

Detector Activities & Plans in U.S.

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US in LHC

- ❖ U.S. groups have made significant contributions to ATLAS, CMS and LHCb experiments to both the original construction and the Phase-1/Phase-2 upgrades.
 - U.S. represents ~20% of ATLAS and ~30% of CMS collaboration
 - Proportional contribution to the detector construction phase
- ❖ U.S. has been actively involved in the original construction, the Phase 1 and now the Phase 2 upgrades for ATLAS, CMS and LHCb in almost all aspects of detector development: Silicon tracker, calorimeter, Muon spectrometer, TDAQ & software.
- ❖ The U.S. is therefore well positioned to make major contributions to FCC.
 - Significant experience and expertise currently contributing to HL-LHC upgrades, but timescales match well for seamless transition to FCC detector development
 - Synergies with other major U.S. projects including EIC and LBNF/DUNE
 - Significant infrastructure/resources at national labs: ANL, BNL, Fermilab, JLAB, LBNL, SLAC
- ❖ During the past decades, U.S. and Europe have built strong partnerships across a number of R&D programs, detector construction and software development. These existing ties will further enable a constructive collaboration in the coming decades.

U.S. process

❖ Similar to the European Strategy, the U.S. has its own process to deliberate and prioritize its efforts.

- Snowmass process, that concluded in 2022, offered the opportunity for the U.S. community to express its interests and vision for the field. Documented now in 100's of reports.
- The Particle Physics Project Prioritization Panel (P5) is charged with laying out the priorities for the field for the next 10 years within a 20-year context.
- <https://www.usparticlephysics.org/p5/>, chair Hitoshi Murayama.
- The P5 committee is currently deliberating; Final report expected in the coming months.
- A strong recommendation from the P5 committee endorsing the need for a U.S. participation in FCC is necessary. We are actively engaged and making that case to P5.

❖ The 2014 P5 panel identified 5 compelling science drivers for the field.

- *“Use the Higgs boson as a new tool for discovery”* was one of them.
- That panel went on to state: *“An e^+e^- collider can provide the next outstanding opportunity to investigate the properties of Higgs in detail”*

Planning in U.S.

- ❖ Coordination team is in place to plan and prepare the case for U.S. participation in FCC.
 - Eight groups focusing on Solid State, Gaseous detectors, Calorimeter, Particle ID, Readout/ASICs, Trigger/DAQ, Software/Computing, Quantum.
 - Close coordination with Linear collider in preparing a common proposal for P5
 - Structure influenced by the ECFA detector roadmap and the U.S. Basic Research Needs (BRN) report.
- ❖ In the past months, the coordinators of these groups have been constructively engaged with the U.S. community to:
 - Assess and document the interests and expertise of the U.S. community
 - Draw up a prioritized list of R&D efforts where U.S. institutes can play a critical role
 - Document the objectives of each R&D through well defined milestones
 - Collaborate and exploit the synergies with other U.S projects and international partners including the recently formed DRD efforts at CERN.
 - Document the resources needed over the next 10 years to meet those objectives
 - Convert this to a funding request
- ❖ I will provide a brief summary of the priorities set by each of these groups.
 - Each slide identifies the primary U.S. FCC contacts for each study group.

Partnership is the key to our success

❖ It must be emphasized that defining the focus of U.S. efforts and responsibilities is an iterative process:

- Engage the U.S. community, Document the interests and expertise in the U.S.
 - This has been ongoing for the last several months led by the various U.S. coordinators.
 - Hence the activities that I will show in my subsequent slides reflect these “raw” interests. Additional factors, incl. international collaboration, available funding, available resources will further focus and define these interests.
- Engage the P5 committee to seek a strong recommendation that will enable U.S. participation in FCC.
 - Ongoing!
- Engage the International partners, the FCC team and the DRD projects to develop a focused, complimentary and cost-effective U.S. program:
 - Discussions have started but far from complete.
 - We recognize the importance of global partnerships and the need to build on existing global efforts. Collaboration and partnerships are the key to our success.
 - We look forward to continuing and further strengthening our international partnership, much like the LHC style – some of these collaborative R&D efforts are already ongoing!

Solid State

US FCC Contacts:
A. Apresyan, C. Haber

❖ Significant expertise in several Labs and institutes and engaged in HL-LHC upgrades

- Large scale silicon pixel and strip detector development for LHC experiments
- Fast timing using LGADs and 4D concepts, design concepts for both ATLAS and CMS
- Low mass carbon-based support structures, power management

❖ Synergies with ongoing efforts with RHIC/EIC on MAPS facilitates close collaboration.

- Deployment of low mass MAPS for Star, EIC design that builds on the ALICE ITS3 model
 - 65 nm TJZ, 12" wafers, 20 mW/cm², 0.05% X₀/layer, 3μm hit precision

❖ Thrust areas where U.S. can play a lead role :

- Development of monolithic CMOS: Large scale prototyping (stitching) in collaboration with a vibrant program already ongoing at CERN.
- LGAD based sensors: Demonstrate technology toward 10 ps timing resolution needed for PID and produce large area sensors with uniform performance.
- Mechanics and fabrication of new low-mass support structures with appropriate cooling methods: Evaluate technologies and demonstrate through prototypes
 - Carbon composite Labs with dedicated autoclaves infrastructure already in use at LBNL
- **System integration issues for developing a low mass tracker.**

Gaseous Detectors

US FCC Contacts:
M. Hohlmann, B. Zhou

❖ Significant expertise in U.S. built over past decades at the L3/Tevatron/LHC and NP experiments:

- Multi-wire muon detectors for LEP
- Drift tube detectors, Cathode Strip chambers and Micromegas/Thin Gap chambers for ATLAS
- Large area GEM detectors for CMS muon forward region (HL-LHC).
- Front-end and back-end electronics for many of the above systems.

❖ Thrust areas identified as key areas of engagement for U.S. include:

- Create a US lab-based R&D facility for Micro Pattern Gas Detectors (MPGDs), similar to CERN MPT.
- Develop robust, large-area muon/gaseous detectors with fast timing and high spatial resolution
 - Evaluate large-area drift tube-based chambers as well as thin gap MPGDs
 - Investigate low-mass gaseous detectors that can serve as an outer tracker
- Develop services and infrastructure for these systems

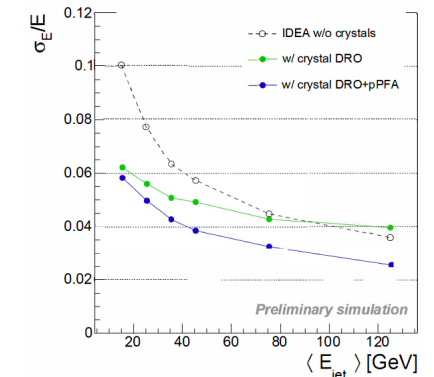
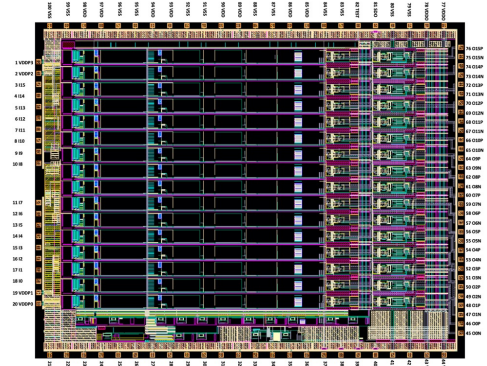
❖ Goal is to develop the infrastructure and capabilities by ~2028 to lay the foundation for a future prototyping/production efforts.

Calorimeter

US FCC Contacts:
H. Chen, C. Tully

- ❖ U.S. groups have been deeply engaged for decades in Calorimetry
 - Strong collaboration with Europe for decades in LHC, LBNF/DUNE, etc. and we want to further build on that collaboration.
 - Experience in the U.S. can be exploited for manufacturing low-noise, high resolution calorimetry suitable for particle flow algorithms targeting FCC.
- ❖ Two thrust areas where U.S. has and can continue to play key roles:
 - **Cryo Front End electronics for Liquified noble gas calorimeters**
 - Superior ($\sim 5x$) SNR with cold electronics, coupled with fine segmentation (12 layers compared to 4 in current ATLAS) provides superior performance.
 - **Hybrid dual readout calorimeter**
 - Segmented homogenous crystal EM calorimeter with SiPM readout and a Cerenkov/Scintillator fiber with time-domain readout for hadronic calorimeter, with fine long/trans segmentation
 - Hybrid mechanism has the potential to achieve 3-4% jet energy resolution for 50-150 GeV jets while maintaining superior EM resolution.
- ❖ Other areas being investigated are Si-W EM calorimeter with MAPS readout, Scintillating Tile with SiPM readout for Hadronic calorimeter

180 nm design for DUNE



Ongoing U.S. R&D in Calorimetry

- ❖ Development of an analog FE ASIC with multiple (16+) channels and programmability. Already ongoing in collaboration with international partners. Key features/challenges incl:
 - High performance *analog front-end block* targeting *future experiments requirements (FCC-ee)*
 - 65 nm CMOS with *thick oxide* → Max Vdd (1.8 V, 2.5 V) to support extended *dynamic range*
 - Fast peaking time (in the order of 10 ns) → support signal processing with stringent *time resolution*
 - Low power consumption → support detector electrodes with *fine segmentations*
 - Cryogenic operation with *long lifetime* → achieve optimum *SNR*
 - Long term goals: fast front-end architecture (\sim GHz bandwidth), high *radiation* tolerance → *FCC-hh*
- ❖ CalVision program, another ongoing international collaboration, focusing on dual readout
 - Funded by DOE for three years!
 - Simulation studies to optimize material/design.
 - Understanding how to make maximum use of the data to optimize performance
 - Verify performance and C/S yields on bench and testbeams
 - Measurement of z-coordinate for timing in fibers
 - Investigate low-cost new materials and low mass mechanical support
 - Investigate new photodetector developments (SPAD, dSiPM)
 - On detector readout electronics development

Particle ID

US FCC Contacts:
M. Artuso, Z. Ye

❖ Particle ID using time of flight, dE/dx, cluster counting is essential for flavor physics studies.

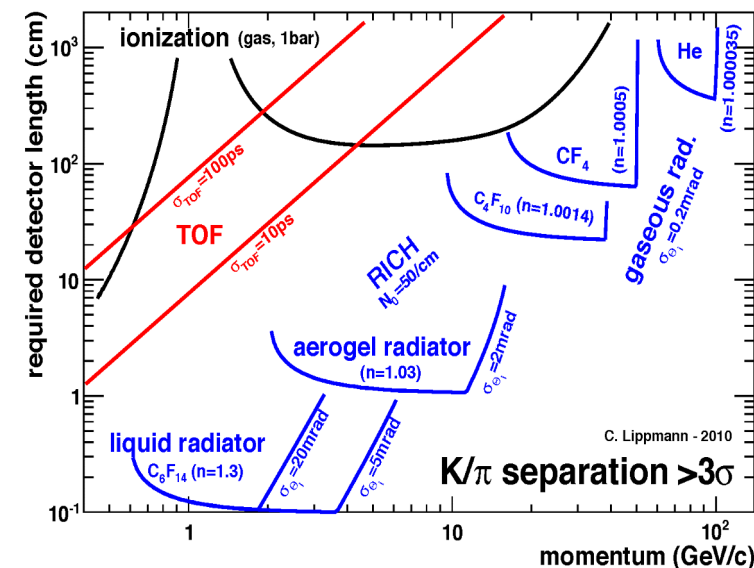
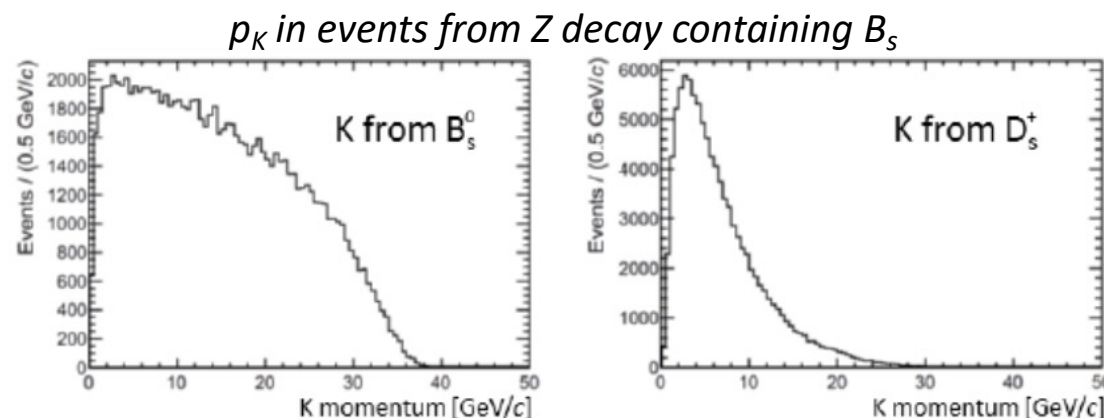
- <https://arxiv.org/pdf/2106.01253.pdf> (FCC-ee analysis)

❖ Significant experience in U.S., particularly in design and development of Low Gain Avalanche detectors (LGADs) that can be considered for high precision timing (\sim picoseconds).

❖ Explore the option for dedicated time of flight systems surrounding the tracker volume or embedded in the calorimeter systems can significantly improve particle identification at low momentum.

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 development of large area TOF detectors using LGADs, low-jitter ASICs to improve timing resolution, and developing integrated system designs.



Readout/ASICs

US FCC Contacts:
J. Gonski, J. Hirschauer

- ❖ U.S. laboratories are already active in several areas of ASIC R&D that are relevant for FCC.
 - 65 nm monolithic sensor ASIC developments
 - 28 nm ASIC developments
 - Building AI/ML functionality in IP blocks such as data compression, feature extraction, front-end programmability.
 - 4D/5D techniques with high performance sampling and precision timing
 - Access and adapt to emerging technologies in microelectronics.
- ❖ Exploiting synergies and providing common cost-effective solutions across systems is vital. Our goal is to build a team of ASIC engineers who can engage with international partners to help implement common solutions across detector systems: design, fabrication and verification.
 - Current experience in ongoing HL-LHC development has highlighted the need to maintain a pool of experienced ASIC engineers. The U.S. can help strengthen this international effort.
 - Significant infrastructure at U.S. Laboratories that can be exploited.

Trigger/DAQ

US FCC Contacts:
Z. Dimiragli, J. Zhang

- Significant expertise at U.S. institutes in trigger/DAQ through their efforts in LHC/HL-LHC can allow for a healthy collaboration with international partners.
 - Ongoing upgrade for HL-LHC includes design of various customized back-end readout and trigger electronics, employing ATCA standards and utilizing cutting-edge FPGAs and serial optical links capable of operating at speeds up to 25 Gb/s with an overall latency of 12.5 μ s.
- Thrust areas where the U.S. can contribute and bring expertise to include:
 - Development of AI, ML, and neuromorphic algorithms and the tools to deploy them at large data volumes and low latency to provide data reduction techniques, if needed
 - Achieving high precision clock timing distribution and synchronization to detectors < 25 ps.
 - Build on the success of HL-LHC and integrate modern heterogeneous computing hardware.
 - Investigation of data streaming design to provide data compression
 - Improving data link performance to anticipate the increased data rates/volume.
 - Developing high speed wireless links.
- Goal is to achieve on-detector real-time, continuous data processing and transmission to reach exascale processing capabilities.

Software & Computing

US FCC Contacts:
H. Gray, O. Gutsche

- ❖ The U.S. have been collaborating with international partners in the software development and computing for decades. There exists significant expertise at U.S. universities and national labs.
 - Strong community efforts in the U.S. already exists, CCE and IRIS-HEP.
 - Major contributions to LHC, HL-LHC R&D efforts in both ATLAS and CMS.
 - In collaboration with CERN, we are in an excellent position to make major contributions to FCC.
- ❖ S&C efforts for FCC and ILC have begun, many efforts led by CERN. Close collaboration with ILC is needed to build on the extensive efforts and the foundation laid by them.
- ❖ 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 ongoing detector design and optimizations..
 - **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:**
 - Contribute to the next generation software and beyond-exascale computing architectures, leveraging from the U.S. experience, to support FCC simulation and other software needs

Quantum Sensors

US FCC Contacts:
M. Demarteay, 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
- Integration of engineered materials and nanostructures into conventional detectors can potentially offer unprecedented tunability and improvements in detector sensitivity and performance compared to conventional bulk materials

❖ Possible thrust areas:

1. Low-threshold detectors:

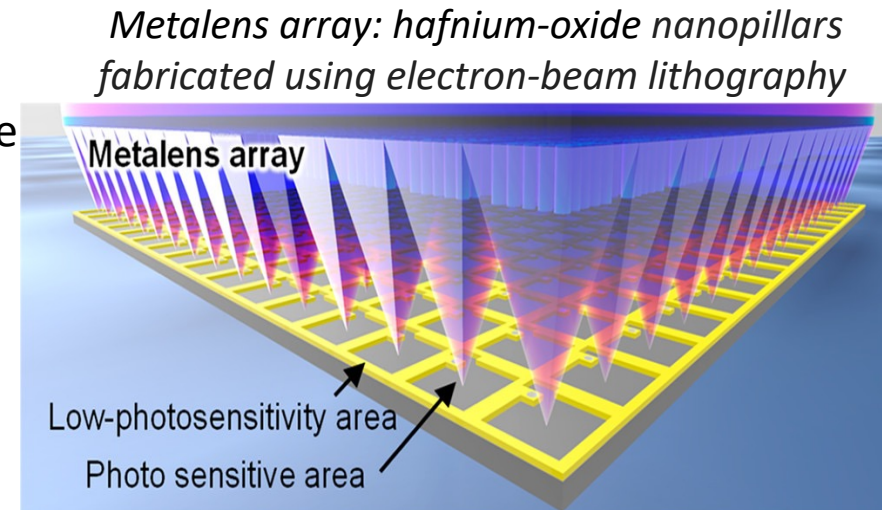
Superconducting nanowire single photon detector (SPNSD) may provide better performance than SPADs.

1. Engineered materials to improve detector efficiencies:

Novel materials embedded into existing material that provide better matching of active medium and detector or increase sensitivity;

2. Clock Networks

Networked array of sensors readout to provide better sensitivity for spatially separated signals;



R&D plan to assess if new developments in quantum detectors can be integrated into the detector designs to achieve superior performance.

Moving forward in the U.S.

- ❖ The HL-LHC upgrade projects are the highest near-term priority.
 - Time scales match well! Completion of HL-LHC, expected approval of FCC, and subsequent ramp-up of FCC effort beyond FY28 will enable us to optimally exploit the expertise in U.S. and provide for a transition plan from HL-LHC to FCC.
- ❖ We have put forward the strongest case to the P5 committee for their consideration:
 - Discussion at an open town hall meeting at Brookhaven.
 - Several people from CERN, including the DG, were present to provide invaluable support.
- ❖ We have put together a ~50-page document summarizing our needs over the next 10 years.
 - It will be submitted to the P5 committee imminently.
- ❖ We remain hopeful that P5 will strongly recommend the U.S. to engage in preparing for the next generation e^+e^- colliders
- ❖ If and when P5 makes a strong recommendation, work with our U.S. funding agencies (DOE and NSF) to develop a funding plan to support the R&D efforts for the next generation experiments.
- ❖ The next steps are crucial: Partner with our international colleagues to pursue the R&D efforts and plan for the next stage in a coherent and cost-effective manner.
 - **We look forward to collaborating with our international partners as we have done at LHC.**