Detector Challenges at Future Circular Colliders

S. Rajagopalan (BNL)

"The [FCC] represents a convincing, visionary and technically feasible answer to the challenges and questions posed by the current high-energy physics landscape"

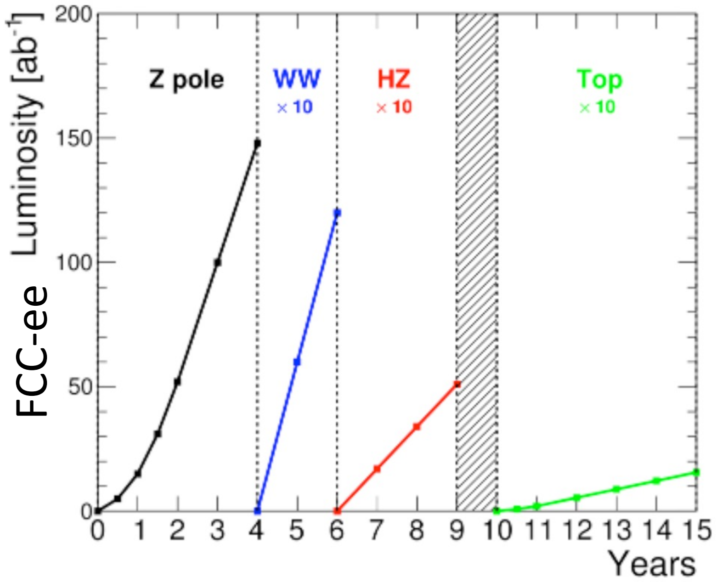
-- The International Advisory Committee for FCC.

Circular Collider [e^+e^-] proposals

❖The physics at circular colliders allow a broad, multi-faceted exploration:

- Measure a comprehensive set of electroweak and Higgs observables with high precision: "*Use the Higgs boson as a tool for new discovery*" [2014 P5 report],
- Tightly constrain a large number of SM parameters,
- Unveil, if any, small but significant deviations from SM predictions,
- Evidence for rare processes/particles beyond SM expectations.

❖FCC-ee proposes a 4-stage operations over 15-year starting ~2045



Ongoing FCC feasibility study expected to be completed in 2025 in anticipation of the next update of the European Strategy (~2026)

- **With a formal possible approval of the FCC program ~2028.**
- Important to note that this is a facility that will evolve to accommodate an FCC-hh/FCC-eh (see Sarah Eno's talk later).

CEPC also updated its plan to a four-stage operation

- With ~60 ab^{-1} integrated luminosity at Z-pole.
- CEPC proposes ("ideal") to begin Operations in mid-2030s.

Timeline (FCC-ee)

CEPC proposes an "ideal" timeline with operations starting mid-2030's

Preparing for the challenges

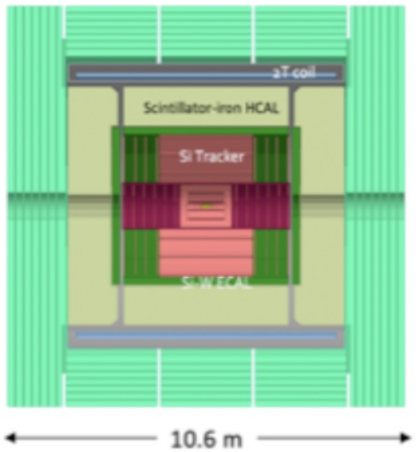
- ❖ Planning for FCC or CEPC did not begin yesterday.
  - Ongoing for several years now, FCC (CEPC) Conceptual Design Report was already published in 2019 (2018) that included strawman detectors concepts: (https://fcc-cdr.web.cern.ch/)
    - FCC design study began in 2014 (first workshop at U. Geneva).
  - The recent report by ECFA (European Committee for Future Accelerators) declared: "*To fully explore the properties of the Higgs boson and study many of the other deepest questions in physics necessitates the development of a roadmap for required detector technologies*"
  - Consequently, the ECFA Detector R&D roadmap was released in 2021 documenting 32 R&D themes across 8 task forces (https://cds.cern.ch/record/2784893).
  - The 2019 BRN (Basic Research Needs in U.S.) report also identified similar R&D thrust areas required for next generation experiments. (https://www.osti.gov/servlets/purl/1659761).
- ❖ Subsequently, a Detector R&D (DRD) organization has been setup in Europe with several DRD collaborations focusing on launching a concerted effort to pursue the R&D required to address the detector challenges for future experiments, including the next generation of planned experiments at CERN, e.g. FCC.
  - CPAD, in U.S., is organizing Generic R&D efforts that are important for FCC-ee/CEPC.
  - Process similar to the RD collaborations setup in 1990 prior in preparation for the LHC phase.

Challenges at FCC-ee (CEPC)

- At the Z pole, high beam currents with bunch spacing 20 (25) ns
  - Almost continuous beam has implications on power management/cooling, density, readout,…
- Extremely high luminosities L ~ 1.8 (1.15) x $10^{36}/cm^2s$ at Z-pole
  - Require absolute luminosity measurements to 10^{-4} to achieve desired physics sensitivity
  - Online/Offline handling of high data rates/total volume.
- Physics interaction rate at Z pole ~ 100 kHz
  - Implications on detector response time, event size, FE electronics and timing
- Beam dynamics
  - 30 (33) mrad crossing angle sets constraints on the solenoid field to 2 T → larger tracker volume
  - Backgrounds from incoherent pair production (IPC) and synchrotron radiation (SR) to a lesser extent (tungsten masks significantly reduces SR toward IP)
- Precision physics
  - Ultra-lightweight material
  - precision momentum ($\sigma(1/p_T) < 3 \times 10^{-5}$ GeV^{-1}) and angular res. (< 0.1 mrad) for 45 GeV muons
  - Excellent EM resolution with low constant term
  - Unprecedented low jet energy resolution to distinguish W/Z/H to dijets.
  - Micron-precision b- and c- tagging capability
  - Particle ID in a broad momentum range, incl. pico-second timing capability

Several Strawman Detector concepts
(2 – 4 detectors planned)

CLD

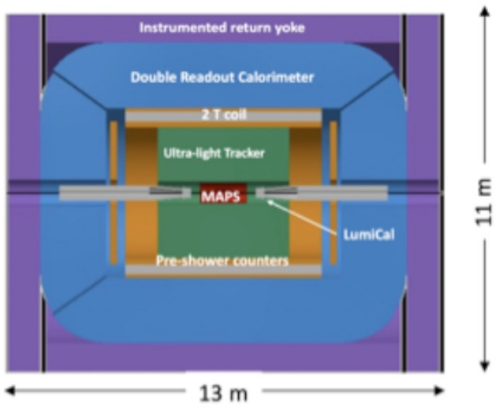


Design (ILC/CLIC/Calice)

- All silicon tracker (pixels + strips)
- Si-W EM calorimeter
  - $22X_0$, 40 long. layers.
- Steel-Scintillator hadronic calo.
  - SiPM readout
- Solenoid outside calorimeter
- RPC based Muon system

https://arxiv.org/pdf/1911.12230.pdf

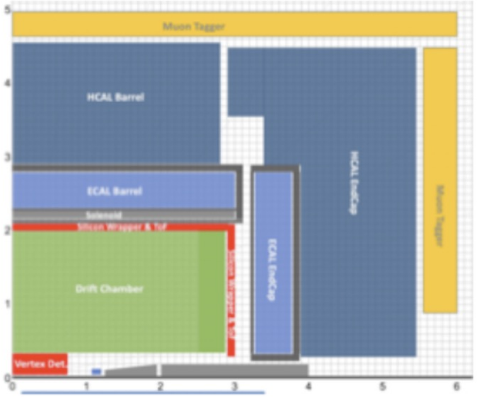
IDEA



- MAPS based vertex detector (1% X_0)
- High-precision low-mass drift chamber with surrounding Si microstrip (t_d < 400 ns).
- pre-shower with MPGD readout
- Lead-Fiber dual readout calorimeter
- Sensitive to both Sci/Cerenkov
  - Hybrid with crystal EM?
- large μ-Rwell muon chambers

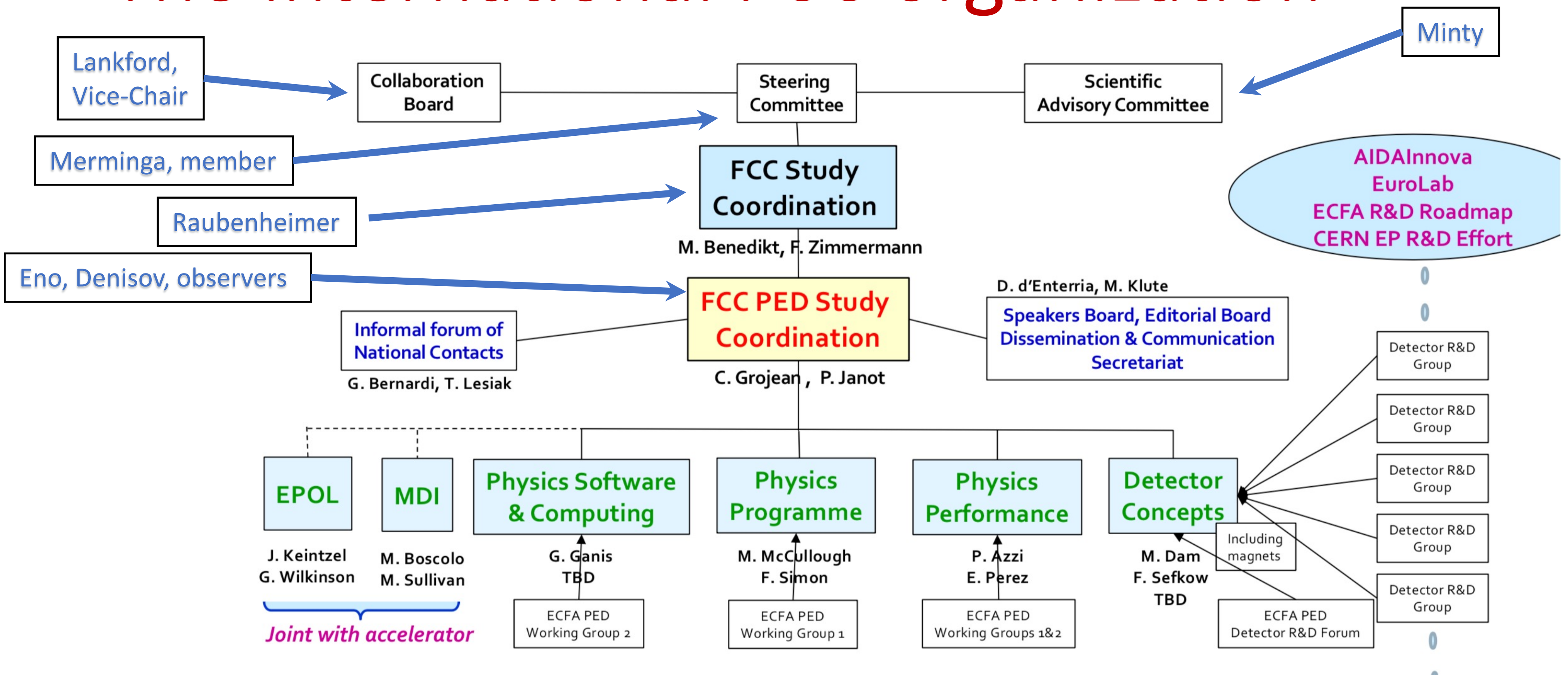
https://inspirehep.net/files/49ec726758c422bc454e270a71f6e59f

Noble Liquid



- Includes a highly granular noble liquid calorimeter
- Possible design being explored are lead/steel absorbers (RM ~4 cm), stacked azimuthally inclined at 50° wrt radial axis with LAr as the active medium.
- Other considerations include Tungsten absorbers and/or Liquid Krypton.
- https://arxiv.org/pdf/2109.00391.pdf

The International FCC organization



The organization and international efforts in Europe are well advanced; active U.S. engagement is beginning to grow, and significant interest exists in the U.S. community to be integrated into the global FCC organization

Engage now

- **The LHC serves as a reference point:**
  - Approved in 1996, but ATLAS and CMS collaborations came into existence in 1992 with dedicated LoIs and soon followed with technical proposals in 1994. (CERN R&D program launched in 1990)
  - The experiments laid the groundwork early to be approved soon after the LHC approval.
- **Expectations of the process will be similar for FCC.**
  - Already, proto-collaborations and detector concept study groups are being formed.
  - Laying the groundwork early to be endorsed soon after the approval of FCC (~2028).
  - DOE and CERN signed an agreement to participate in the FCC Feasibility Study in Dec. 2020
- **The U.S. must engage now:**
  - Invest in detector R&D leading to a conceptual design for an "LHCC type" endorsement
  - Exploit the expertise and facilities in U.S. that can make significant contribution.
  - Engage in the internationally-driven DRD and FCC collaboration process
- **We want to be partners, and not participants!**
  - Investing and engaging early is the key to become major partners in the next generation collider experiments at CERN.

Enabling engagement in FCC

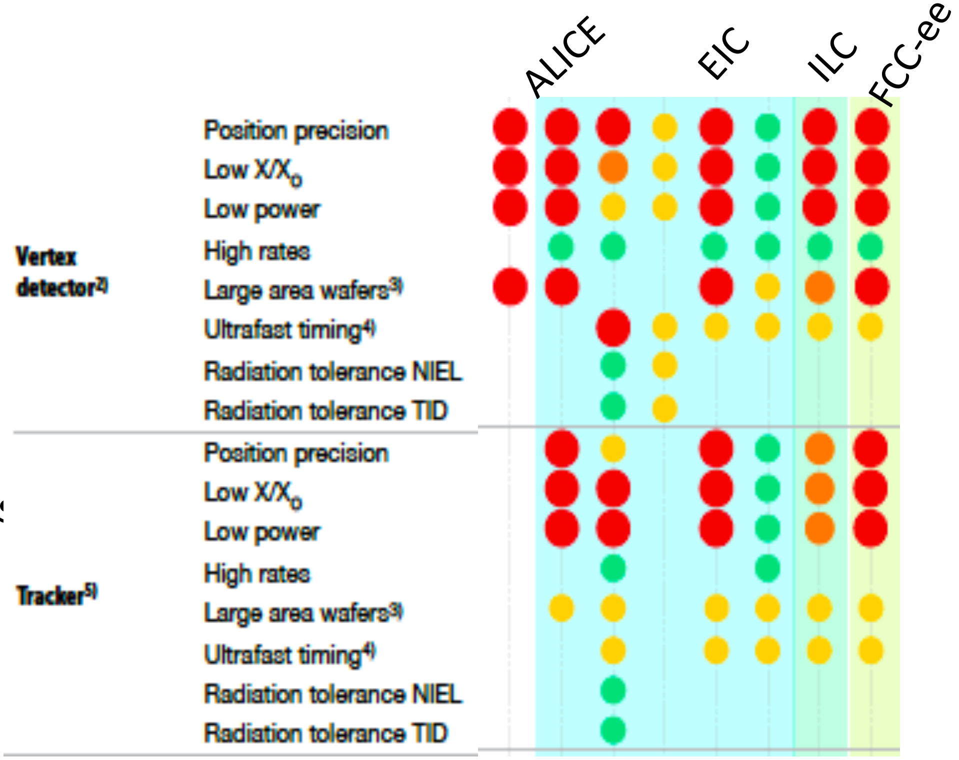
- We have formed a U.S. wide coordination body to drive the US FCC effort:
  - Organized by various technological areas including software and computing
  - Each working panel convened by two experts.
  - Each panel has reached out to the U.S. community to gauge expertise and interests (several meetings held thus far).
  - Consequently, we are developing a bottom-up prioritized scope of required US efforts over the next 10-years (under a 20-year vision), focusing on targeted R&D that will enable a strong U.S. participation leading to a conceptual design by ~2031 and ultimately to a project.
- Exploiting synergies with other programs is crucial
  - We are collaborating closely with ILC that has similar detector requirements and similar timescales as the FCC-ee.
  - We have reached out to EIC to benefit from their ongoing efforts in detector development, particularly in MAPS and gaseous detectors.
  - We are collaborating closely with the DRD panels and the international FCC collaboration
- Detector challenges for CEPC are similar to FCC-ee, many common elements

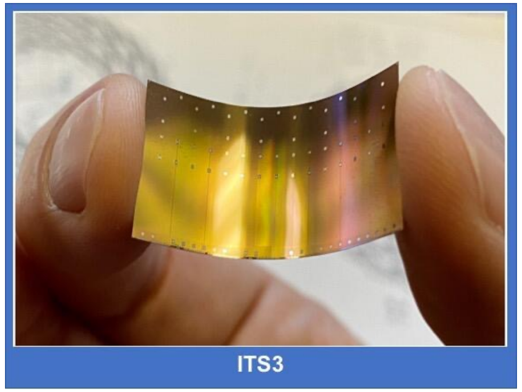
The US FCC Coordination Team

Solid State	Artur Apresyan (Fermilab), Carl Haber (LBNL)
Gaseous Detectors	Marcus Hohlmann (FIT), Bing Zhou (Michigan)
Calorimeter	Hucheng Chen (BNL), Chris Tully (Princeton)
Particle ID	Marina Artuso (Syracuse), Sarah Eno (Maryland)
Readout/ASICs	Julia Gonski (Columbia), Jim Hirschauer (Fermilab)
Trigger/DAQ	Zeynep Demiragli (Boston), Jinlong Zhang (ANL)
Software/Computing	Heather Gray (Berkeley), Oliver Gutsche (Fermilab)
Quantum	Marcel Demarteau (ORNL), Cristian Pena (Fermilab), Si Xie (CalTech)
Advisers	Karl Jakobs (ECFA), Andy Lankford (ILC)
ex-officio	Abid Patwa (DOE), Helmut Marsiske (DOE), Jonathan Asaadi (CPAD)
Chair	Srini Rajagopalan (BNL)

Solid State (A. Apresyan, C. Haber)

- Significant expertise in several Labs and institutes
  - Pixel and Strip design, fast timing and 4D concepts
  - Low mass mechanics, power management
  - Continuous beams puts demands low-power, cooling.
- Thrust areas where U.S. must play a lead role leading to CDR:
  - Monolithic CMOS, 3D integration and LGAD based sensors
  - Mechanics and new low-mass materials and fabrication techniques
  - Development of readout ASIC optimized for tracking & timing
  - Beyond CMOS technologies, intelligent local & distributed systems
- Synergies with ongoing efforts in HL-LHC upgrade & EIC with MAPS and timing
  - 65 nm TJZ, 12” wafers, 20 mW/cm^2, 0.05% X_0/layer, 3μm hit precision
  - Necessitates close collaboration.
- Collaborate with existing efforts and build on them prior to CDR:
  - Optimize position precision with low-power/large-wafer and quantify performance vs pitch and thickness in the range of 10 – 30 μm.
  - Implementation of precision timing : 4D tracking
  - Explore optimal cost-effective vertex/tracker designs





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Gaseous Detectors (M. Hohlmann, B. Zhou)

- Significant expertise in U.S. built over past decades at the Tevatron/LHC and NP experiments: 11 institutes with ~50 physicists have already expressed interest.
- Three thrust areas identified as key areas of engagement for U.S.:
  - Develop robust, large-area muon/gaseous detectors with fast timing and high spatial resolution.
    - Muons play a key role in precision measurement of Higgs as well as searches for long lived particles
    - $Z \rightarrow \mu\mu$ provides a key benchmarking point
  - Create a US-based R&D facility for Micro Pattern Gas Detectors (MPGDs) at a national lab
  - Develop services and infrastructure for these systems
- Develop and test the initial prototypes and electronics and establish the MPGD facility by ~2028 (FCC approval) to lay the foundation for a significant participation.
  - Large Area (at low cost)
  - Time resolution (< 1 ns)
  - Single technology capable of providing trigger & high spatial resolution → momentum resolution
  - High-rate capability of $O(10\ \mathrm{kHz/cm^2})$
  - Low mass detectors when used as inner tracking devices

Calorimeter (H. Chen, C. Tully)

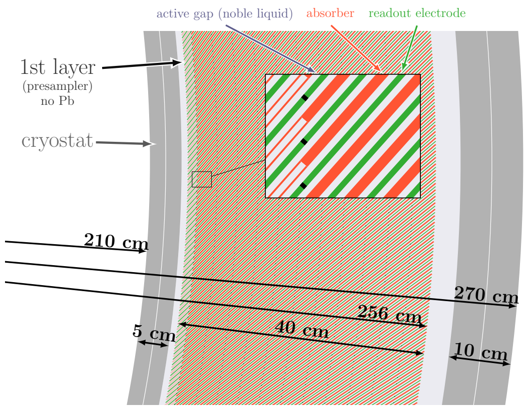
Ref: https://arxiv.org/pdf/2109.00391.pdf

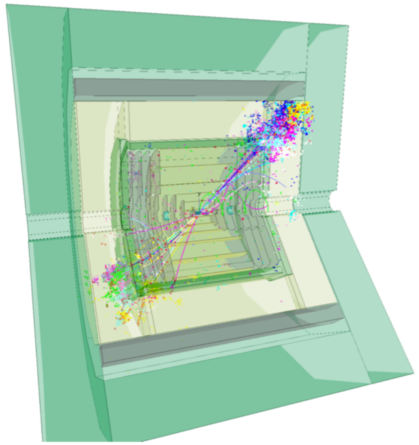
❖ U.S. groups have been deeply engaged for decades in Calorimetry

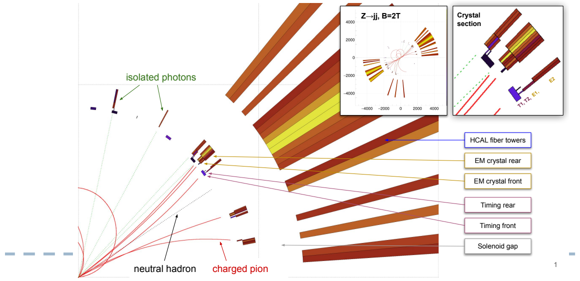
- Further investments will strengthen U.S. leadership and manufacturing in low-noise, high resolution calorimetry suitable for particle flow algorithms

❖ Three thrust areas where U.S. has and continue to play key roles:

1. Liquified noble gas calorimeters
   - Prototype a High granularity LAr calorimeter test-beam module with cryogenic readout
     - Finer longitudinal (12 vs. 4 in ATLAS) segmentation and superior (~5x) SNR with cold electronics
2. High granularity Si-W sampling calorimeters
   - Prototype a Si-W calorimeter demonstrator with embedded large area MAPS readout at full rate.
3. Optical calorimeters: Hybrid crystal with dual-fiber readout calorimeter
   - Prototype a hybrid S/C crystal and fiber dual-readout optical calorimeter test-beam module
     - Longitudinal and fine transverse segmentation for PFA, S/C dual-SiPM readout on crystal to achieve superior EM/Had resolution.
   - Develop a Front/interleaved precision timing layer demonstrator



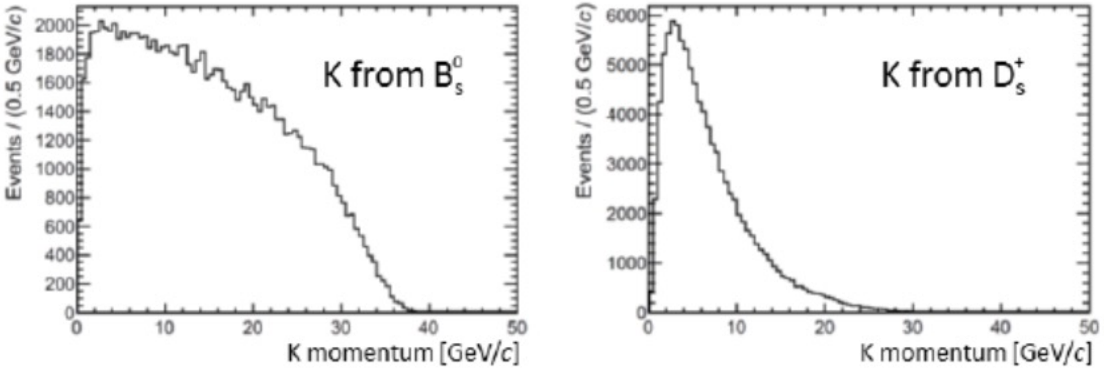




Particle ID (M. Artuso, S. Eno)

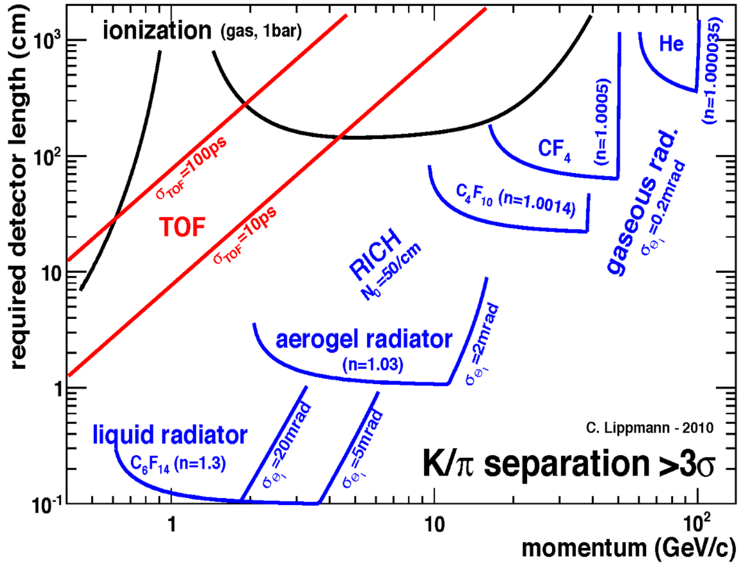
- Particle ID using time of flight, dE/dx, cluster counting is essential for flavor physics studies.
    - https://arxiv.org/pdf/2209.14486.pdf (CEPC analysis)
    - https://arxiv.org/pdf/2106.01253.pdf (FCC-ee analysis)
- Significant experience in U.S., particularly in design and development of Low Gain Avalanche detectors (LGADs) that can be considered for high precision timing (~picoseconds).
- Dedicated time of flight systems surrounding the tracker volume or embedded in the calorimeter systems can significantly improve particle identification at low momentum.

p_K in events from Z decay containing B_s



For a 2m path length (outer tracker radius), a 10 ps timing resolution can achieve a 3σ π/K separation for p < 5 GeV/c.

U.S. can play a key role in the design and prototype of sensors and front-end ASICs to demonstrate proof of concept and make it a viable option for FCC-ee



Readout/ASICs (J. Gonski, J. Hirschauer)

- Several targeted common developments across different detector areas, including:
  - 65 nm Monolithic sensor ASIC developments
  - 28 nm ASIC developments
  - Coping with increased data density and high data rates with highly configurable, AI/ML-driven FE electronics to achieve required data compression/selection/featurization.
  - Power management
  - 4D/5D techniques with high performance sampling and precision timing
  - Access and adapt to emerging technologies incl. 3D heterogenous integration, silicon photonics, open-source fabrication/development.
- Exploiting synergies and providing common cost-effective solutions across systems is vital.
- We need to build a team of ASIC engineers who can engage with various sub-systems to help implement common solutions: design, fabrication and verification.
  - Current experience in ongoing HL-LHC development has highlighted the urgent need.
  - Laboratories are a natural place to coordinate across a U.S. pool of ASIC engineers who can substantially contribute to targeted ASIC developments across detector systems.

Trigger/DAQ (Z. Demiragli, J. Zhang)

- Significant expertise at U.S. institutes in trigger/DAQ through their efforts in LHC/HL-LHC.
- The BRN process was instrumental in identifying a number of thrust areas that must be pursued for FCC-ee/CEPC.
  - High-bandwidth, low-power data links
  - Real-time processing hardware
  - Online data processing on heterogeneous hardware
  - Fast artificial intelligence and neuromorphic computing on real-time hardware
  - Advanced feature extraction for trigger
  - Triggerless readout
  - Develop technologies for autonomous detector systems
    - Autonomous operations; Self-calibration and alignment
  - Develop timing distribution with picosecond synchronization
- Goal is to achieve on-detector real-time, continuous data processing and transmission to reach exascale processing capabilities.

Software & Computing (H. Gray, O. Gutsche)

- The U.S. have been pioneers in the software development and computing infrastructure for many experiments, with significant expertise at universities and national labs.
  - S&C efforts for FCC have begun, lead by CERN
  - Strong community efforts in the U.S. exist, lead by CCE and IRIS-HEP
  - U.S. has strong current leadership in many R&D efforts, including the HL-LHC
- The U.S., therefore, is in an excellent position to make major contributions to e^+e^- colliders and integrate into the international efforts. U.S. contributions are fundamental to S&C needs of next generation high data throughput experiments. Contributions can be broken into three phases:
- Immediate Near Term (starting now):
  - Generators, fast/full simulation, framework and reconstruction software, analysis facilities and computing infrastructure to support detector design and optimization studies.
  - This is critical to complete the needed pre-CDR/TDR detector optimization and design studies.
- Medium Term:
  - Forward looking R&D, exploiting ML and GPUs for simulation and reconstruction to exploit the latest technologies for intelligent and faster reconstruction/analysis.
- Longer Term:
  - Development of next generation software and beyond-exascale computing architectures, leveraging from the U.S. experience, to support FCC simulation and other software needs

Quantum Sensors (M. Demarteau, C. Pena, S. Xie)

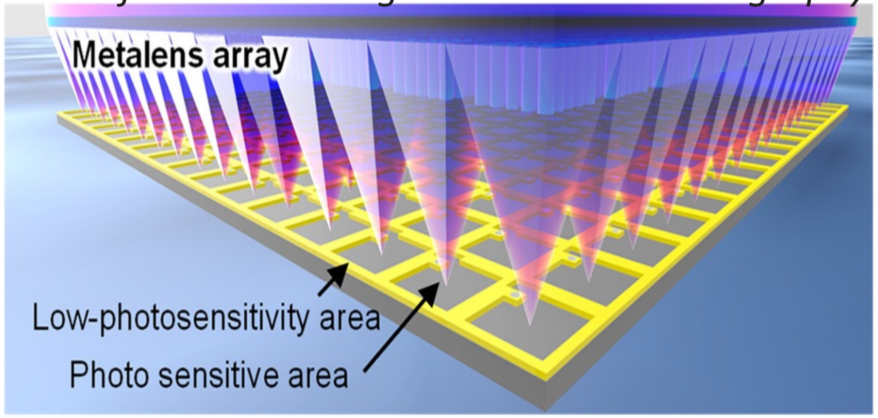
Strong interest in this topic at U.S. institutes and national labs;

- Labs have extensive infrastructure that can be applied to explore these technologies for an FCC
- Engineering of materials identified as a crucial aspect for the development

❖ Emerging thrust areas:

1. **Low-threshold detectors:**
   localized deployment of, potentially superconducting, low-threshold detectors to increase sensitivity to small signals (milli-charged particles)
2. **Engineered materials to improve detector efficiencies:**
   Novel materials that provide better matching of active medium and detector or increase sensitivity;
3. **Clock Networks**
   Networked array of sensors readout to provide better sensitivity for spatially separated signals;
4. **Input from theory for non-collider detector concepts at FCC**
   New challenging ideas that exploit quantum advantage.

Metalens array: hafnium-oxide nanopillars fabricated using electron-beam lithography



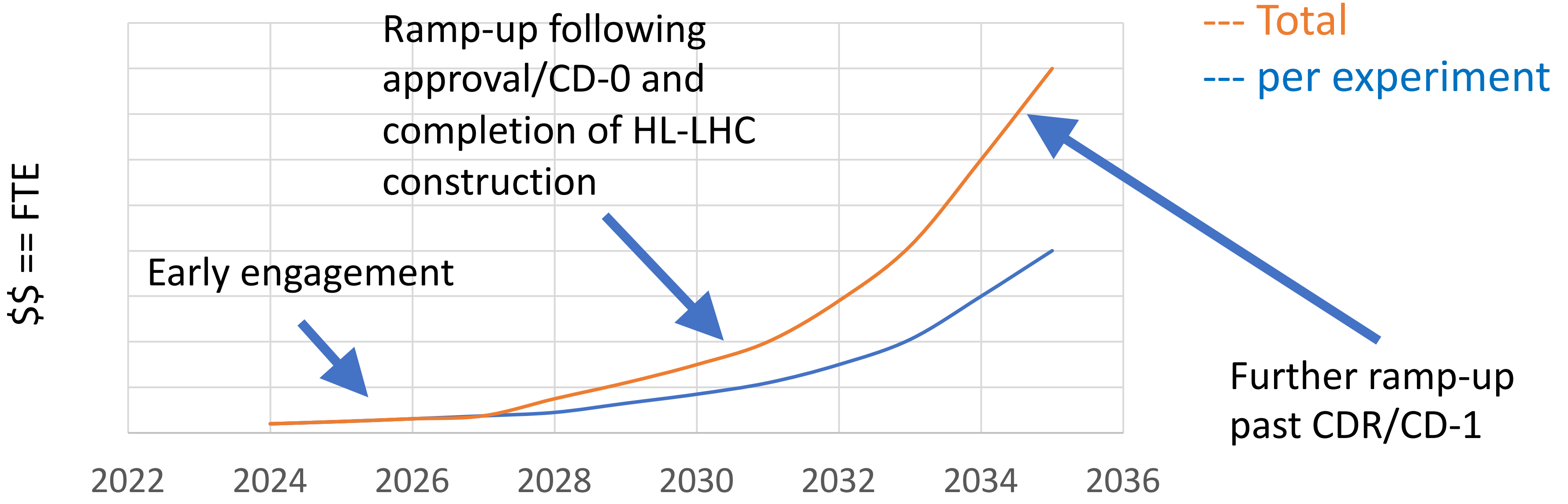
Important to assess if new developments in quantum sensors can be integrated into the detector designs to achieve superior performance.

Moving forward

- ❖Assuming the approval of FCC in ~2028, we can expect DOE CD-0 (mission need) and the creation of the US FCC Project Office to follow , similar to the LHC process.
  - **CD-0 and possibly CD-1 is within the 10-year window of consideration by this P5 committee.**
- ❖While a formal US FCC Project office can only be formed following CD-0 (which must wait for a formal approval of the FCC project), it is critical that the community comes together now to develop a strategic and coherent US program.
  - The formation of a US proto-collaboration or an interim Project **now** that can prioritize, scope and channel the U.S. efforts into a focused and coherent effort on FCC-ee detectors is necessary.
  - Funding for targeted detector R&D at a range of $5M-$10M per year in the early phase and subsequently ramping up following the approval of FCC is essential to meet the objectives.
    - Targeted R&D can address the FCC-ee and also ILC/C^3 needs during the early phase.
    - Level of funding consistent with scale of targeted R&D funds during pre-CD0 HL-LHC phase.
- ❖Early engagement and investments in accelerator/detector R&D is crucial to seed our role in the next generation of experiments and allow the U.S. to be in a position of strength and be significant stakeholders in future international projects.

Ramping resources

- ❖ The HL-LHC upgrade projects must be considered as the highest priority.
  - We cannot and must not deprive resources from HL-LHC to facilitate future collider programs
- ❖ But the time scales match well!
  - Expected approval of FCC, the completion of HL-LHC and subsequent ramp-up of FCC effort beyond FY28 in preparation for CDR/TDR can exploit the expertise in U.S. and provide for a transition plan from HL-LHC to FCC.
- ❖ At some point ahead of the FCC approval, will split into ~2+ targeted pre-projects



Summary

- ❖ Higgs Factory is slated to be the next high priority Energy Frontier project following the completion of HL-LHC.
  - FCC-ee, ILC and CEPC have similar challenges and comparable timelines advocated by resp. Labs.
  - This makes it essential for these communities to coordinate on detector technologies targeting these projects, at least for the next few years until respective project approvals.
- ❖ We encourage the P5 to comment in its report that:
  - *Following the completion of the HL-LHC construction, the highest priority project is the development of an e^+e^- collider that will allow significant opportunities for precision measurements in the electroweak and the Higgs sector. With support from the agencies, the U.S. must begin to organize its efforts to develop a cohesive and strategic program, invest in the required and targeted detector development efforts, and prepare the groundwork for a significant participation in these projects following their respective approvals.*
- ❖ and recommend:
  - *Motivated by the strong scientific importance of FCC as a Higgs factory, and the initiative at CERN to host it including the FCC feasibility study, the U.S. must promptly engage, at appropriate levels, in targeted accelerator and detector design and prepare the groundwork to projectize these efforts in anticipation of an FCC approval in 2028.*