REPORT FROM THE INSTRUMENTATION FRONTIER

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SNOWMASS RP FRONTIER WORKSHOP

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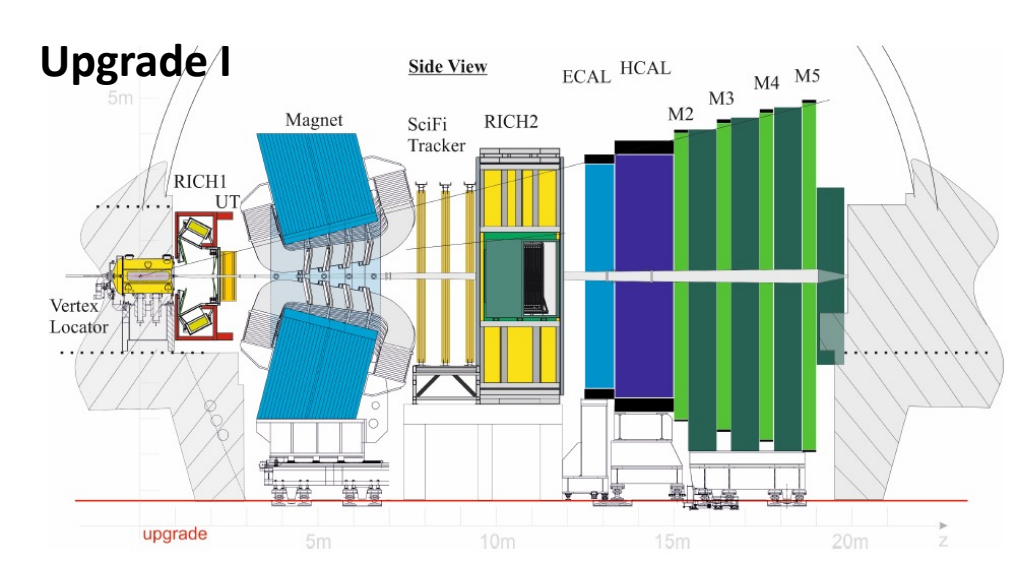
OUTLINE

- CAVEAT: personal selection of experiments and technologies; trying to identify synergies and common R&D directions
- Overview of some of the major experiments and upgrades
- More in-depth look at select technologies
- Addressing key technological challenges

SELECTED EXPERIMENTS

LHCB UPGRADE II

Expected 40 interactions/BX leading to extremely high occupancies and radiation → **increased granularity and timing**



- **Tracking System:** Vertex Locator with increased rad hardness (up to 400 MRad/yr) and fast timing capability (20ps), Upstream Tracker with high granularity, new magnet side chambers (improved efficiency at low momentum), downstream Mighty Tracker with scintillating fiber and silicon pixels with high granularity

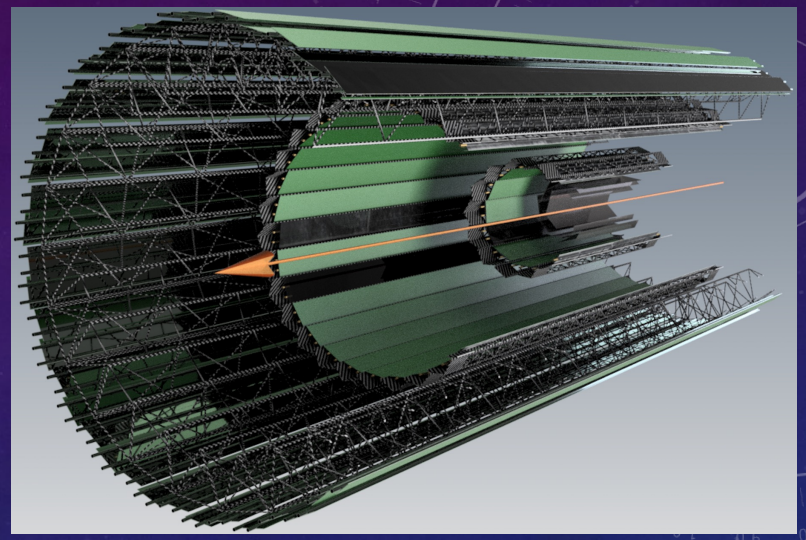
  → **R&D into rad-hard MAPS with ps timing capabilities**

- **PID:** two RICH detectors for hadron ID, calling for R&D for high-efficiency, rad-hard SiPMs; ECAL (withstand up to 100 MRad/yr) with dedicated timing layers; four muon stations; time-of-flight (TORCH) for better pion-kaon-proton distinction at low momentum; aiming for time resolution of ~10ps for PID and background rejection

  → **transformative R&D into meta-materials, such as photonic crystals, as RICH radiator; alternative silicon-based calorimeter (high granularity, 5D info) – synergistic with HL-LHC/ILC**

- **DAQ:** Need for intelligent detectors and increased GPU usage (~32 Tb/s)

BELLE-II UPGRADE



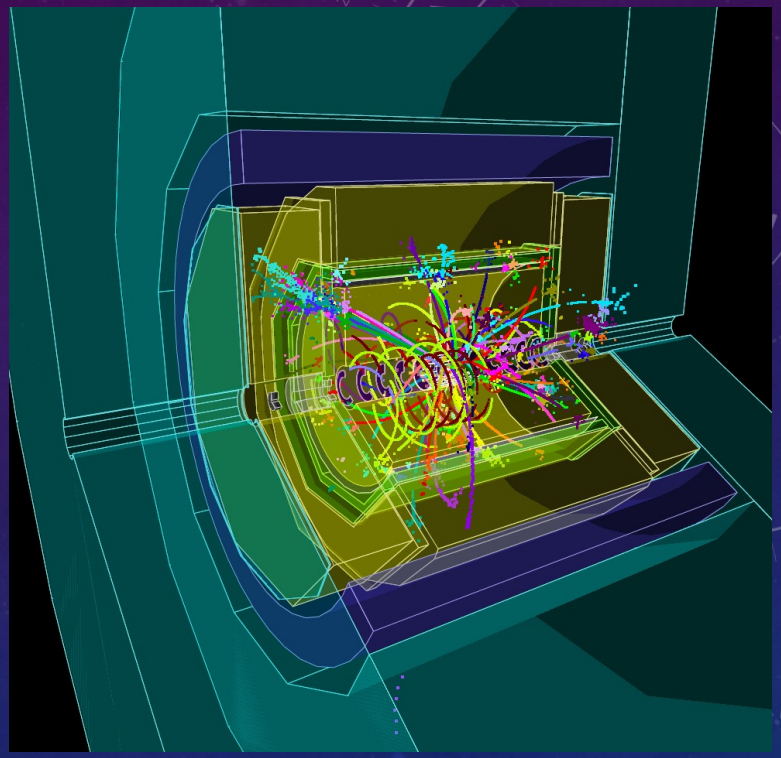
- **Vertex Detector:** need good spatial resolution (<15μm) and low material budget (0.2-0.7% X_0 per layer); various options considered: improved DEPFET pixels (faster signal processing, reduced readout gates) and thin double-sided strip sensors (including L1 track trigger); or 5-layer MAPS (fast, light, granular, low occupancy), including all-silicon ladder concept in inner layers – synergy with ALICE; alternative pixel concepts (DuTIP based on SOI technology) – synergy with ILC

- **Tracker:** current drift chamber needs upgraded electronics; or replace inner part with silicon; or replace with TPC with MPGD readout
- **PID** (TOP, ARICH): replace photodetectors (SiPM, LAPPD) and add timing detectors (LGAD)
- **Calorimeter** (ECL): add pre-shower and replace CsI(TI) with faster crystals (pure CsI) – synergy with Mu2e-II
- **GAZELLE:** dedicated forward detector for Long-Lived Particle detection

NEW TECHNOLOGIES FOR ILC

Various R&D on new technologies for near-term experiments ongoing that can benefit future experiments like ILC. Some examples listed here:

- **LGAD detectors** for ps timing information: specifical interest in inverted LGADs, trench-isolated LGADs and AC-coupled LGADs
- **Low mass silicon** sensors and support structures: very thin MAPS sensors with integrated support structure and cooling channels, either in silicon, Kapton or CFoam; loosely guided gas flow and micro-channel CO_2 cooling; on-detector electronics, power and signal lines integrated on silicon sensor itself
- **Calorimetry:** dual readout taking advantage of scintillation and Cerenkov light; SiPMs and early R&D on digital dSiPMs; crystal ECAL for better EM resolution (<3%/√E); noble-liquid calorimeters for high energy resolution, excellent linearity, uniformity, stability and radiation hardness; digital pixel calorimeter using binary-readout CMOS pixels (R&D to scale up in size)



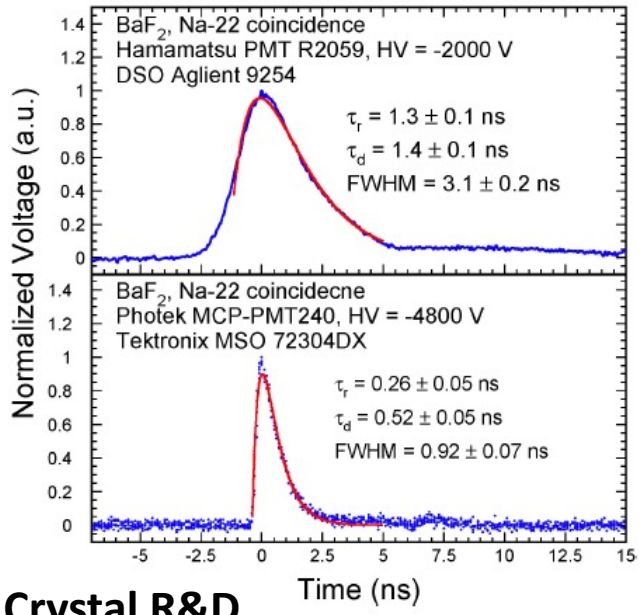
MU2E-II

Moving from Mu2e to Mu2e-II: increased muon intensity and improved sensitivity requirements lead to: improving momentum resolution, handling detector occupancy, surviving higher radiation rates

- **Tracker:** reduce straw wall thickness from 15 to 8 μm; challenge to maintain structurally sound detector; R&D to test rad hardness of thinner straws; need to develop rad-hard ASICs and other readout components. Alternative tracker designs: e.g. enclosing a drift tracker in an ultra-light gas vessel, could replace straws with drift cells a la MEG-II drift chamber; alternatively, use foils instead of wire layers; R&D for optimal gas choice
- **Calorimeter:** in first disk, replace CsI crystals with BaF2 (more rad-hard and higher rates); main challenge is slow component at 300nm compared to fast scintillation light at 220nm → R&D on Yttrium doping to suppress slow component; R&D on solar-blind photodetectors to reduce gamma-ray induced readout noise (LAPPD, APD, SiPM)
- **Cosmic-Ray-Veto:** needs improved shielding, e.g. Barite and Boron-loaded concrete and plastics; increased granularity counters, improved geometry to reduce gaps

Straw R&D

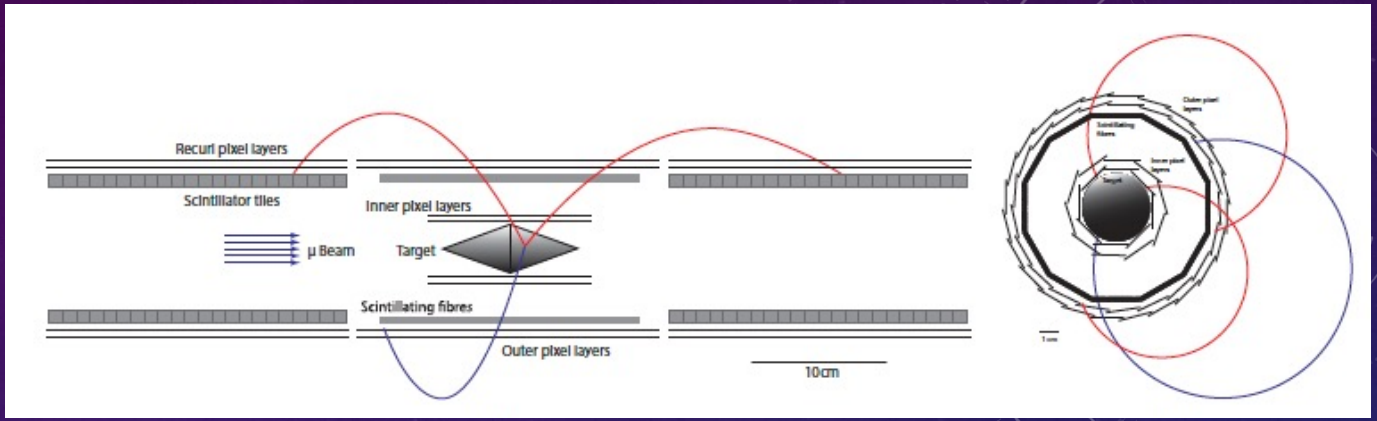
	Mu2e	Mu2e-II
Wall thickness (μm)	18.1	8.2
Al thickness (μm)	0.1	0.2
Au thickness (μm)	0.02	0.0
Linear Density (g/m)	0.35	0.15
Pressure limits (atm)	0–5	0–3
Elastic Limit (gf)	1600	500



Crystal R&D

FIG. 26. A comparison of BaF_2 pulse shape measured with a Hamamatsu R2059 PMT (top) and a Photek MCP-PMT 240 (bottom).

MU3E EXPERIMENT

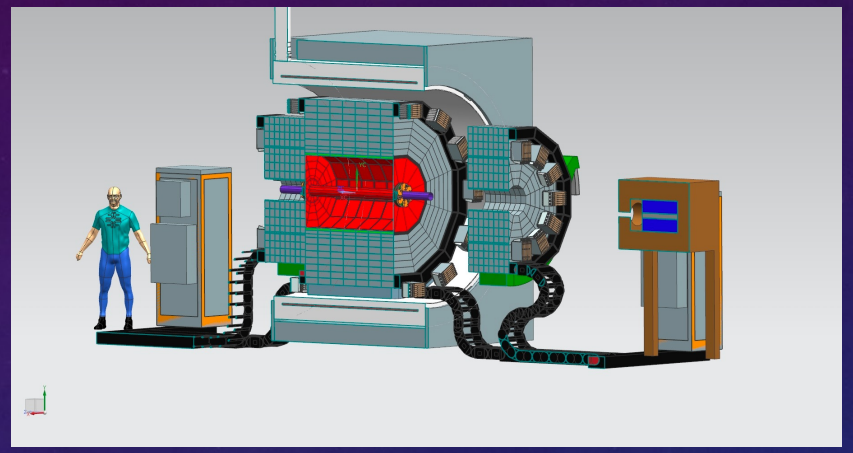


- Phase-1 detector design:
  - very thin HV-MAPS with small pixels for optimal momentum and vertexing resolution for low-energy electrons (0.1% X_0 per layer for full assembly)
  - scintillating fiber detector for time measurement (250ps resolution at 0.2% X_0)
  - upstream and downstream recurl stations, consisting of additional pixel layers surrounding scintillator tiles
  - continuous, triggerless readout with fast online track reco
- Phase-2 developments:
  - upgrades to timing detectors and possible improvements to pixel sensors to improve time resolution to deal with higher occupancies, as well as extensions to detector stations to increase acceptance

REDTOP EXPERIMENT

Need hermetic detector covering entire solid angle, that can correctly identify final state particles

- **Vertex detector**, two options:
  - wafer-scale silicon sensors based on R&D for Alice ITS3 (20μm thick wafer with CMOS sensors, 90cm long using stitching
  - fiber tracker with identical technology as for LHCb upgrade
  - keep the material budget as low as possible to reduce multiple scattering



- **Central tracker**: needs to reconstruct relatively low momentum, very low material budget, good time resolution for PID, two options:
  - low-mass LGAD: current sensor options sufficient; only passive cooling; minimize heat output
  - Optical TPC: threshold choice to minimize background; readout with LAPPD or SiPMs with pixel size of few mm^2
- **Calorimeter**, ADRIANO2: good energy and time resolution; fast response; trigger input
  - dual readout technique aiming to achieve energy compensation in hadronic showers
  - higher granularity using tiles; readout with SiPMs or SPADs
- Thin Cerenkov radiator layer to detect particles above Cerenkov threshold provided by quartz; to measure TOF of these particles
- Optional AC-LGAD timing layer based on design planned for the EIC
- Multi-level trigger system

	spatial res.	material budget	momentum res.	time res.	energy res.	detector response
vertex	<20μm	~0.03% X_0/layer				
tracker		~0.1% X_0/layer	2×10^{-3} GeV^{-1} @ 1 GeV	<30 ps		
calo				<80 ps/cell	3%/√E	within 100 nsec
timing		<1% X_0/layer		<30 ps/hit		

ADMX G2
SQuAD
Quantum Sensors
Atomic Clocks
Underground Laboratories
Nuclear Clocks
ALPHA
Atom Interferometers
Optical Cavities
Magnetometers
Lxe TPC
HAYSTAC
MADMAX
ALPS II
LHe TPC
Molecular Clocks
Mechanical Resonators
Torsion Balances
DMRadio-m3
LAMPOST
BREAD
ORGAN
IAXO
DMRadio-GUT
Optical Interferometers
Muon Decay
Muon Conversion
SRF Cavities
ADMX EFR
TES
Molecular Absorption DM Detectors
CASPEr-electric
ABRACADABRA
Multiplexed Readout
ARIADNE
MKID
CASPEr-gradient
COMET
DeeMe
LDMX
DarkQuest
RADES

INSTRUMENTATION FRONTIER: ADDRESSING KEY TECHNOLOGICAL CHALLENGES

IF1 QUANTUM SENSORS

- Quantum Sensors for HEP Science - Interferometers, Mechanics, Traps, and Clocks: https://arxiv.org/abs/2203.07250
- Quantum Sensors for high precision measurements of spin-dependent interactions: https://arxiv.org/abs/2203.09488

IF2 PHOTON DETECTORS

- Future Advances in Photon-Based Neutrino Detectors: https://arxiv.org/abs/2203.07479
- Photon counting from the vacuum ultraviolet to the short wavelength infrared using semiconductor and superconducting technologies: https://arxiv.org/abs/2203.12542

IF3 SILICON TRACKING & VERTEXING

- Simulations of Silicon Radiation Detectors for High Energy Physics Experiments: https://arxiv.org/abs/2203.06216
- Novel Sensors for Particle Tracking: https://arxiv.org/abs/2202.11828
- 4-Dimensional Trackers: https://arxiv.org/abs/2203.13900
- Integration and Packaging: https://arxiv.org/abs/2203.06093
- Light-weight and highly thermally conductive support structures for future tracking detectors: https://arxiv.org/abs/2203.14347
- Monolithic Active Pixel Sensors on CMOS technologies: https://arxiv.org/abs/2203.07626

IF4 TDAQ

- Innovations in trigger and data acquisition systems for next-generation physics facilities: https://arxiv.org/abs/2203.07620
- Readout Technologies for Future Detectors: https://arxiv.org/abs/2203.14894
- Physics Community Needs, Tools, and Resources for Machine Learning: https://arxiv.org/abs/2203.16255
- Applications and Techniques for Fast Machine Learning in Science: https://arxiv.org/abs/2110.13041

IF5 MPGD

- MPGDs: Recent advances and current R&D: https://arxiv.org/abs/2203.06562
- Micro Pattern Gaseous Detectors for Nuclear Physics: https://arxiv.org/abs/2203.06309
- Recoil imaging for dark matter, neutrinos, and physics beyond the Standard Model: https://arxiv.org/abs/2203.05914
- MPGDs for TPCs at future lepton colliders: https://arxiv.org/abs/2203.06267
- MPGDs for tracking and Muon detection at future high energy physics colliders: https://arxiv.org/abs/2203.06525

IF6 CALORIMETRY

- Precision timing for collider-experiment-based calorimetry: https://arxiv.org/abs/2203.07286
- Materials for Future Calorimeters: https://arxiv.org/abs/2203.07154
- Particle Flow Calorimetry: https://arxiv.org/abs/2203.15138
- Dual-Readout Calorimetry for Future Experiments Probing Fundamental Physics: https://arxiv.org/abs/2203.04312

IF7 ELECTRONICS & ASICS

- Enabling Capabilities for Infrastructure and Workforce in Electronics and ASICs: https://arxiv.org/abs/2204.07285
- Readout for Calorimetry at Future Colliders: https://arxiv.org/abs/2204.00098
- Electronics for Fast Timing: https://arxiv.org/abs/2204.00149
- Fast (optical) Links: https://arxiv.org/abs/2203.15062
- Smart sensors using artificial intelligence for on-detector electronics and ASICs: https://arxiv.org/abs/2204.13223
- RF Electronics: https://arxiv.org/abs/2204.01809

IF8 NOBLE ELEMENT DETECTORS

IF08 organized Executive Summary pages instead of white papers:

- Low-Threshold Noble Element Detectors
- Pixels
- Charge Gain
- Recoil Directional Sensitivity and Micron-Precision Spatial Reconstruction
- Increasing Light Collection
- Metastable Fluids
- New Modalities in Existing Infrastructure
- Next-generation large scale detectors
- Detector Microphysics/Characterization

IF9 CROSS CUTTING & SYSTEMS INTEGRATION

- Cryogenic User Facilities for R&D on Noble Liquid Detectors and Low Temperature Devices: https://arxiv.org/abs/2203.06146
- A Facility for Low-Radioactivity Underground Argon: https://arxiv.org/abs/2203.09734
- Test Beam and Irradiation Facilities: http://arxiv.org/abs/2203.09944

IF10 RADIO DETECTION

- Instrumentation Development for Radio Detection of High-Energy Neutrinos
- Large-Format, Transmission-Line-Coupled Kinetic Inductance Detector Arrays for HEP at Millimeter Wavelengths: https://arxiv.org/abs/2203.15902

DOE BASIC RESEARCH NEEDS STUDY ON HEP DETECTOR RESEARCH & DEVELOPMENT IN 2019

Guidance and structure of BRN is excellent resource to formulate future plans →
The BRN has both a physics section to motivate scientific goals and a very detailed technology section outlining where we are and what is needed: https://science.osti.gov/hep/Community-Resources/Reports

Science	Timescale	Technical Requirement (TR)	PRD
Search for new physics though rare flavor interactions	medium term	TR 5.1: Timing resolution at the level of $10-30$ ps per hit in the silicon-pixel vertex detectors and $10-30$ ps per track for both PID detectors (RICH, TORCH) and electromagnetic calorimeters	2, 10, 18
	medium term	TR 5.2: Development of radiation-hard, fast and cost-effective photosensors for TORCH and RICH detectors and tracking systems with optical readout	9, 11
	medium term	TR 5.3: Development of the next generation ASICS to extract the large data rate (and possibly pre-process it) out of inner pixel layer detectors in a very challenging radiation environment	16, 17
	medium term	TR 5.4: Radiation-hard silicon pixel detectors (fluences of 5×10^{16} n_{eq}/cm^2)	18, 20
Tests of the CKM quark mixing matrix description	medium term	TR 5.5: Cost-effective electromagnetic calorimeter with granularity of typically 2×2 cm^2, resolution of $\frac{\sigma(E)}{E} \sim \frac{10\%}{\sqrt{E}} \oplus 1\%$ and timing resolution of a few tens of ps; total radiation dose of ~ 200 Mrad	1
	medium term	TR 5.6: Real-time processing of large amount of data (400-500 Tb/sec) and development of radiation-hard, high-rate optical links, with tight constraints of low-power consumption and low mass	16, 17, 21, 22
	long term	TR 5.7: Fast-timing resolution at the level of 1 ps per track for $\pi/K/p$ separation up to 50 GeV	3, 10
	long term	TR 5.8: Further ASICS development to extract and pre-process on detector the large data rate of inner layers detectors in an extreme radiation environment	16, 17
Studies of Lepton Flavor Universality	long term	TR 5.9: Radiation-hard, ultra-fast silicon pixel detectors (fluences of 10^{18} n_{eq}/cm^2)	18, 19, 20
	long term	TR 5.10: Very high granularity calorimeters preserving an energy resolution of $\frac{\sigma(E)}{E} \sim \frac{10\%}{\sqrt{E}}$	1, 2, 7, 9
	long term	TR 5.11: Real-time processing of large amount of data (1Exabytes/sec) and development of radiation-hard, high-rate optical links, with tight constraints of low-power consumption and low mass	16, 17, 21, 22, 23

Table 10: Technical Requirements to enable the physics program of heavy flavor and the map to Priority Research Directions. The "medium-term" timescale refers to experiments that will begin operation in the late 2020s and early 2030s. The "long-term" timescale refers to experiments that will begin operation in the 2040s and beyond.

Priority Research Directions for Tracking Detectors:

- ✓ Create building blocks for Systems-on-Chip for extreme environments
- ✓ Adapt new materials and fabrication/integration techniques for particle tracking
- ✓ Realize scalable, irreducible mass trackers
- ✓ Achieve on-detector, real-time, continuous data processing and transmission to reach the exascale

Primary Research needs related to Timing Detectors:

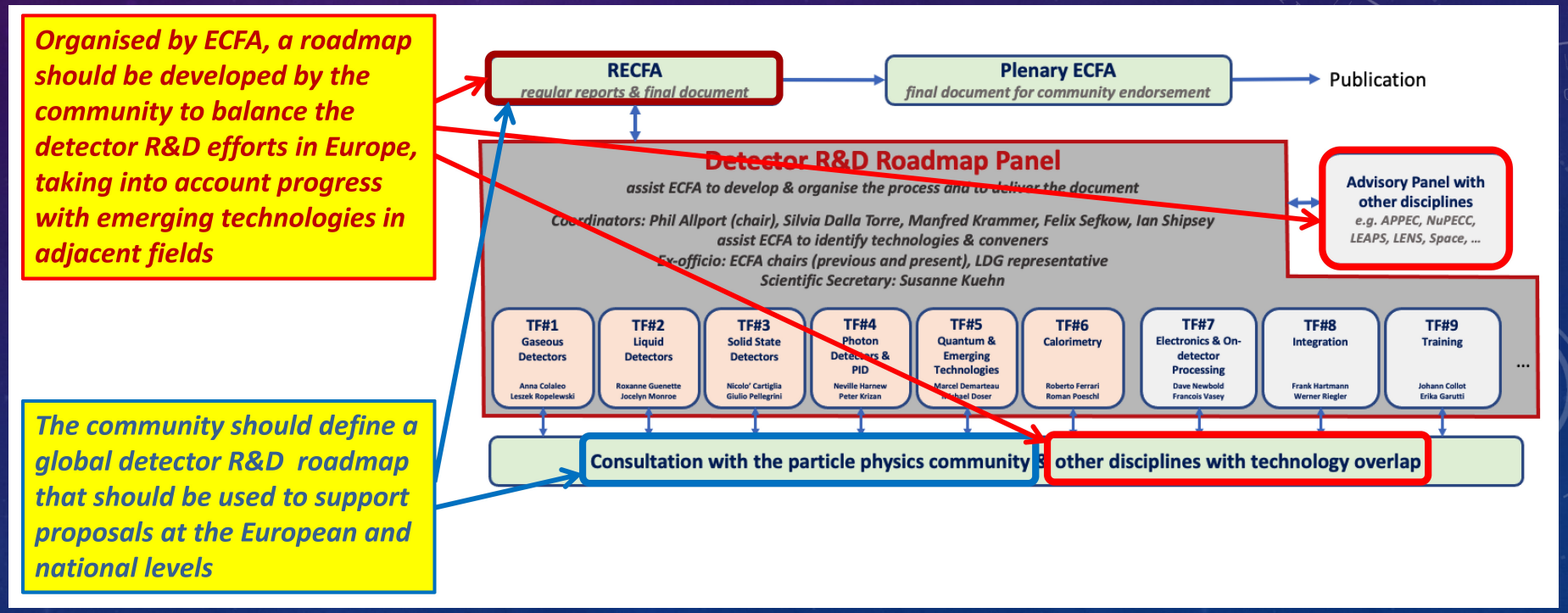
- ✓ Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments
- ✓ Design new devices and architectures to enable picosecond timing and event separation (for photo-detectors).
- ✓ Develop high spatial resolution pixel detectors with precise per-pixel timing information
- ✓ Time resolution to resolve individual interactions in high-collision-density environments (for solid state detectors).

ECFA DETECTOR R&D ROADMAP

ECFA
European Committee for Future Accelerators

- ✓ Focus on the technical aspects of detector R&D requirements given the 2020 EPPSU deliberation document listed "*High-priority future initiatives*" and "*Other essential scientific activities for particle physics*" as input and organize material by Task Force.
- ✓ Task Forces started from the future science programs to identify main detector technology challenges to be met (both mandatory and highly desirable to optimize physics returns) to estimate the period over which the required detector R&D programs may be expected to extend.
- ✓ Within each Task Force create a time-ordered technology requirements driven R&D roadmap in terms of capabilities not currently achievable.

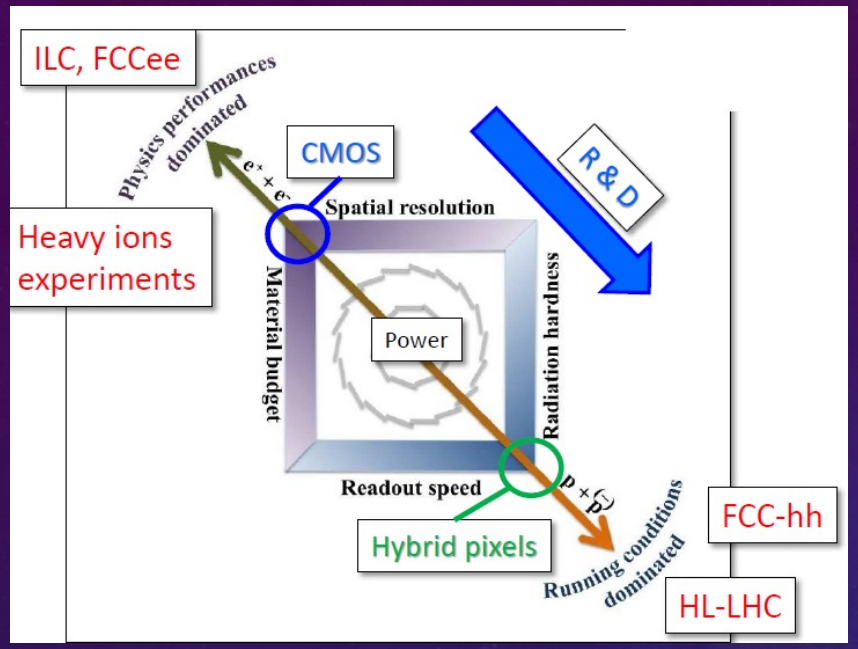
"... The roadmap identifies and describes a diversified detector R&D portfolio that has the largest potential to enhance the performance of the particle physics programme in the near and long term."



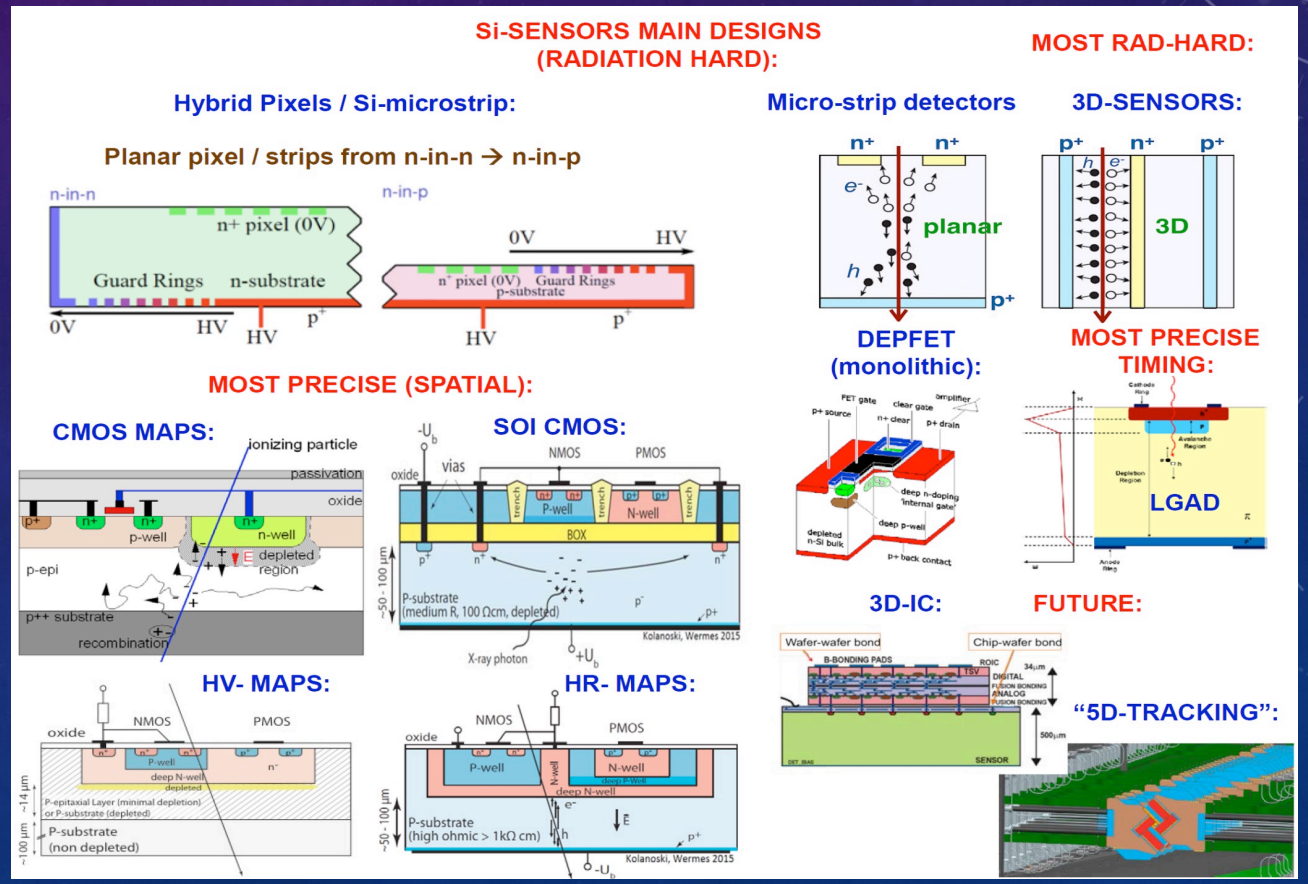
Final report released in Dec. 2021: https://cds.cern.ch/record/2784893

KEY TECHNOLOGICAL CHALLENGES

ENABLING TECHNOLOGIES FOR LOW-MASS TRACKING



- ✓ Basic applications are optimized for two different realms of interest : electron and hadron colliders → different optimizations/requirements (pp: radiation hardness, speed; e+e-: granularity, material budget)
- ✓ Design problems include: granularity vs power (particularly for precision timing) and the inactive material to service power and data readout etc. for both accelerator types. Radiation hardness and a strong emphasis on data reduction / feature extraction for on-detector electronics



Hadron Colliders:
- ✓ Hybrid pixel detectors (planar & 3D)
- ✓ HV/HR-CMOS for outer pixel layers
- ✓ LGADs for ps-timing

Lepton Colliders:
- ✓ CMOS (STAR HFT, ALICE ITS)
- ✓ DEPFET (Belle II)
- ✓ Chronopix
- ✓ SoI
- ✓ FPCCD
- ✓ 3D-IC (Global Foundries, LAPIX, TJas,…industries)

Needs: collect requirements for different collider types / experiments
→ IF topical group summary, and more importantly to make sure the developments in the community meet the experimental need

ENABLING TECHNOLOGIES FOR PICOSECOND TIMING

Picosecond-level timing was not the part of initial HL-LHC detector requirements

Became available through pioneering R&D on LGAD / crystals / precise timing with Si:

Burst of development of precise timing sensors:

- ✓ 4D pattern recognition for HL-LHC pile-up rejection: tracking ~O(10) μm & timing detectors ~O(10) ps
- ✓ ps-timing reconstruction in calorimetry (resolved hadron showers, background rejection, PID)
- ✓ TOF and TOP (RICH DIRC) PID → new DIR applications (~ 10s of ps & 10s of μm per MIP/pixel) → both at hadron / lepton colliders
- ✓ General push for higher luminosity at LHC, Belle-II, Panda, EIC → Fast timing is needed at colliders, fixed target, and neutrino experiments

Photo-detectors

- ➢ Regular PMTs → large area, … but slow
- ➢ MCP-PMT → fast, but small, and not available in quantities to cover large areas:
  - → ultimate time resolution ~ 3.8 ps (single-pixel devices)
  - → radiation hardness up to ~ 20 C/cm (HPK, ALD-coated MCP-PMT°

Detector	Experiment or beam test	Maximum rate	Maximum anode charge dose	Timing resolution	Ref.
MRPC presently	ALICE	~500 Hz/cm^2 *** (tracks)	-	~60 ps/track (present)***	[4]
MRPC after upgrade	ALICE	Plan: ~50 kHz/cm^2 ** (tracks)	-	Plan: ~20 ps/track	[4]
MCP-PMT	Beam test	-	-	< 10 ps/track *	[7,8,9]
MCP-PMT	Laser test	-	-	~27 ps/photon *	[14]
MCP-PMT	PANDA Barrel test	10 MHz/cm^2 * (laser)	~20 C/cm^2 *	-	[11]
MCP-PMT	Panda Endcap	~1 MHz/cm^2 ** (photons)	-	-	[28]
MCP-PMT	TORCH test	-	3-4 C/cm^2 *	~90 ps/photon *	[27]
MCP-PMT	TORCH	10-40 MHz/cm^2 ** (photons)	5 C/cm^2 **	~70 ps/photon **	[24-27]
MCP-PMT	Belle-II	< 4MHz/MCP *** (photons)	-	80-120 ps/photon ***	[23]
Low gain AD	ATLAS test	~40 MHz/cm^2 ** (tracks)	-	~ 34 ps/track/single sensor *	[34,35]
Medium gain AD	Beam test	-		< 18 ps/track *	[39]
Si PIN diode (no gain)	Beam test (electrons)	-		~23 ps/32 GeV e$^-$	[8]
SiPMT (high gain)	Beam test – quartz rad.	-	< 10^{10} neutrons/cm^2	~ 13 ps/track *	[8]
SiPMT (high gain)	Beam test - scint. tiles	-	< 10^{10} neutrons/cm^2	< 75 ps/track *	[41]
Diamond (no gain)	TOTEM	~3 MHz/cm^2 * (tracks)	-	~ 90 ps/track/single sensor *	[36]
Micromegas	Beam test	~100 Hz/cm^2 * (tracks)	-	~24 ps/track *	[31,32,40]
Micromegas	Laser test	~50 kHz/cm^2 * (laser test)	-	~76 ps/photon *	[31,32,40]

* Measured in a test
** Expect in the final experiment
*** Status of the present experiment

Challenges:

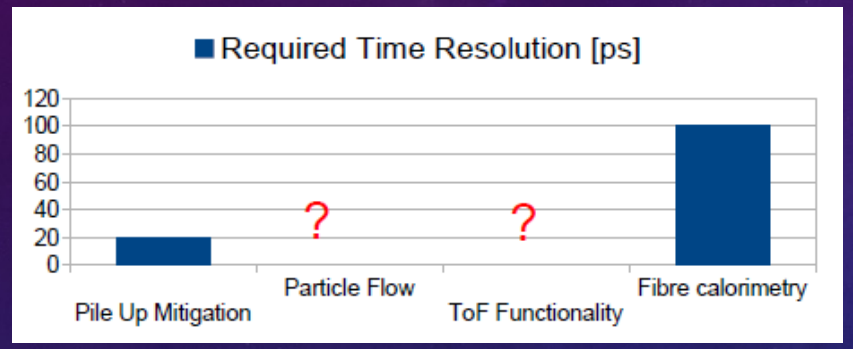
- ✓ Radiation hardness: LGAD-sensors, 3D-trench Si sensors, …
- ✓ Large scale applications : system aspects of timing detectors
- ✓ "5D reconstruction": space-points / ps-timing are available at each point along the track
- ✓ LAPPD → large-area ps- PID/TOF for hadron/lepton colliders → cost still has to be controlled

IMAGING CALORIMETERS: THE 5TH DIMENSION?

Impact of 5D calorimetry (x,y,z, energy, time) needs to be evaluated more deeply to understand optimal time accuracy

What are the real goals (physics wise)?

- Mitigation of pile-up (basically all high rates)
- Support for full 5D PFA → uncharted territory
- Calorimeters with ToF functionality in first layers?
- Longitudinally unsegmented fiber calorimeters



✓ **Trade-off between power consumption and timing capabilities (maybe higher noise level)**

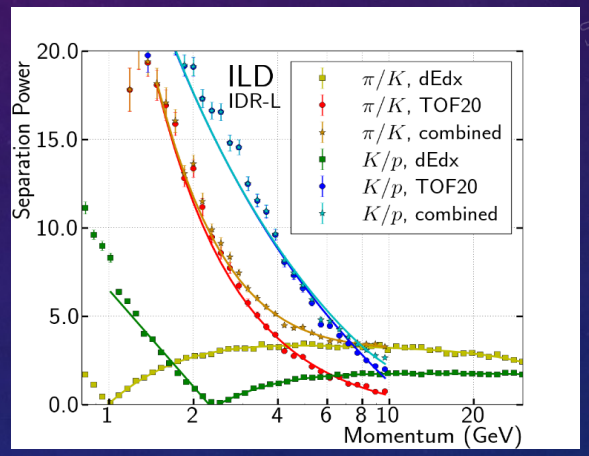
✓ **Timing in calorimeters / energetic showers?**

→ **intelligent reconstruction using O(100) hits & NN can improve "poor" single cell timing**

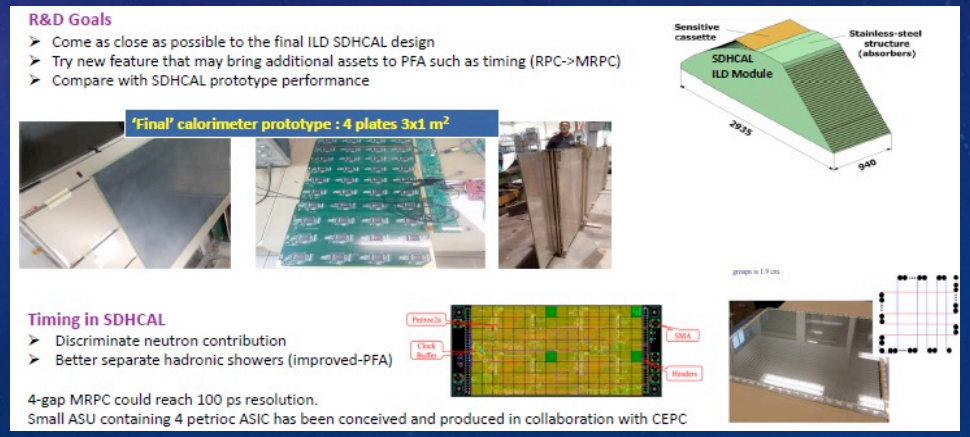
→ **can help to distinguish particle types: usable for flavour tagging (b/c/s), long-lived searches, enhance σ(E) / E**

Replace (part of) ECAL with LGAD for O(10 ps) timing measurement

20 ps TOF per hit can separate π/k/p up to 5-10 GeV



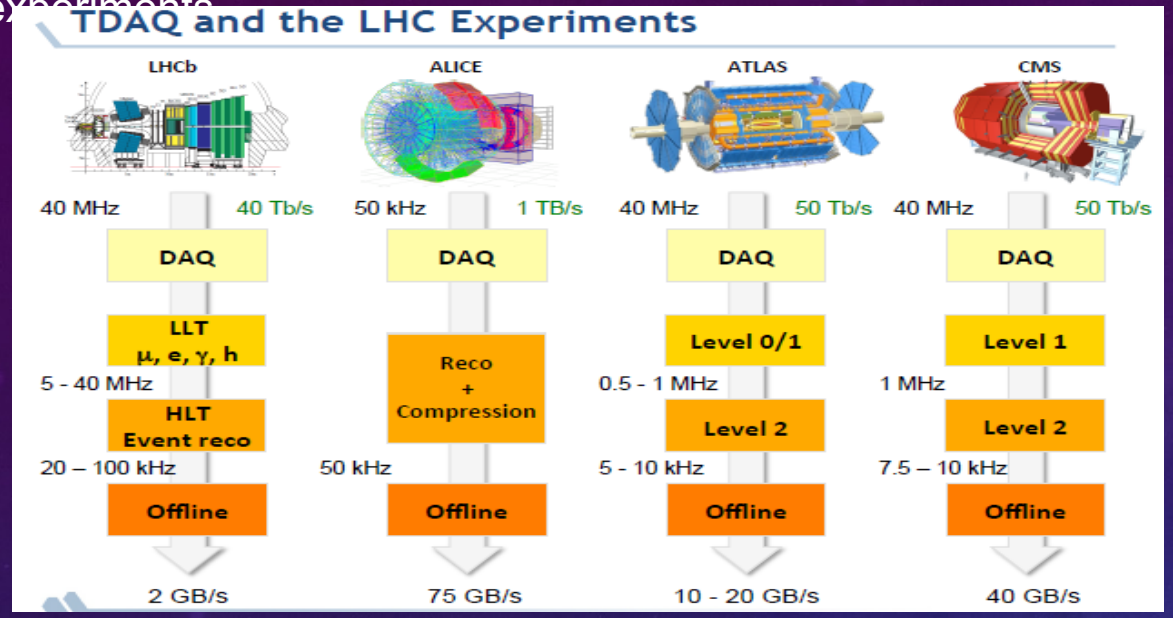
sDHCAL R&D: improved timing with replacement of RPC with (multi-gap) MRPC → O(20-100) ps

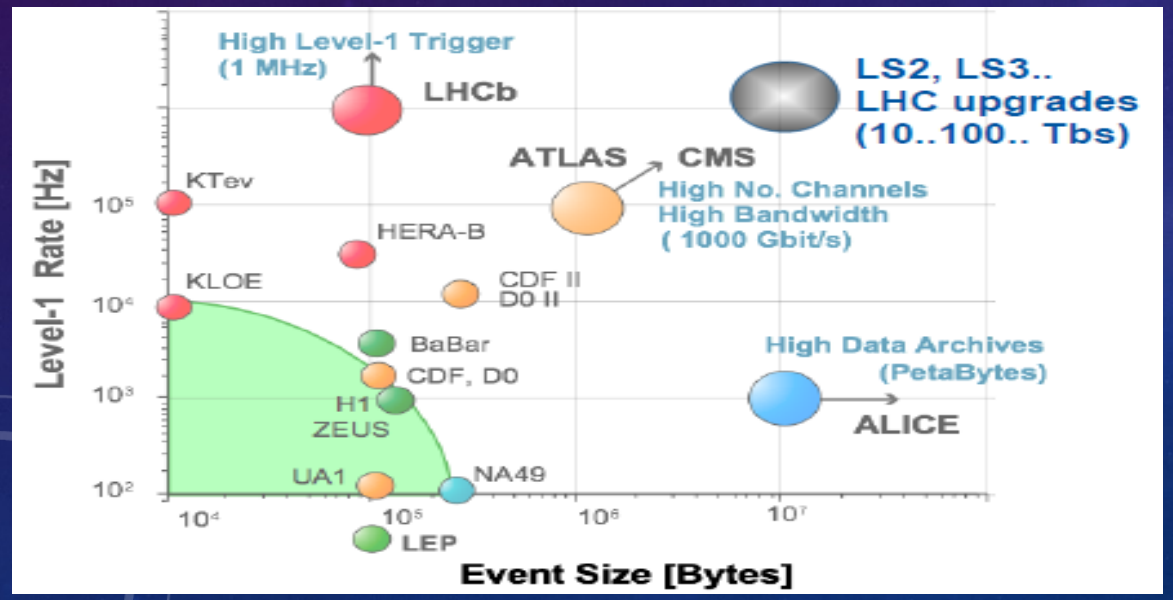


The added value of timing information is recognized
→ Gain in scientific return of complete analysis still to be quantified
(Tracking PID ? Calorimetry PID ? Shower development ?)

ADVANCED CONCEPTS IN TRIGGER AND DAQ

Massive amounts of data coming out of upgraded and next generation experiments





- Optical data transmission is key in modern HEP detector readout:
  - ✓ Current links at 10 Gb/s, and limited to 5 x 10^{15} n_{eq}/cm^2, 100 Mrad in radiation tolerance; → current state-of-the art – VCSEL
  - ✓ R&D into Silicon photonics for optical conversion and multiple amplitude modulation can provide high bandwidth
- R&D into Wireless transmission (60 GHz), could allow on-detector data reduction (e. g. for trigger readout of trackers) → promising upcoming alternative

Trigger Architecture:

→ multi-layered (event building, event processing); triggerless, multi-level trigger

Trigger Tools:

→ ASICs, ATCA, FPGA, CPU, GPU

Trade-offs:

→ on-detector data reduction + triggerless readout vs multi-level trigger system

Future direcection:

Self-calibrating, and « self-driving » detectors using AI/ML everywhere (ASIC, FPGA, GPU, CPU)

CONCLUSIONS

- Many synergies for R&D in common technologies between RPF and other frontiers
  - focused here on EF and collider detector technologies
  - but also NF and CF technologies highly relevant, e.g. quantum sensors, TPCs, photo detectors

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