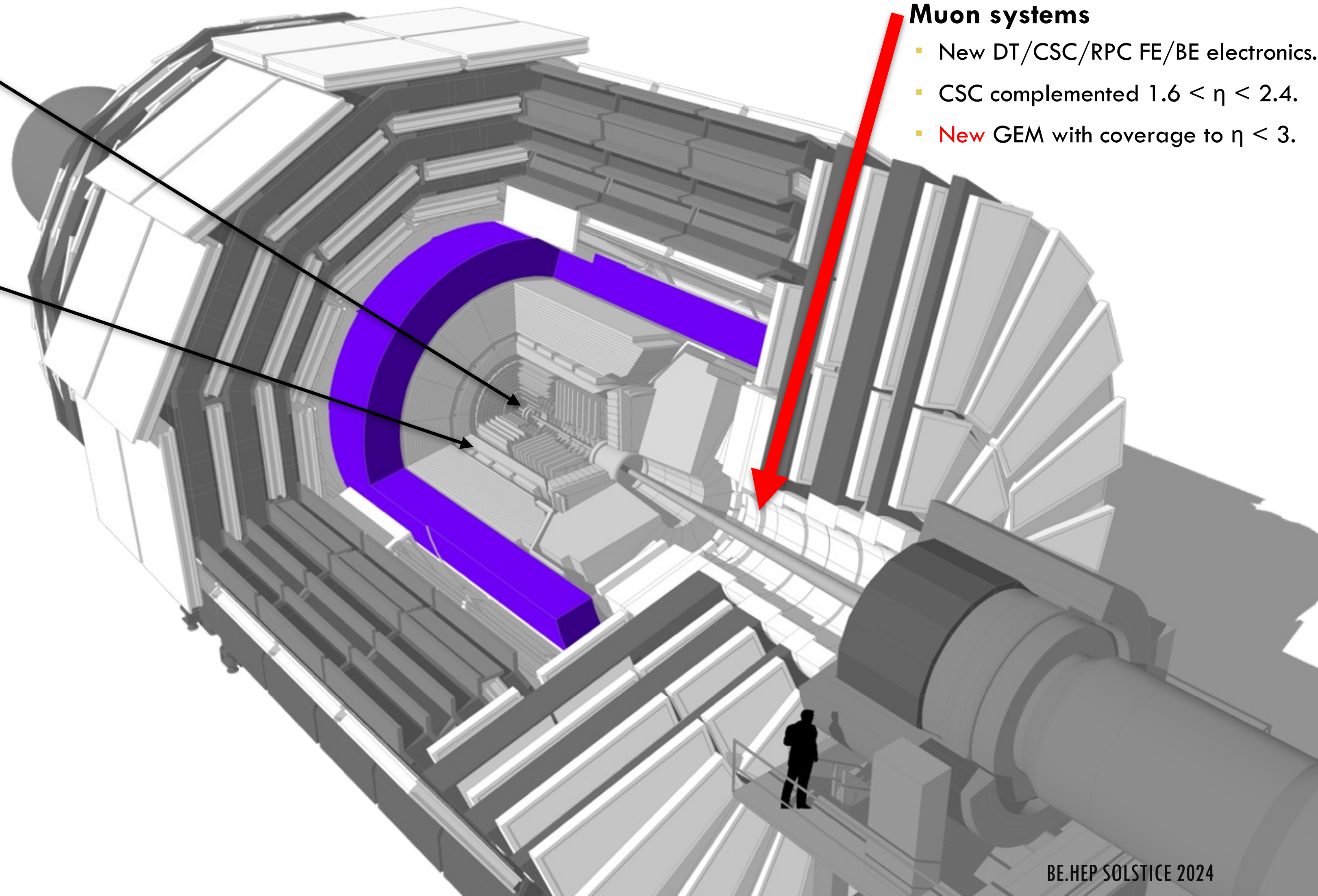

Muon systems
- New DT/CSC/RPC FE/BE electronics.
- CSC complemented $1.6 < \eta < 2.4$.
- New GEM with coverage to $\eta < 3$.

CMS PHASE-2 UPGRADES IN A NUTSHELL

Trigger/DAQ
- Tracker information at 40 MHz.
- 12.5 μs latency.
- HLT input/output at 750/7.5 kHz.
- 7.4 MB/event.

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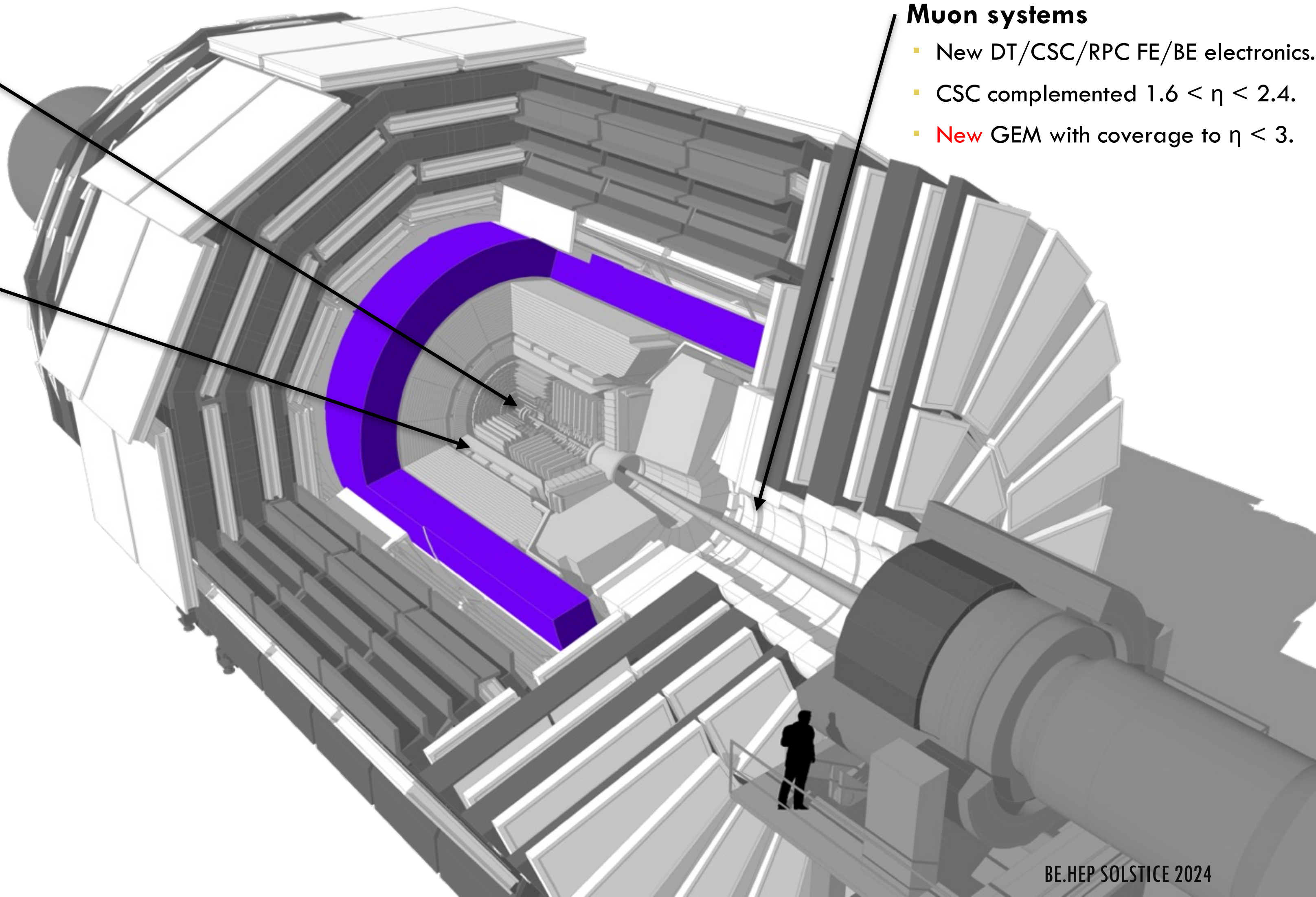

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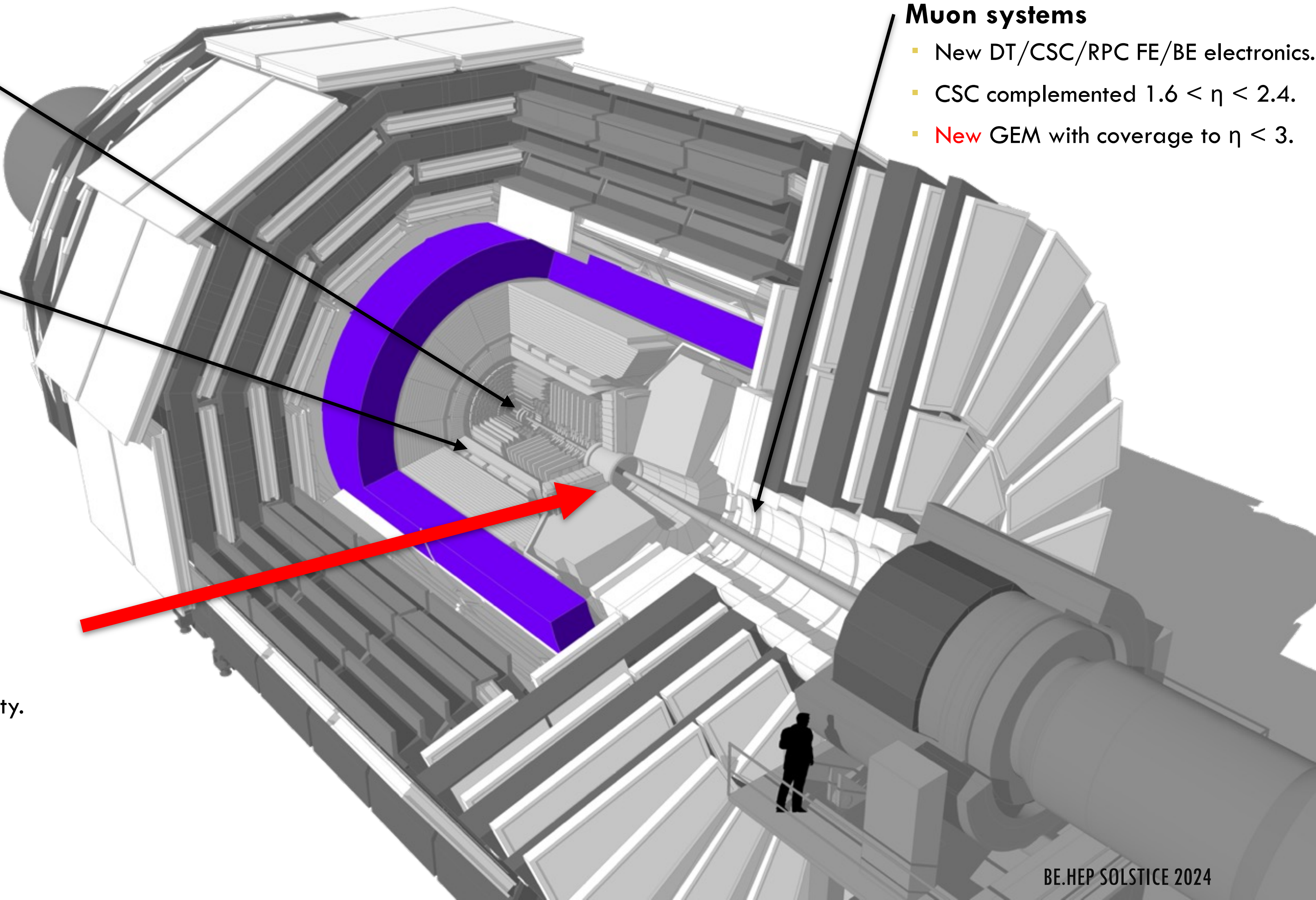
New Endcap calorimeter

- Si radiation tolerance.
- High longitudinal and transverse granularity.
- Precise timing of showers.



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New MIP precision-timing layer

- Barrel: crystals + SiPM.
- Endcap: low-gain avalanche detector.

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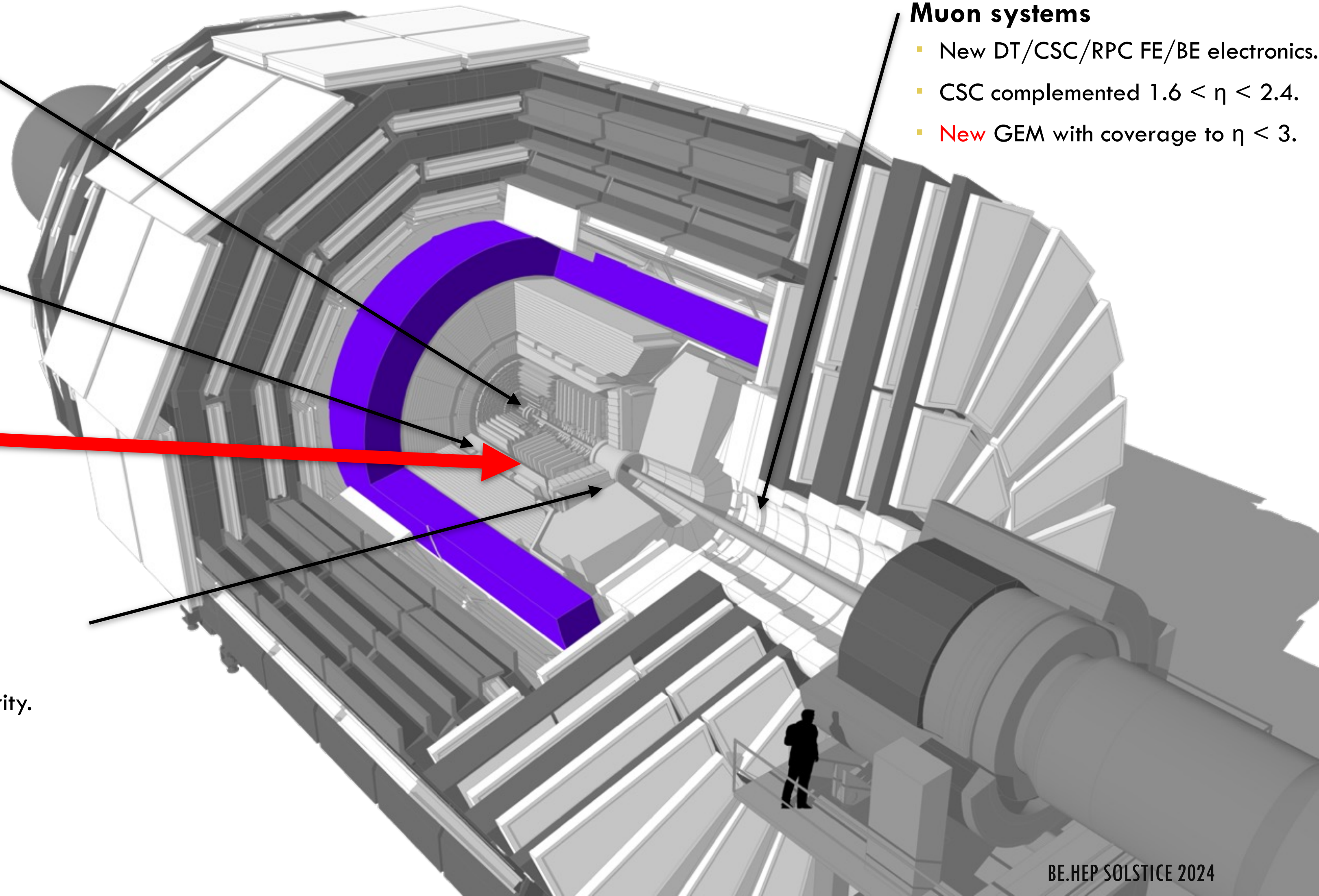

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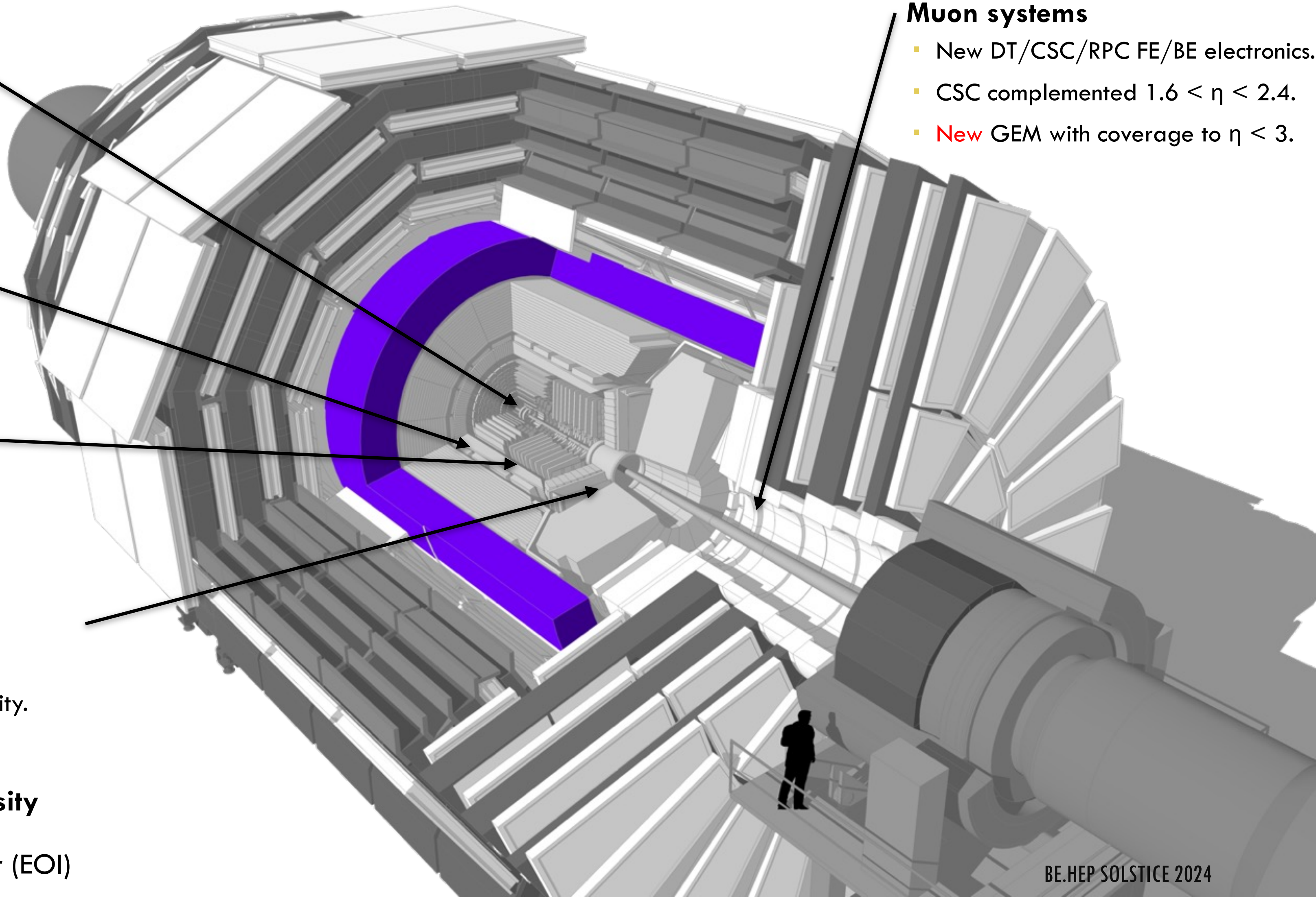

Beam radiation and luminosity

Precision proton spectrometer (EOI)

CMS PHASE-2 UPGRADES IN ACTION

Trigger/DAQ
- Tracker information at 40 MHz.
- 12.5 μs latency.
- HLT input/output at 750/7.5 kHz.
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Barrel EM calorimeter
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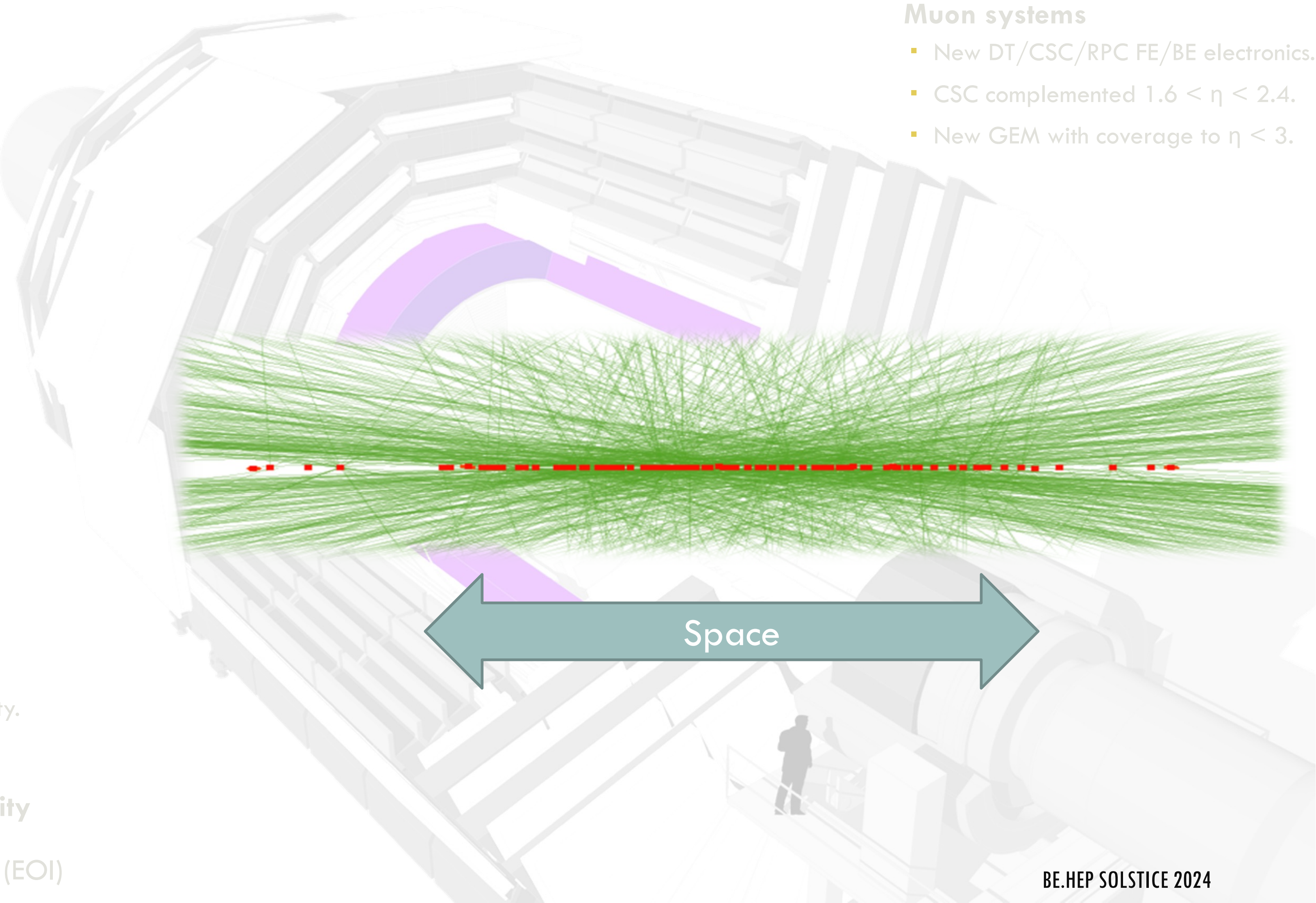
Beam radiation and luminosity

Precision proton spectrometer (EOI)



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Muon systems
- New DT/CSC/RPC FE/BE electronics.
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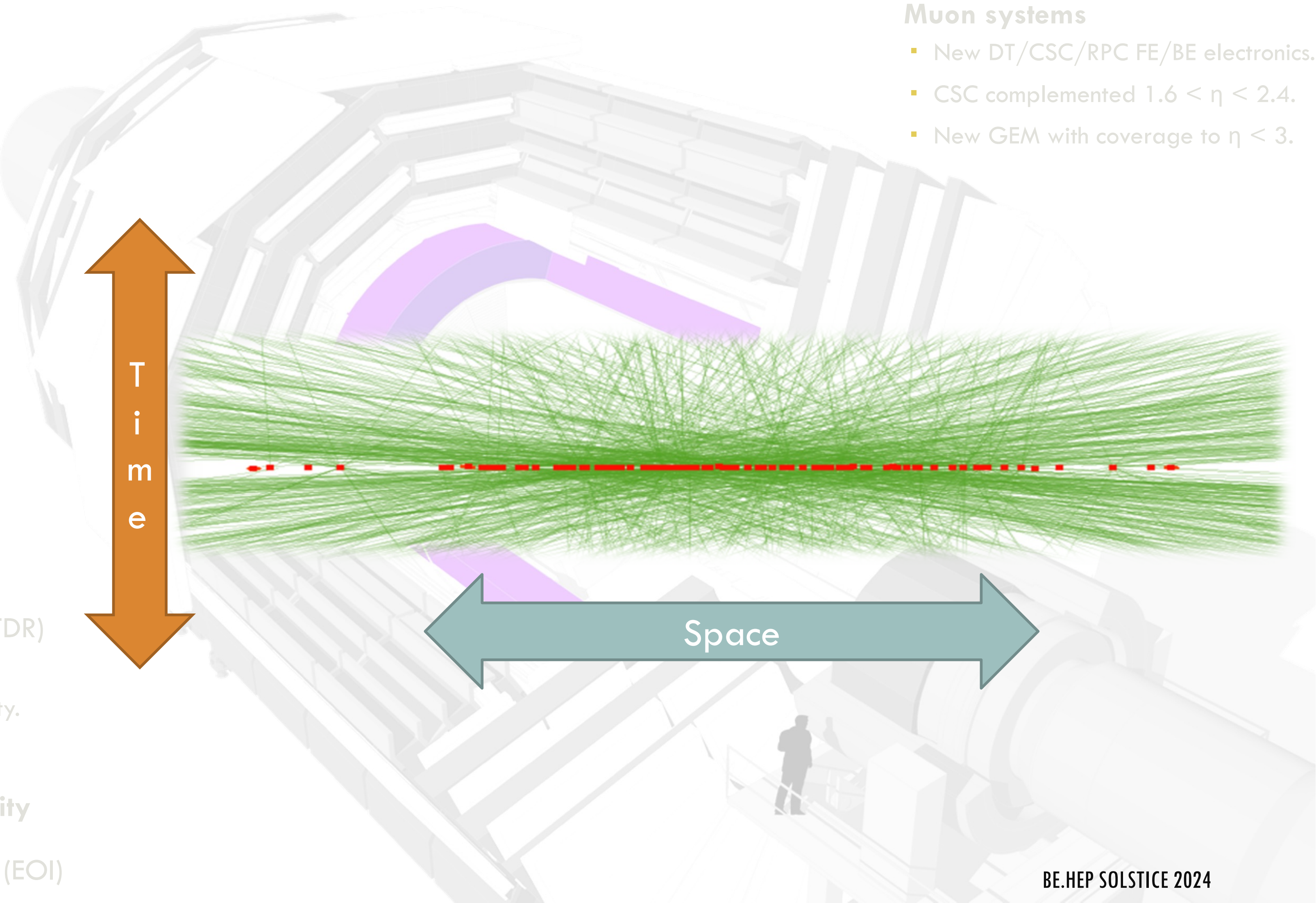
- New GEM with coverage to η < 3.

New tracker
- More granular and lighter.
- L1-trigger p_T information.
- Coverage extended to η < 4.

Barrel EM calorimeter (TDR submitted)
- New 160 MHz FE electronics.
- Full granularity L1 trigger.
- Lower running temperature (9C).

New MIP precision-timing layer
- Barrel: crystals + SiPM.
- Endcap: low-gain avalanche detector.



New Endcap calorimeter (impending TDR)
- Si radiation tolerance.
- High longitudinal and transverse granularity.
- Precise timing of showers.

Beam radiation and luminosity

Precision proton spectrometer (EOI)

CMS PHASE-2 UPGRADES IN ACTION

Trigger/DAQ

- Tracker information at 40 MHz.
- 12.5 μs latency.
- HLT input/output at 750/7.5 kHz.
- 7.4 MB/event.

Muon systems

New tracker

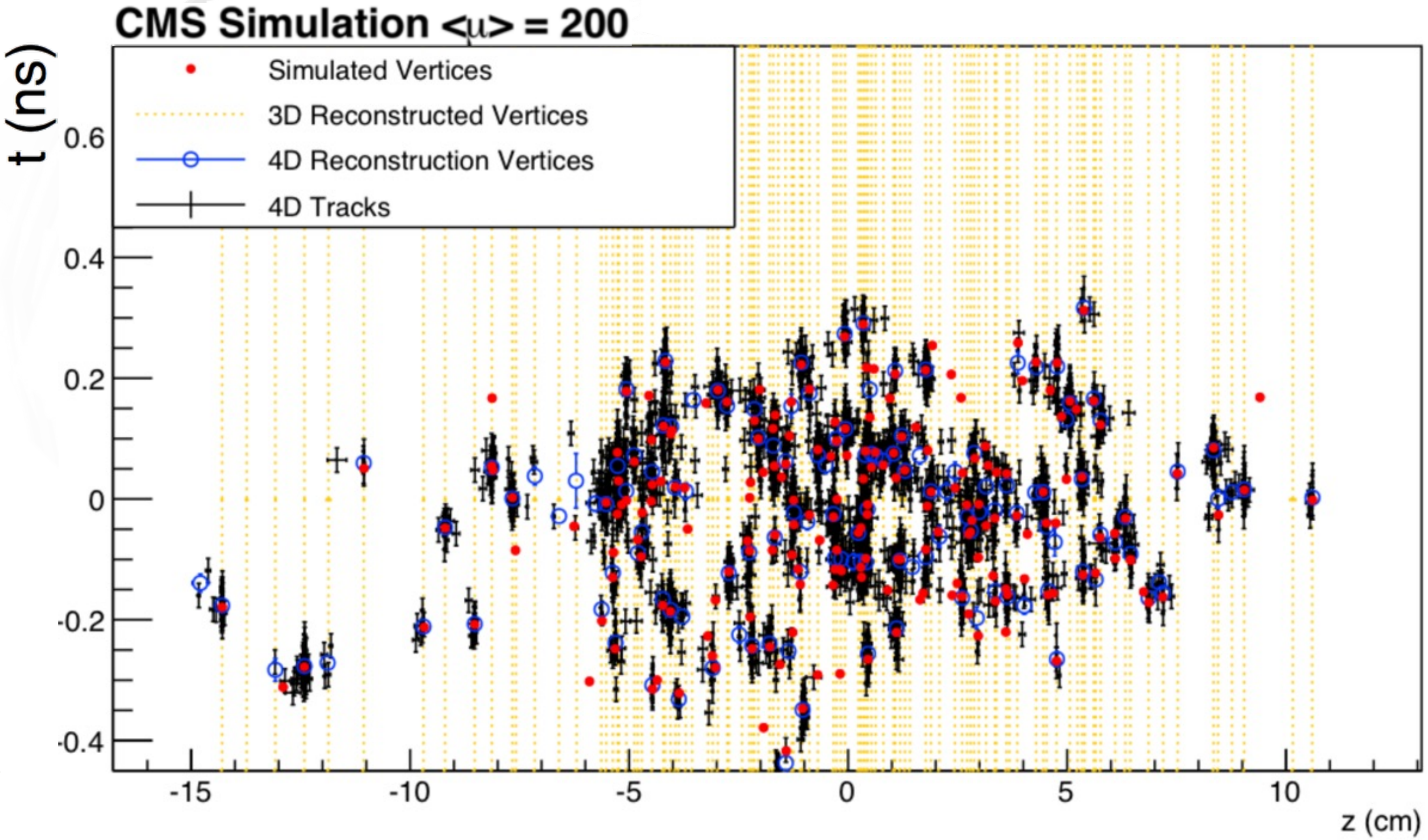
- More granular and lighter.
- L1-trigger p_T information.
- Coverage extended to $\eta < 4$.

Barrel EM calorimeter

- New 160 MHz FE electronics.
- Full granularity L1 trigger.
- Lower running temperature (9C).

New MIP precision-timing layer

- Barrel: crystals + SiPM.
- Endcap: low-gain avalanche detector.



New Endcap calorimeter

- Si radiation tolerance.
- High longitudinal and transverse granularity.
- Precise timing of showers.

Beam radiation and luminosity

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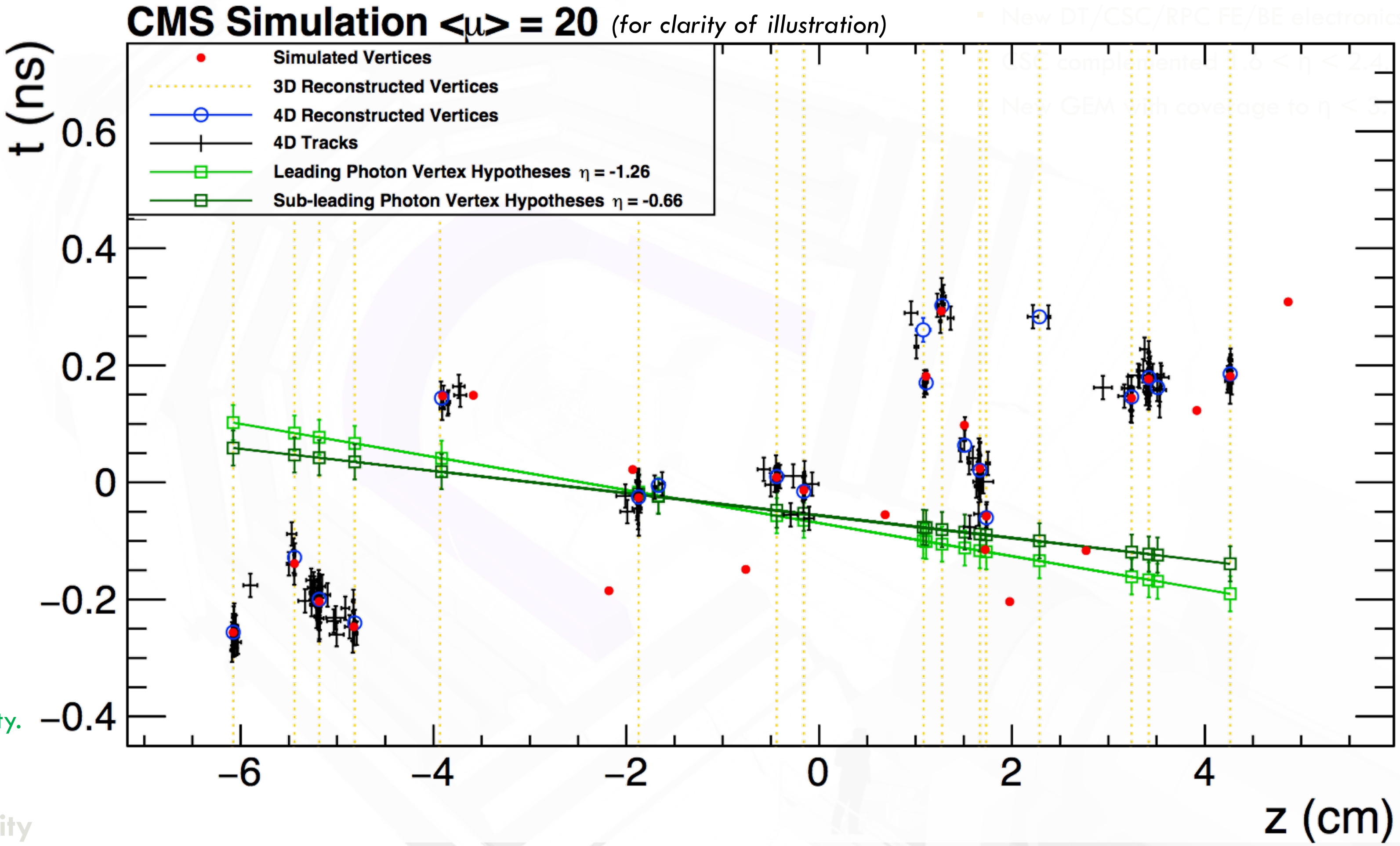


Beam radiation and luminosity

Precision proton spectrometer (EOI)

NEW TRACKER

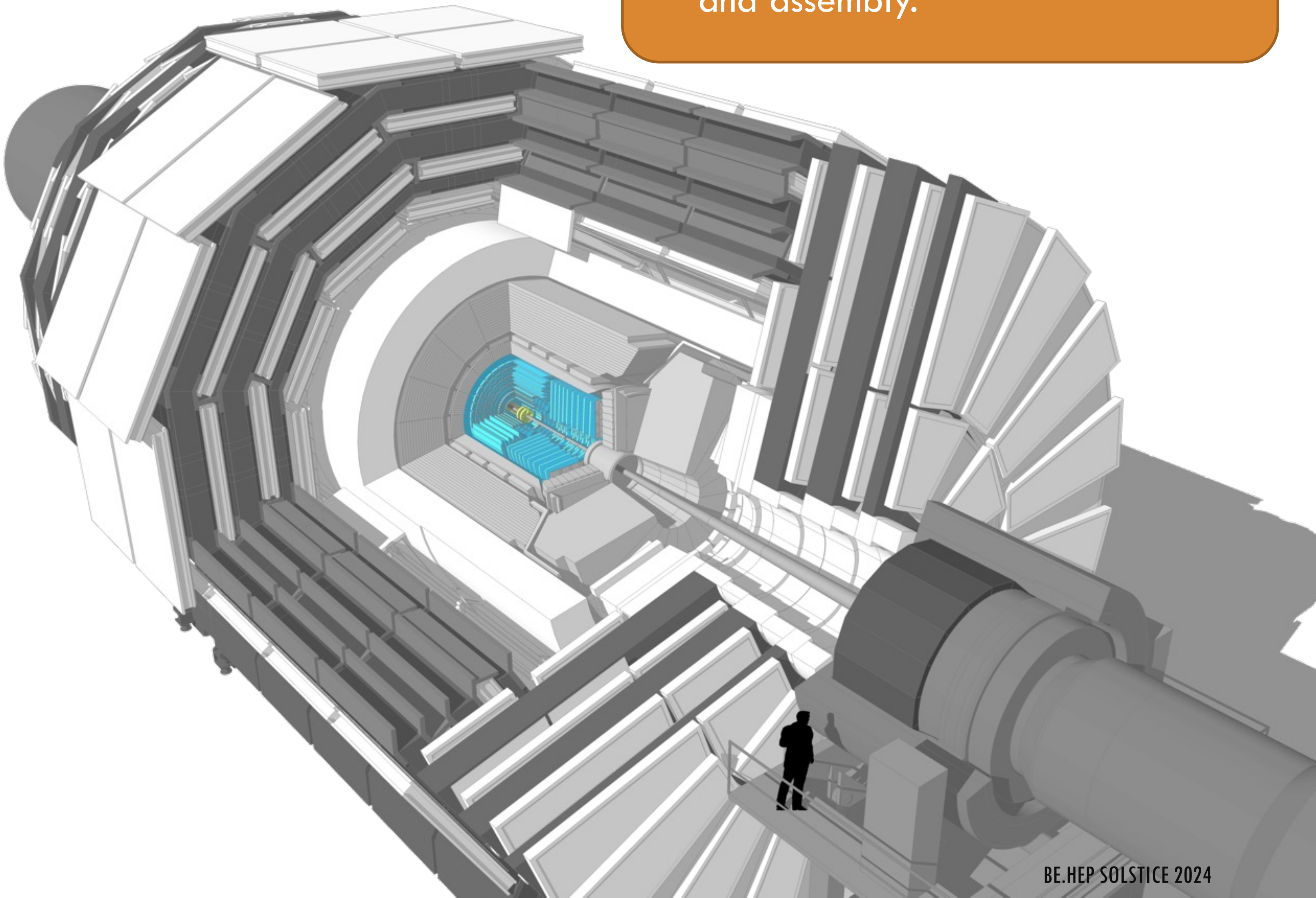
Key challenge:

- Large-scale distributed production and assembly.

Increased performance:

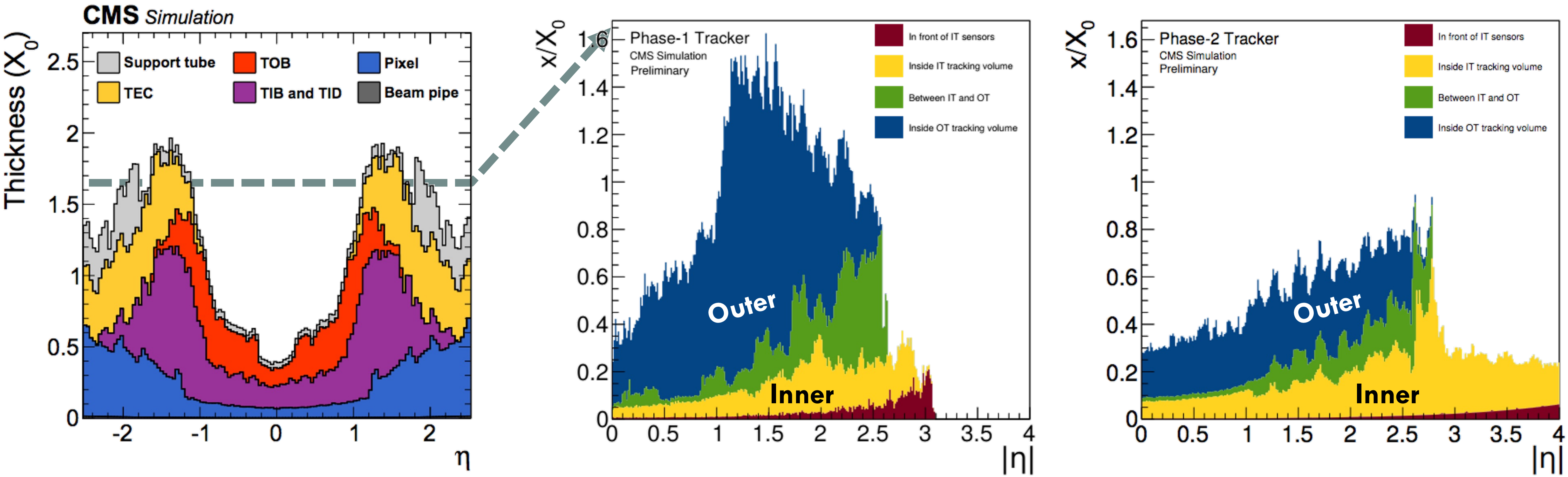
- Radiation tolerance.
- Rate capability.
- Acceptance to $\eta < 4$.
- Granularity and better resolution.

Outer tracker contribution to Level-1 trigger at 40 MHz.



NEW TRACKER MATERIAL BUDGET

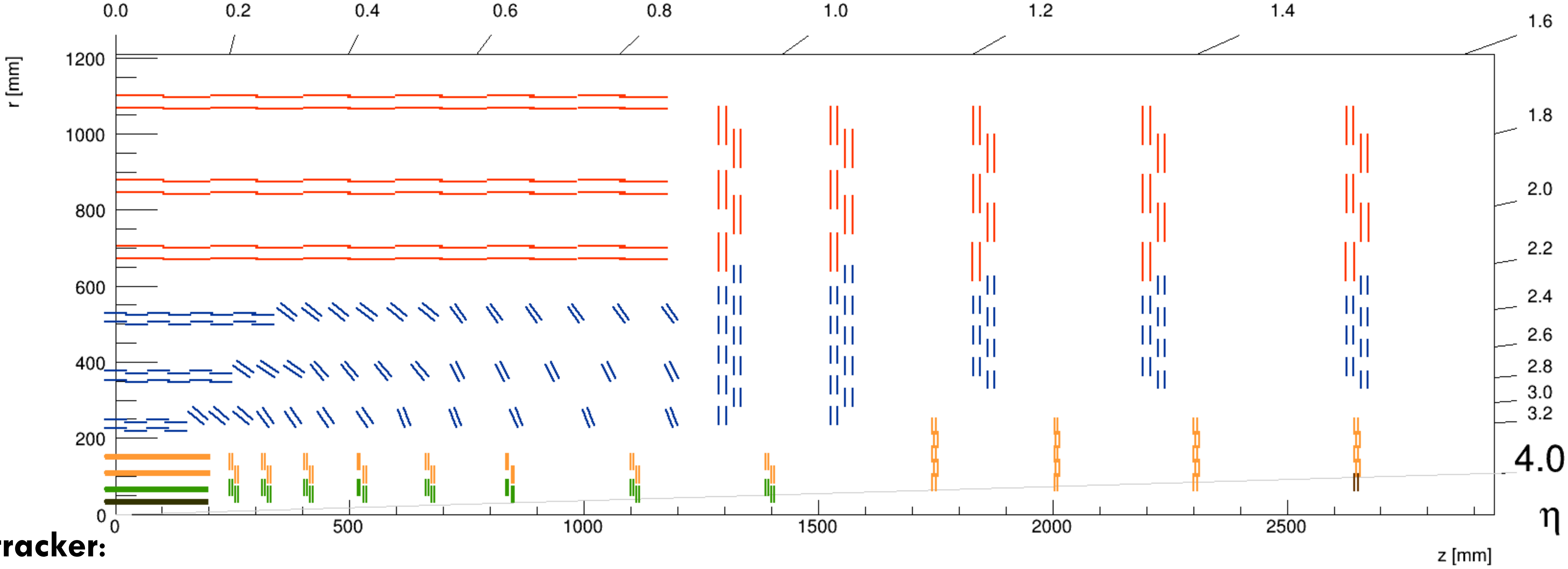
Phase-0 Phase-1 (now) **Phase-2**



NEW TRACKER

Outer tracker:

- **strip+strip (SS)** and **strip+macro-pixel (PS)** double modules:
  - **42M strips** (192 m^2) and **170M macro-pixels** ($25m^2$).

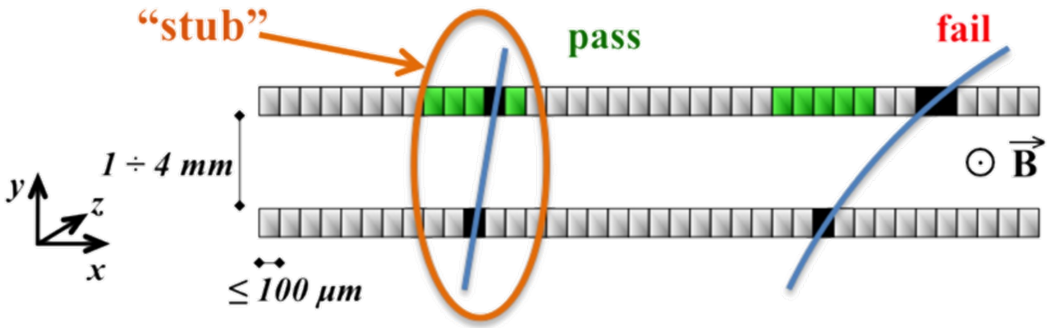


Inner tracker:

- **1×2** and **2×2** modules: **2×10^9 hybrid pixels** (4.9 m^2).
- 6× smaller pixel size than Phase-1.
- 65 nm CMOS readout.

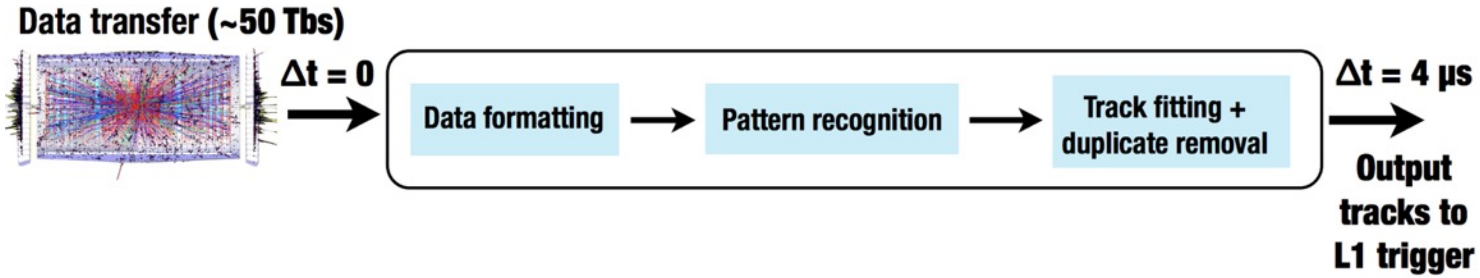
RD50 RD53

NEW OUTER TRACKER TRIGGER



p_T front-end local discrimination

- Hit correlation between closely-spaced sensors.
- **Stubs**: cluster pairs from $p_T > 2$ GeV track:
  - Reduce trigger data (by 10-20 times).
  - Input to track-finding.

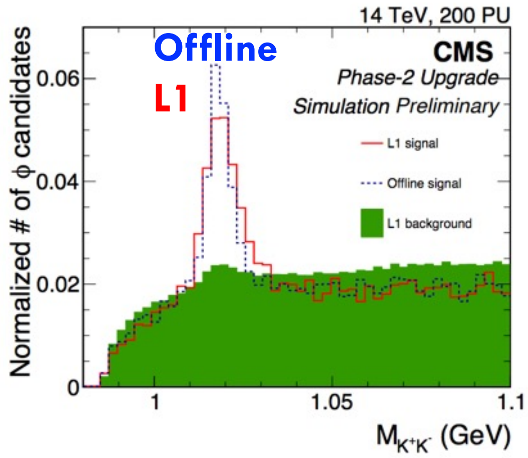


Two-stage FPGA-based system:

- Algorithm development currently on-going.

Level-1 track trigger:

- Local p_T reconstruction.
- Reconstruct tracks with $p_T > 2$ GeV.
- z_0 precision ~1mm.



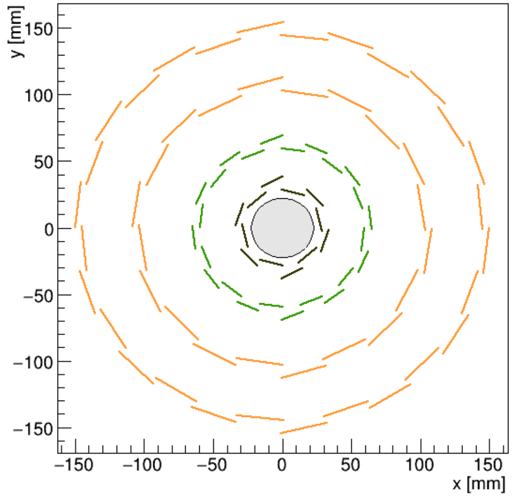
NEW INNER TRACKER

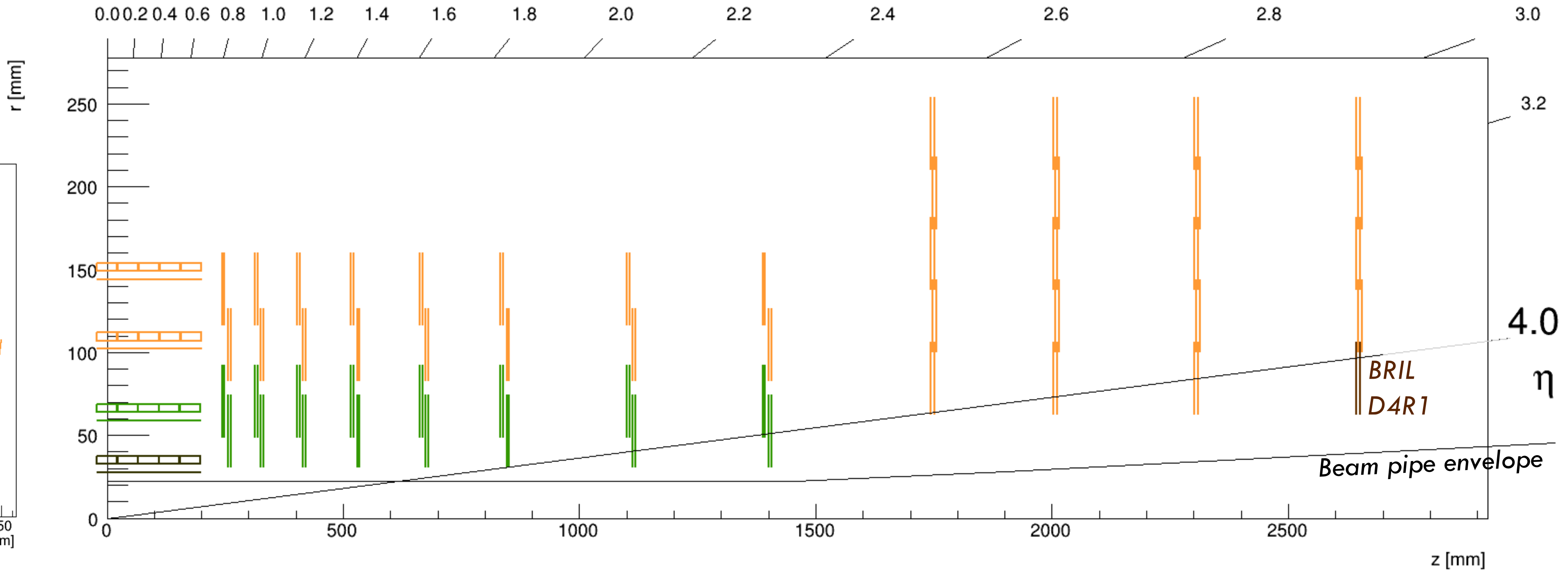
Replaceable first layer by design.

Inner tracker sensor technologies:

- First barrel layer: 3D pixels.
- **Other layers and disks**: planar sensors.

Poised to **shape inner tracker technology options for detectors beyond HL-LHC.**





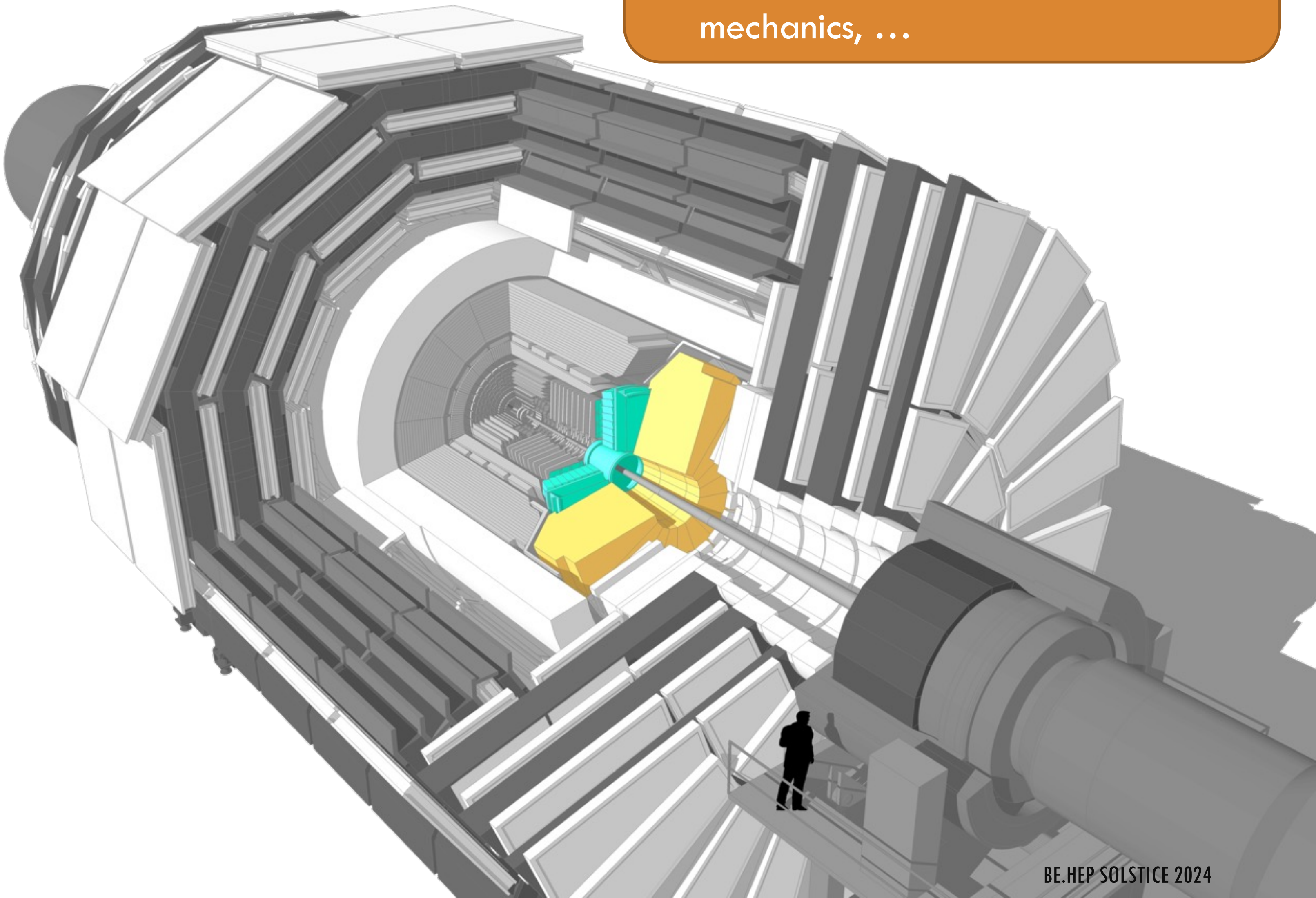
NEW ENDCAP CALORIMETER

Key challenge:
- Channel density ⇒ ASIC design, power, services, connectivity, mechanics, …

Full-volume operated at -30C.

Silicon imaging (EM) calorimeter:
- **6M silicon pads** (620 m^2).
- Hexagonal silicon sensors.
  - 100/200/300-µm thick.
  - 8” wafer process.
  - 26k modules.

Mixed layers in back (hadronic) section:
- **240k plastic scintillator tiles** (370 m^2).
- SiPM-on-tile readout.



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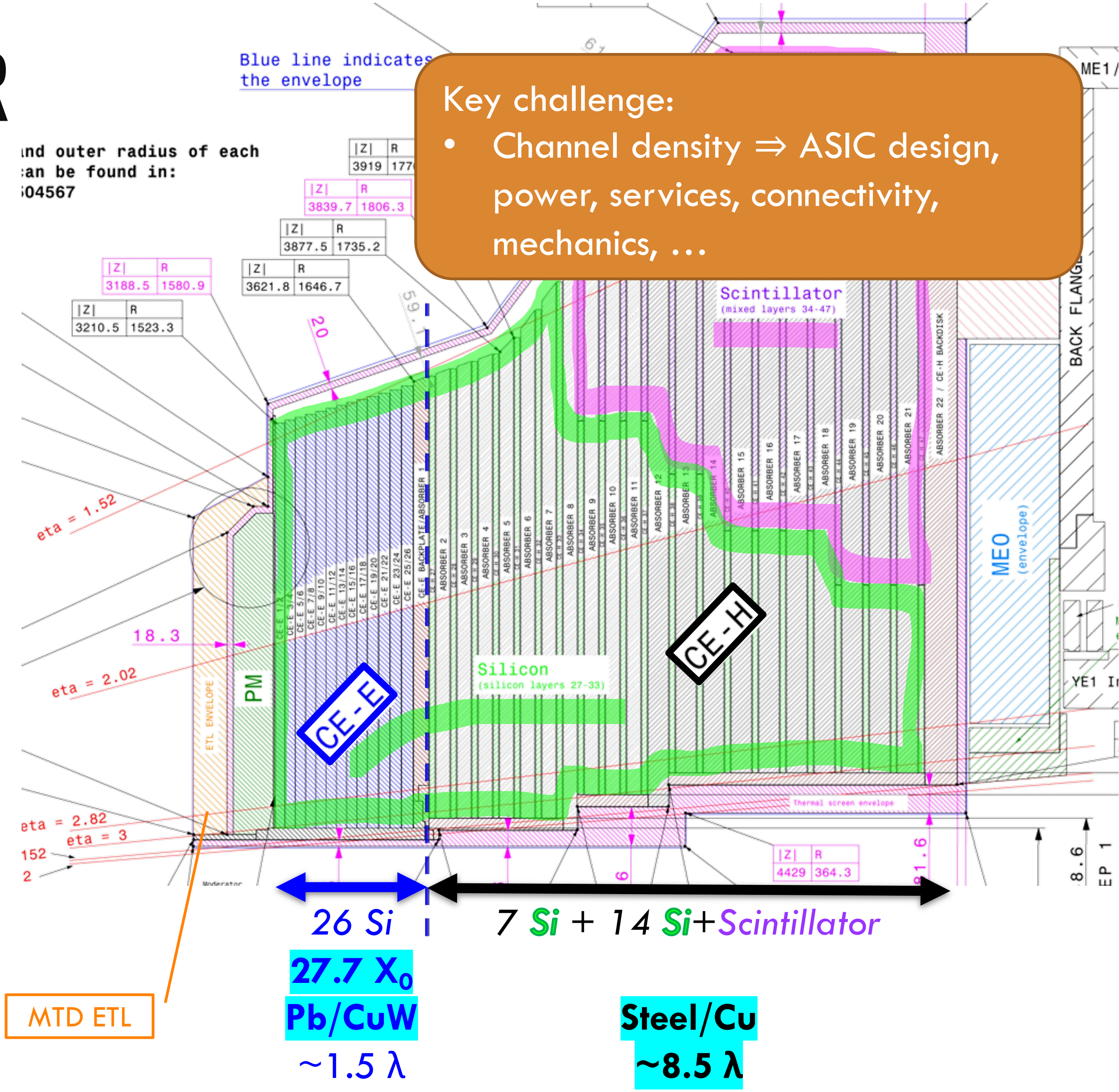


RD18

BARREL EM CALORIMETER

Key challenges:
- Time needed to replace FE.
- Precise clock distribution.
- Cooling of large mass.

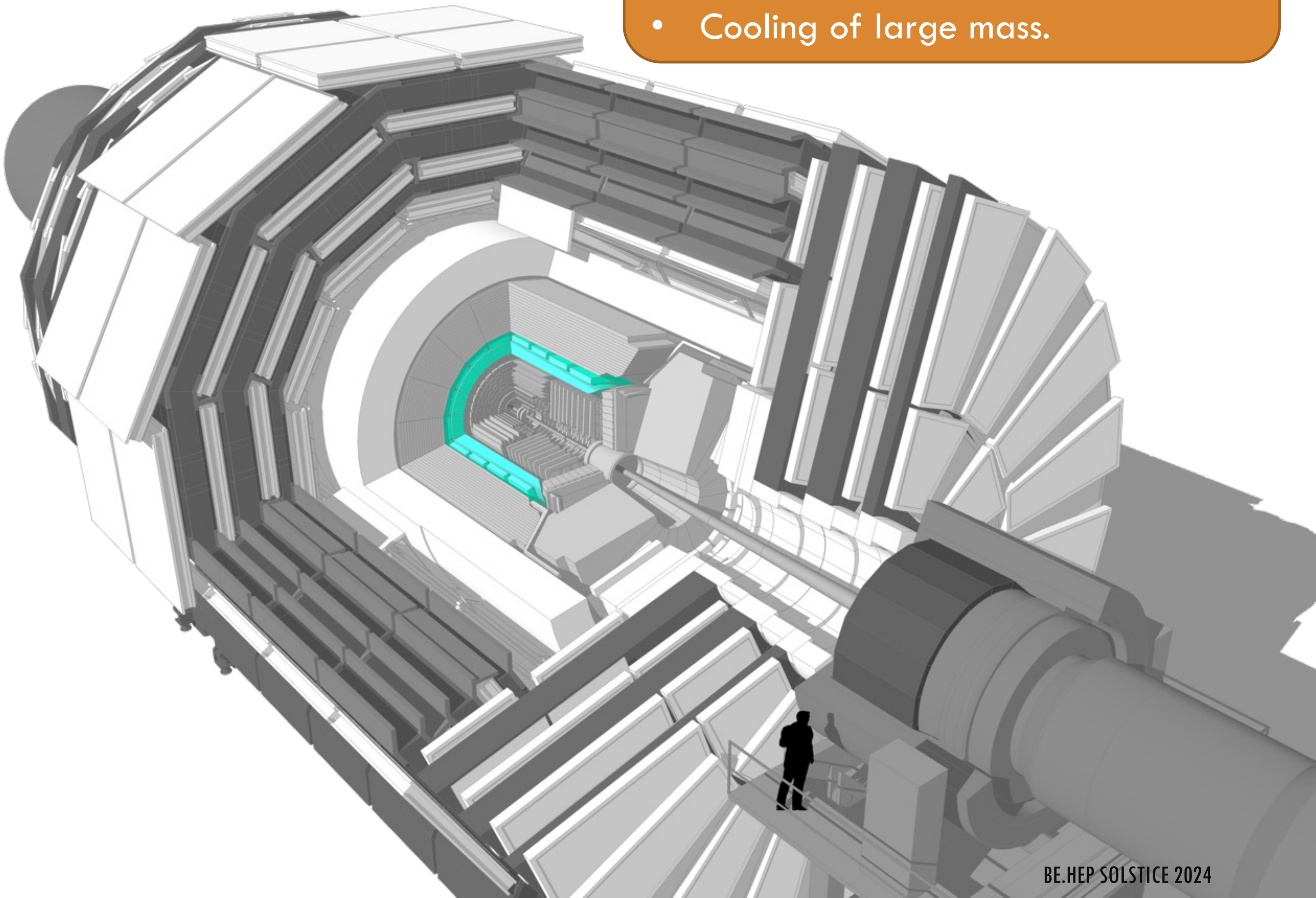
Homogeneous crystal calorimeter.

FE electronics replacement:

- Enable **30 ps resolution** for H⟶γγ photons.
- **25× better granularity at Level-1 trigger** (individual crystals).
- Improved rejection of anomalous signals (spikes).

Reduce photo-diode dark current:

- Lowered operating temperature (18C to 9C).



BARREL EM CALORIMETER

Homogeneous crystal calorimeter.

FE electronics replacement:

- Enable 30 ps resolution for H⟶γγ photons.
- 25× better granularity at Level-1 trigger (individual crystals).
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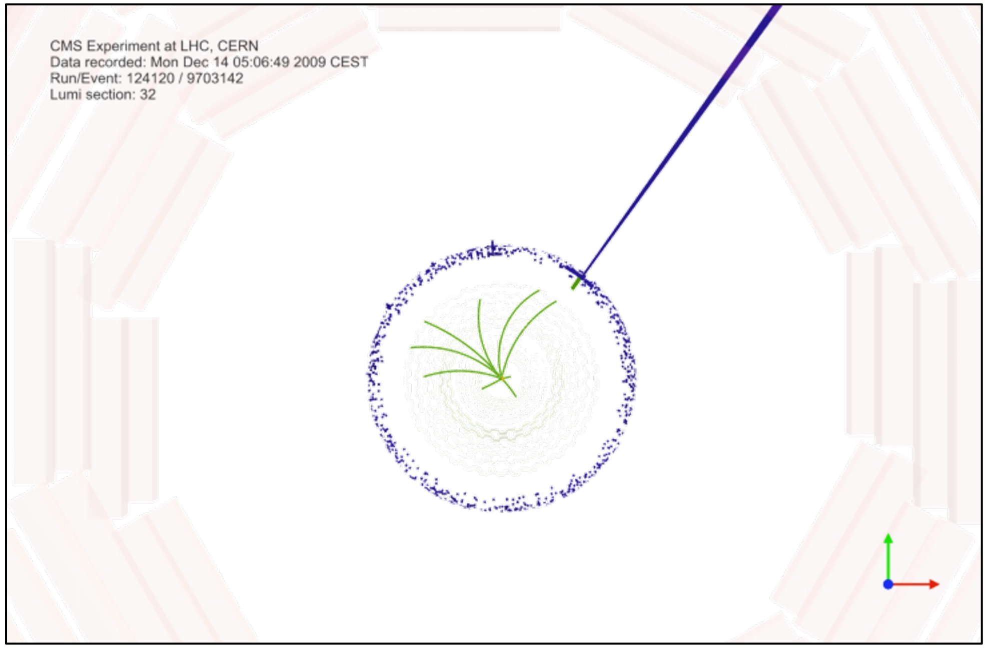
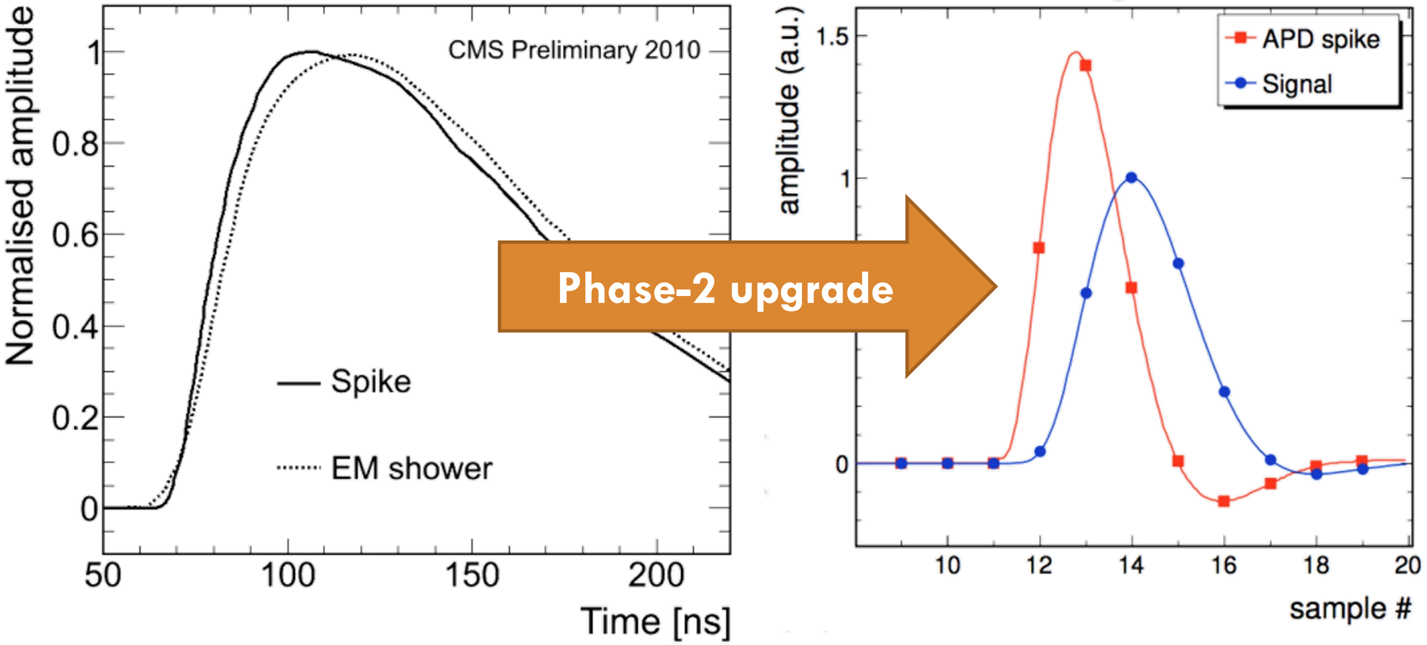
Reduced photo-diode dark current:

- Lowered operating temperature (18C to 9C).





RD51

MUON SYSTEMS

Key challenges:

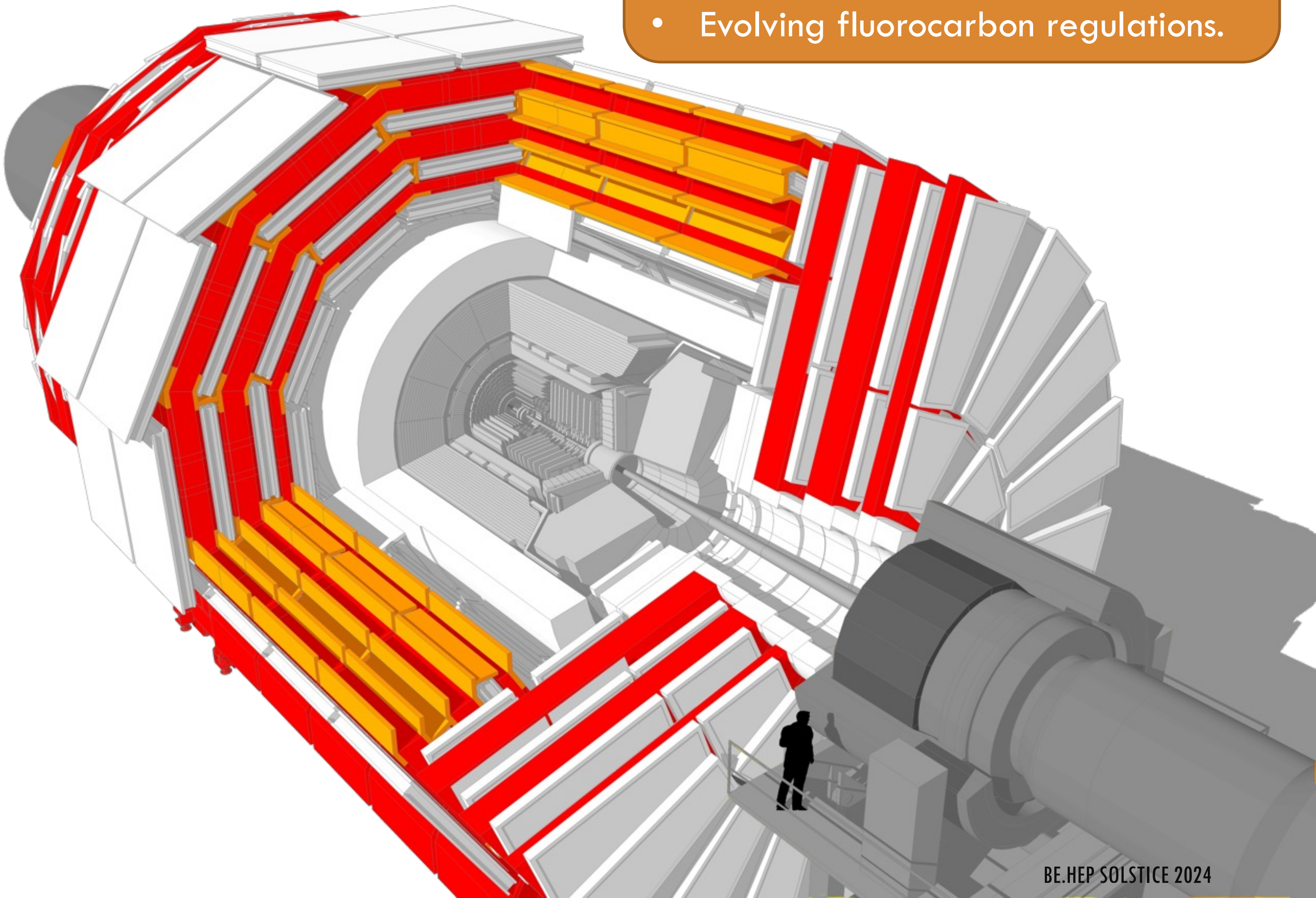
- Reduce trigger thresholds.
- Ageing of 30+-year-old detectors.
- Evolving fluorocarbon regulations.

DT/CSC/RPC:

- New front-end and back-end electronics.

New detectors:

- LS2:
  - **GE1/1**: ~50 m^2, two-layer triple-GEM.
- Between LS2 and LS3:
  - **GE2/1**: ~100 m^2, two-layer triple-GEM.
  - **RE3/1, RE4/1**: ~90 m^2, single-layer iRPC.
- LS3:
  - **ME0**: ~60 m^2, six-layer triple-GEM.



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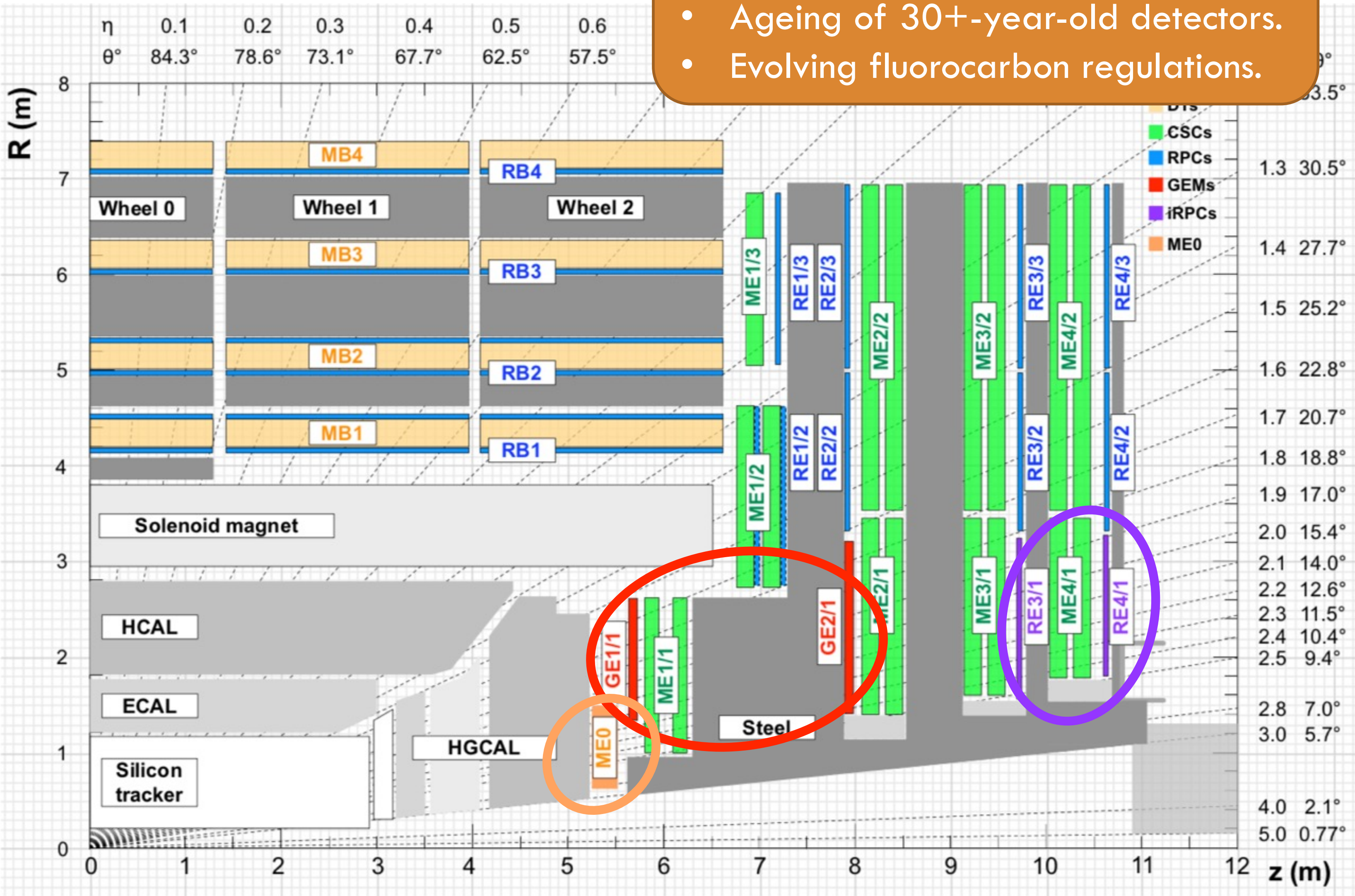

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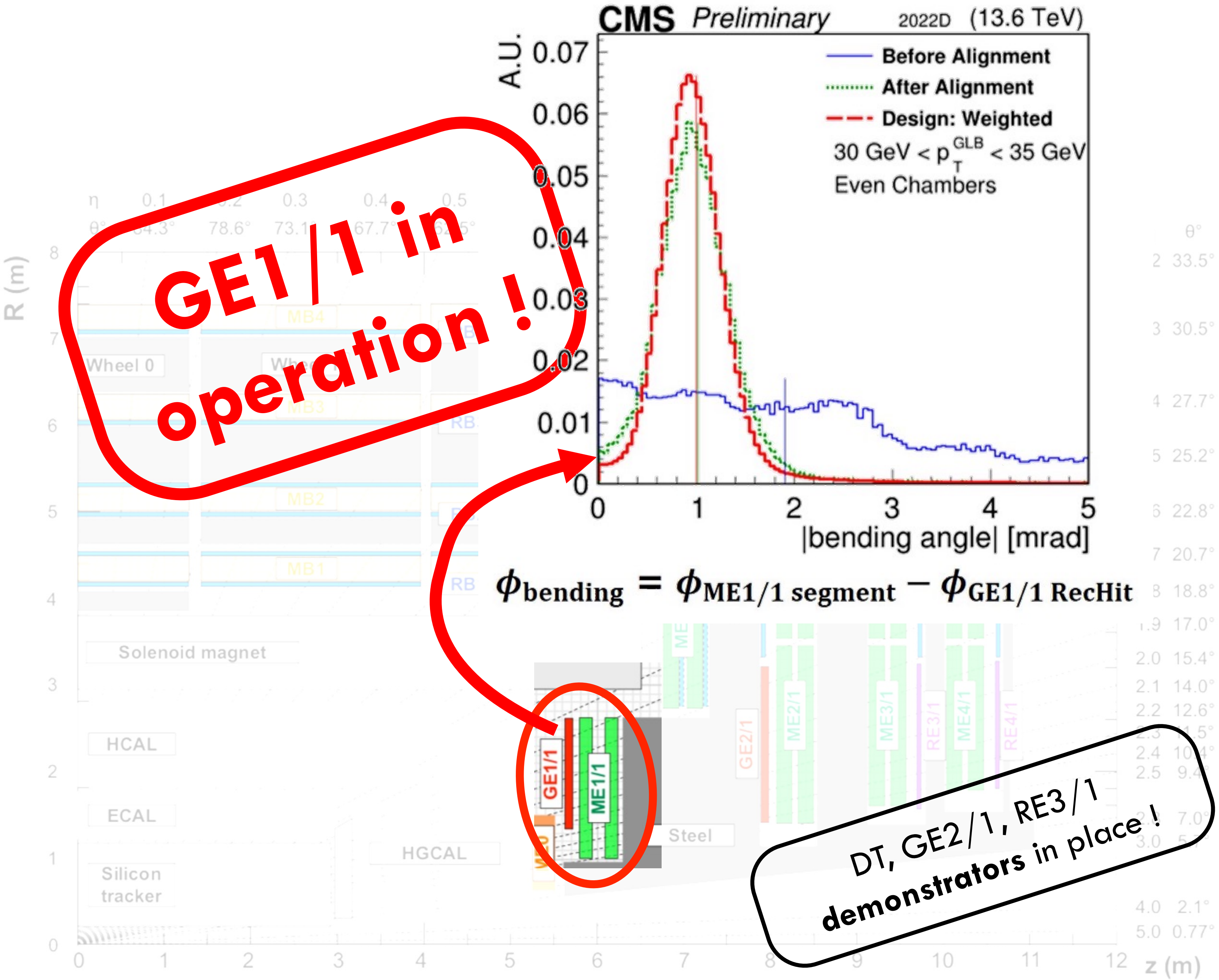


RD18 RD50

NEW MIP PRECISION-TIMING LAYER

Key challenges:

- Precise clock distribution.
- Novel sensor technology.
- Challenging timescale.

30-ps-resolution tagging of individual tracks to η < 3.

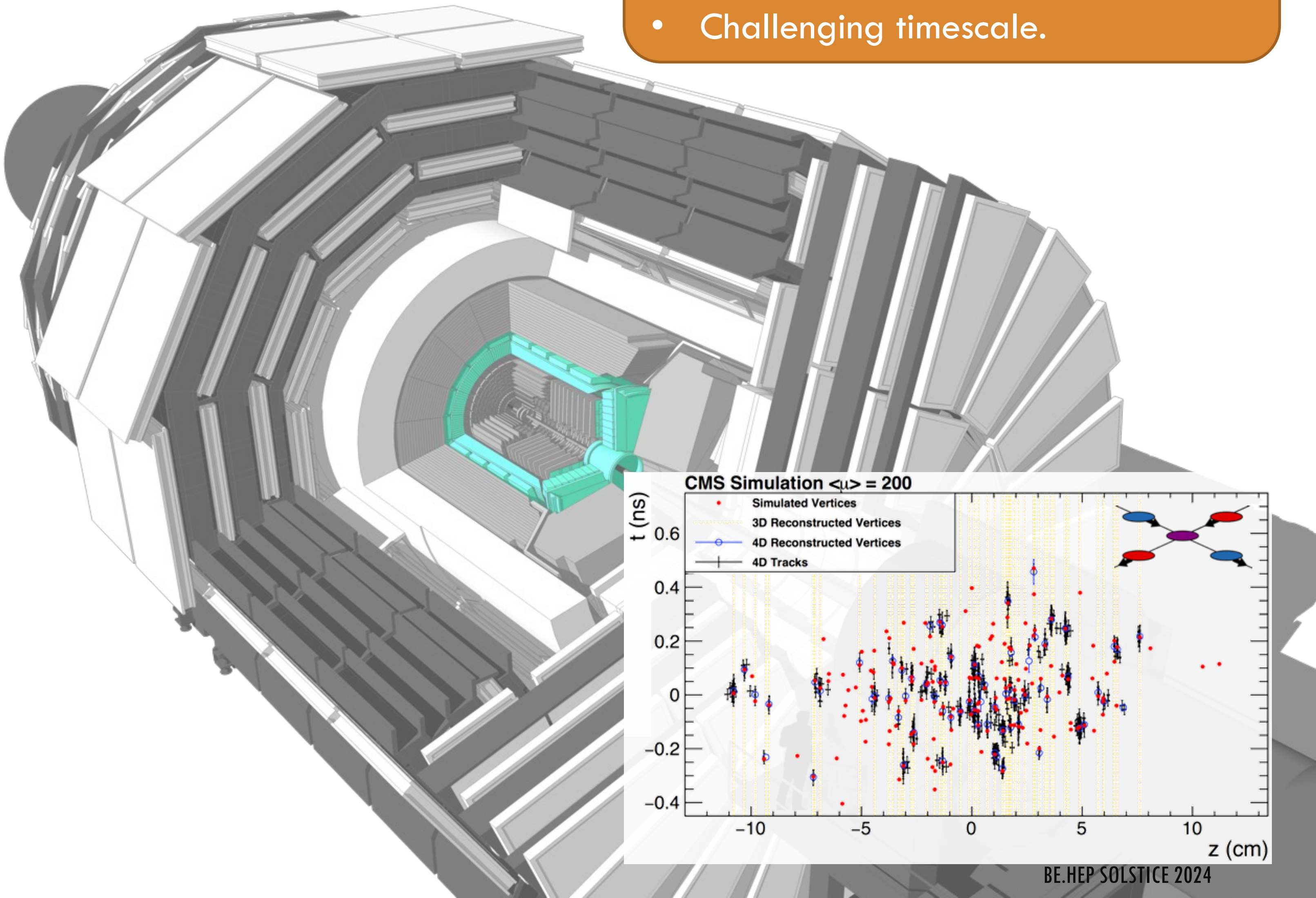
- Barrel: **LYSO crystals + SiPM** (40 m^2).
- Endcap: **low-gain avalanche detector** (10 m^2).

BTL headed into production:

- LYSO+SiPM performance tuning.
- SiPM radiation hardness qualified.

ETL finalizing prototyping:

- **LGAD silicon** sensor qualified.
- **Large-area** scaling and production.



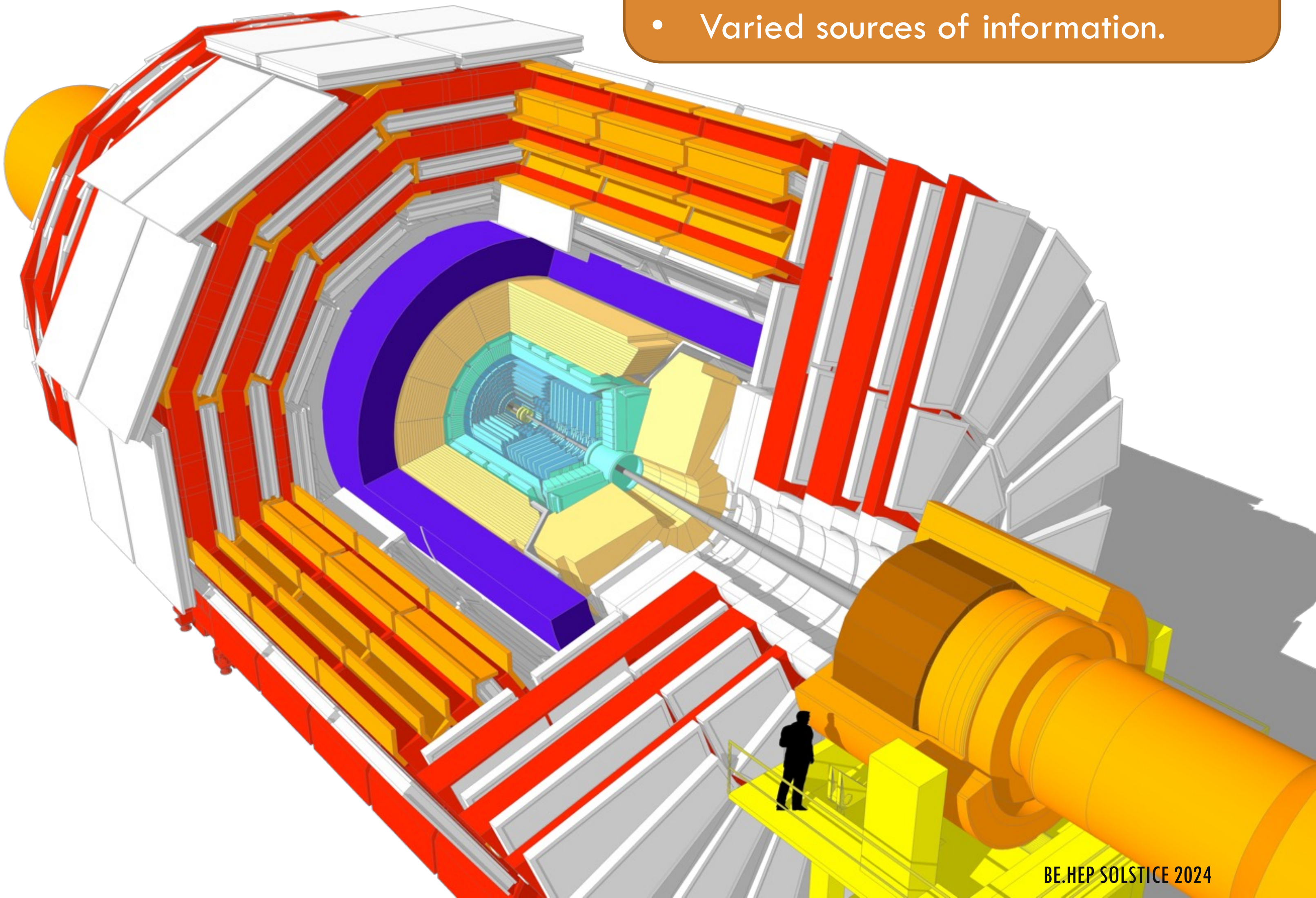
THE BRIL CONSTELLATION

Key challenges:
- Bunch-by-bunch luminometry.
- 1% lumi. uncertainty with 200 PU.
- Varied sources of information.

Fourteen systems brought to bear:
- **Dedicated Fast-BCM** Si pad hits.
- **Online TEPX** pixel clusters and coincidences.
  - **Disk 4 Ring 1** ($\eta > 4$) read out at 825 kHz.
- **BRIL trigger board**.
- **Outer Tracker** Layer 6 L1T track stubs.
- **40 MHz scouting** of L1T objects.
- **Muon barrel** L1T primitives.
- **HF** rings 31 and 32.
- …

Maximum commonality in design.

“Always on” BRILDAQ.



EXPERIMENTAL TECHNOLOGIES – A VIEW

Programming hardware ❄ Synthesizing software

For different levels and aspects, different R&D activities, commonality, and stakeholders.

	Source/Concept	Processing/Implementation	Supporting aspects
O(ps to ns) Analog real-time *"Hardware"*	***Signal formation*** Si sensors, Crystals, Fibers, …	***Signal readout*** Amplifiers, Digitizers, ASICs, …	Cooling, Mechanics, Gas supplies, …
O(µs) Discrete real-time *"Firmware"*	***Signal representation*** Information content, Data format, …	***Signal interpretation*** Electronics systems, Firmware, Trigger systems, …	ATCA, EMI, Power, …
O(ms to s) Online and offline *"Software"*	***Reconstruction algorithms*** Mathematics, O(N logN), …	***Programming*** Languages, GPU/FPGA accelerators, Frameworks/libraries, …	Grids, Clusters, Clouds, …

(Not exhaustive and not exclusive; future needs will mix and match as needed.)

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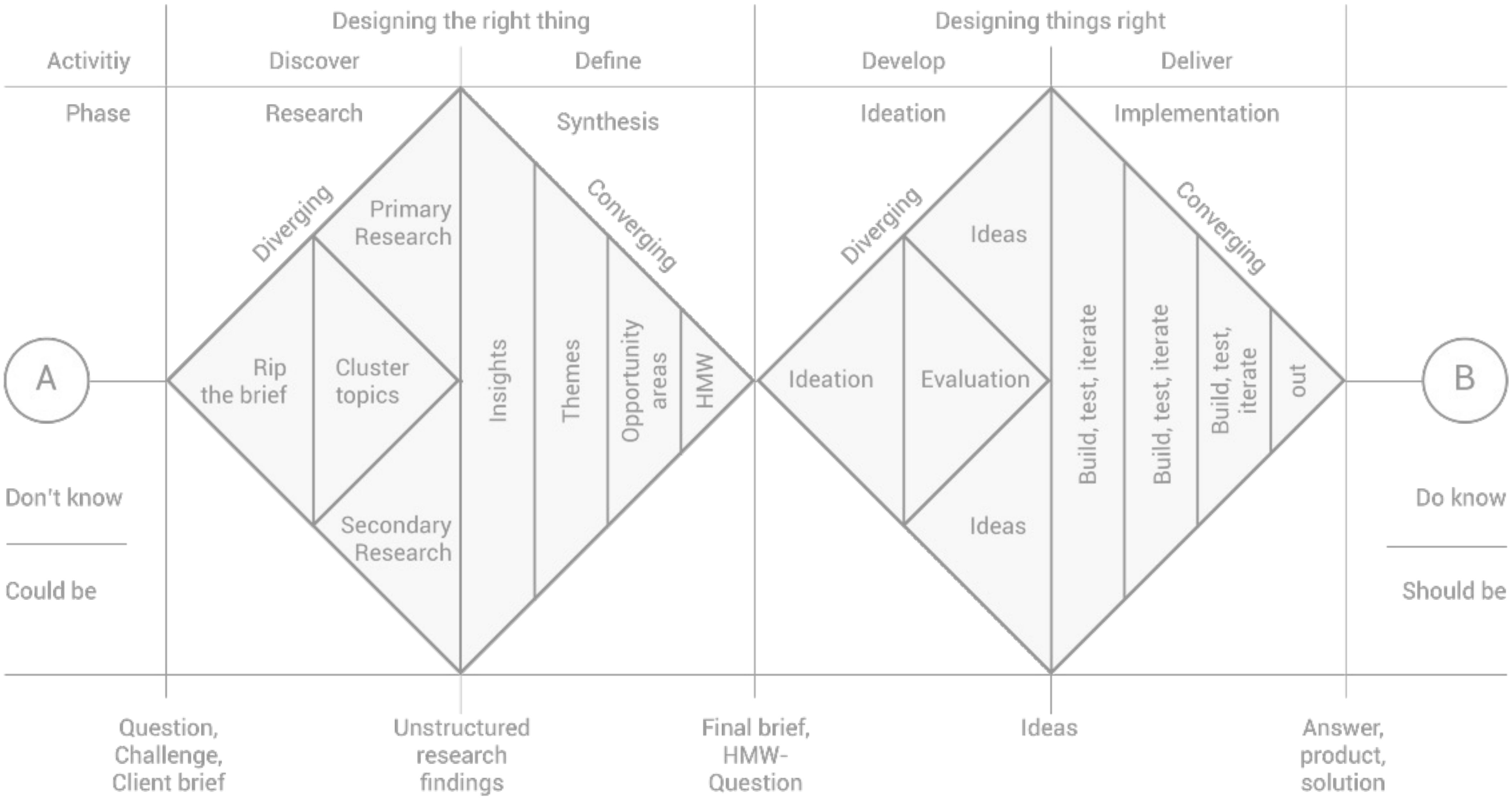
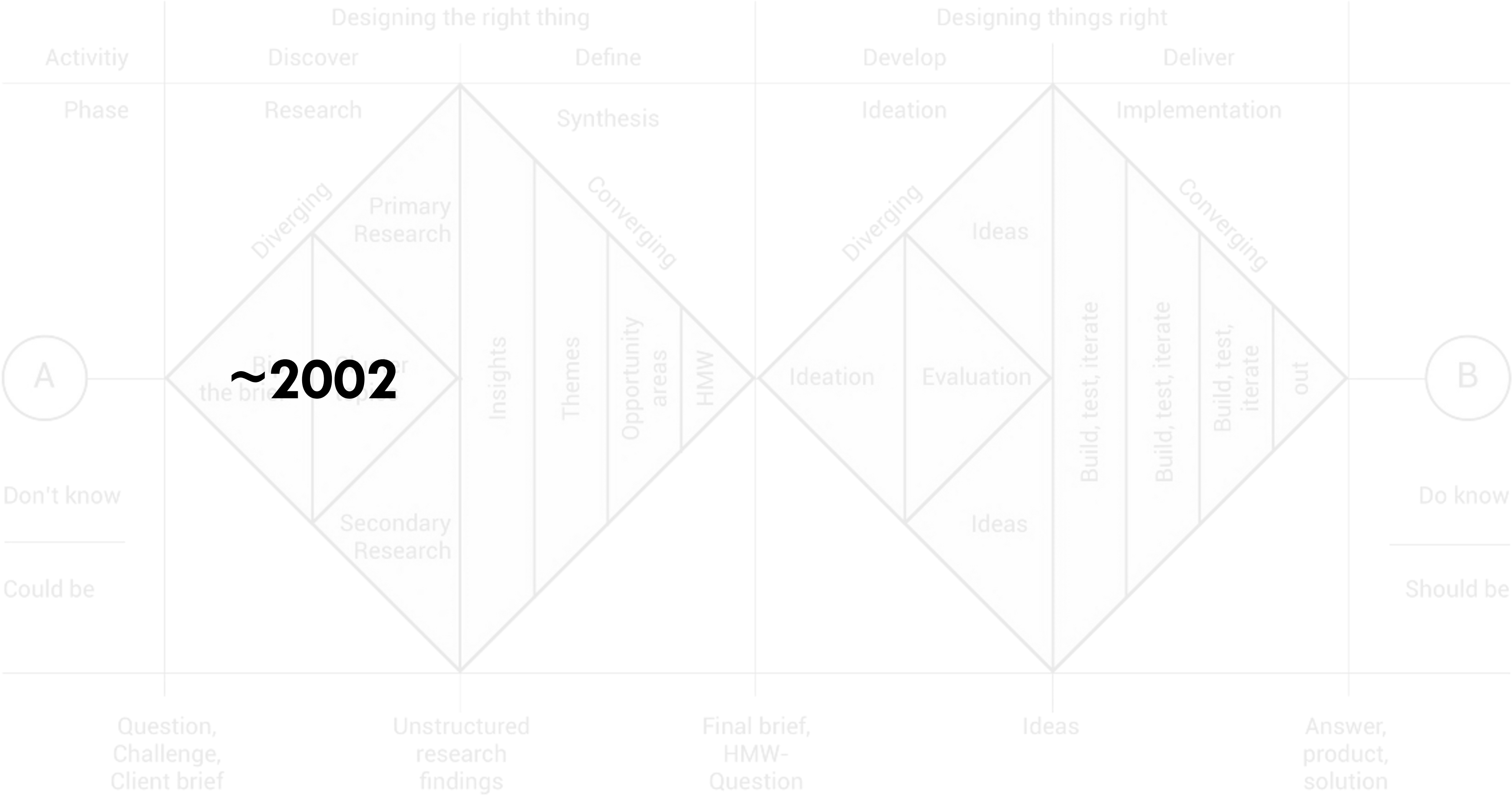
https://medium.com/digital-experience-design/how-to-apply-a-design-thinking-hcd-ux-or-any-creative-process-from-scratch-b8786efbf812

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Designing things right
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Could be
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Question, Challenge, Client brief
Unstructured research findings
Final brief, HMW-Question
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Answer, product, solution

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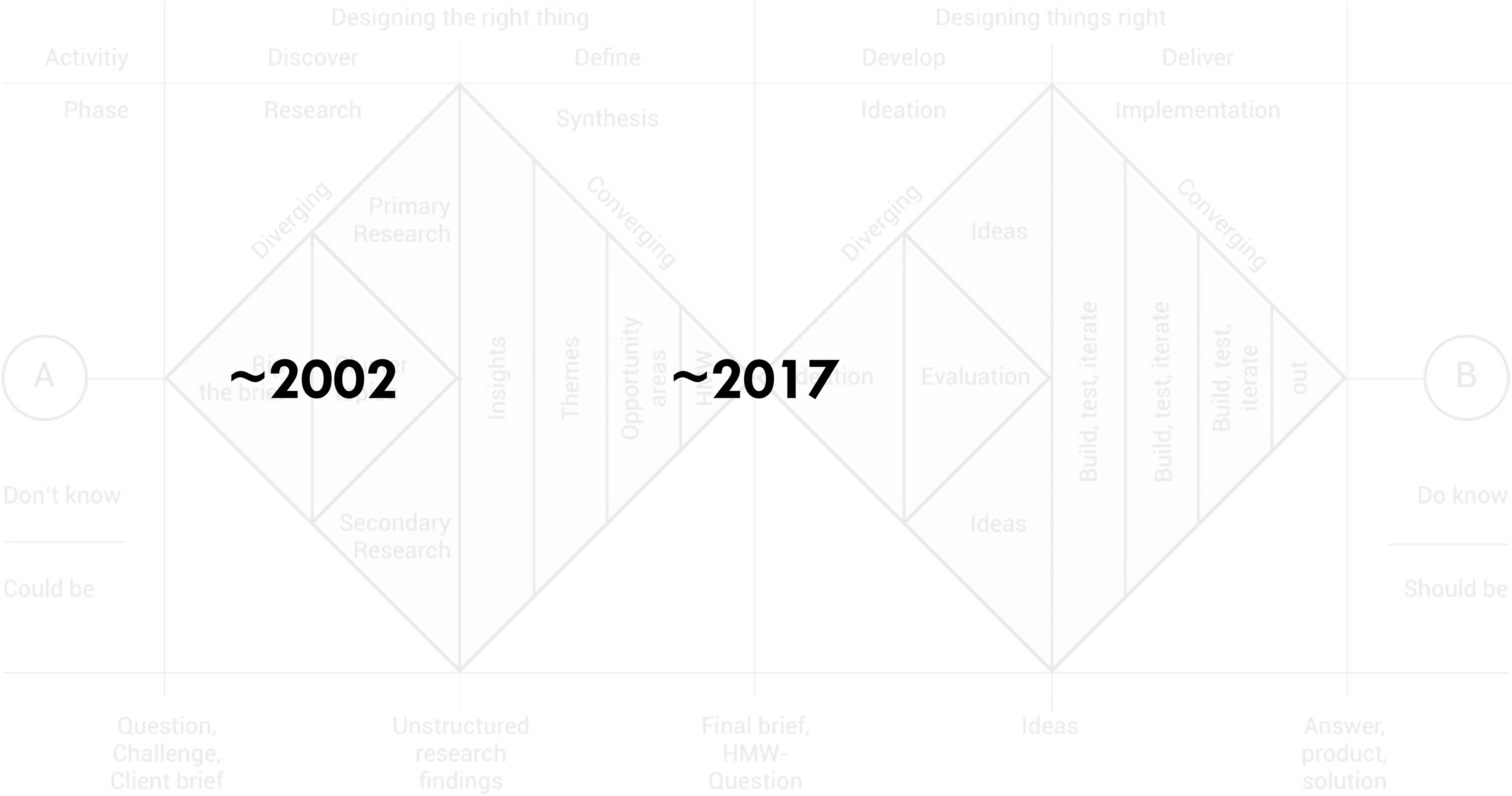
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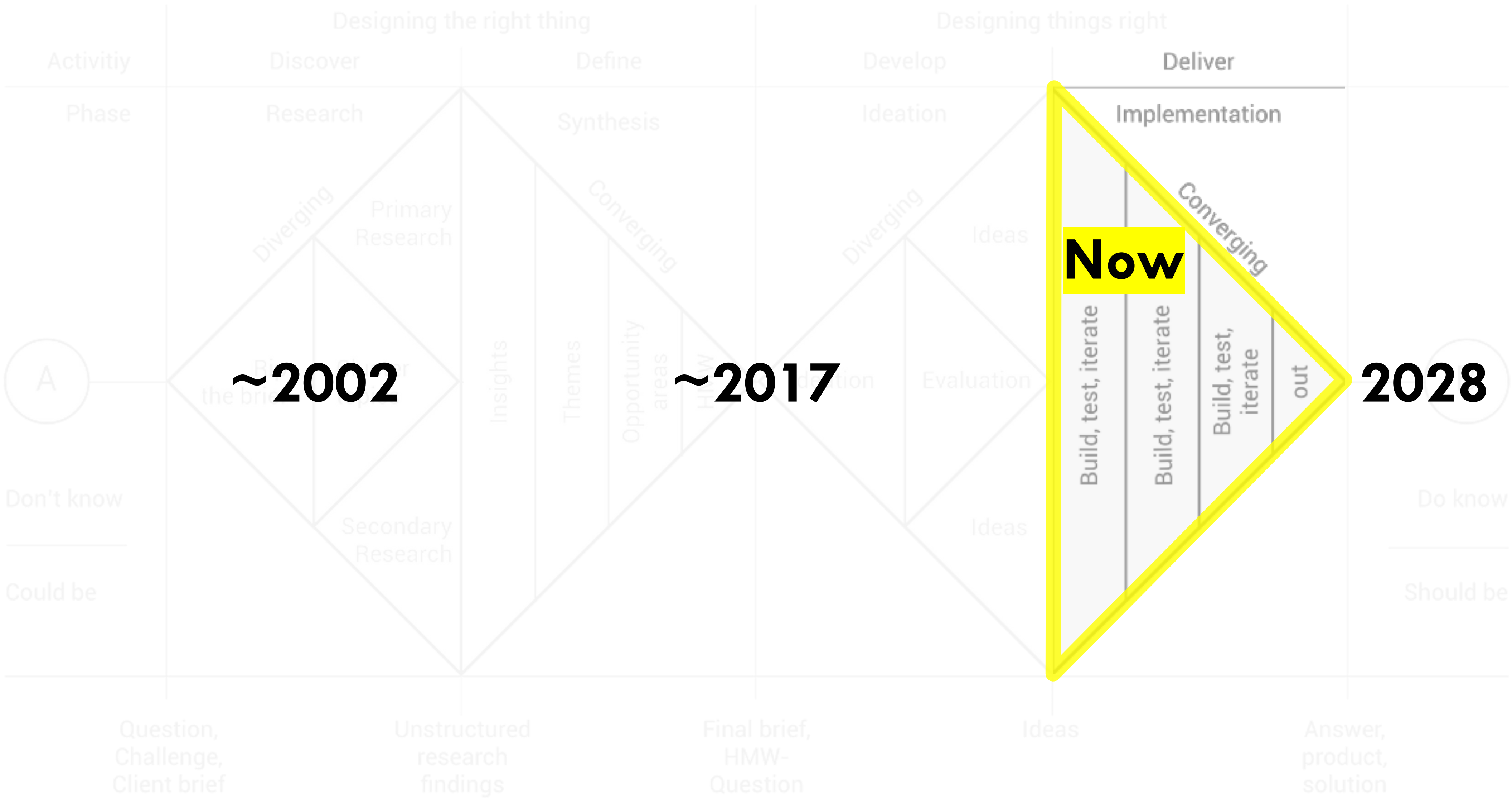
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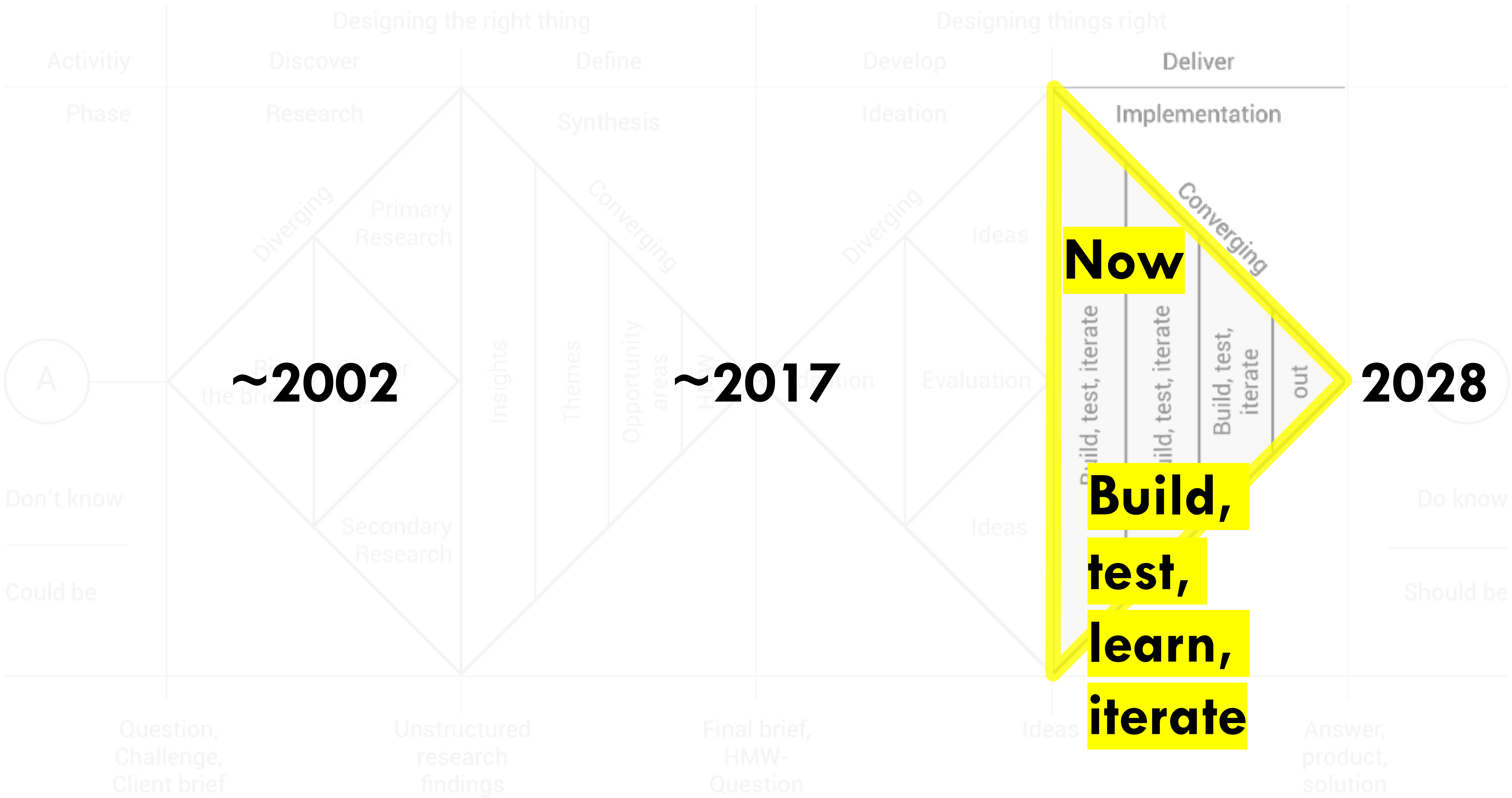
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ON THE WAY TO POINT 5

https://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm

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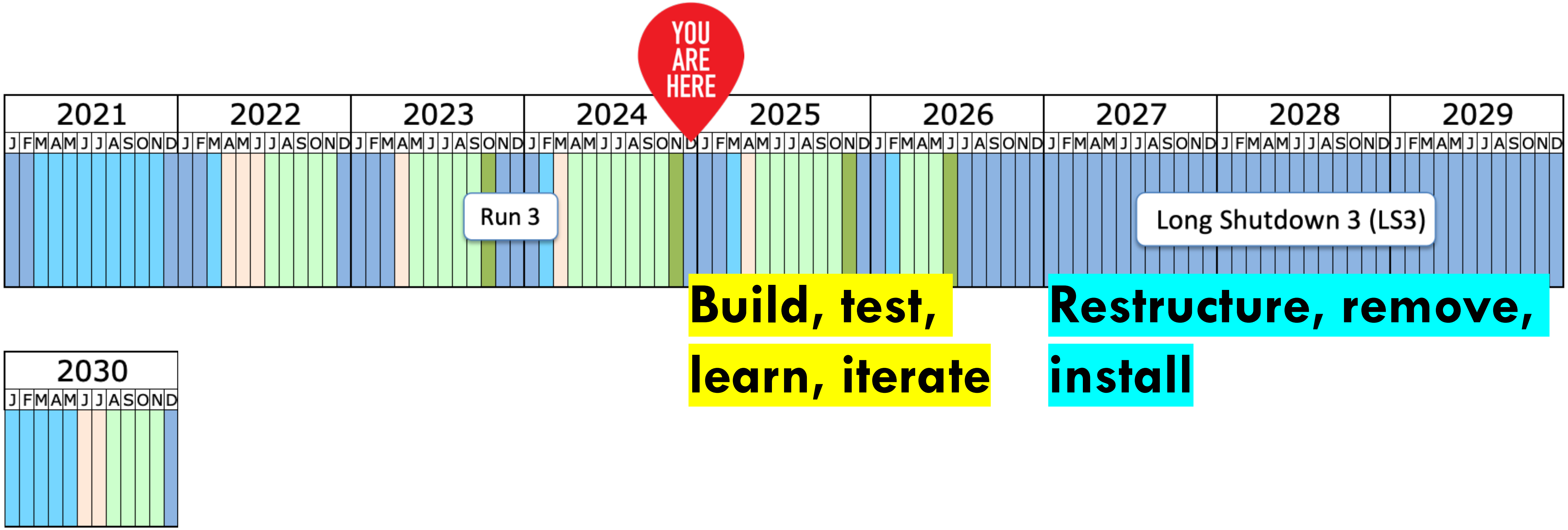

Build, test, learn, iterate

Restructure, remove, install

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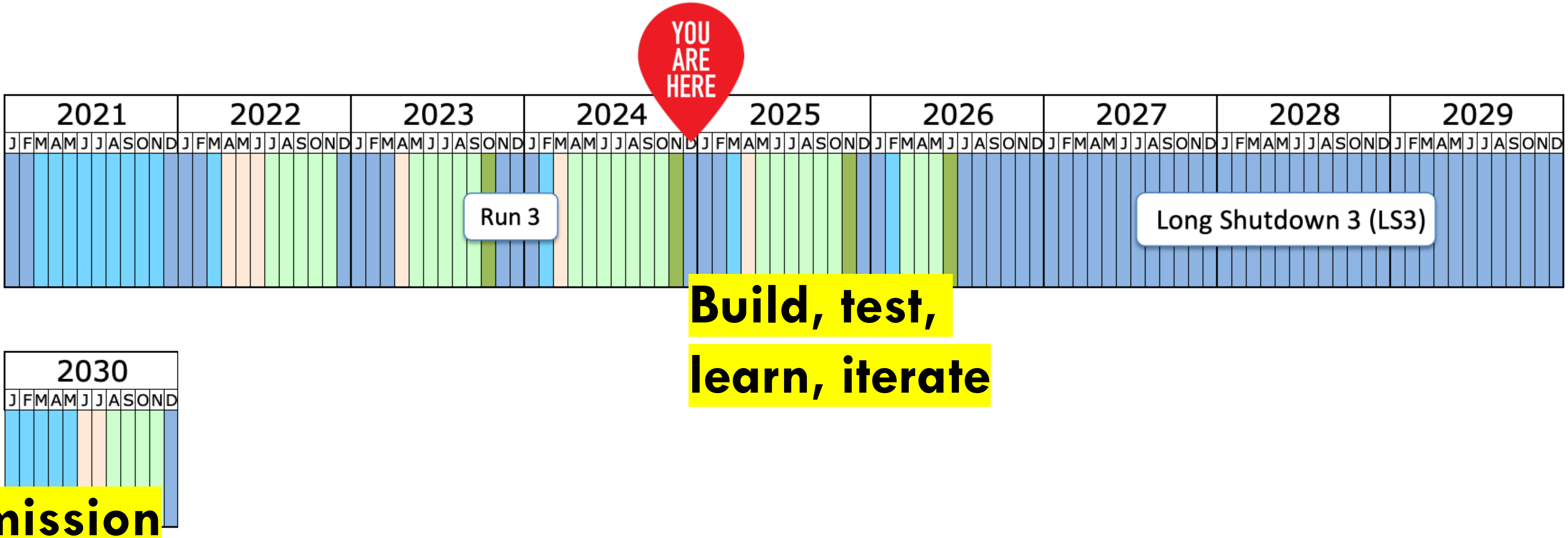
ON THE WAY TO POINT 5



Build, test, learn, iterate

Commission

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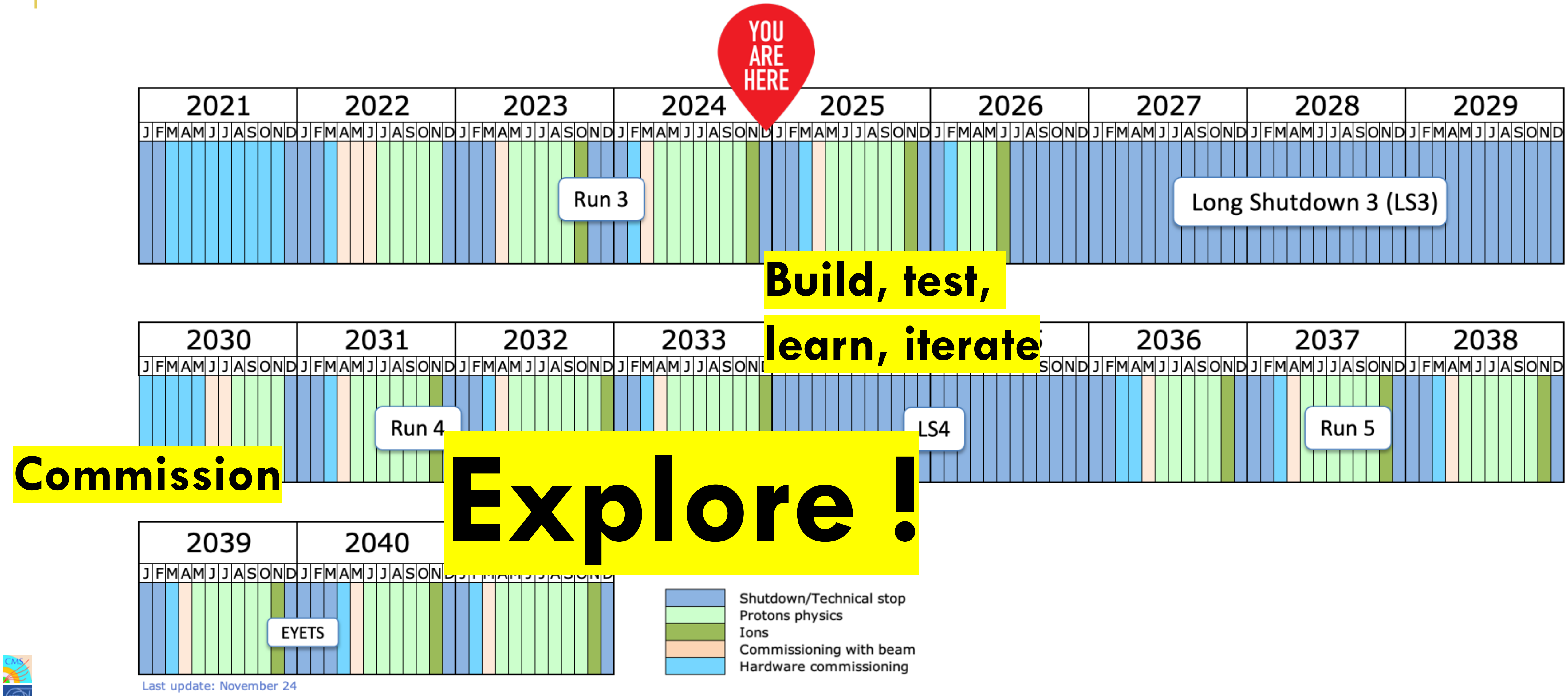


Event display courtesy of M. Rovere

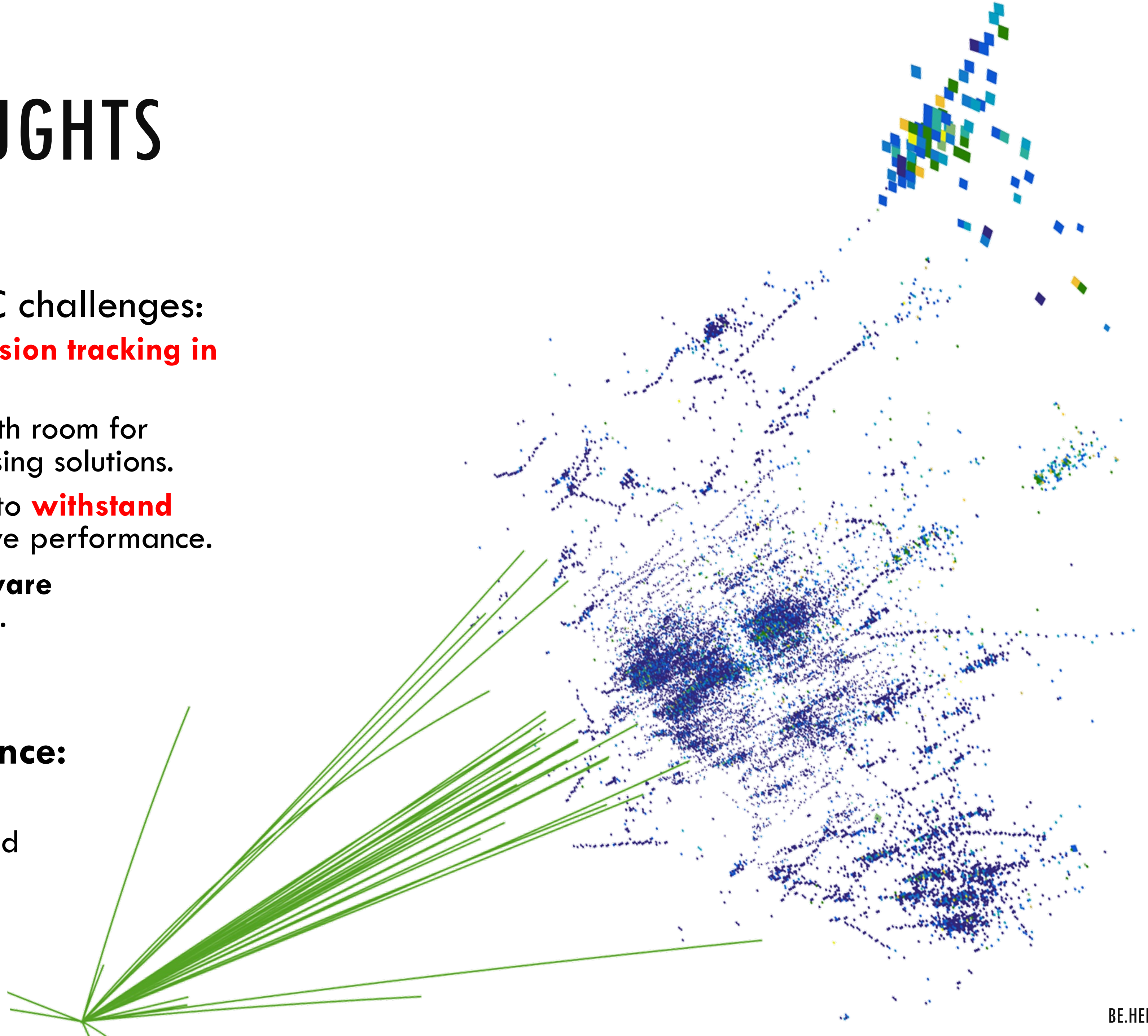
PARTING THOUGHTS

Working to meet HL-LHC challenges:

- All-new detectors with **precision tracking in space and time**.
- **All-new trigger systems** with room for creative information-processing solutions.
- Extant detectors upgraded to **withstand radiation levels** and improve performance.
- **Software, firmware, hardware boundaries** becoming fuzzy.

You can make a difference:

- **build a detector,**
- **commission the system,** and
- **explore nature** with CMS 2.



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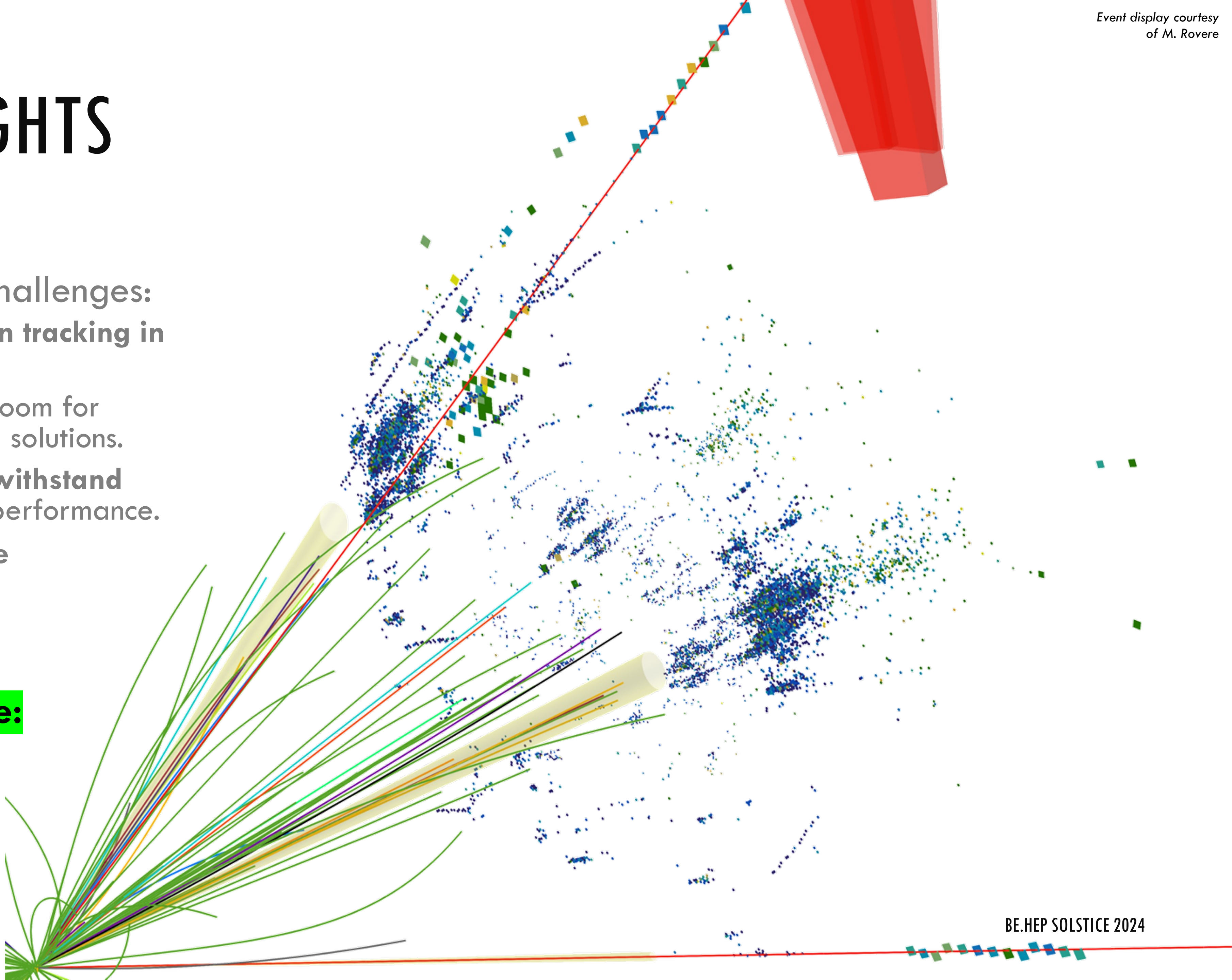

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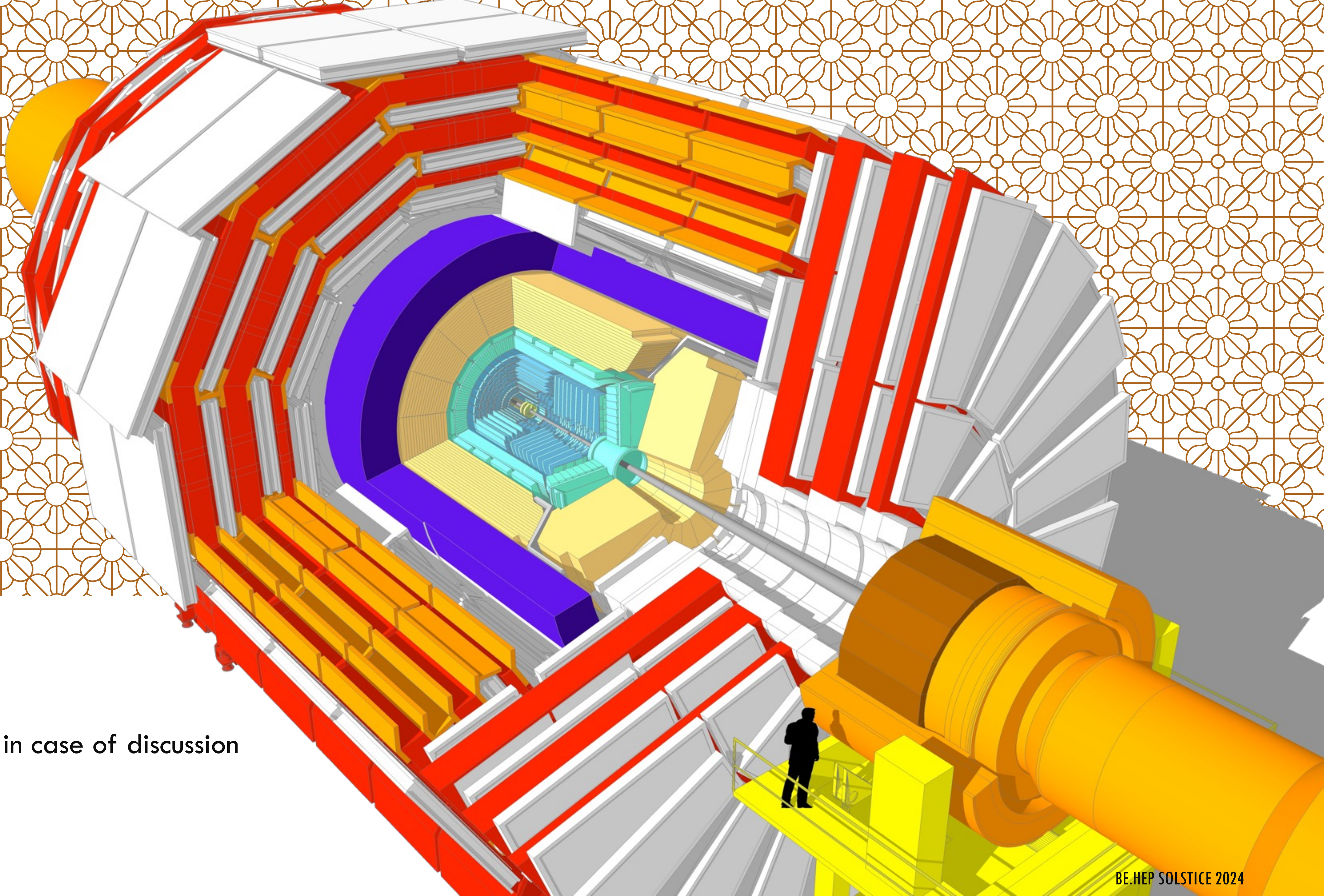


Use in case of discussion

https://www.consilium.europa.eu/en/meetings/european-council/2024/12/19

NOT FAR FROM HERE

European Council

European Council, 19 December 2024

Agenda highlights

The EU in the world

EU leaders will hold a strategic discussion on how the EU can consolidate its role on the international stage and defend our interests and promote our positions.

> Looking beyond our continent, we need to acknowledge the challenges and grasp the opportunities of a plural, multipolar, diverse world.

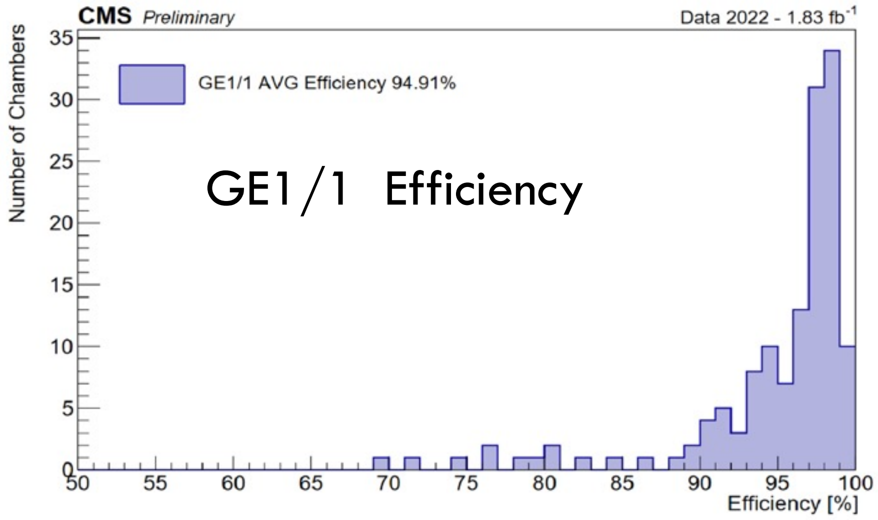
— President of the European Council, António Costa, 7 December 2024

THERE WAS NOT ENOUGH TIME TO SAY THAT…

HCAL barrel off-detector electronics complete replacement needed in LS3.

GE1/1 operation in Run 3 paves the way to other muon upgrades.

- DT, GE2/1, RE3/1, RE4/1 demonstrators also in place.



https://arxiv.org/abs/2103.02752

PRECISION PROTON SPECTROMETER – A PROPOSAL

EOI submitted.

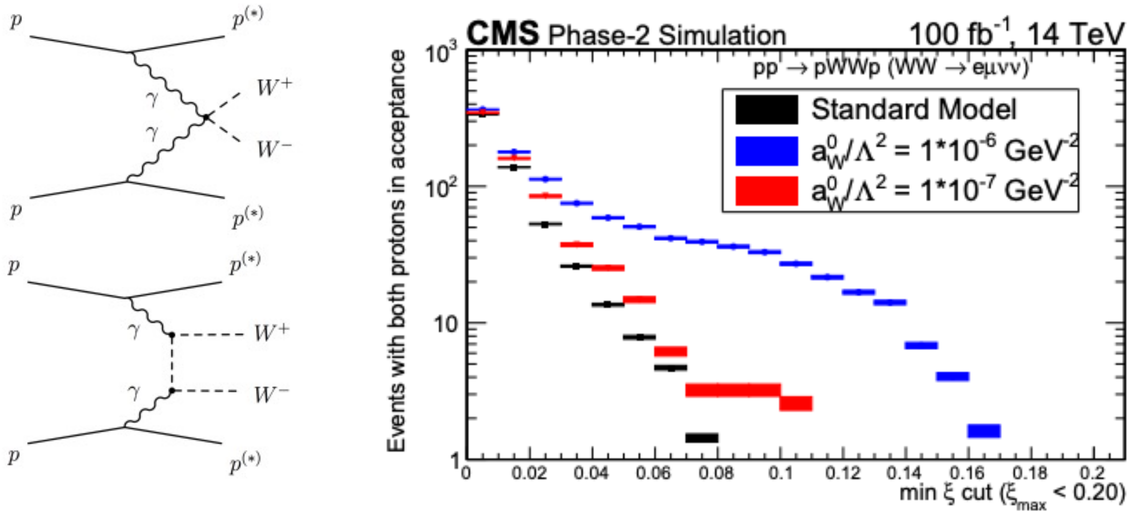
- Presently not in CMS Phase 2 scope.

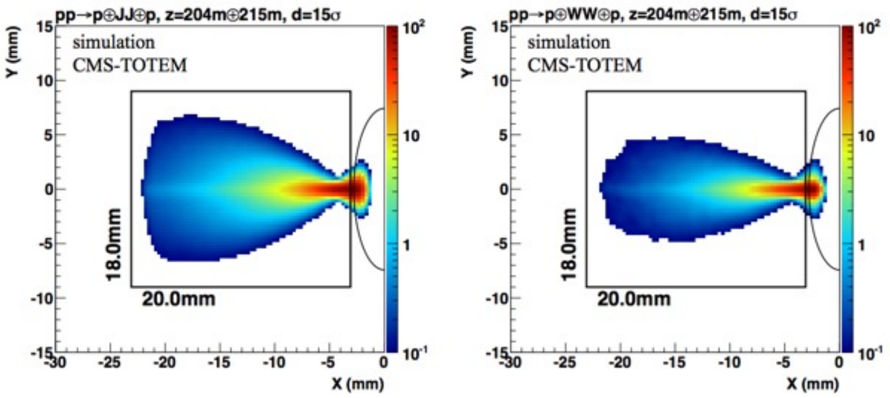
SM and BSM reach.

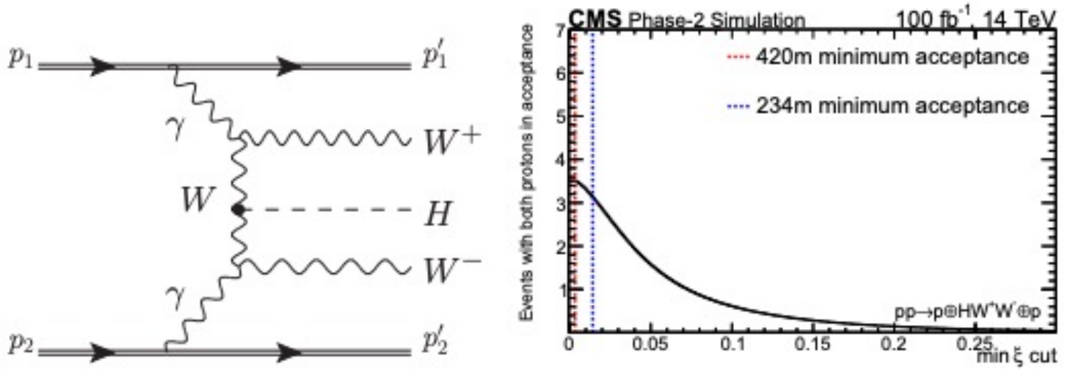
Technologies under consideration:

- **Diamond**: time-of-flight measurements,
- **3D pixel**: tracking, possibly also for timing,
- **UFSD/LGAD**: alternative for timing.

Presently limited by **irradiation inhomogeneity of readout chip.**







TRIGGER TECHNOLOGIES

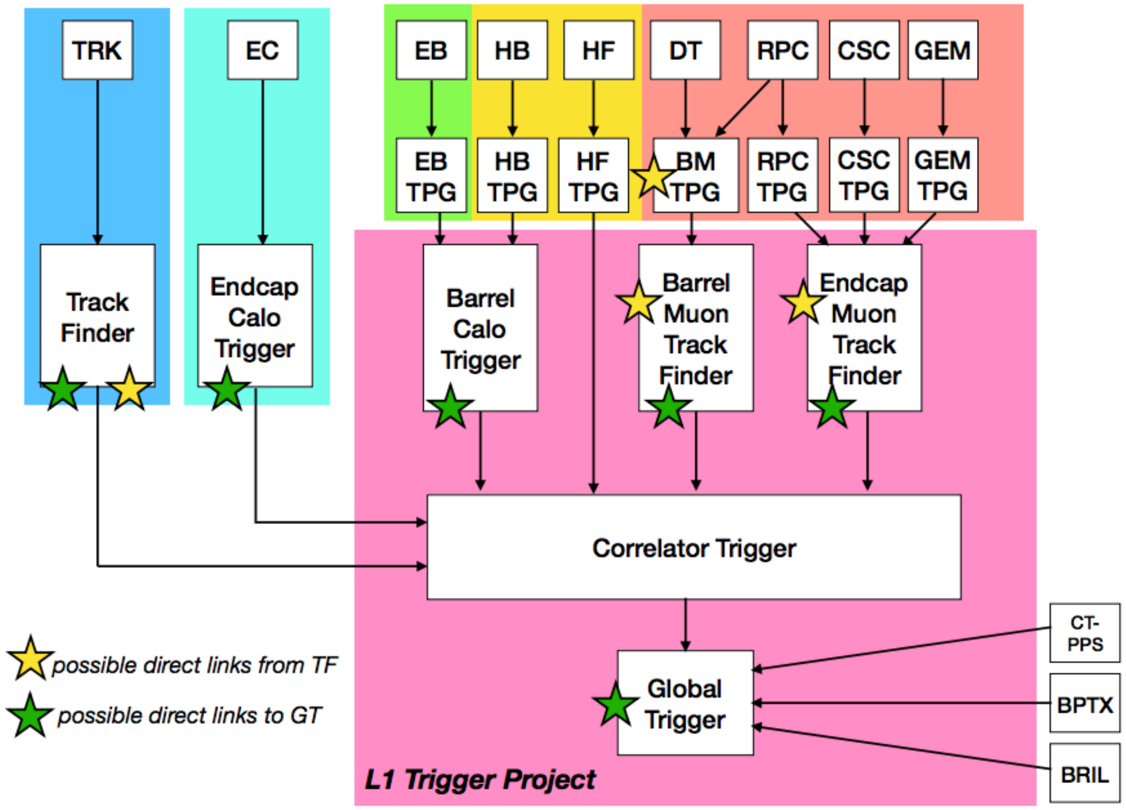
Unprecedented information available after 5 μs:
- Outer tracker tracks.
- Endcap calorimeter 3D clusters.
- Barrel calorimeter full granularity.
- Improved muon system timing.

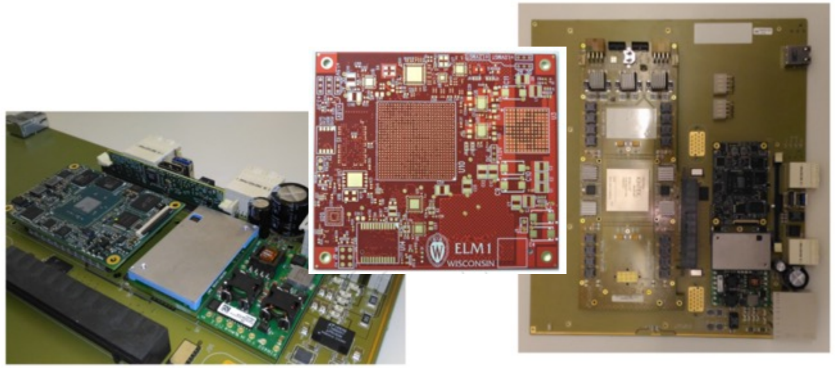
Bringing **particle flow algorithm to Level-1.**

Potential hardware commonalities:
- ATCA motherboards.
- FPGA (compute) solutions.
- Optical (interconnect) links.

Multi-purpose hardware/firmware solutions being pursued.

Excellent use of Run 3 as testing/proving grounds.





PROGRAMMING HARDWARE ❄ SYNTHESIZING SOFTWARE

Convergence of technologies:

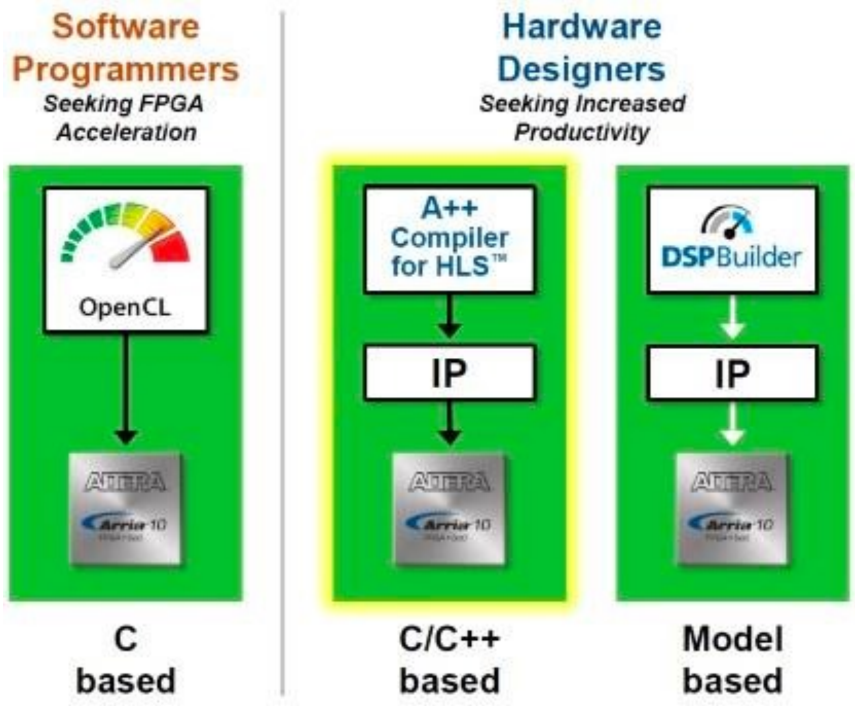
- FPGAs/GPUs used as accelerators for offline.
- Online hardware programmed using high-level languages.

Touches multiple aspects:

- Level-1 trigger extensively uses **FPGAs: algorithms written by physicists.**
- **Acceleration of high-level trigger and offline** computing.
- Similar issues for **machine learning** in online/offline applications.

Many opportunities for collaboration:

- Common accelerator platform (standard) without vendor lock-in.
- Possibility of turnkey solutions (from IT).



- A radical change in programming habits is ahead of us, through advanced software development tools and parallel algorithms

(P. G. Innocenti, Evian, 1992)