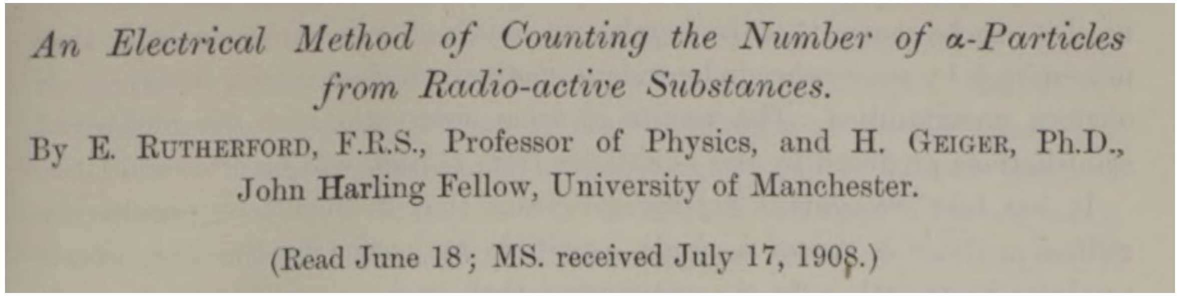


An Electrical Method of Counting the Number of α-Particles from Radio-active Substances.

By E. Rutherford, F.R.S., Professor of Physics, and H. Geiger, Ph.D., John Harling Fellow, University of Manchester.

(Read June 18; MS. received July 17, 1908.)

First Stored memory computer Manchester, 1948

Detector & Computing: Research & Development

- Research Examples & Emerging Themes
- Cross-community initiatives
  - 8 Detector R&D (DRD) Collaborations

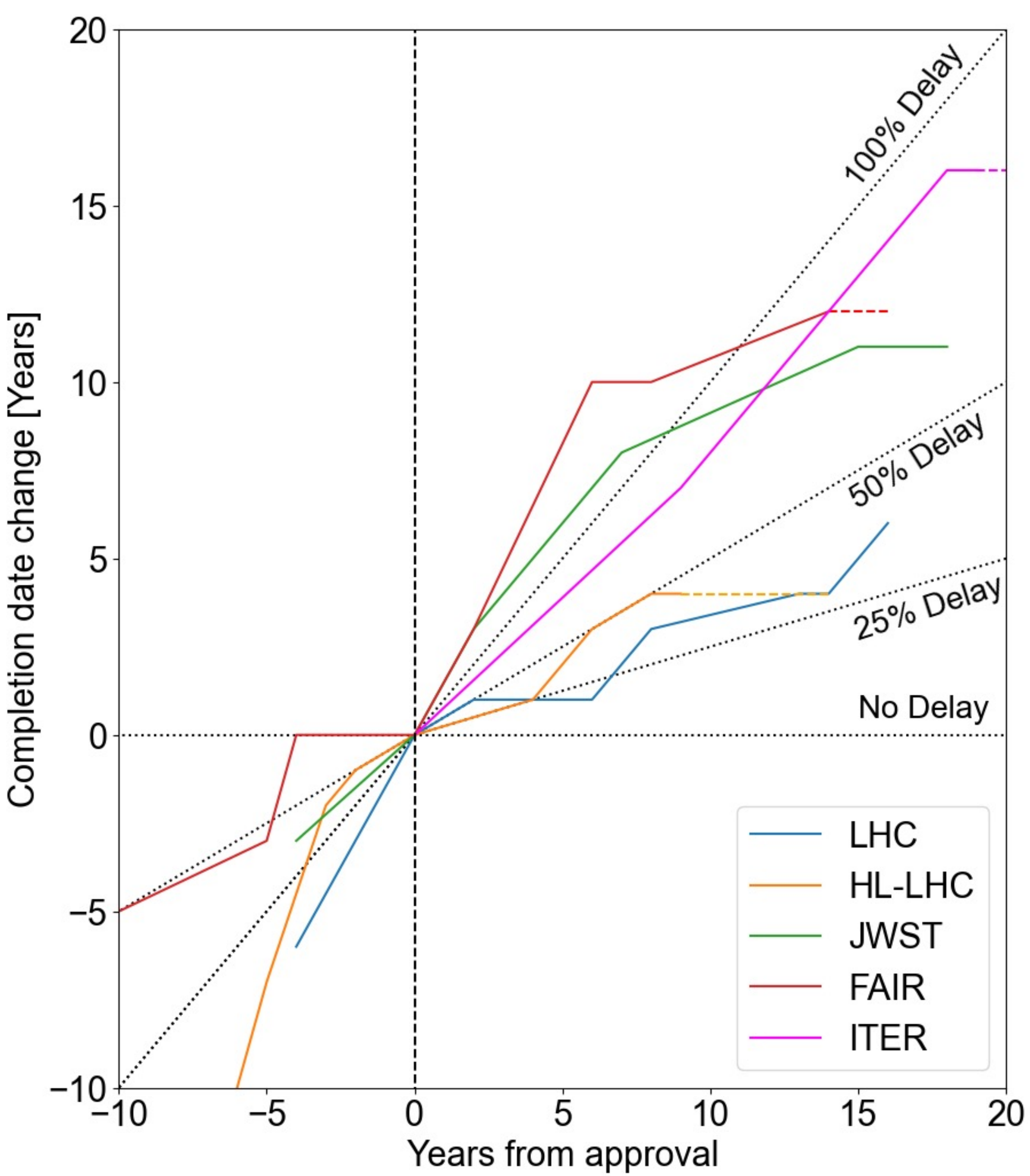
Gas	Liquid	Solid State	Photon & PID	Quantum	Calorimetry	Electronics Processing	Mechanics & Cooling

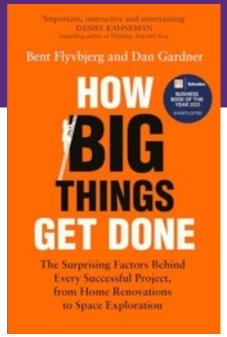
  - HEP Software Foundation / WLCG, including

Simulation	Generators	Analysis	Triggers & Tracking	GRID

Chris Parkes, University of Manchester

How long will *my* mega-project take ?



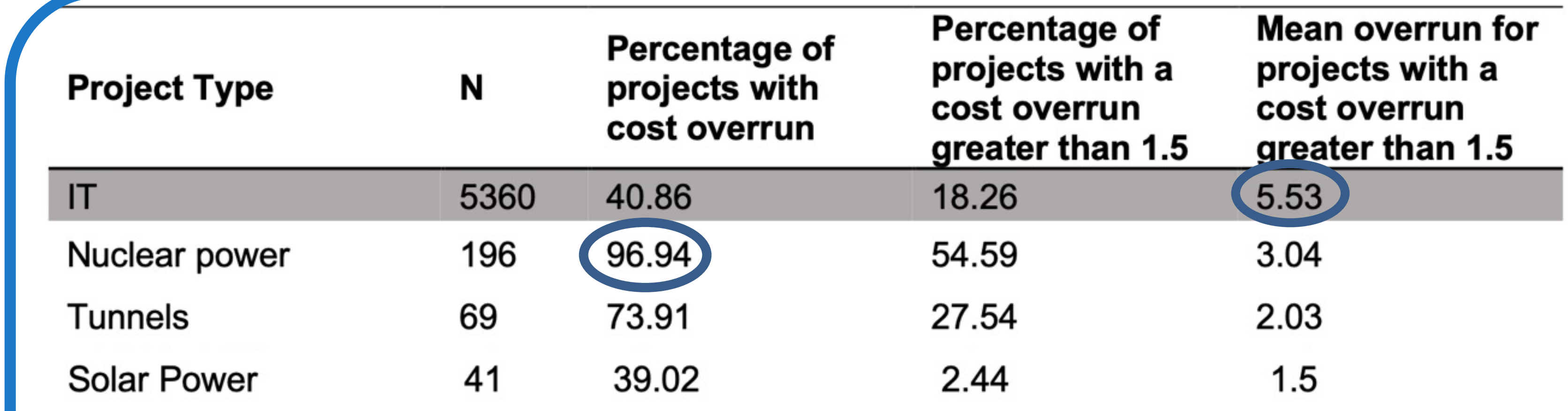


- Underestimate our project schedules
  - – Plan based on similar projects **not** hours/widget
  - – Political interests have strong effect

R&D Phase

critical to project success

How much do *other* mega-projects overrun ?



Project Type	N	Percentage of projects with cost overrun	Percentage of projects with a cost overrun greater than 1.5	Mean overrun for projects with a cost overrun greater than 1.5
IT	5360	40.86	18.26	5.53
Nuclear power	196	96.94	54.59	3.04
Tunnels	69	73.91	27.54	2.03
Solar Power	41	39.02	2.44	1.5

from B. Flyvbjerg, et al. "The Uniqueness of IT Cost Risk: A Cross-Group Comparison of 23 Project Types"
May, 2025. https://ssrn.com/abstract=5247223

- *One-of-a-kind* projects **commonly** go over budget/schedule

  and are fat-tailed (tails follow Pareto distribution)
- Reduce risk:

"Lego" pieces

Long planning

Proven technology

& Short construction

R&D Phase

critical to project success

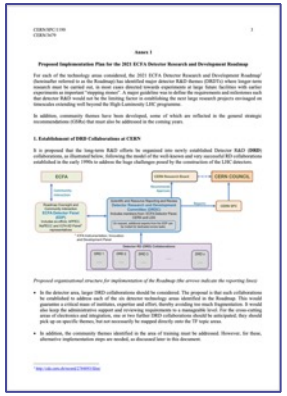
Detector R&D & HEP Software Foundation

“The community should define a global detector R&D roadmap” ESPPU 2020

Roadmap **Implementation**


THE 2021 ECFA DETECTOR
RESEARCH AND DEVELOPMENT ROADMAP

The European Committee for Future Accelerators
Detector R&D Roadmap Process Group


Annex 1

Proposed Implementation Plan for the 2021 ECFA Detector Research and Development Roadmap

1. Establishment of DRD Collaborations at CERN

DRD

I - 8

- 8 DRD collaborations
- Strategic recommendations
- Under ECFA auspices, CERN hosted

https://indico.cern.ch/category/6805/

- “Facilitates coordination and common efforts in HEP software and computing internationally”

Roadmap 2017 **Update 2025**


HSF-CWP-2017-01
December 15, 2017

arXiv:1712.06982v5 [physics.comp-ph] 19 Dec 2018

A Roadmap for
HEP Software and Computing R&D
for the 2020s

HEP Software Foundation


The Critical Importance of Software for HEP

Prepared by the HEP Software Foundation, with inputs from the HEP community.

Edited by:

This document has been endorsed by the following experiments and communities:

ALICE, ATLAS, Belle II, CMS, DUNE, ePIC, LHCb, MCnet, WLCG

HEP Software Foundation

- 13 activity areas

http://hepsoftwarefoundation.org/

Evolve our computing infrastructure

WLCG
Worldwide LHC Computing Grid

Post-Blue Sky & Pre Construction

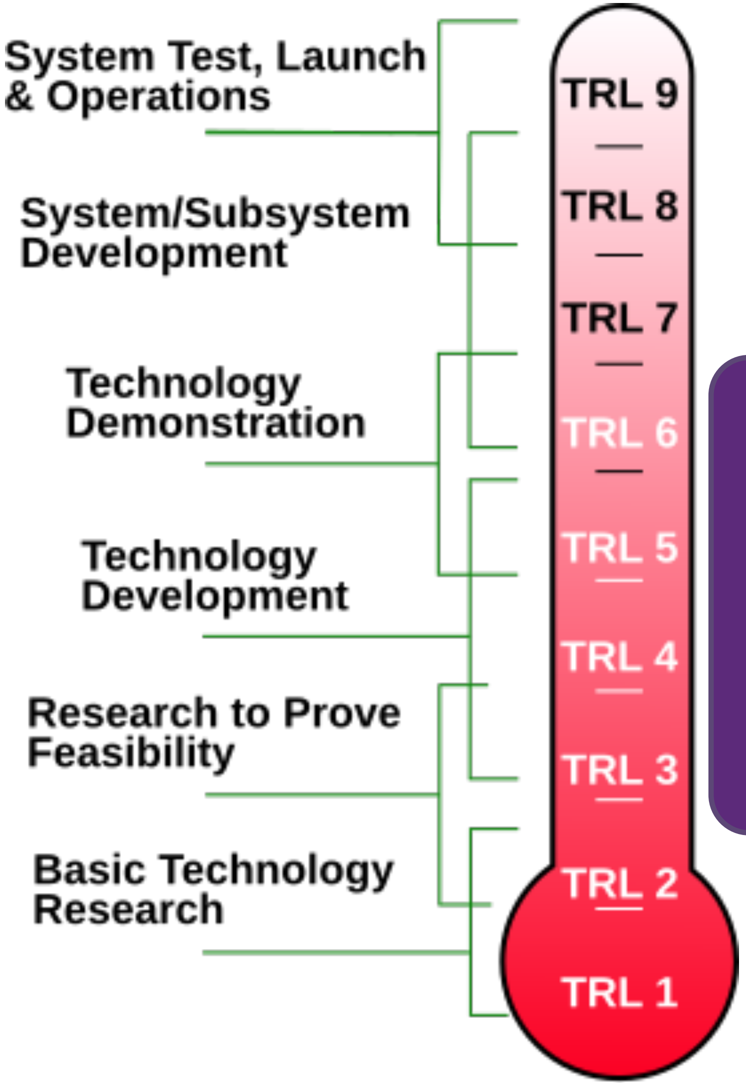
Targeted R&D
(pre-TDR)
e.g.:

- ALICE III
- LHCb Upgrade II
- DUNE Phase II
- SHIP
- ePIC at EIC….

Experiment agnostic R&D

- Technology development
- Performance & options
- Longer timescale projects (FCC etc…)

Technology Readiness Levels


System Test, Launch & Operations

System/Subsystem Development

Technology Demonstration

Technology Development

Research to Prove Feasibility

Basic Technology Research

TRL 9

TRL 8

TRL 7

TRL 6

TRL 5

TRL 4

TRL 3

TRL 2

TRL 1

Collaborative R&D

Training, Common Tools

Detector R&D – general themes

Gas | Liquid | Solid State | Photon & PID | Quantum | Calorimetry | Electronics Processing | Mechanics & Cooling

- Precision timing (10-50ps)
  - Separate LHC primary vertices, Particle ID
- CMOS Detectors
  - Integrated sensor & electronics
- Novel technologies
  - Quantum technologies

Strategic Recommendations

- Facilities (testbeam, irrad.)
- Engineering support
- Software support
- Industry engagement
- Training
- Open Science

- Environmental Impact

Gas

DRD1: Gaseous Detectors

- 130 Institutes (prior to MoU signing) ,30 countries
- Established from previous RD51 – enlarged scope
- First to proceed with **Memo. of Understanding**

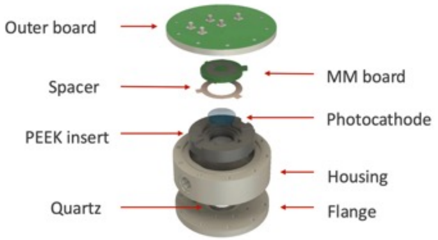
Time + Space

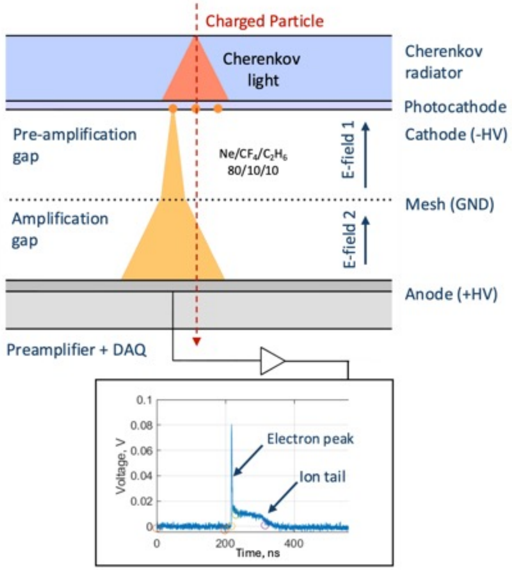
dE/dx

Environment

TPCs

Picosec





- Cherenkov Radiator ~ 20ps

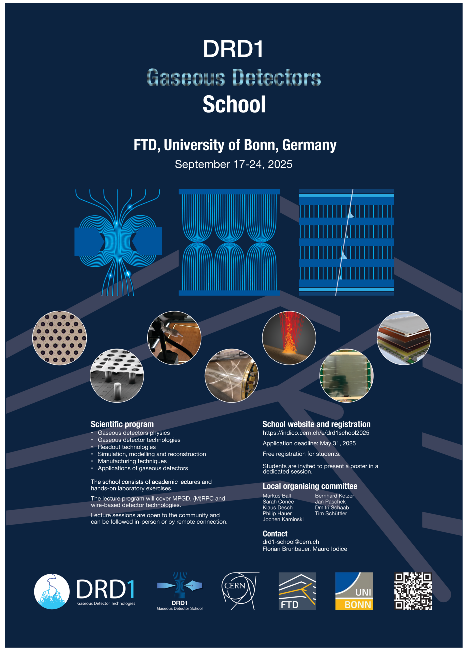
Beyond HEP WP

Muography

Medical

Neutron

Training



DRD1
Gaseous Detectors
School

FTD, University of Bonn, Germany
September 17-24, 2025

Scientific program
- Gaseous detectors physics
- Gaseous detector technologies
- Readout technologies
- Simulation, modelling and reconstruction
- Manufacturing techniques
- Applications of gaseous detectors

The school consists of academic lectures and hands-on laboratory exercises.

The lecture program will cover MPGD, (M)RPC and wire-based detector technologies.

Lecture sessions are open to the community and can be followed in-person or by remote connection.

School website and registration
https://indico.cern.ch/e/drd1school2025

Application deadline: May 31, 2025

Free registration for students.

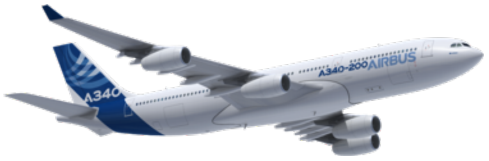
Students are invited to present a poster in a dedicated session.

Local organising committee
Markus Ball
Sarah Conée
Klaus Desch
Philip Hauer
Jochen Kaminski
Bernhard Ketzer
Jan Paschek
Dmitri Schaab
Tim Schüttler

Contact
drd1-school@cern.ch
Florian Brunbauer, Mauro Iodice

Environmental Impact

- Largest detector/computing impact is high global warming potential gas emissions (80% LHC – ATLAS/CMS RPCs)



100,000 tCO2e /annum =
fully occupied A340 London → New York per day

Environmental sustainability in basic research
A perspective from HECAP+

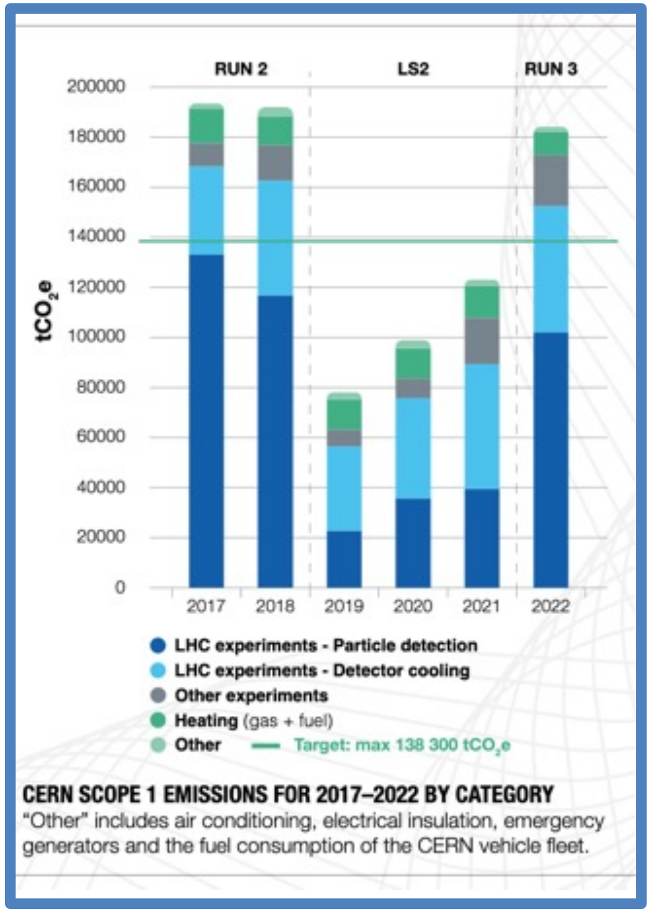
Sustainable HECAP+ Initiative

arXiv:2306.02837v2 [physics.soc-ph] 18 Aug 2023

Abstract
The climate crisis and the degradation of the world's ecosystems require humanity to take immediate action. The international scientific community has a responsibility to limit the negative environmental impacts of basic research. The **HECAP+ communities (High Energy Physics, Cosmology, Astroparticle Physics, and Hadron and Nuclear Physics)** make use of common and similar experimental infrastructure, such as accelerators and observatories, and rely similarly on the processing of big data. Our communities therefore face similar challenges to improving the sustainability of our research. This document aims to reflect on the environmental impacts of our work practices and research infrastructure, to highlight best practice, to make recommendations for positive changes, and to identify the opportunities and challenges that such changes present for wider aspects of social responsibility.

Version 2.0, 18 August 2023
Please read this document in electronic format where possible and refrain from printing it unless absolutely necessary. Thank you.

CERN Environment Report 2021-2022



CERN SCOPE 1 EMISSIONS FOR 2017–2022 BY CATEGORY
"Other" includes air conditioning, electrical insulation, emergency generators and the fuel consumption of the CERN vehicle fleet.

5th DRD1 Collaboration Meeting and Topical Workshop Towards Sustainable Gas Mixtures for Future Detectors

Sealing

Recirculate
Recuperate

Alternative
Gases

- SF6 GWP 23,000
- ATLAS alternative gas,

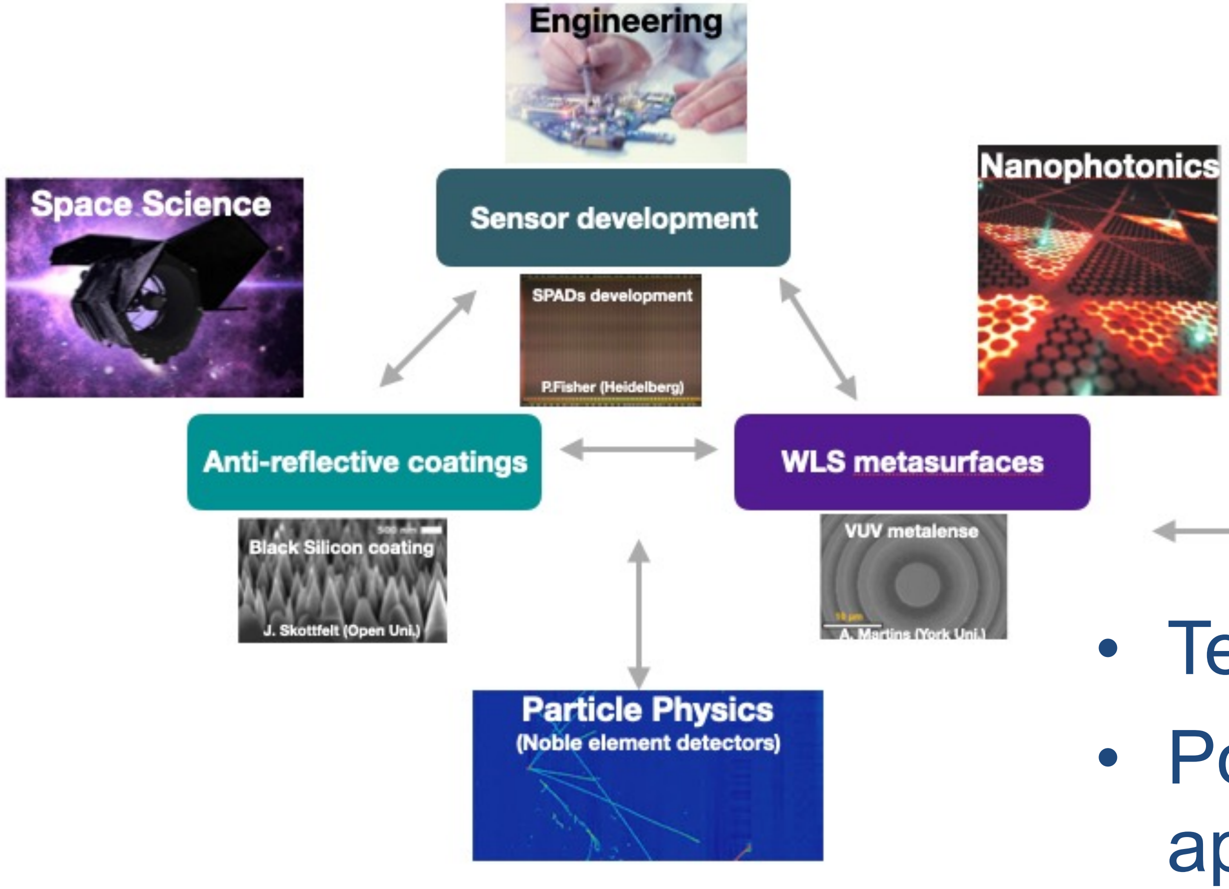
25% GWP reduction

- Continued use of technology mandates replacement

Liquid

DRD2: Liquid detectors

- 86 institutions,17 countries
- **Diverse communities** & facilities **working together** as network (neutrino, dark matter), new collaborations & funding applications

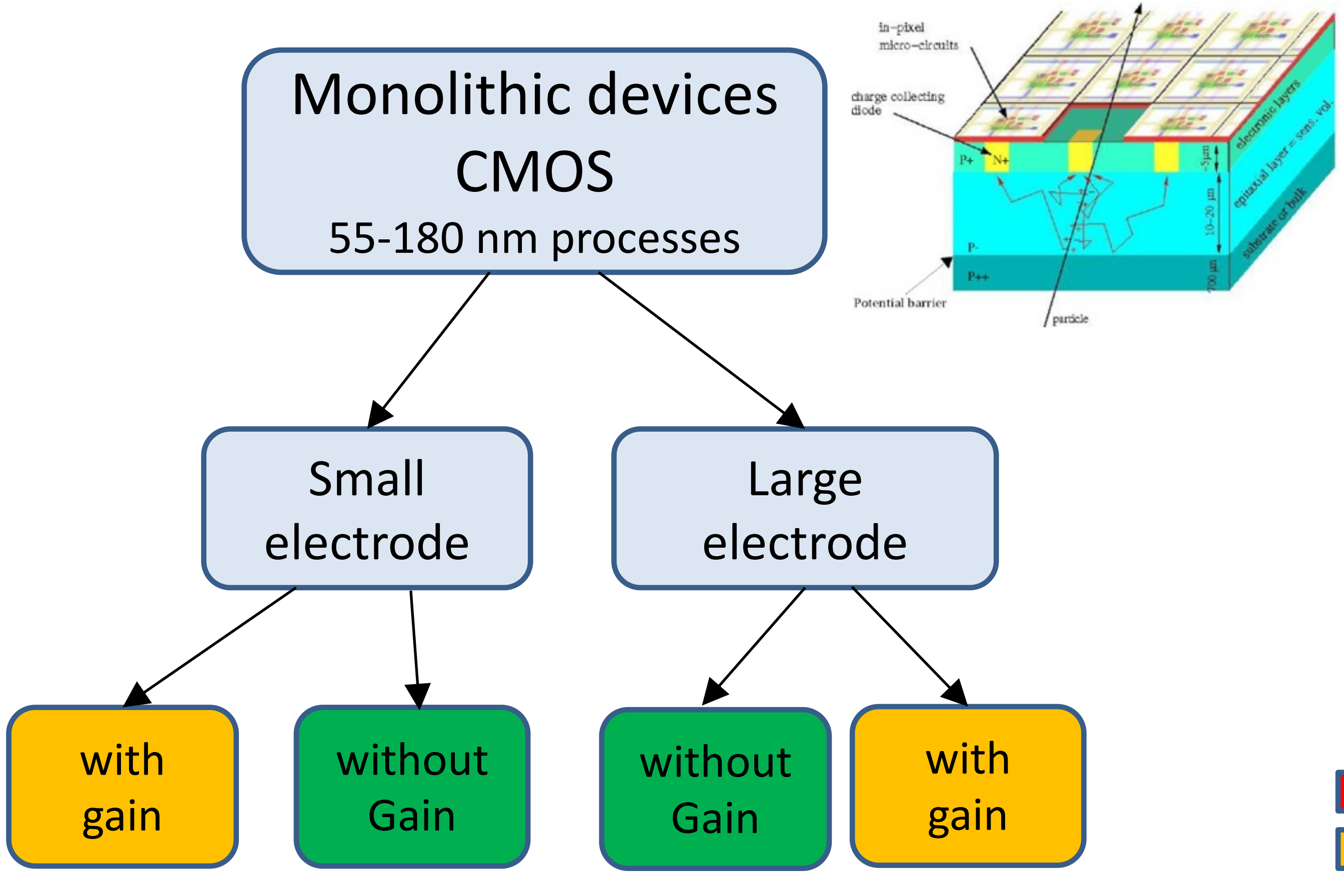


- Vacuum ultra-violet sensors
  - – Detector eff. typically ~20% thus not suited to Ar/Xe detectors

- Team attacks this from multiple angles
- Potential space-science & commercial applications

DRD3: Solid State Detectors

- 146 institutes, 30 countries
- Formed from RD50 (rad hard Si) & RD42 (Diamond)



Monolithic devices
CMOS
55-180 nm processes

Small electrode

Large electrode

with gain

without Gain

without Gain

with gain

Optimal power, resolution

Optimal rad. hard, timing

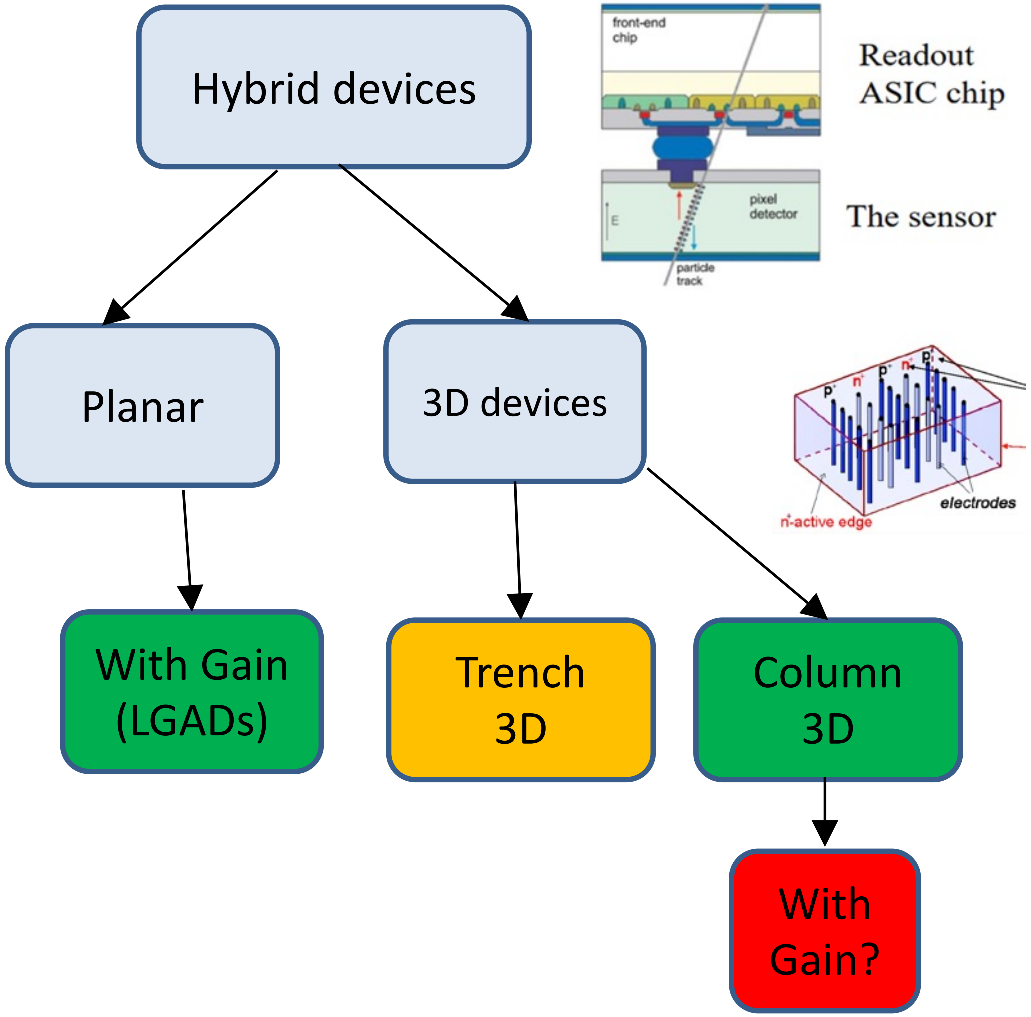
- Monolithic sensor & readout for tracking
  - high spatial resolution
  - high data rate
  - high radiation tolerance
  - Uniform eff. over cell
  - Timing capabilities, gain layer

🟥 ideas
🟨 recent
🟩 demonstrated

Solid State

DRD3: Solid State Detectors

- 146 institutes, 30 countries
- Formed from RD50 (rad hard Si) & RD42 (Diamond)



Hybrid devices

Planar

3D devices

With Gain (LGADs)

Trench 3D

Column 3D

With Gain?

- Towards 4D tracking

Dense tracking environment, PID

- – 10x10x10 **µm**^{2}, **ps**

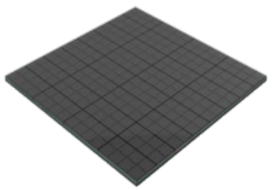
- **LGADs:**
  - fill factor, radiation hardness
- **3D:**
  - Cell size, column width

🟥 ideas
🟨 recent
🟩 demonstrated

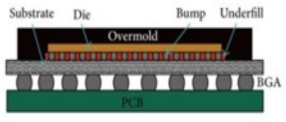
DRD4: Photon Detectors & Particle Identification

Photon & PID

- 67 institutes, 20 countries
- RICH detectors as a main focus
- also includes Scintillating Fibre & Transition Radiation Tracking

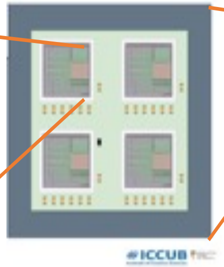


3x3mm2 SiPM Array

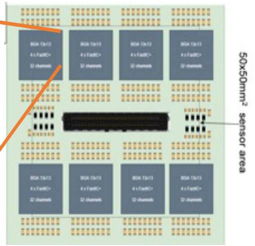


FastIC+
(collab. CERN ICCUB)
Low power
Chip

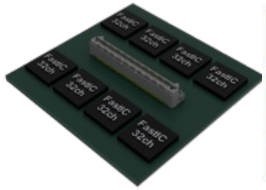
2024 Produced and

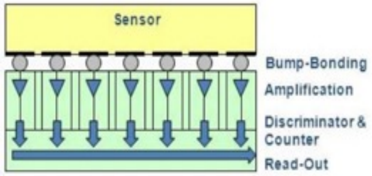


design &
luction end of
2025



256 Ch 5x5cm2
Module proposal





Ultra granular SiPMs

Long term goal
1x1mm2 SiPM array

- SiPM use becoming widespread – replacing vacuum and gas based detectors in some applications
  - Improving timing of SiPMs ~ 20ps
  - Vertical integration to Front End Electronics
  - Integration with integrated cooling

DRD5: Quantum & Emerging Technologies

- 112 institutes, 26 countries and growing…..wide community outside HEP
- Quantum detectors – e.g. below ionisation limit

Cryogenic

Superconducting

Spin-based
NV-diamond

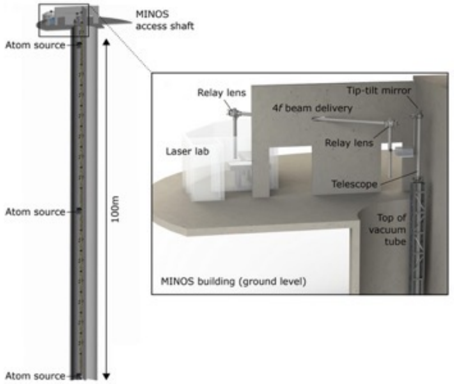
Metamaterials
0,1,2 D materials

Dedicated Experiments e.g.

Atom Interferometry

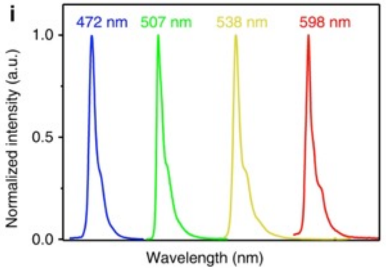
Absolute Neutrino mass

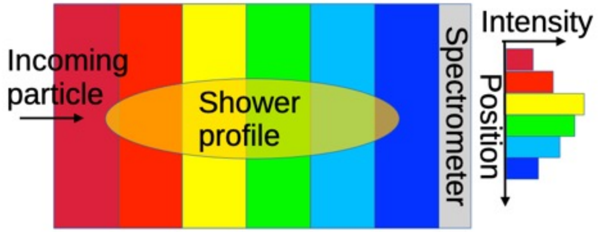
Axion tunable cavities



Technology Applications e.g.

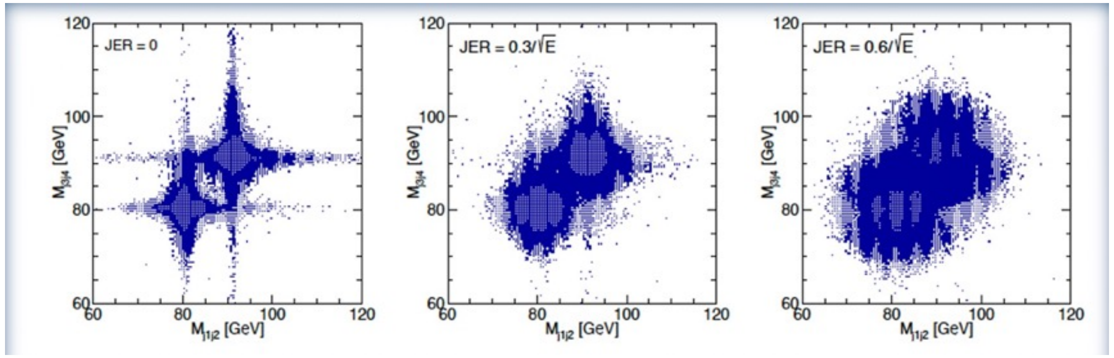
Quantum Dot Chromatic Calorimetry





DRD6: Calorimeters

- 128 institutes, 28 countries – component from CALICE but much wider
- Focus on calorimeters for future projects, FCC-ee a main driver



- Disentangle W/Z Peaks

Jet energy: $\delta E_{jet}/E_{jet} \simeq 30\% / \sqrt{E}$ [GeV]

Position (3D) | **Timing** | **Energy**

Gaseous →DRD1

Solid State →DRD3

Optical →DRD4

Quantum Dots →DRD5

Electronics →DRD7

Sandwich calorimeters with embedded electronics

Liquified Noble Gas calorimeter

Optical calorimeters

DRD7: Electronics and On-Detector Processing

- 67 institutes, 19 countries
- R&D not a service for other DRDs- Strong opportunities but high costs

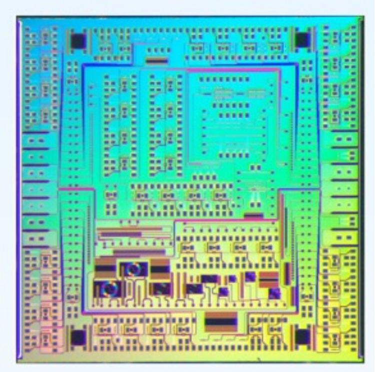
Some example developments

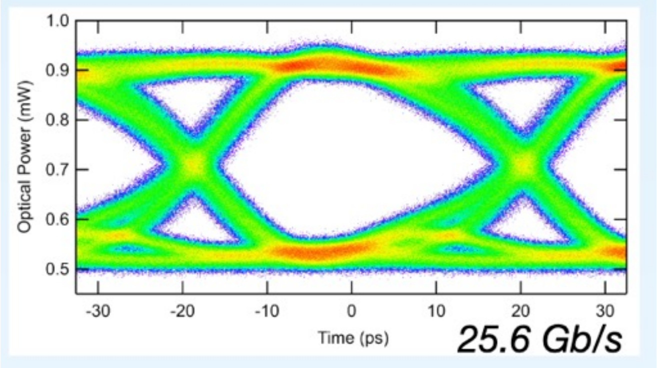
Silicon photonics
100Gb/s

Intelligence on Front End
Fewer more versatile FE electronics

Front End to DAQ
Custom off the shelf – “no back end”

Cryogenic operation





- ASIC development commonly schedule limiting for experiments
- **“Tools & Technologies” WG**
  - Accessing technologies, tools
  - Collaboration & coordination

Of development & fabrication

DRD8: Mechanics & Cooling for Future Vertex and Tracking Systems

- 40 institutes, 14 countries and growing…
- Developed from Forum on Tracking Detector Mechanics
- Much is silicon det. driven – but expanding, interest large gas detectors

New materials
Additive manufacture

Global systems

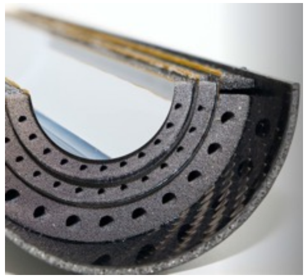
Low mass mechanics
& thermal management

Cooling

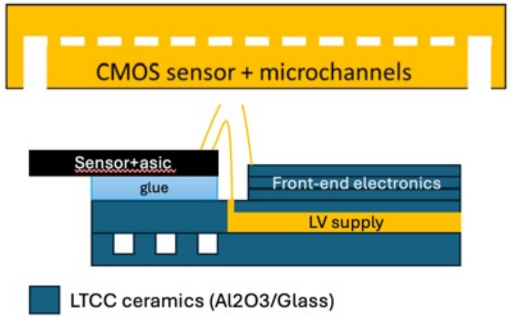
Design &
Qualification Tools

example developments

Curved sensors
Hits closer to
interaction point
Low mass mechanics



Microchannels
Integrated/ceramics



- Mechanics & Cooling a key detector performance driver
- **Schedule**: R&D continues much later in project than you think
  – share information

Computing – general themes

- Coordination and common efforts in HEP Software and infrastructure

- **GPUs**

Supercomputer list dominated by CPU-GPU systems

- **Machine Learning** (Triggers, Tracking)
- **Triggerless, Streaming readout**
- Cross-experiment collaboration, **interoperability**
  - Huge array of tools: community & industry

- International collaboration

only 36 FTE

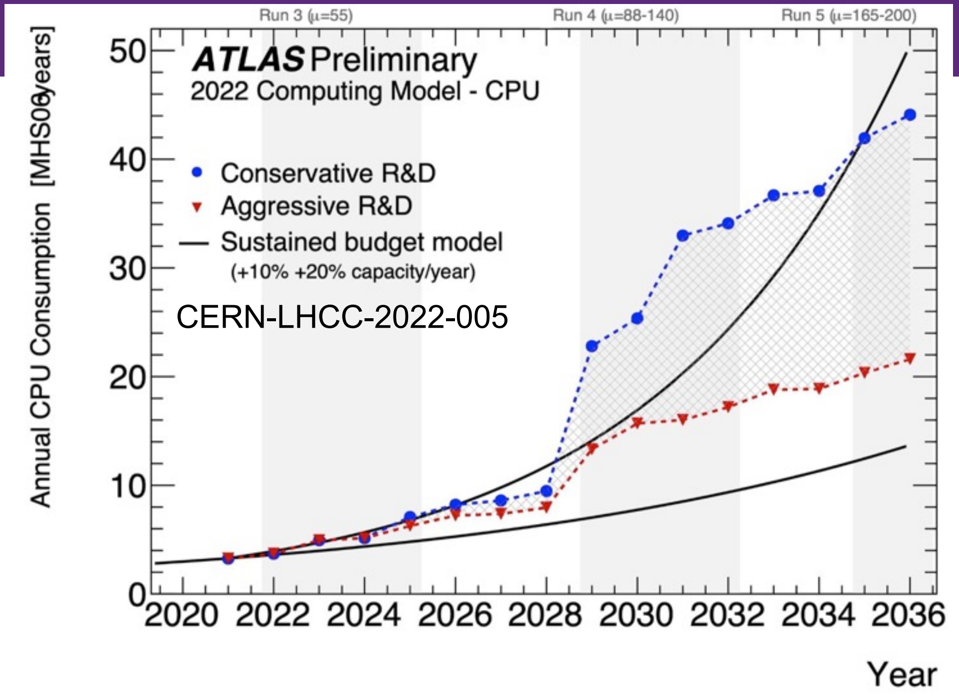
Gaudi

PyHEP

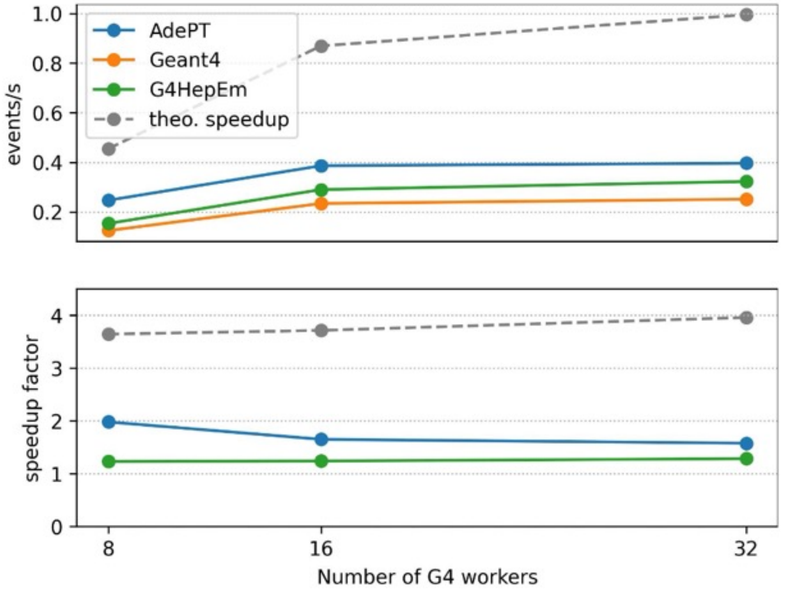
Detector Simulation

- Overall CPU for HL-LHC mitigated by
  - – software Improvements
    - Fast simulation & reconstruction
  - – HL-LHC schedule delays

- EM showers: up to $\frac{2}{3}$ of run time in collider expts (G4HepEm)
- Photons: 99% of run-time neutrino, dark-matter, LHCb RICH
- GPU-CPU combined architectures
  - **Geant4 plugins** (AdePT, Celeritas, ML approaches), promising, geometry bottleneck



CERN-LHCC-2022-005



https://indico.cern.ch/event/1528440/

Generators

Monte Carlo N(N)LO event generators

- ~ 20% of CPU demands during HL-LHC

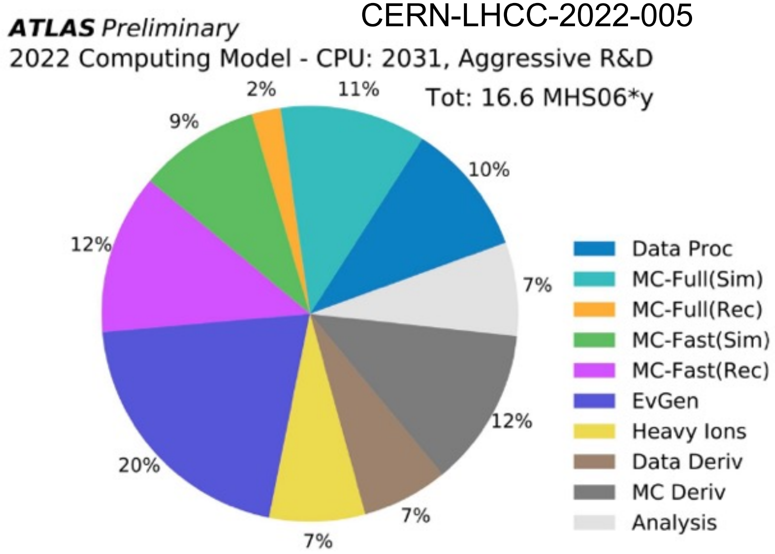
Approaches include:

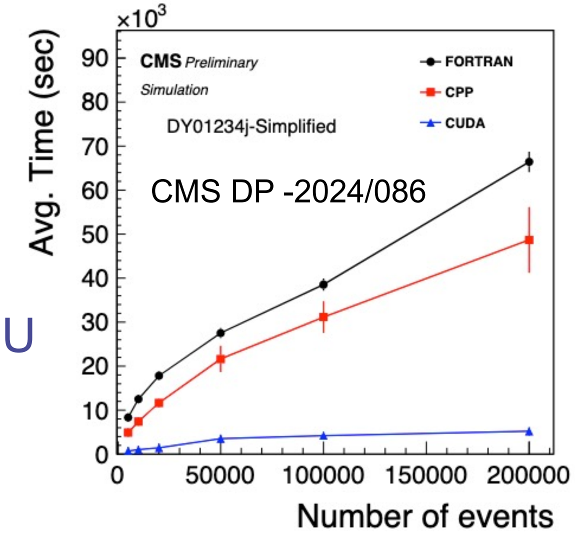
- Reducing negative weights through weight redistribution

- **Matrix element calculations in GPUs**

- ML in event generation

CERN-LHCC-2022-005





CMS DP -2024/086

MadGraph4GPU

7x speed up

User data analysis trends

- **What will an HL-LHC analysis look like ?**

Central Processing **OR** Distributed Resources that feel like

Single Machine Analysis

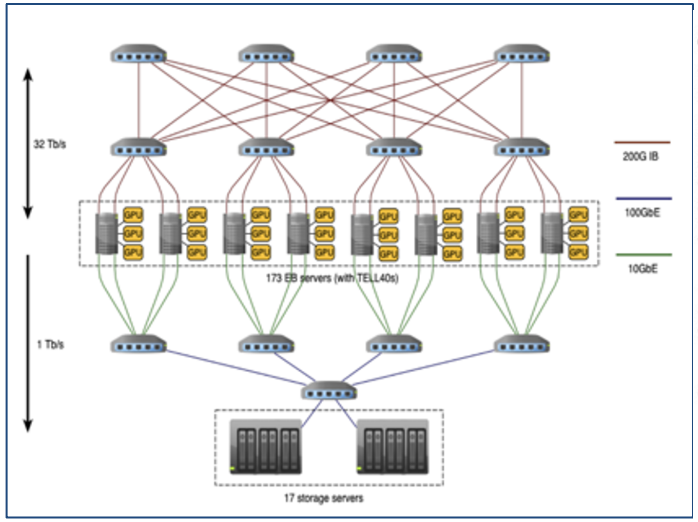
Analysis Grand Challenge
Analyst Surveys

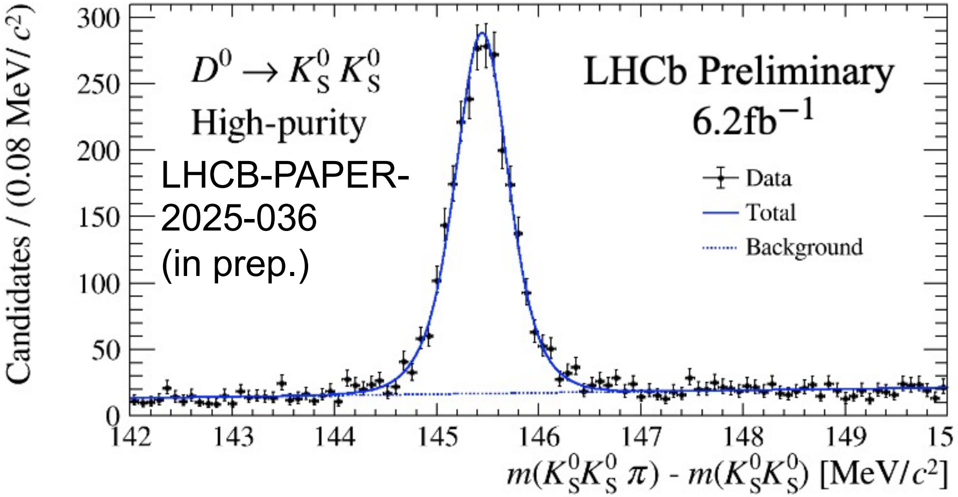
- **Data access time – Disk / tape cost trends, round-robin access**
- **Interoperability** - wide range of tools in HEP today
- Languages: C++ performance, Python usability – interest in Julia
- Improving integration with computing infrastructure (multi-threading, distributed computing)
- Machine Learning – statistical inference, automatic differentiation
- Data and Workflow Management Systems,
- FAIR principles, open data, preservation
- Reinterpretation of results (RIVET)

Software Triggers & Tracking

- Run 3 GPU Software Trigger Farms
  - Real time analysis, tracking & triggering
    - discard raw data, keep reconstructed data
- ML in trigger, including in FPGAs
  - Anomaly detection, b-tagging, Jet reconstruction….
- HI-LHC frontier – 4D tracking, hit-time information

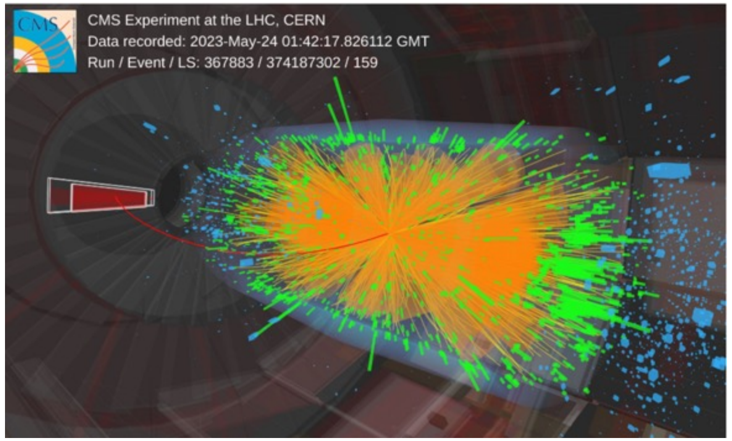
LHCb Run 3 Trigger/ Upgrade I – 3 x efficiency D→KsKs





LHCB-PAPER-2025-036 (in prep.)

CMS DP-2023/079
ML based trigger in FPGA



GRID – data centre h/w and our s/w

- Funding agencies favour interdisciplinary infrastructures
  - HPC centres as pledged resources or as opportunistic resources
- HPC centres increasingly offering GPU capacity
  - Demand from AI/ML communities.
  - Low precision GPU for ML training – poor match to simulation needs
- Our codebases generally optimized for x86 64 bit CPUs
  - require modernization to run efficiently on different architectures
  - Portability libraries will assist kokkos
- An opportunity:
  - millions of lines of software
    - streamline the code for maintainability
    - improve its performance

Training, Infrastructures, Industry, Societal Engagement

- Discoveries are facilitated by technologies
- Our funding mechanisms often under-emphasise leadership in detectors & computing – career paths
- Mutually beneficial relationship with industry
  - Skills pipeline - training
  - Collaborative developments

- Field-wide initiatives

often provide better mechanisms

for training & industry

Engagement at scale

THE CARPENTRIES

HSF Training Center

Training and educational material for the High Energy Physics community.

Acknowledgements

Many thanks to the many people who have generously given their time and effort in assisting with the preparation of this presentation, including:

- Graeme Stewart
- Nicole Skidmore
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- Gregor Kramberger
- Massimiliano Fiorini
- Steve Worm
- Roman Poeschl
- Gabriella Gaudio
- Frank Simon
- Burkhard Schmidt
- Thomas Bergauer
- Didier Contardo

Summary

- **Role of community wide bodies**
- **8 DRD Collaborations** active

Interaction with Funding Agencies to develop

- GPU computing
- Machine Learning
- Analyses - interoperability

HSF
HEP Software Foundation

- Precision Timing
- CMOS detectors
- Novel technologies

DRD
1-8

Quai de la
Fraternité

R&D

Key progress through **Fraternité**

Facilitates tomorrow's discoveries

Critical to project success cost, schedule