SNOWMASS PERSPECTIVE WITH RESPECT TO THE INSTRUMENTATION FRONTIER

Snowmass IF wiki: https://snowmass21.org/instrumentation/start

Maxim Titov

RD51 Collaboration Meeting, June 16, 2022

The Charge of the Snowmass Process (2020-2022)

“define the most important questions in the field of particle physics and identify promising opportunities to address them.”

✓ **Long-term planning exercise for the particle-physics community**

→ Develop community long-term physics aspirations

→ Communicate opportunities for discovery in particle-physics to broader community and to the (US) government

✓ **Physics-driven effort**

→ Covers all areas of particle physics and facilitates cross-cutting

→ Develop overarching physics studies

✓ **Global context**

→ Input from non-US community is essential

→ Input from recent international studies, for example HL-LHC, European Strategy Particle Physics Update (ESPPU), future colliders, ECFA Detector R&D Roadmap Panel, etc …

✓ **Timescale:**

→ Planning for 2025-2035 with a view toward 2050

→ Sponsored by Division of Particles and Fields of the American Physical Society

Past Snowmass (2013) and P5 (2014) Efforts

Snowmass (2013): new successful model

- ✓ Energy Frontier
- ✓ Intensity Frontier
- ✓ Cosmic Frontier
- ✓ Cross-cutting groups: Facilities, Instrumentation, Computing, Theory, Communication.

Report: https://www.slac.stanford.edu/econf/C1307292/

P5 (2014): identified **five science drivers**

- ✓ Use the Higgs boson as a new tool for discovery.
- ✓ Pursue the physics associated with neutrino masses.
- ✓ Identify the new physics of dark matter.
- ✓ Understand cosmic acceleration: dark energy and inflation.
- ✓ Explore the unknown: new particles, interaction, and physical principles.

Report: https://www.usparticlephysics.org

Using Snowmass's scientific input and budget scenarios provided by US DOE, P5 developed and presented to DOE, via HEPAP, a 10-year execution plan, with priorities & recommendations, for the field in the US, with an eye also towards the 10 years after

P5 has a broad mandate but tends to focus on large projects and facilities

The Range of Snowmass Discussions (2020-2022)

There are **ten** Snowmass Frontiers spanning (with Liaisons in-between)

- **Five scientific areas** of particle physics addressing fundamental questions about the universe
  - → Accelerator Frontier
  - → Cosmic Frontier
  - → Energy Frontier
  - → Neutrino Frontier
  - → Rare Processes and Precision

- **Four complementary areas** which enable scientific work
  - → Computational Frontier
  - → Instrumentation Frontier (in this talk)
  - → Theory Frontier
  - → Undergrounds Facilities

And Community Engagement Frontier addressing the community development needed to maintain a vibrant profession and to engage with society

Instrumentation Frontier and Liaisons Among Frontiers

Instrumentation Frontier – Topical Groups & Conveners:

Topical Group	Co-Conveners			
Quantum Sensors	Thomas Cecil (ANL)	Kent Irwin (SLAC)	Reina Maruyama (Yale)	Matt Pyle (Berkeley)
Photon Detectors	Juan Estrada (FNAL)	Mayly Sanchez (ISU)	Abigail Vieregg (Chicago)	
Solid State Detectors and Tracking	Tony Affolder (UCSC)	Artur Apresyan (FNAL)	Lucie Linssen (CERN)	
Trigger and DAQ	Darin Acosta (Florida)	Wes Ketchum (FNAL)	Stephanie Majewski (Oregon)	
Micro Pattern Gas Detectors	Bernd Surrow (Temple)	Maxim Titov (SACLAY)	Sven Vahsen (Hawaii)	
Calorimetry	Andy White (UTA)	Minfang Yeh (BNL)	Rachel Yohay (FSU)	
Electronics/ASICS	Gabriella Carini (BNL)	Mitch Newcomer (Penn)	John Parsons (Columbia)	
Noble Elements	Eric Dahl (Northwestern)	Roxanne Guenette (Harvard)	Jen Raaf (FNAL)	
Cross Cutting and System Integration	Jim Fast (PNNL)	Maurice Garcia-Sciveres (LBL)	Ian Shipsey (Oxford)	

Liaisons provide high-level and bi-directional communication b/w Frontiers:

- They will provide high-level and bi-directional communication b/w Frontiers.
- They will be people with interests in both communities.
- **Official IF Liaisons: (between Instrumentation and Other Frontiers)**
  - Energy Frontier: Caterina Vernieri (SLAC), Maksym Titov (CEA Saclay)
  - Neutrino Physics Frontier: Mayly Sanchez (ISU), NF10
  - Rare Processes and Precision: Marina Artuso (Syracuse)
  - Cosmic Frontier: Kent Irwin (SLAC), Hugh Lippincott (UCSB)
  - Accelerator Frontier: Andy White (UTA)
  - Computational Frontier: Darin Acosta (Florida)
  - Underground Facilities: Eric Dahl (Northwestern), Maurice Garcia-Sciveres (LBNL)
  - Community Engagement: Farah Fahim (FNAL)

IF1 Quantum Sensors

- Snowmass 2021: 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: a Contribution to the Snowmass Community Planning Exercise of 2021: https://arxiv.org/abs/2202.11828
- 4-Dimensional Trackers: https://arxiv.org/abs/2202.13900
- Integration and Packaging: https://arxiv.org/abs/2203.06093
- Mechanics, lightweight materials, cooling: authors expect to submit soon
- 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 MPGDs

- 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

IF5 (MPGDs) White Papers & Letter of Interests

IF05 WP1: MPGDs: Recent Advances and Current R&D

LOI title	Contact
Development of the Micro-Pattern gaseous detector technologies: an overview of the CERN-RD51 collaboration	awhite@uta.edu / klaus.dehmelt@stonybrook.edu
High precision timing with the PICOSEC micromegas detector	sebastian.white@cern.ch
Optical readout of MicroPattern Gaseous Detectors: developments and perspectives	florian.brunbauer@cern.ch
Pixelated resistive MicroMegas for high-rates environment	massimo.della.pietra@cern.ch
Trigger extensions for the scalable readout system SRS	hans.muller@cern.ch
A high-gain, low ion-backflow double micro-mesh gaseous structure	zhzhy@ustc.edu.cn
LOI from NSCL	cortesi@nscl.msu.edu

IF05 WP2: MPGDs for Nuclear Physics Experiments

LOI title	Contact
Advanced Micro-Pattern Gas Detectors for Tracking at the Electron Ion Collider	hohlmann@fit.edu
Development of large micro pattern gaseous detectors for high rate tracking at Jefferson Lab	kgnanvo@virginia.edu
LOI from NSCL	cortesi@nscl.msu.edu
The role of MPGD-based photon detectors in RICH technologies	Silvia.DallaTorre@ts.infn.it
Snowmass 2021 Expression of Interest: MPGD-based Transition Radiation Detector	yulia@jlab.org

IF05 WP3: Recoil Imaging for DM, neutrino and BSM physics

LOI title	Contact
CYGNUS: a nuclear recoil observatory with directional sensitivity to dark matter and neutrinos	sevahsen@hawaii.edu
Optical readout of MicroPattern Gaseous Detectors: developments and perspectives	florian.brunbauer@cern.ch
Towards directional nuclear recoil detectors: tracking of nuclear recoils in gas Argon TPCs	David Caratelli (davidc@fnal.gov)
Dual-Readout Time Projection Chamber: exploring sub-millimeter pitch for directional dark matter and tau identification in vτC C interactions.	Elena Gramellini, elenag@fnal.gov
Directional detectors for CEvNS and physics beyond the Standard Model	Difft@oxy.edu Daniel Snowden Ifft
Trigger extensions for the scalable readout system SRS	Hans.Muller@cern.ch
The International Axion Observatory (IAXO): MPGD development	E. Ferrer Ribas esther.ferrer-ribas@cea.fr

IF05 WP4: MPGDs for TPCs at Future Lepton Colliders

LOI title	Contact
Belle II detector upgrades	for TPC: Peter Lewis; lewis@physik.uni-bonn.de
Time projection chamber R&D	qihr@ihep.ac.cn
A time projection chamber using advanced technology for the International Large Detector International Linear Collider	alainb@physics.carleton.ca
A high-gain, low ion-backflow double micro-mesh gaseous structure	zhzhy@ustc.edu.cn

IF05 WP5: MPGDs for Tracking and Muon Detection at Future High Energy Colliders

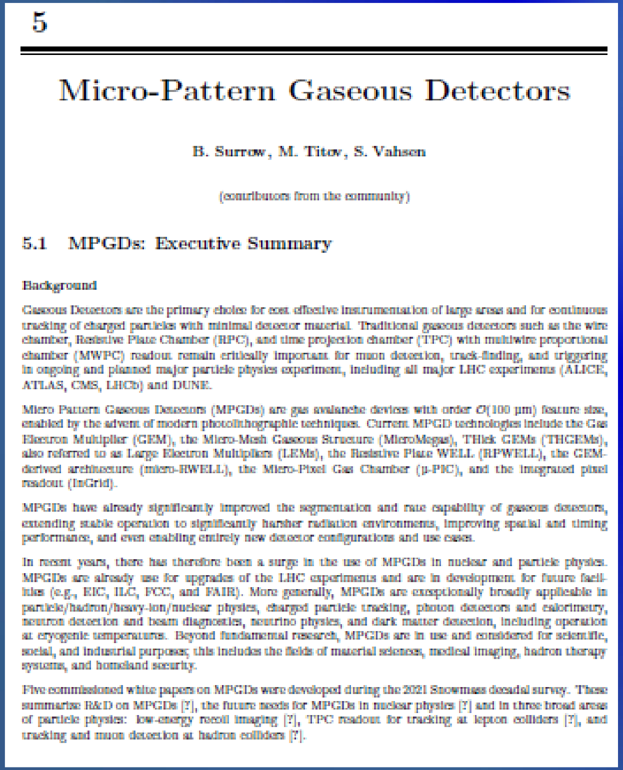
Title	LOI title	Contact(s)	Chapter
Introduction		Anna.Colaleo@cern.ch Kevin.Black@cern.ch	ok
	MPGDs for tracking and muon detection: progress review and updated R&D roadmap	hohlmann@fit.edu	No feedback from proponent.
High granularity resistive Micromegas for high rates	Pixelated resistive MicroMegas for high-rates environment	paolo.iengo@cern.ch	ok
Advanced GEM detectors for future collider experiments	Advanced GEM detectors for future collider experiments	Antonello.Pellecchia@cern.ch, Jeremie.Merlin@cern.ch	ok
μ-RWELL for HEP experiments	micro-RWELL detector	Giovanni.Bencivenni@lnf.infn.it	ok
Gas system for HEP		Beatrice.Mandelli@cern.ch Roberto.Guida@cern.ch	ok

IF5 White Papers

	Topic	Executive Summary Length	White Paper Leads
1	MPGDs: Recent advances and current R&D	3	Klaus Dehmelt, Andy White
2	MPGDs for nuclear physics experiments	1.5	Kondo Gnanvo, Matt Posik
3	Recoil imaging for DM, neutrino, and BSM physics*	1.5+1.5+1.5 (IF+NF+CF)	Dinesh Loomba, Ciaran O'Hare
4	MPGDs for TPCs at future lepton colliders	1.5	Alain Bellerive
5	MPGDs for muon detection at future colliders	1.5	Anna Colaleo, Kevin Black
	Grand summary table + text	1	IF5 conveners

*Multi-frontier paper with Cosmic and Neutrino Frontiers

Basis for 10-page summary of IF5



5

Micro-Pattern Gaseous Detectors

B. Surrow, M. Titov, S. Vahsen

(contributors from the community)

5.1 MPGDs: Executive Summary

Background

Gaseous Detectors are the primary choice for cost effective instrumentation of large areas and for continuous tracking of charged particles with minimal detector material. Traditional gaseous detectors such as the wire chamber, Resistive Plate Chamber (RPC), and time projection chamber (TPC) with multiwire proportional chamber (MWPC) readout remain critically important for muon detection, track-finding, and triggering in ongoing and planned major particle physics experiment, including all major LHC experiments (ALICE, ATLAS, CMS, LHCb) and DUNE.

Micro Pattern Gaseous Detectors (MPGDs) are gas avalanche devices with order $\mathcal{O}$(100 μm) feature size, enabled by the advent of modern photolithographic techniques. Current MPGD technologies include the Gas Electron Multiplier (GEM), the Micro-Mesh Gaseous Structure (MicroMegas), THick GEMs (THGEMs), also referred to as Large Electron Multipliers (LEMs), the Resistive Plate WELL (RPWELL), the GEM-derived architecture (micro-RWELL), the Micro-Pixel Gas Chamber (μ-PIC), and the integrated pixel readout (InGrid).

MPGDs have already significantly improved the segmentation and rate capability of gaseous detectors, extending stable operation to significantly harsher radiation environments, improving spatial and timing performance, and even enabling entirely new detector configurations and use cases.

In recent years, there has therefore been a surge in the use of MPGDs in nuclear and particle physics. MPGDs are already use for upgrades of the LHC experiments and are in development for future facilities (e.g., EIC, ILC, FCC, and FAIR). More generally, MPGDs are exceptionally broadly applicable in particle/hadron/heavy-ion/nuclear physics, charged particle tracking, photon detectors and calorimetry, neutron detection and beam diagnostics, neutrino physics, and dark matter detection, including operation at cryogenic temperatures. Beyond fundamental research, MPGDs are in use and considered for scientific, social, and industrial purposes; this includes the fields of material sciences, medical imaging, hadron therapy systems, and homeland security.

Five commissioned white papers on MPGDs were developed during the 2021 Snowmass decadal survey. These summarize R&D on MPGDs [?], the future needs for MPGDs in nuclear physics [?] and in three broad areas of particle physics: low-energy recoil imaging [?], TPC readout for tracking at lepton colliders [?], and tracking and muon detection at hadron colliders [?].

Dedicated MPGD development facilities: Currently, the majority of MPGD developers and users in the U.S. rely on production facilities and expertise, diagnostic facilities, and standardized readout electronics associated with the RD51 collaboration and CERN. This significantly slows down the R&D cycle and limits the speed of innovation in the US. It also means all production for US-led experiments has to be outsourced.

A U.S.-based MPGD Center of Excellence is needed and would address this issue. We envision a facility similar in nature to the Gaseous Detector Development (GDD) lab at CERN or the SiDet facility at FNAL. Such a facility would benefit both the nuclear physics and particle physics communities in the US. There are also ample opportunities for commercialization and collaboration with industry.
We envision such a facility hosted by one of DOE's National Laboratories, such as Jefferson Lab or Brookhaven National Laboratory.

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. They will be located at: https://snowmass21.org/instrumentation/noble_elements

- Pixel readout for noble element time projection chambers
- Charge gain for noble element time projection chambers
- Light Collection for noble element time projection chambers
- Low-threshold TPCs
- Enabling directionality and micron precision in noble element time projection chambers
- Metastable Fluids detectors
- Enhancing physics reach at existing noble element infrastructure
- Barium Tagging in Xenon TPCs
- Scaling challenges for noble element detectors
- Noble element detector characterization and calibration

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

❖ More papers of general interest has been submitted to the Snowmass 2021 Proceedings - Instrumentation Frontier: https://snowmass21.org/submissions/if

❖ Several IF Topical Groups need to coordinate sections in their summary reports with Topical Groups in other Frontiers (incl. Energy Frontier)

❖ Plan to organize either TG-level working meetings or IF-wide workshop with other Frontiers' TGs between now and Seattle

DOE Basic Research Needs Study on HEP Detector Research & Development in 2019

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

The transformative physics goals include 4 inspiring & distinct directions:

- Higgs properties @ sub-%
- Higgs self-coupling @ 5%
- Higgs connection to DM
- New multi-TeV particles

Science	Measurement	Technical Requirement (TR)	PRD
Higgs properties with sub-percent precision Higgs self-coupling with 5% precision	TR 1.1: Tracking for e^+e^-	TR 1.1.1: p_T resolution: $\sigma_{p_T}/p_T = 0.2\%$ for central tracks with $p_T < 100$ GeV, $\sigma_{p_T}/p_T^2 = 2 \times 10^{-5}$/GeV for central tracks with $p_T > 100$ GeV TR 1.1.2: Impact parameter resolution: $\sigma_{r\varphi} = 5 \bigoplus 15\ (p\ [\mathrm{GeV}]\ \sin^{\frac{3}{2}}\theta)^{-1}\ \mu m$ TR 1.1.3: Granularity : $25 \times 50\ \mu m^2$ pixels TR 1.1.4: 5 μm single hit resolution TR 1.1.5: Per track timing resolution of 10 ps	18, 19, 20, 23
Higgs connection to dark matter	TR 1.2: Tracking for 100 TeV pp	Generally same as e^+e- (TR 1.1) except TR 1.2.1: Radiation tolerant to 300 MGy and $8 \times 10^{17}\ n_{eq}/cm^2$ TR 1.2.2: $\sigma_{p_T}/p_T = 0.5\%$ for tracks with $p_T < 100$ GeV TR 1.2.3: Per track timing resolution of 5 ps rejection and particle identification	16, 17, 18, 19, 20, 23, 26
New particles and phenomena at multi-TeV scale	TR 1.3: Calorimetry for e^+e^-	TR 1.3.1: Jet resolution: 4% particle flow jet energy resolution TR 1.3.2: High granularity: EM cells of $0.5 \times 0.5\ cm^2$, hadronic cells of $1 \times 1\ cm^2$ TR 1.3.3: EM resolution : $\sigma_E/E = 10\%/\sqrt{E} \bigoplus 1\%$ TR 1.3.4: Per shower timing resolution of 10 ps	1, 3, 7, 10, 11, 23
	TR 1.4: Calorimetry for 100 TeV pp	Generally same as e^+e- (TR 1.3) except TR 1.4.1: Radiation tolerant to 4 (5000) MGy and $3 \times 10^{16}\ (5 \times 10^{18})\ n_{eq}/cm^2$ in endcap (forward) electromagnetic calorimeter TR 1.4.2: Per shower timing resolution of 5 ps	1, 2, 3, 7, 9, 10, 11, 16, 17, 23, 26
	TR 1.5: Trigger and readout	TR 1.5.1: Logic and transmitters with radiation tolerance to 300 MGy and $8 \times 10^{17}\ n_{eq}/cm^2$ TR 1.5.2: Total throughput of 1 exabyte per second at 100 TeV pp collider	16, 17, 21, 26

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:

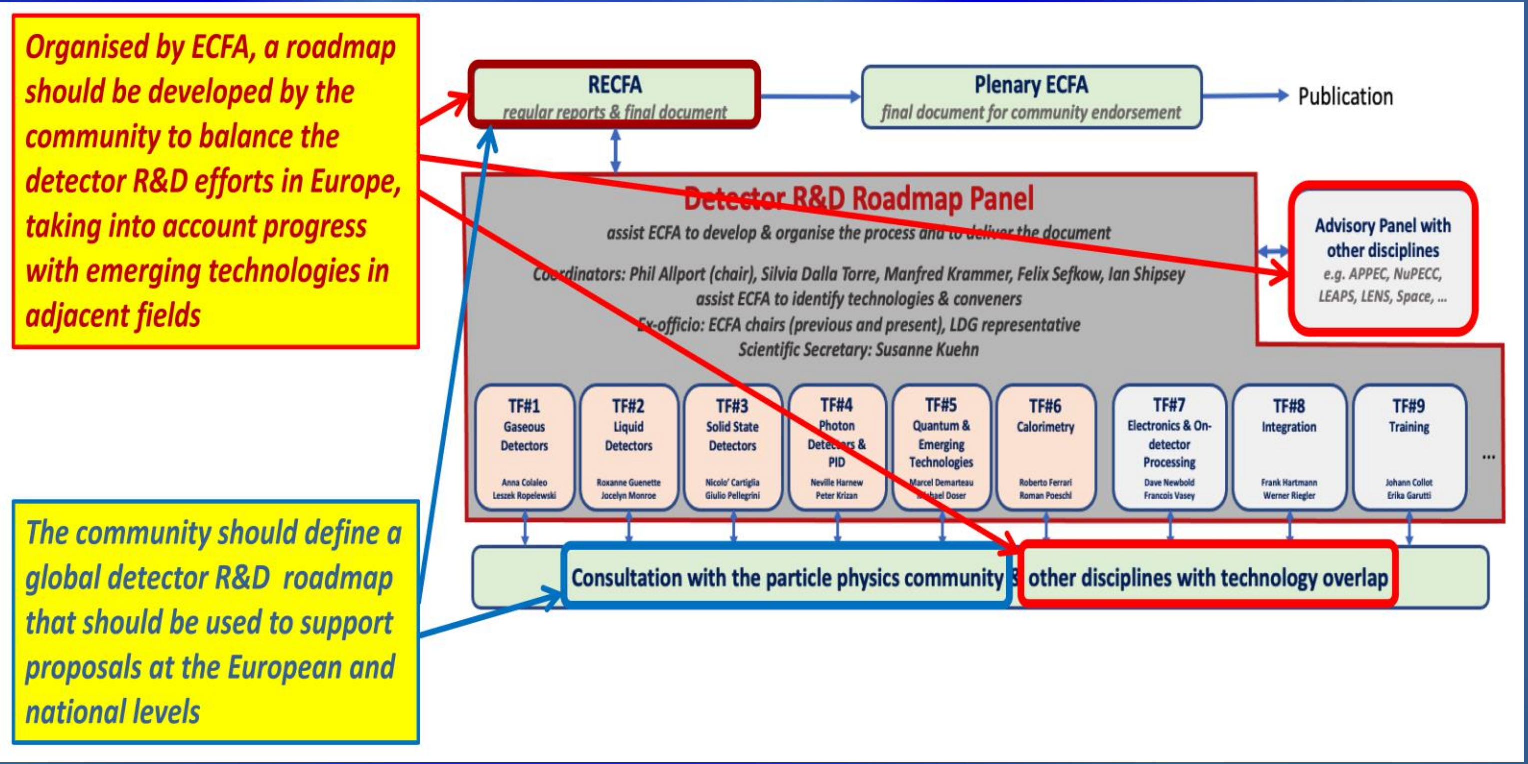
- ✓ Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments
- ✓ Design new devices and architectures to enable picosecond timing and event separation (for photo-detectors).
- ✓ Develop high spatial resolution pixel detectors with precise high per-pixel
- ✓ 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

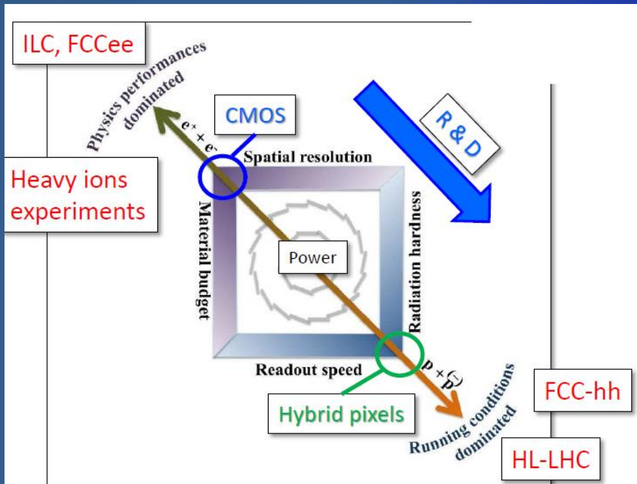
- Focus on the technical aspects of detector R&D requirements given the 2020 EPPSU deliberation document listed "*High-priority future initiatives*" and "*Other essential scientific activities for particle physics*" as input and organise material by Task Force.
- Task Forces start from the future science programmes to identify main detector technology challenges to be met (both mandatory and highly desirable to optimise physics returns) to estimate the period over which the required detector R&D programmes 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 identify and describe 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**

Enabling Technologies for Low-Mass Tracking Detectors



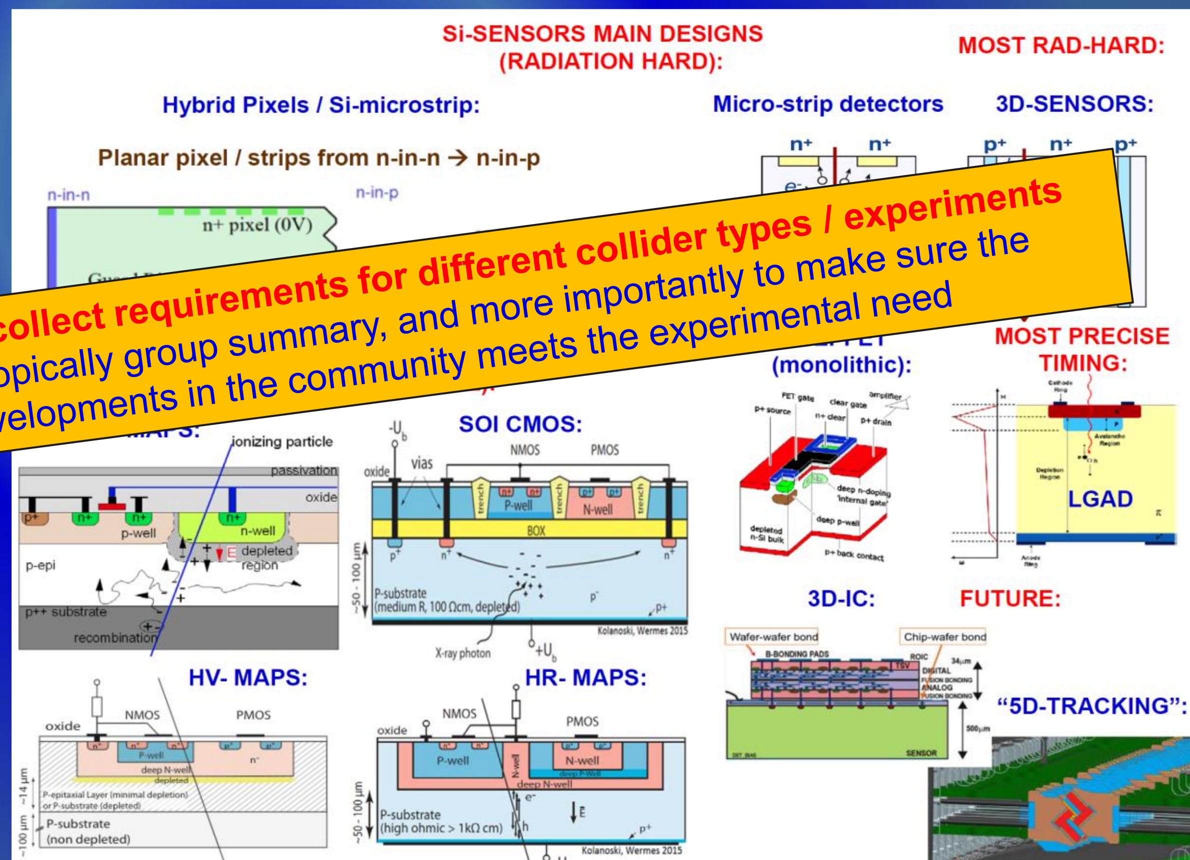
- ✓ Basic applications are optimized for two different realms of interest : electron and hadron colliders → different optimizations/requirements (pp: radiation hardness, speed; e+e-: granularity, material budget)
- ✓ Design problems include: granularity vs the power (particularly for precision timing) 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 the on-detector electronics are particular issues for hadron colliders.

Hadron Colliders:

- ✓ Hybrid pixel detectors (planar & 3D)
- ✓ HV/HR-CMOS for outer pixel layers for HL-LHC upgrades;
- ✓ 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 topically group summary, and more importantly to make sure the developments in the community meets the experimental need

Enabling Technologies for Picosecond-Timing Detectors

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:

Fast development of precise timing sensors:

- ✓ 4D pattern recognition for HL-LHC pile-up rejection: tracking ~O(10's) μm & timing detectors ~O(10's) ps

4-Dimensional Trackers

Doug Berry[1], Valentina Cairo[2], Angelo Dragone[3], Matteo Centi[illegible] Giacomini[5], Ryan Heller[1], Sergo Jindariani[1], Adriano Lai[6], Lucie Linssen[2], Ron Lipton[1], Chris Madrid[1], Bojan Markovic[3], Simone Mazza[7], Jennifer Ott[7], Ariel Schwartzman[3], Hannsjörg Weber[8], and Zhenyu Ye[9]

arXiv: 2203.13900

- ✓ ps-timing reconstruction in calorimetry (resolve develop. of hadron showers, triangulate H → γγ prim. vertices)
- ✓ TOF and TOP (RICH DIRC) PID → new DIRC applications (~ 10's of ps & 10's of μm per MIP/pixel) → both at hadron / lepton colliders
- ✓ General push for higher luminosity at LHC, Belle-II, Panda, Electron-Ion Collid. → Fast timing is needed at colliders, fixed target, and neutrino experiments

- ➢ Regular PMTs → large area, … but slow
- ➢ MCP-PMT → fast, but small, and not available in quantities to over 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

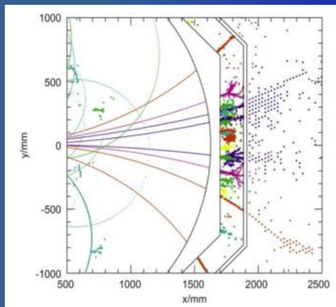
Challenges:

- ✓ 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 → LHCb EoI for LS4 is of general interest across experiments;
- ✓ LAPPD → large-area ps- PID/TOF for hadron/lepton colliders
  Incom Inc. company started to produce LAPPDs → cost still has to be controlled

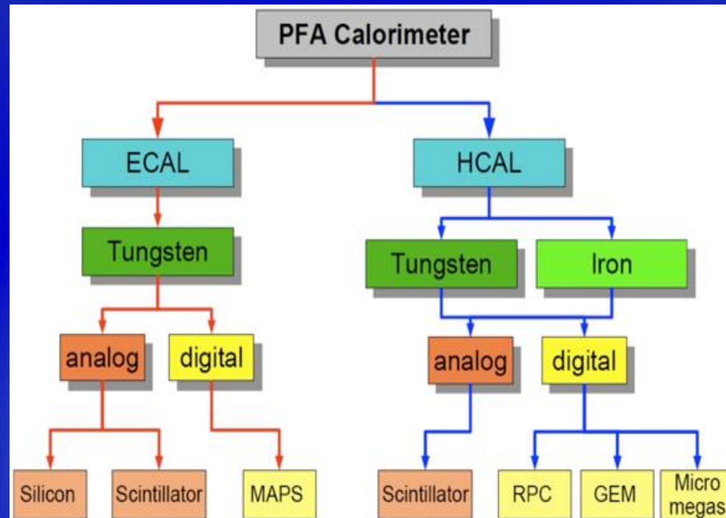
Particle Flow Calorimeters: CALICE Collaboration

Development and study of finely segmented / imaging calorimeters: initially focused on the ILC, now widening to include developments of all imaging calorimeters, e.g. CMS HGCAL for Phase II):

Imaging Calorimetry → high granularity (in 4D), efficient software (PFA).



Issues: overlap between showers, complicated topology, sep. "physics event" from beam-induced bkg.



Example: **ILD detector for ILC**, proposing **CALICE** collaboration tech.

	ECAL option	ECAL option	HCAL option	HCAL option
Active layer	silicon	scint+SiPM	scint+SiPM	glass RPC
Absorber	tungsten	tungsten	steel	steel
Cell size (cm×cm)	0.5×0.5	0.5×4.5	3×3	1×1
# layers	30	30	48	48
Readout	analog	analog	analog	Semi-dig (2 bits)
Depth # (X_0/Λ_{int})	24 X_0	24 X_0	5.5 Λ_{int}	5.5 Λ_{int}
# channels [10^6]	100	10	8	70
Total surface	2500	2500	7000	7000

Mixture of matured concepts and advanced ideas:

MATURED (CALICE):

- **SiW-ECAL**
- **SciW-ECAL**
- **AHCAL**
- **DHCAL (sDHCAL)**

→ (Almost) ready for large-scale prototype
→ Prepare for quick realization of 4-5 years to real detector

ADVANCED (beyond CALICE):

- **MAPS ECAL**
- **Dual-readout ECAL**
- **LGAD ECAL (CALICE)**

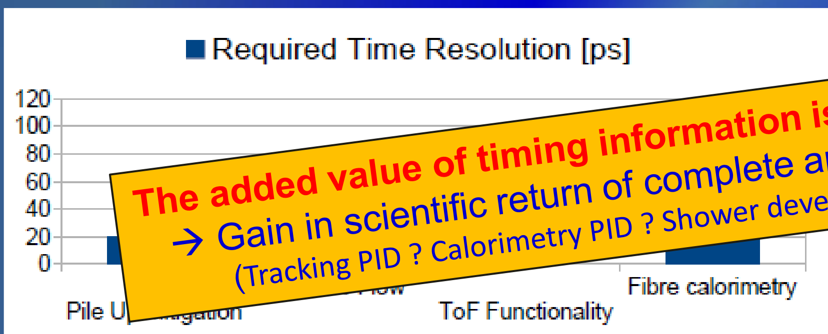
→ Evaluate additional physics impact to ILC experiment
→ Needs intensive R&D effort to realize as real detector

Imaging Calorimeters: The 5th Dimension ?

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

What are the real goals (physics wise)?

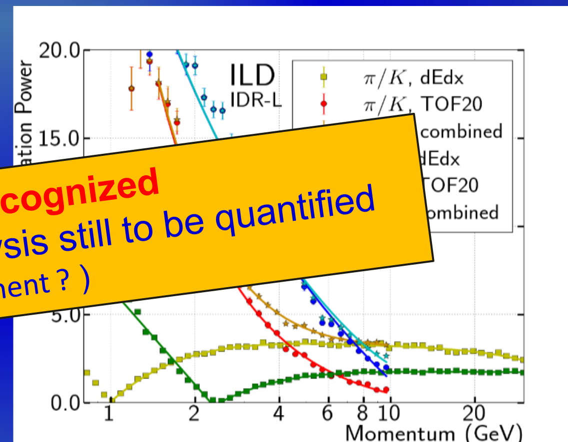
- Mitigation of pile-up (basically all high rates)
- Support for full 5D PFA → unchartered territory
- Calorimeters with ToF functionality in first layers?
- Longitudinally unsegmented fibre calorimeters



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 ?)

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




Test beam at Tohoku October 2021

Timing resolution
Is affected by noise

Sensor	Amp. th.	Time reso.
S8664-50K (inverse)	20 mV	123 psec
	40 mV	63 psec
S2385 (normal)	20 mV	178 psec
	40 mV	89 psec

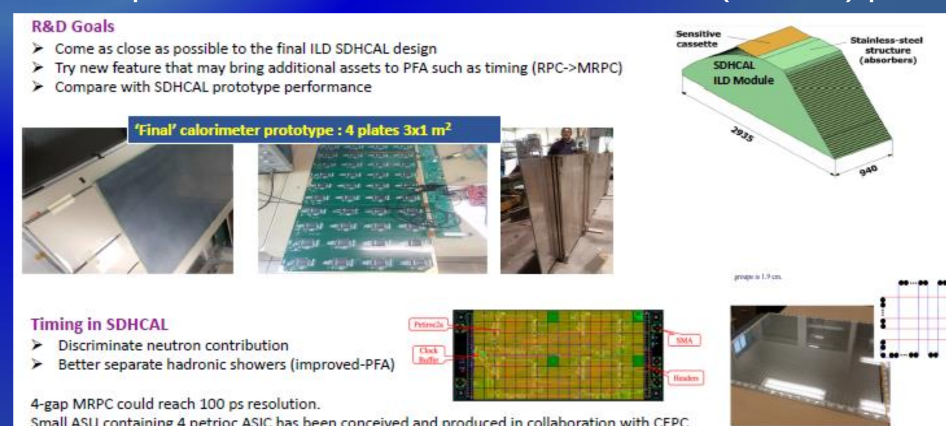
✓ **Trade-off between power consumption and timing capabilities (maybe higher noise level)**

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

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

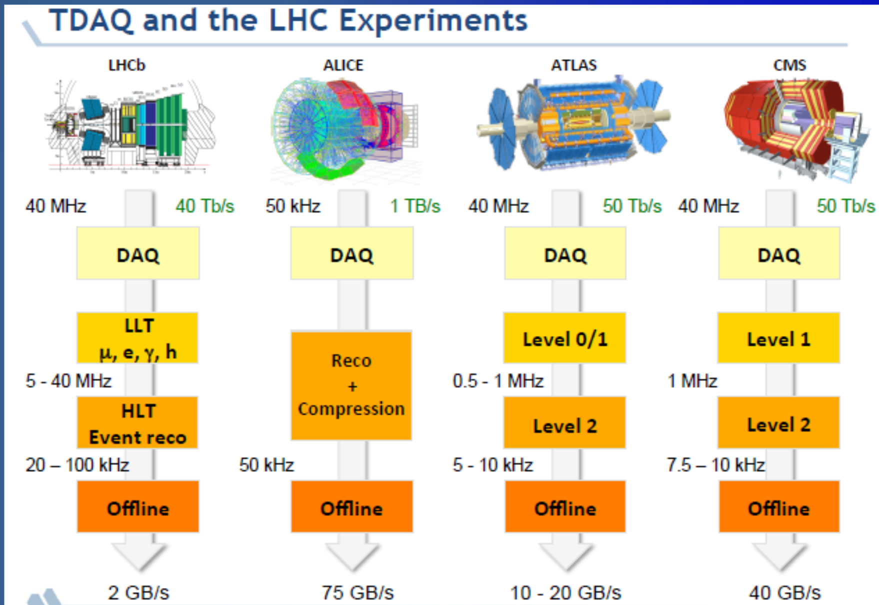
→ can help to distinguish particle types:
usable for flavour tagging (b/c/s),
long-lived searches (decaying to neutrals) ,
enhance σ(E) / E

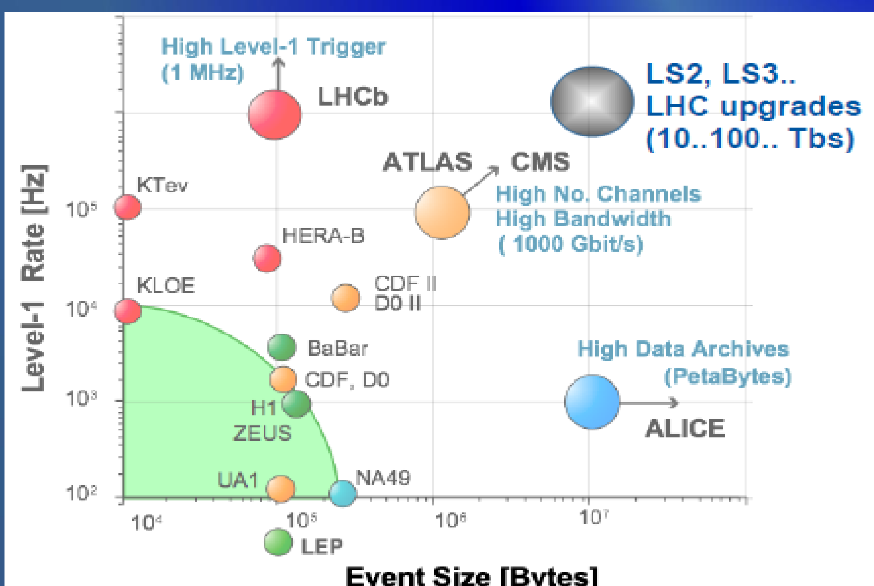
sDHCAL R&D: improved timing with replacement of RPC with MRPC → O(20-100) ps



Advanced Concepts in TRIGGER and DAQ (TDAQ)

Massive amounts of data coming of upgraded and next generation experiments





- Optical data transmission is key in readout modern HEP detectors:
  - ✓ 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;
  - ✓ Silicon photonics for optical conversion and multiple amplitude modulation can provide high bandwidth;
- 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

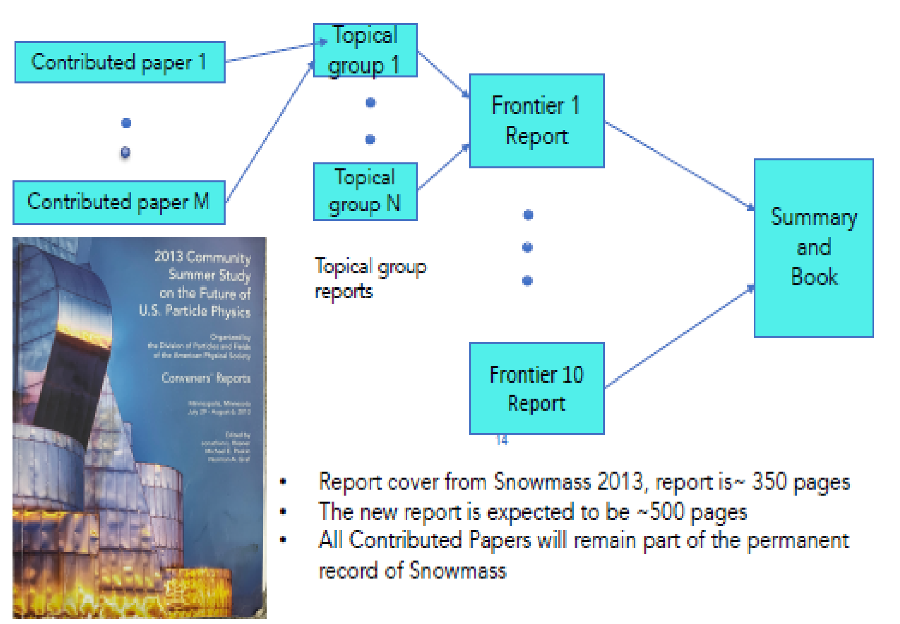
- General trend: progressive replacement of the complex multi-stage trigger system with a single level trigger system and a large farm of Linux computers for the final online selection:

➢ ATLAS TDAQ → single-level hardware trigger (max. rate 1 MHz and 1 um latency);
➢ ALICE and LHCb will be triggerless (no hardware trigger) after LHC Phase I upgrade

Snowmass 2021: Timeline for Snowmass Book

4/20-12/20 Snowmass Planning 1/21-7/21 Pause/ Slowdown	8/30-9/3/21 EF Restart Workshop	3/15/22 Contributed Paper Submission	3/28-4/1/22 EF Workshop (Brown U.)	5/31/22 Prelim. TG Reports	6/30/22 Prelim. Frontier Reports	7/17-26/22 **Community Summer Study (Seattle)**	9/30/22 Final Reports	10/31/22 Snowmass Book & ArXiv docs

- ✓ **March 15: Contributed papers (a.k.a. White Papers)**
- ✓ May 31: Preliminary Topical Group Reports
- ✓ **June 30: Preliminary Frontier Reports**
- ✓ **July 17 – 26: Converge on reports for all the frontiers and produce executive summaries representing the views of their communities and providing the basic input needed for P5**
- ✓ September: draft Executive Summary and Report Summary
- ✓ **October- November: Snowmass Book finalized and ready for submission**



Snowmass Community Summer Study Workshop

- July 17-26, 2022 at the University of Washington, Seattle
  - → **http://seattlesnowmass2021.net/**
  - → The frontiers were asked to propose topics that they particularly wanted to communicate to the whole community

	Sunday, July 17 Day 1	Monday, July 18 Day 2	Tuesday, July 19 Day 3	Wednsday, July 20 Day 4	Thursday, July 21 Day 5	Friday, July 22 Day 6	Saturday, July 23 Day 7	Sunday, July 24 Day 8	Monday, July 25 Day 9	Tuesday, July 26 Day 10	Wednesday, July 27
07:30 - 08:00 AM	Registration										LIGO Hanford Tour
08:00 - 08:30 AM		Parallel	Parallel	Parallel	Parallel	Parallel	Parallel		AF/CEF		
08:30 - 09:00 AM									CF/CompF		
09:00 - 09:30 AM									EF/IF	Closeout Plenary	
09:30 - 10:00 AM	Introductory Plenary								NF/RPF		
10:00 - 10:30 AM								Parallel	TF/UG		
10:30 - 11:00 AM									G Communicating HEP to the public and the govt		
11:00 - 11:30 AM											
11:30 - 12:00 PM											
12:00- 12:30 PM	Lunch	Lunch, Poster & Exhibit	Lunch, Poster & Exhibit	Lunch, Poster & Exhibit	Lunch	Lunch	Lunch	Lunch	Lunch		
12:30 - 01:00 PM											
01:00 - 01:30 PM											
01:30 - 02:00 PM											
02:00 - 02:30 PM	Introductory Plenary	S: COMPF:AI/ML UG:Underground	G Panel: Careers and Training the Next Generations	S: Neutrino; RP& AMO	I Rare Processes	I Underground	I Cosmic	G Snowmass Early Career	G Panel: Interconnections between frontiers and with other fields		
02:30 - 03:00 PM											
03:00 - 03:30 PM											
03:30 - 04:00 PM		S: AF: The next accelerators; TF:LQCD	S: EF, Lepton Colliders; CF:Cosmic	I Instrumentation	I Accelerator	I Theory	I Computing	S:Panel:Underrepresented Minorities; Instr awards	Coffee		
04:00 - 04:30 PM	Coffee								G Panel: where will we find new physics?		
04:30 - 05:00 PM	G Planning US HEP, past, present, future										
05:00 - 05:30 PM		Coffee	Coffee		Coffee	Coffee	Coffee	Coffee			
05:30 - 06:00 PM		G DEI: Talks and Panel	I Community engagement		I Energy	I Neutrino	G Quantum Information Science in HEP	G DOE, NSF, FNAL Director, other US labs	G International Status and Plans		
06:00 - 06:30 PM											
06:30 - 07:00 PM											
07:00 - 07:30 PM		Reception and Poster and Industry									
07:30 - 08:00 PM			Industry Networking	Adam Riess Public Lecture	Physics Slam	Conference Dinner					
08:00 - 08:30 PM							ColliderScope				
08:30 - 09:00 PM											
09:00 - 09:30 PM											
09:30 - 10:00 PM		NSF or DOE:: parallel Program Manager Sessions		NSF or DOE: two parallel Program Manager Sessions	DOE: two parallel Program Manager Sessions						
10:00 - 10:30 PM											
10:30 - 11:00 Pm											

I : Long plenary for Primary presentation of the Frontiers (10)

S : Shared session (two topics in parallel. Secondary presentations by Frontier (5x2)

G : General topic (not specific to any frontier) (10)