Detector needs for future collider experiments

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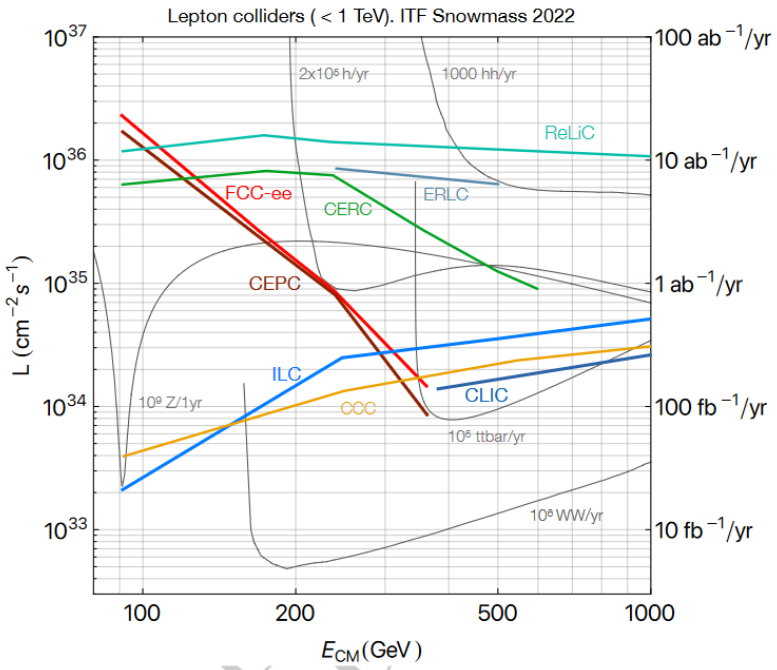
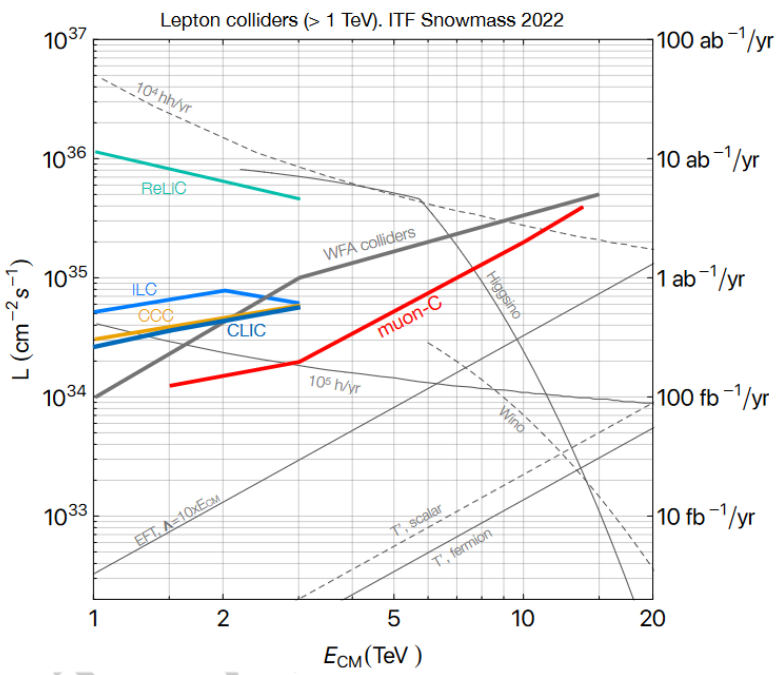
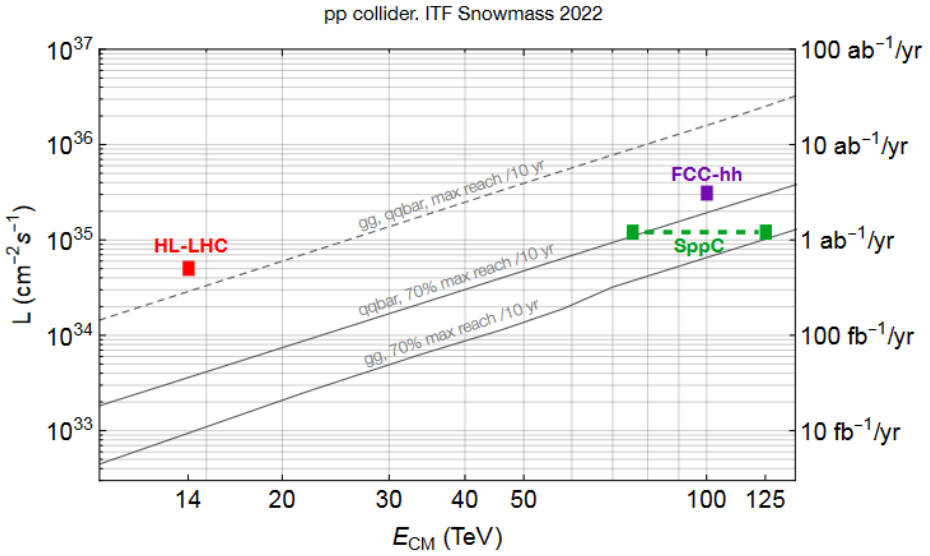
Seattle Snowmass Summer Meeting 2022

With thanks to the Instrumentation Frontier Topical Group Conveners
who provided essential input

Future Colliders







Lepton Colliders
"Higgs Factories"

High Energy Lepton Colliders

High Energy Hadron Colliders

Snowmass'2021 AF-EF-TF: Collider Implementation Task Force Report

Detector needs for future collider experiments

Detector areas to be covered:

- IF03: Tracking
- IF05: MPGD
- IF06: Calorimetry
- IF04: Trigger/DAQ
- IF07: Electronics/ASICS

Input received from each of these Instrumentation Frontier Topical Groups.

Tracking

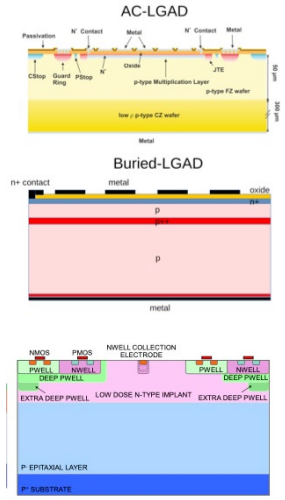
Tracking detector requirements

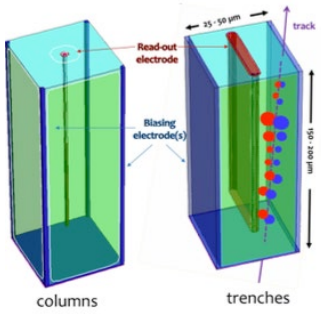
- Tracking detectors are of vital importance for collider-based HEP experiments
  - The performance requirements from the community require an evolution of tracking systems,
- Requirements for future trackers are significantly more demanding than currently available technologies
  - Precision timing resolution in a tracking environment
  - Segmentation and position resolution 2-4 times finer
  - Tolerance to fluences 1-2 orders of magnitude higher
  - Larger areas at lower costs
  - Radiation length per layer from 0.1-1% X0
  - Advanced materials, fabrication techniques, edge-processing

Technology directions

Tracking

- High granularity measurements: spatial and timing resolution
  - AC-LGADs, LGAD optimizations (buried layer, double-sided, etc)
  - 3D sensors, Induced Current sensors
  - Monolithic pixel sensors
- New materials, fabrication techniques
  - 4H-SiC, 3D silicon and diamond, 3D-sensors with gain, 3DIC SiPM, thin films, quantum dots
  - Advanced packaging, wafer-to-wafer bonding
- Light-weight support/cooling structures
  - Integrated services and cooling, novel materials, new cooling and composite manufacturing
- New approaches to front-end processing
  - Edge-computing, nanotechnologies to reduce power on the front-end, wireless
- Development of simulation tools
  - Invaluable in the development of new technologies





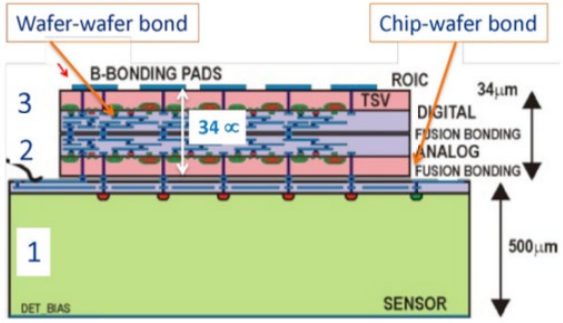
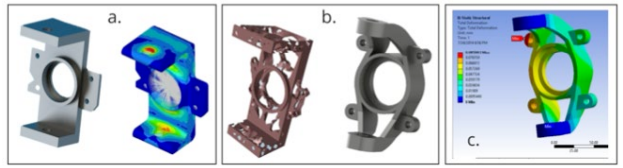


Figure 1: Example of 3D integration of sensor and readout chip.

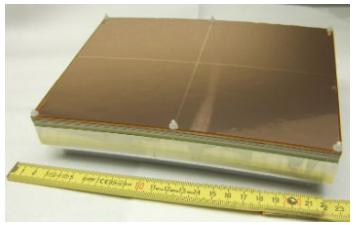


Technology priorities

- Developments of sensor technologies
  - Achieve 4D-capability from timing sensors with fine segmentation and able to cope with high occupancies and radiation tolerance
  - Large area sensors with improved uniformity, both traditional, LGADs, and wafer-scale MAPS
  - Major advances in ASIC development and approaches: bandwidth optimization, low noise, small area and low power dissipation
  - New materials for sensor and electronics : unified design of full systems
- Advanced packaging and edge-computing paradigms
  - Vertical integration of multi-tier processing electronics and sensors, optimization of detector thickness
  - Industry partnerships and adoption of new technologies
- Radiation hard technologies and more effective cooling
- Simulation tools
  - Unified radiation damage model, prescription for uncertainties in TCAD models
  - Measurements of damage factors
  - Feedback between full detector systems and per-sensor models

Tracking: MPGD

MPGDs have major roles in TPCs and large area muon detection systems.
Essential features – large area, low material budget



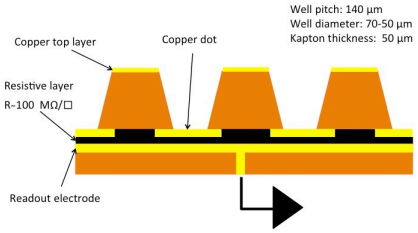
Triple-GEM r/o module for LCTPC

TPCs – ILD/ILC, potential Belle II wire chamber replacement, for a detector at CEPC
MPGD readout – GEM, GridPix,…
Synergy with Si ASIC development – wafer post-processing, gas amplification on top of pixelized r/o chip
Negligible ExB effect with e.g. GEM due to ~100µm hole spacing

Muon detection systems
Precise muon tracking, trigger and tagger for collider detectors
Instrument large areas, high efficiency, in high background, high radiation environment

NOTE: There is ongoing discussion about the need for a MPGD facility in the U.S. like the CERN GDD Group facility

Challenges
Discharge protection (e.g. micro R-well), miniaturization of readout elements



Micro R-well

FCC-hh very forward endcap regions
Multi-TeV Muon Collider –Fast Timing MPGD – use timing to mitigate beam-induced background.

Calorimetry – Techniques (PFA/DRO)

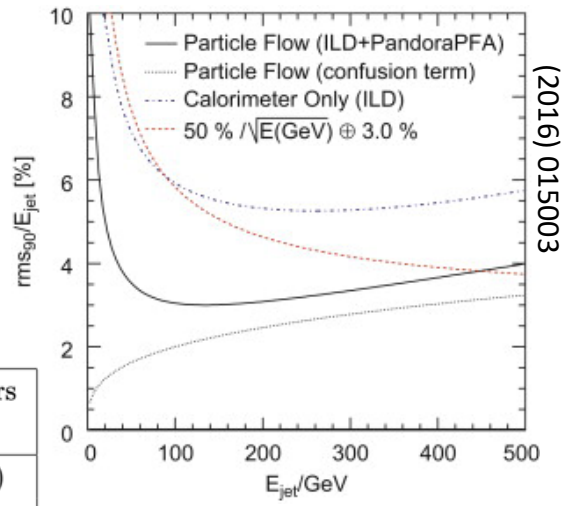
Particle Flow:

- Motivation: ultra-precise measurements of hadronic jets to discriminate between W, Z, and H bosons reconstructed in multijet final states
- Target performance: stochastic term of 30%/√E[GeV]

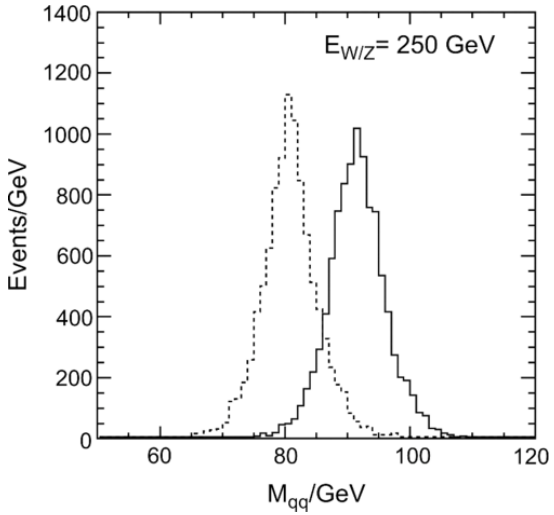
name	purpose	project	active material	channel size	readout	# of layers (depth)
CALICE SiW ECAL	ECAL	ILC[a]	silicon	5×5 mm^2	analog	30 ($24X_0$)
SiD ECAL	ECAL	ILC	silicon	13 mm^2	analog	30 ($26X_0$)
HGCAL Si	ECAL[b]	HL-LHC	silicon	52-118 mm^2	analog	28 ($25X_0$)
FoCal	ECAL	HL-LHC	silicon	30×30 μm^2	digital	28 ($25X_0$)
CALICE Sci-ECAL	ECAL	ILC[c]	SiPM-on-tile	5×5 mm^2[d]	analog	30 ($24X_0$)
RADiCAL	ECAL	FCC-hh	crystal + WLS[e]	4×4 mm^2[f]	analog	29 ($25X_0$)
CALICE AHCAL	HCAL	ILC[g]	SiPM-on-tile	3×3 cm^2	analog	40 ($4\lambda_I$)
HGCAL Scint	HCAL	HL-LHC	SiPM-on-tile	6-30 cm^2	analog	22 ($7.8\lambda_I$)[h]
CALICE DHCAL	HCAL	ILC	RPC	1×1 cm^2	digital	40 ($4\lambda_I$)
CALICE SDHCAL	HCAL	ILC	RPC	1×1 cm^2	semi-digital	40 ($4\lambda_I$)

Extensive interest from e^+e^- community, which has driven much R&D

First realization in HL-LHC, motivated by radiation hardness and pileup

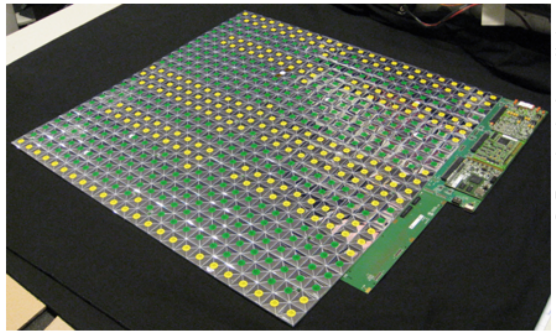


Rev. Mod. Phys. **88** (2016) 015003



Rev. Mod. Phys. **88** (2016) 015003

- R&D continues to advance along many fronts
- Challenges remain:
  - Scaling to 10-100M channels at reasonable cost
  - Thermal and power management of front end ASICs
  - Compact design (minimizing gaps between sampling layers)



https://ftc.desy.de/hcal/index_eng.html

Calorimetry – Techniques (PFA/DRO)

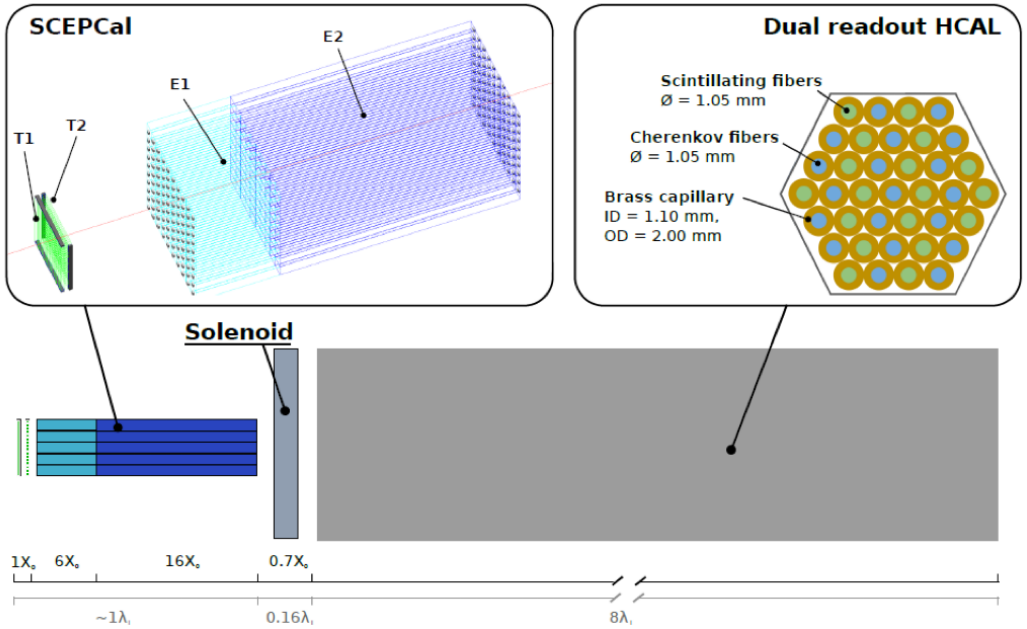
Dual readout

- Shower-by-shower energy scale correction as a function of number of inelastic collisions.
- Total energy of all ionizing particles estimated from scintillation light (plastic or crystals).
- Energy due to relativistic ionizing particles estimated from Čerenkov light (clear fibers)

Examples

Spaghetti calorimeter with clear (Čerenkov) and scintillating fibers installed in a tower of passive material - IDEA (FCC-ee or CEPC)

Homogeneous scintillating crystals with two filter-SiPM readout assemblies, sensitive to either Čerenkov or scintillation light - SCEPCAL (FCC-ee or CEPC)



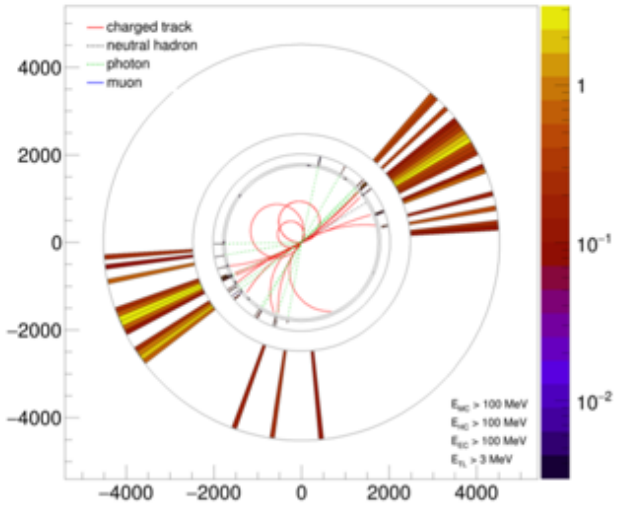
Challenges remain:

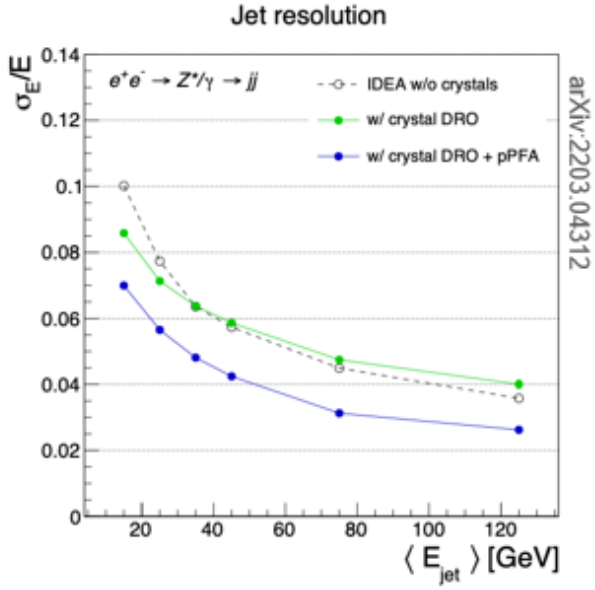
Mechanics, integration, and costing of a realistic spaghetti calorimeter

Red-sensitive SiPMs and novel optical materials to boost the Čerenkov signal/noise in homogeneous crystal setups

Particle flow and Dual readout

- ADRIANO2 for proposed η factory
  - Highly granular particle flow-like sampling calorimeter, but alternating lead glass absorber/scintillator (sensitive to Čerenkov) and plastic scintillator
  - Discrimination between photons, neutrons, and π^0s
- Spaghetti calorimeter with individual SiPM readout of each fiber
- SCEPCAL for CEPC or FCC-ee
  - Coarser longitudinal segmentation than CALICE-style particle flow
  - Tuned particle flow reconstruction algorithm + dual readout information yields better results than dual readout alone
- Both concepts being considered for a muon collider detector





SCEPCAL

Calorimetry - Precision Timing

Timing as an extra dimension to calorimeter systems

What can be achieved with O(10ps), few-ps, or even sub-ps level timing?

Higgs factories – improving event reconstruction, 5-D (x,y,z,E,t), energy resolution, reduced uncertainties on Higgs BRs etc.

- Particle ID e.g. for h –> ssbar and for long-lived particle searches

Hadron colliders – pile-up mitigation, reduction of confusion, improved event reconstruction

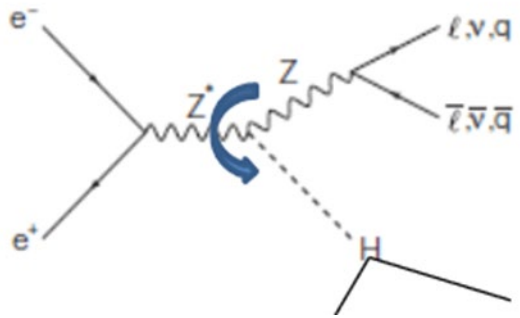
Implementing precision timing in calorimeters (volume/cell level, dedicated layers)

Technologies for precision timing

Calorimetry – Precision Timing

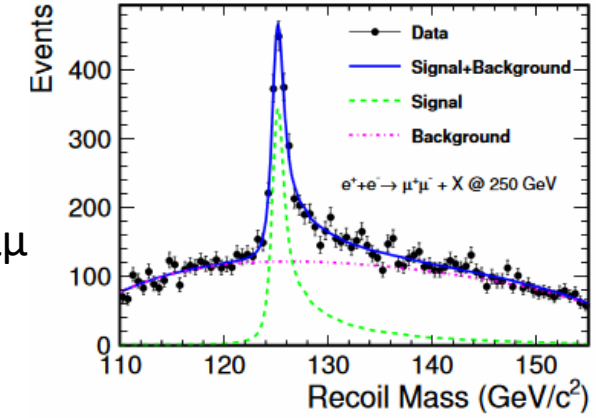
Higgs factories – improving overall precision of event reconstruction, particle ID

e+e- -> ZH
Higgs to invisible analysis



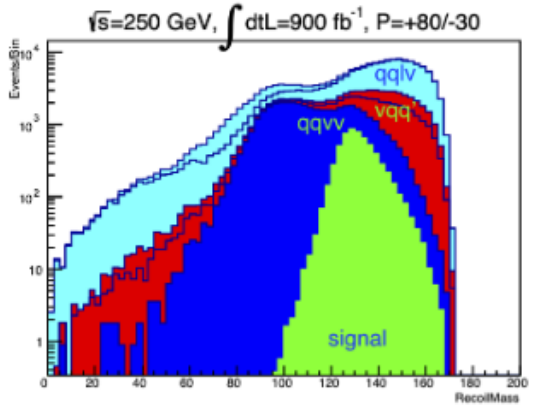
Z -> μμ

Physics goal



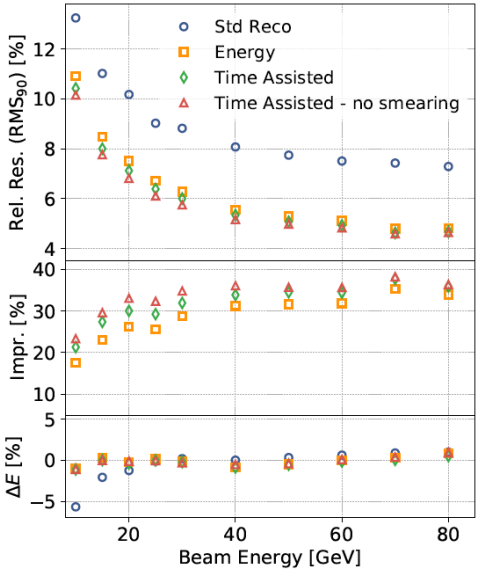
Excellent momentum resolution to obtain the best possible recoil mass measurement

Z-> qqbar

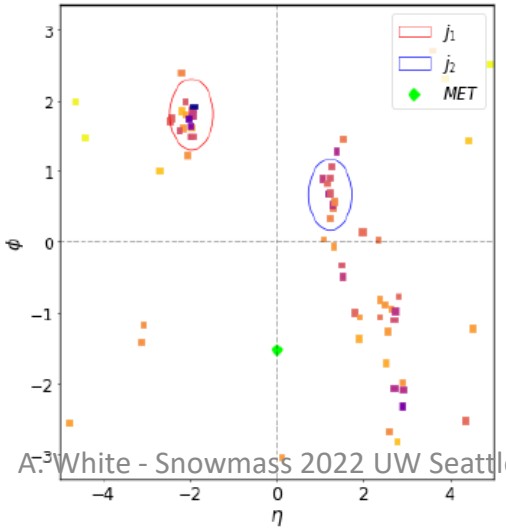


SiD h -> inv, C. Potter et al.

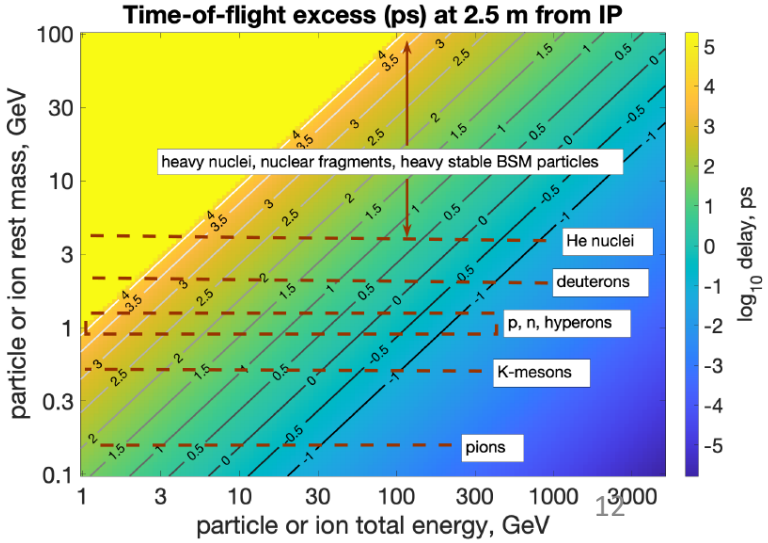
Including timing information
Study based on CALICE AHCAL (Scint tile/SiPM)



? How to use timing data in ML-based analyses?



Particle ID
Typical barrel layer

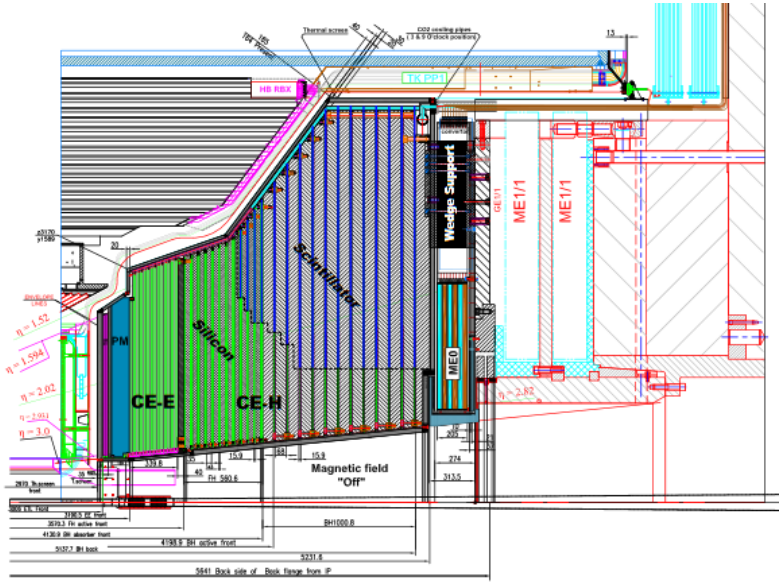


Calorimetry – Precision Timing

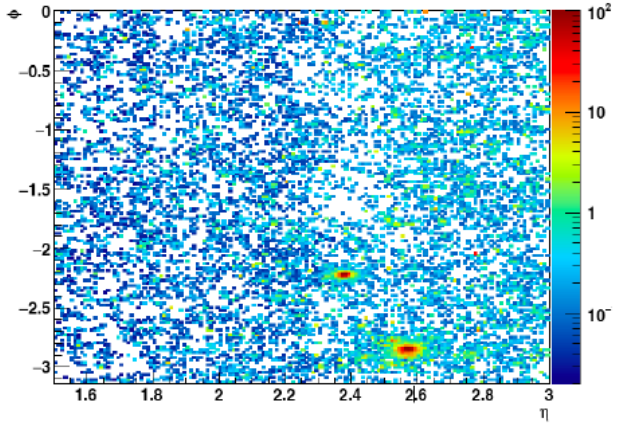
Hadron colliders – pile-up mitigation, reduced confusion/backgrounds

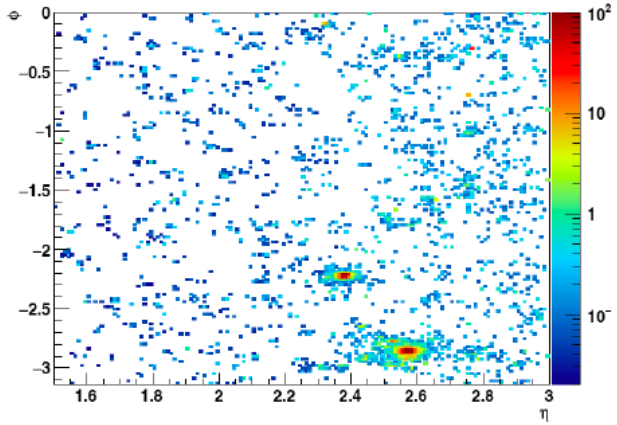
Example: CMS HGCAL

HL-LHC:
Expect up to 200 simultaneous collisions



Before/after cut on time of particles (Hits > 12 fC, |Δt| > 90ps)





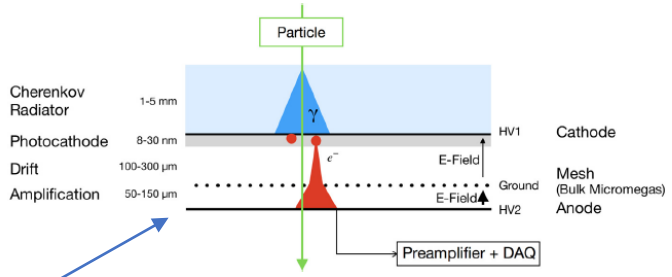
FCC-hh:
Expect O(1000) pile-up events

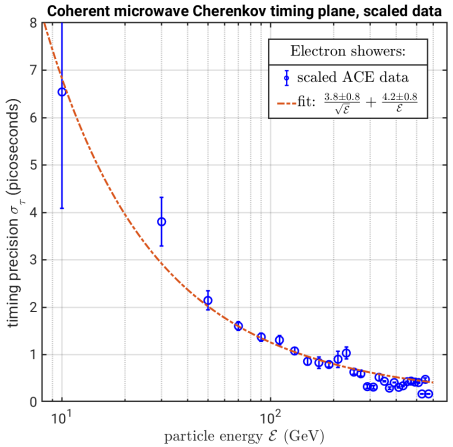
90% assigned tracks/central region – achieved with 5-10ps timing cut
-> keep effective pile-up below one/bunch crossing

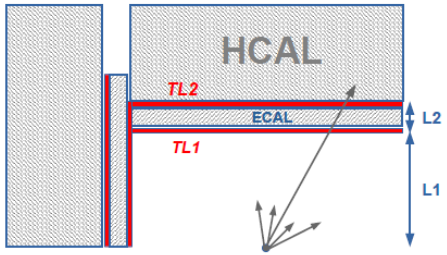
Technologies for layer and volume timing

Timing layers

- Low-Gain Avalanche Detectors (LGADs) ~30ps and 1mm spatial resolution
- Ultra-fast silicon monolithic sensors with integrated readout (CMOS) 10-20ps
- Micro-channel plate (MCP) detectors detection of single ionizing particles ~few ps
- 2-stage Micromegas detector + Cherenkov radiator equipped with a photocathode < 100ps
- LYSO crystals + SiPM few x10 ps
- Deep diffused avalanche photodiodes ~40ps
- Coherent microwave Cherenkov detectors ~0.3 – 3ps



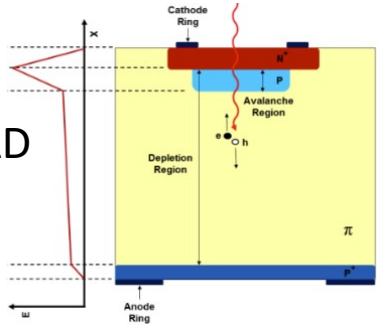




Volume timing

- Silicon tiles e.g. LGADs few x10 ps
- Plastic scintillator tiles or strips with SiPM readout sub-ns -> few x10ps
- Multi-gap RPCs sub-100ps
- Highly granular crystal-based detectors, using a highly segmented readout

LGAD



Issues: *R&D needed on electronics* to support timing resolution satisfying the constraints on power consumption associated with highly integrated systems with extreme channel counts

Calorimeter Materials

- (Issues) stringent challenges to calorimeter materials in radiation tolerance, energy resolution, time response and project cost
  - Enhance calorimetry energy resolution for precision electroweak mass and missing energy measurements.
  - Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments.
  - Develop ultrafast media to improve background rejection in calorimeters and improve particle identification.
- WP summarized materials in the form of inorganic, liquid (oil- and water-based), and plastic scintillators from LOIs and consortiums
  - BaF_2:Y → feasible to TOF system; Mu2e-II, (also by RADiCAL)
  - LYSO:Ce or LuAG:Ce → best fit to radiation hardness; HL-LHC, FCC-hh (RADiCAL)
  - BGO, PWO, Glass → good EM and jet resolutions; Higgs-Factory, ILC and FCC-ee (CalVision and HHCAL)
  - Liquid (oil- and water-based) and plastics scintillators (from neutrino and other particle physics experiments)
- Inorganic scintillator crystals dominate the calorimetry applications
  - New glass materials (OGS) are promising
  - Organics scintillators are less selected, but could have usages in future large volume (cost) calorimeters

Calorimeter Materials

High density, good optical quality, high light-yield, fast decay time, good radiation hardness and low cost

- Materials for Future Calorimeters : arXiv:2203.07154

Materials (noble gas not included)	LY (ph/MeV)	Cost (per kg)	Time (ns)	General Comments
Inorganic Scintillator Crystals	1000~30000	$1000s	10s~100s[2]	High density, easy deployment, low optical, scale-up challenge (cost/volume); WLS[3]
Organic Scintillator Plastics	1000s	$10s	1s	Medium density, easy deployment, <m-optical, scale-up challenge (3D-print?), WLS[3]
(Z-doped, 1s%) Organic Liquid Scintillator[1]	9000-14000	$1s	Sub	~10m-optical, low density (mitigated by high-Z?), large volume; WLS-doped
(Z-doped, 10s%) Water-based Liquid Scintillator	1000s	<$1s	Sub	~10m-optical, low density (mitigated by high-Z?), environmentally-friendly, large volume, WLS-doped

Optical and scintillation properties of candidate inorganic scintillators for CalVision and the HHCAL concept

	BGO	BSO	PWO	PbF_2	PbFCl	Sapphire:Ti	AFO Glass	DSB:Ce Glass[1]	DSB:Ce,Gd Glass[2,3]	HFG Glass[4]
Density (g/cm³)	7.13	6.8	8.3	7.77	7.11	3.98	4.6	3.8	4.7 - 5.4	5.95
Melting point (°C)	1050	1030	1123	824	608	2040	980[5]	1420[6]	1420[6]	570
X_0 (cm)	1.12	1.15	0.89	0.94	1.05	7.02	2.96	3.36	2.14	1.74
R_M (cm)	2.23	2.33	2.00	2.18	2.33	2.88	2.89	3.52	2.56	2.45
λ_I (cm)	22.7	23.4	20.7	22.4	24.3	24.2	26.4	32.8	24.2	23.2
Z_{eff} value	72.9	75.3	74.5	77.4	75.8	11.2	42.8	44.4	48.7	56.9
dE/dX (MeV/cm)	8.99	8.59	10.1	9.42	8.68	6.75	6.84	5.56	7.68	8.24
Emission Peak[a] (nm)	480	470	425 420	\	420	300 750	365	440 460	440 460	325
Refractive Index[b]	2.15	2.68	2.20	1.82	2.15	1.76	\	\	\	1.50
LY (ph/MeV)[c]	7,500	1,500	130	\	150	7,900	450	3,150	2,500	150
Decay Time[a] (ns)	300	100	30 10	\	3	300 3200	40	180 30	120, 400 50	25 8
d(LY)/dT (%/°C)[c]	-0.9	?	-2.5	\	?	?	?	-0.04	-0.04	-0.37
Cost ($/cc)	6.0	7.0	7.5	6.0	?	0.6?	?	2.0	2.0?	?

a. Top line: slow component. Bottom line: fast component.
b. At the wavelength of the emission maximum.
c. At room temperature (20°C).

1. D. Auffray, et al., Nucl. Instr. Meth. A 821, 104-109 (2016)
2. R. A. McCauley, et al., Phys. Rev. Mater. 1, 065602 (2017)
3. V. Dormenev , et al., the ATTRACT Final Conference
4. E. Auffray, et al., NIMA 380 (1996), 524-536
5. R. A. McCauley et al., Trans. Br. Ceram. Soc., 67, 1968
6. I. G. Oelsch[illegible]gel, Glastech. Ber. 44, 1971

Low density crystals/glasses

Fast Machine Learning in TDAQ

- "Fast" (<ms) machine learning is useful in many scientific domains, and many different kinds of detectors, to extract the science with increased TDAQ constraints on timing, bandwidth, etc:
  - LHC detectors
  - neutrino detectors
  - dark matter detectors
  - detectors at the EIC
  - gravitational wave detection
  - …

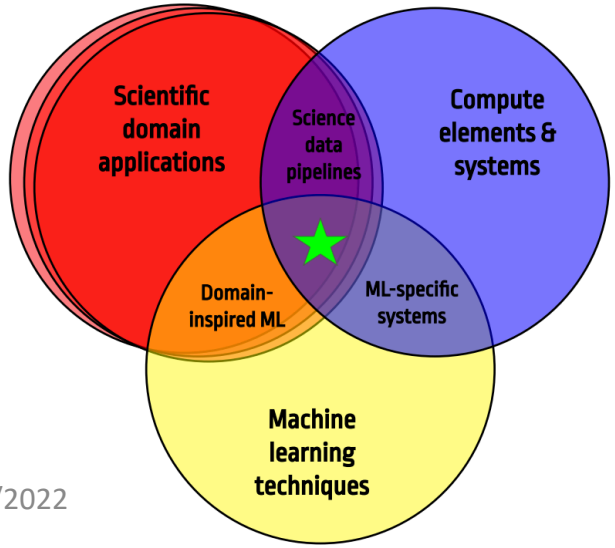


Table 2. Domains and practical constraints: systems are broadly classified as soft (software-programmable computing devices: CPUs, GPUs, and TPUs) and custom (custom embedded computing devices: FPGAs and ASICs)

Domain	Event Rate	Latency	Systems	Energy-constrained
Detection and Event Reconstruction				**No**
LHC & intensity frontier HEP	10s Mhz	ns-ms	Soft/custom	
Nuclear physics	10s kHz	ms	soft	
Dark matter & neutrino physics	10s MHz	μs	Soft/custom	
Image Processing				
Material synthesis	10s kHz	ms	Soft/custom	
Scanning probe microscopy	kHz	ms	Soft/custom	
Electron microscopy	MHz	μs	Soft/custom	
Biomedical engineering	kHz	ms	Soft/custom	Yes (mobile settings)
Cosmology	Hz	s	soft	
Astrophysics	kHz–MHz	ms-us	Soft	Yes (remote locations)
Signal Processing				
Gravitational waves	kHz	ms	Soft	

"Fusing powerful ML techniques with experimental design decreases the 'time to science' and can range from embedding real-time feature extraction to be as close as possible to the sensor all the way to large-scale ML acceleration across distributed grid computing datacenters."

Tracking Triggers

- Early-stage triggers based on tracking information can preserve interesting events for study.
  - Emphasis to expand capability to include long-lived low momentum particles, very-short-lived high momentum particles, …
- Hardware-based tracking explored and/or used in multiple previous detectors (at Tevatron, LHC, at future experiments…)
- Multiple approaches: associated memory/pattern bank, use of different kinds of machine learning techniques

Example from contributed Snowmass white paper,
highly-parallelized graph computing architecture using FPGAs.

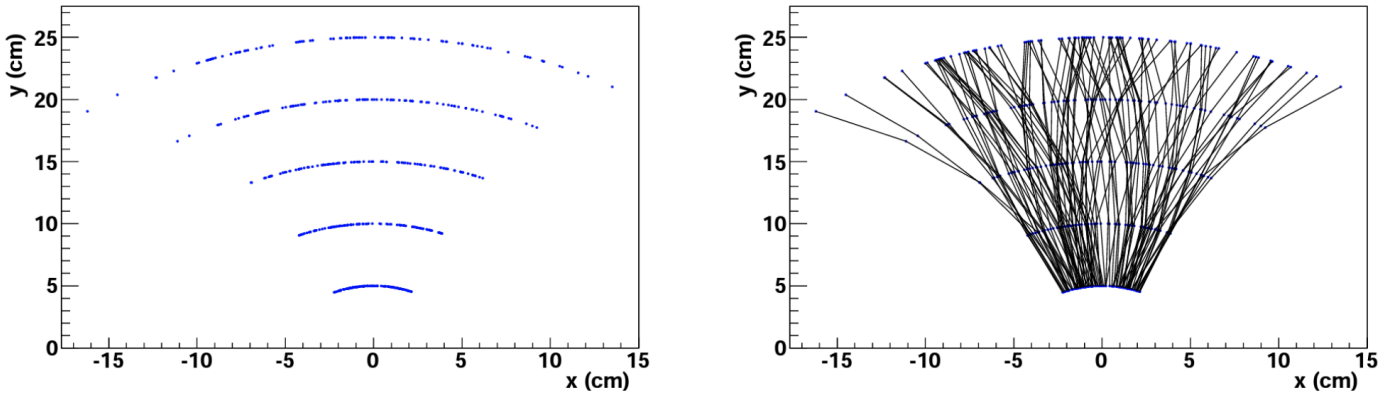


Figure 4-1. *(left) An example of the point cloud generated by 100 particles in an azimuthal sector of the silicon pixel detector of width one radian. The silicon sensors are placed in concentric circles with radial separation of 5cm.(right)The reconstruction of 100 tracks from the point cloud. [1]*

TDAQ-Readout Technologies

- Improvements in readout technologies are necessary to handle high data rate of future detectors
  - Reduce the data rate close to the detector
  - Increase data bandwidth per material/power cost
- Wireless communication
  - Could enable designs with localized readout and fast analysis/triggering to reduce data volumes
  - Microwave-based technologies have strong momentum, but reaching upper physical limit in bandwidth
  - Free-space optics operating in mid-IR regime show promise for Tb/s bandwidths
- Next-generation Rad-hard links
  - Move beyond current bandwidth-limited VCSEL-based links
  - Silicon photonics can integrate directly to chips, and offer ~x2 bandwidth at less power
  - Wavelength Division Multiplexing (WDM) can reduce data aggregation layers by transmitting individual serial links at different wavelengths
- See readout technologies white paper: https://arxiv.org/abs/2203.14894

Electronics/ASICS

Higher Collisions Rates & Channel counts → Huge Increase in Sensor Data

- Control Data Content
  - Implement data reduction techniques for low and moderate occupancy sensors.
  - Utilize High Level Feature extraction techniques (eg. Hough transforms for groups of sensors) on detector to increase physics content/bit transferred off detector.
  - Sparsify readout applying trigger selection .. utilize AI/ML techniques etc.
- Increase off Detector Data Throughput
  - Implement high speed Rad hard Optical links @ rates tx > 10Gbps rx ~1Gbps (in 28nm technology)
  - Reduce footprint/Minimize Power of Optical modules.
  - Investigate/Implement direct ASIC to fiber transceivers. (Bi-CMOS – Optical ASICs)

Challenges for Next Generation Collider Detector Systems

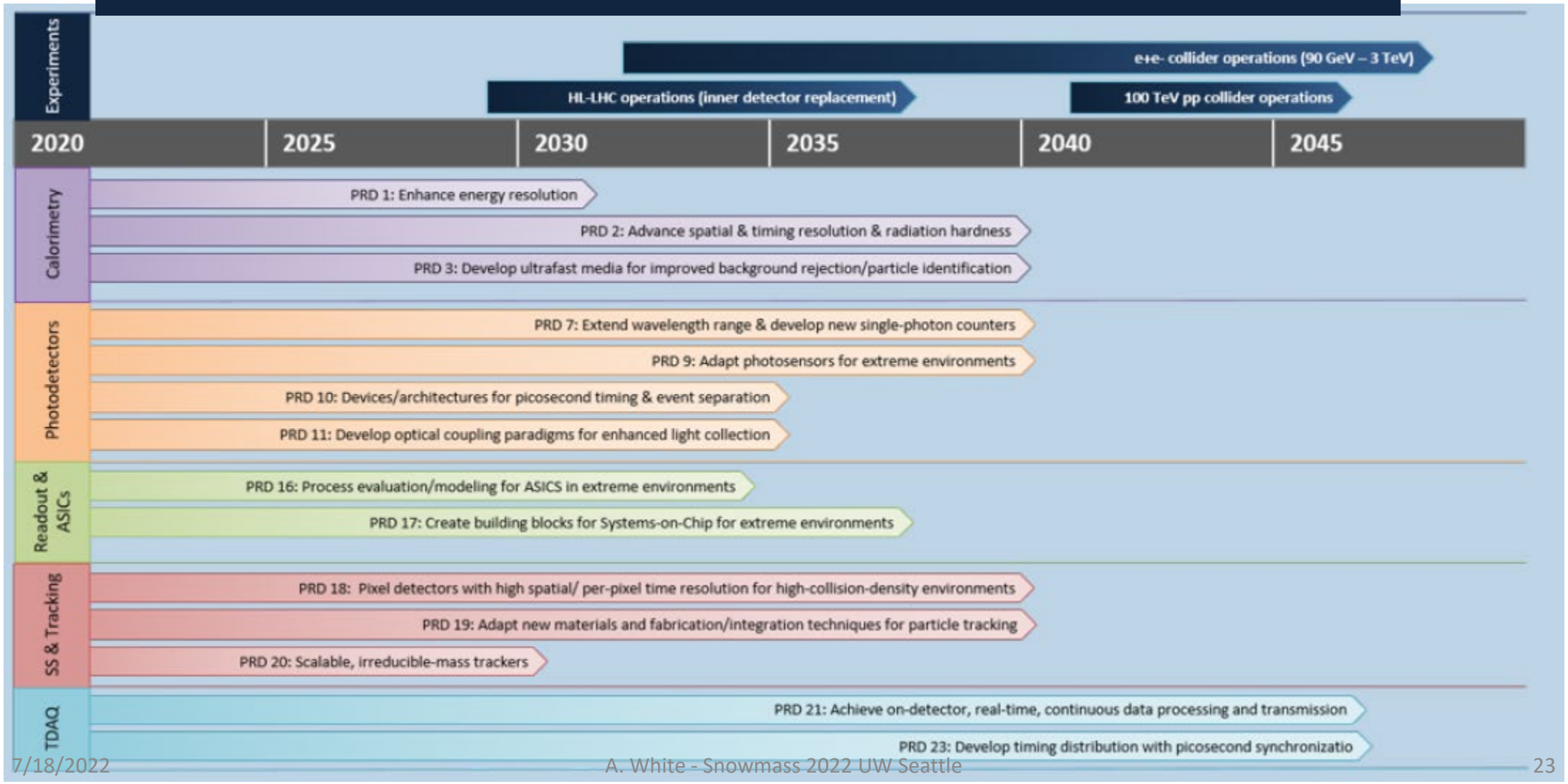
- Tracking
  - 4D Silicon strips and Pixels with data concentrators to provide tracklet 4 vectors instead of hit data. ~50um geometric resolution & 2-3mm time derived track association.
    - Geometric resolution from pixel position sensor thickness
    - ~ 10-15ps hit time resolution (dependent on clock distribution jitter)
- Calorimetry
  - Dual Readout high transverse granularity with precision timing for shower readout.
    - Simultaneous low latency readout of Scintillation and Cherenkov signals with precision timing information
      - More than Doubles the Data of traditional Calorimeter readout
      - Challenges for analog front end / data storage / trigger selection

Electronics/ASICS

Workforce & Infrastructure Support

- Ensure Institutional Retention of >2 decades of collider detector Instrumentation Design & Development experience:
  - System Design → moving towards Co-design/Co-simulation
  - Hierarchical Approach to Design & Simulation of High Channel detector sub-systems
  - Integrated sensors & readout on single / multiple parallel susbstrates eg. MAPS
  - Engage designers in building Radiation Tolerant ASIC blocks for Future Systems On a Chip (SoC) → to maintain State of Art Readiness
    - Front End Readout
    - Local Memory
    - On Chip Supply conversion DCDC and LDO's
- Maintain HEP specific (Rad Tolerant/Cryo) Web Resource for Tutorials/Examples/References
- Future Designs will require broad (multi-institutional) access to:
  - Advanced Technology Nodes for ASIC fabrication
  - CAD Design and Design management tools and training
  - Hierarchical System Simulation tools

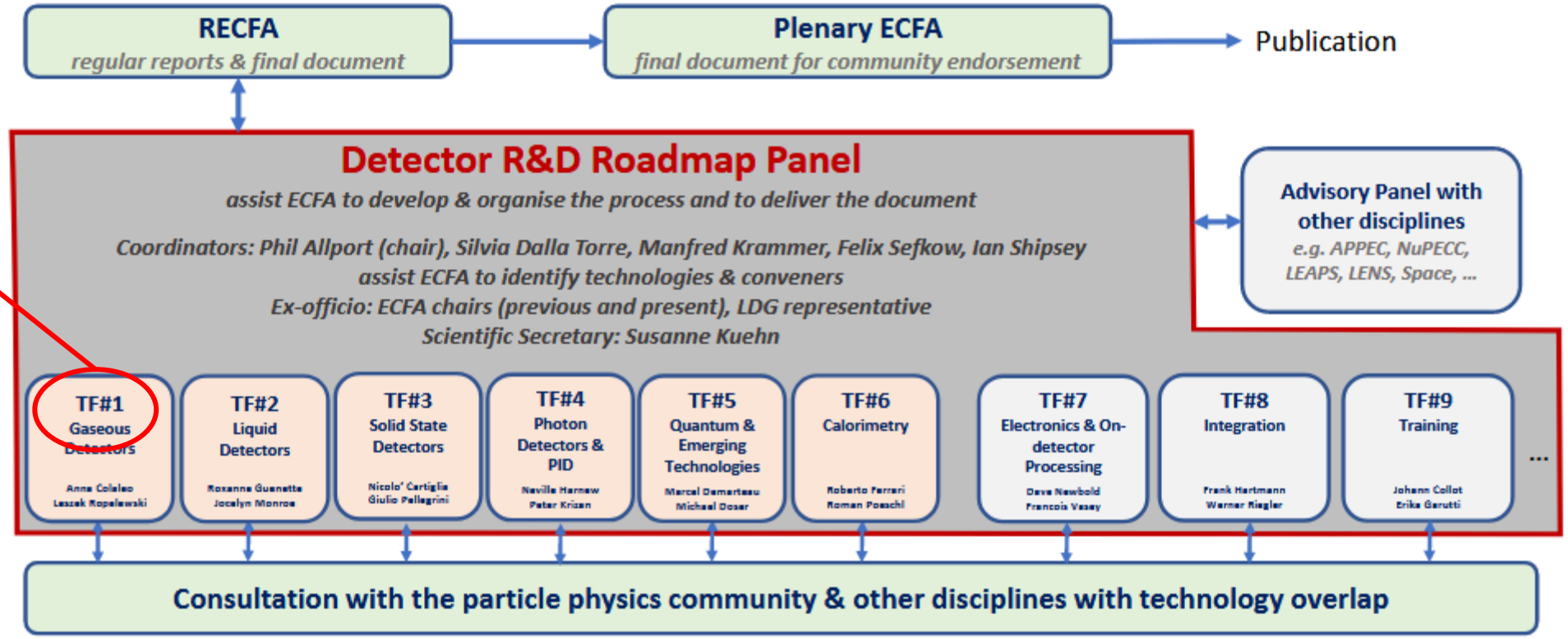
Basic Research Needs for High Energy Physics Detector Research & Development



ECFA

European Committee for Future Accelerators

The Detector R&D Roadmap Process



New "DRD" Group for each area

- US participation in new DRDC groups
- Avoiding duplication of R&D across regions

Moving forward…

The Energy Frontier also supports the possibility of a Higgs factory in the US. Given global uncertainties, consideration should also be given to the timely realization of a possible domestic Higgs factory, in case none of the currently proposed global options are realized. To enable the realization of a Higgs factory in the shortest possible timescale, a targeted program on detector R&D for Higgs factories should be supported. In order for the US to build a strong community of young physicists engaged in Higgs factory research, the EF community supports the case for the establishing a program for detector R&D that covers the range of proposed accelerator facilities, with initial emphasis on areas that are applicable across facilities.

Energy Frontier – Snowmass draft report

- A Higgs Factory is emerging as a strong medium-term priority
- The US needs to build a strong community to participate in the e+e- experiments/physics
- Significant investments already made elsewhere (esp. Europe)
- Urgent need for a detector R&D program directed towards Higgs Factory participation by U.S. HEP.

Conclusions

- There are many challenges to be met to have successful detector designs and implementation for future collider detectors.

- Challenges in spatial and timing precision, channel counts, radiation hardness, high data volumes/rates, power requirements, materials and material profiles, high speed low noise electronics,…

- Many new approaches to solving these challenges!

- Significant Detector R&D support will be needed in the U.S. to ensure effective participation in future collider programs.

- Essential that these Detector R&D needs are effectively communicated in the Snowmass Report and conveyed to P5.

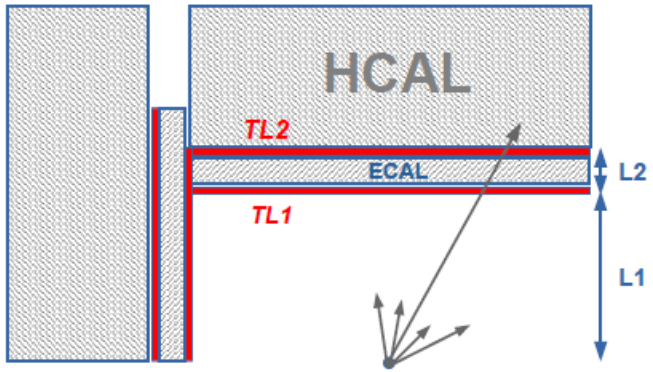
Extra slides

Implementing precision timing in calorimeters

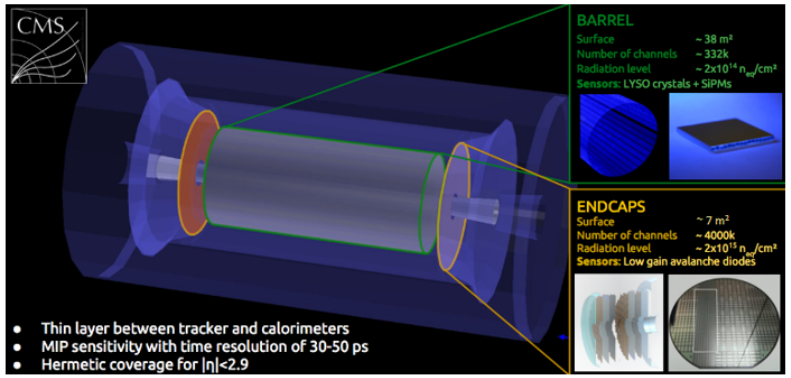
Various possible schemes for timing – timing resolution/performance/cost considerstions

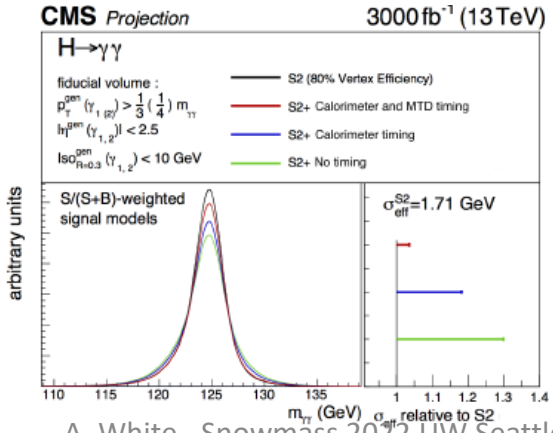
Volume timing – timing for all active cells in calorimeter
- -> 5-D (x, y, z, E, t) in highly granular calorimeter
- -> benefits for pattern recognition, shower reconstruction/separation, energy measurement
- -> BUT – potentially high cost
- -> Explore benefits of full digital calorimetry – needs much R&D

Timing layers – small number of dedicated timing layers
- -> e.g. before/after Electromagnetic calorimeter
- -> layers in Hadron Calorimeter



CMS MIP Timing Detector





Trigger and Data Acquisition

Future directions:

- application of Machine Learning (ML) to TDAQ systems, particularly considering co-design of hardware and software to apply ML algorithms to real-time hardware and in other novel uses of ML to make future experiments more operationally efficient while increasing sensitivity for new physics;
- the design of TDAQ system architectures to enable more intelligent aggregation, reduction, and streaming of data from detectors to higher-level trigger systems and offline data processing; and,
- the development of improved readout technologies to increase data bandwidth, that are capable of operating in extreme environments while fitting the material and power budgets of future experiments.