Strategic Plans of the Future Colliders Organization

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Sergo Jindariani

Fermilab PAC Meeting June 7-10, 2021

Introduction

- Physics at the Energy Frontier is of paramount importance! Fermilab's leadership role at the Energy Frontier must continue!
- The **Future Colliders** organization in the Particle Physics Division has been formed with the following objectives:
  - Develop Fermilab's engagement plans in future collider projects, across aspects of accelerators, technology, particle physics and detectors
  - Provide a forum to synergize efforts on future colliders/accelerators of interest to Fermilab
  - Develop a roadmap for further (design) studies and R&D for future colliders.
  - In the near term, the focus is to produce input for Snowmass.
- Group Composition (About 15 people*):
  - Pushpa Bhat (PPD, Lead), Sergo Jindariani (PPD, Deputy)
  - Co-conveners of the SAC Energy Frontier Working Group
  - Representatives from various divisions (AD, APSTD,ND,SCD,Theory)
  - Representative from detector R&D
  - Liaison to Integrated Planning and Performance Management (IPPM)

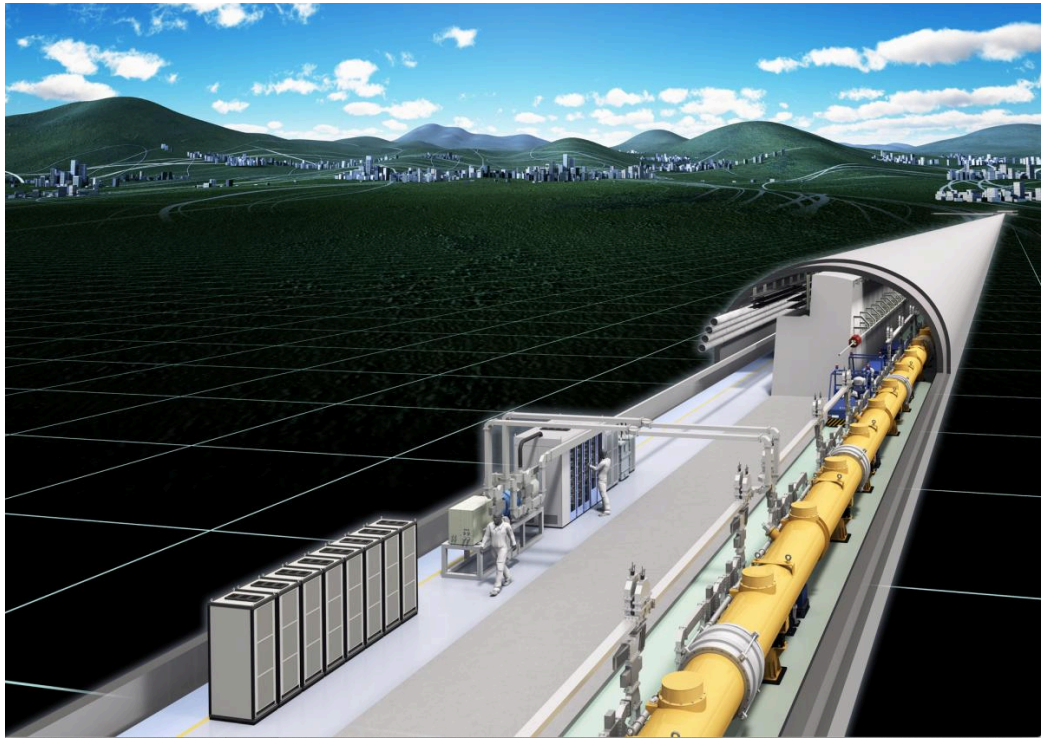
* Each member devoting only a fraction of her/his time.

Plans and Activities

- Develop plans for Fermilab's participation and national leadership in international projects (ILC, FCC, Muon Collider collaboration)
  - Sub-groups/task forces for specific topics; group members serve as liaisons
  - The full group meets regularly to discuss status, plans, proposals for participation and strategies. (Work coordinated with universities or other labs where pertinent.)
  - Group will host open forums to inform/engage the Lab community.
- Coordinate and support synergistic studies/activities that are of interest to Fermilab scientists (e.g., Muon Collider, nuSTORM, precision muon experiments).
  - Create cross-frontier task forces, oversee studies, monitor progress.
- In the short term, facilitate Fermilab participation and produce summary reports for Snowmass.
- Develop a roadmap for the longer-term studies and R&D for future colliders and potential facilities
  - Accelerator design studies (which inform R&D needs)
  - Develop plans for R&D, e.g., robust high field magnet R&D

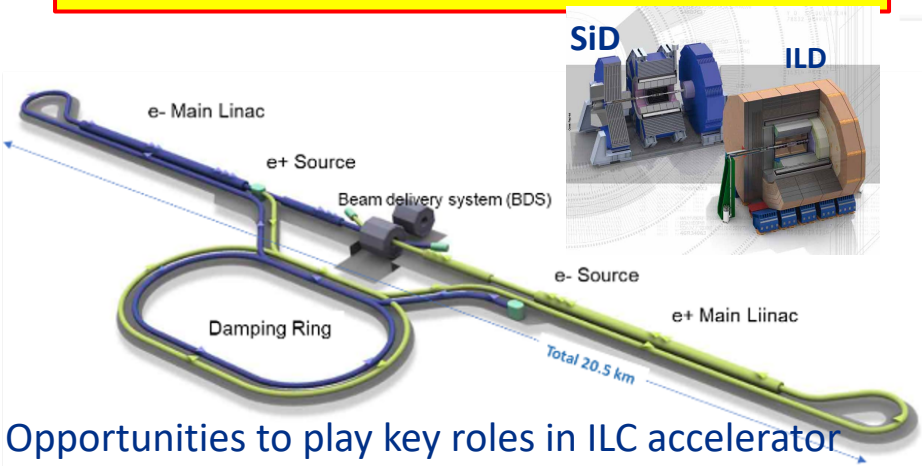
Engagement in Global Projects

The International Linear Collider



The International Linear Collider

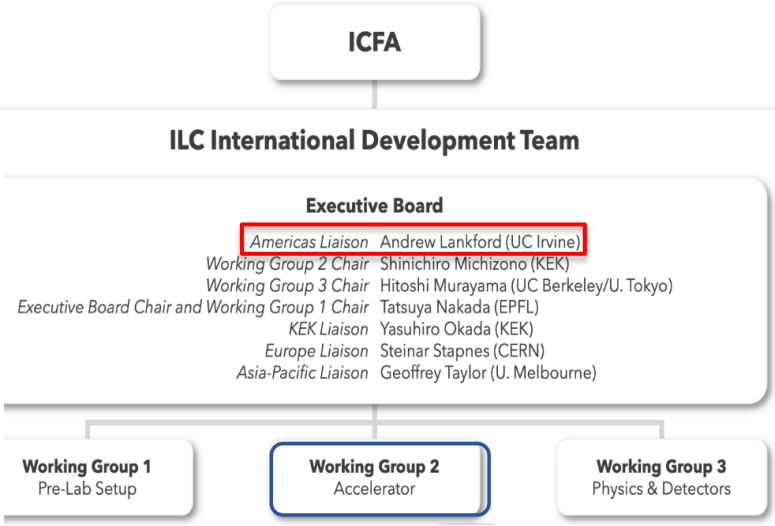
The International Linear Collider in Japan (**ILC250**), if approved, could start construction in this decade and start operations by 2035.



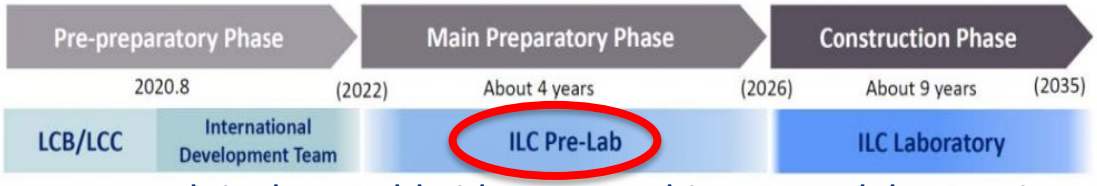
Opportunities to play key roles in ILC accelerator and detectors/physics

ICFA launched the ILC-IDT in Aug. 2020

International Development Team (IDT)



Timeline:



Pre-Lab is the worldwide partnership among laboratories

ILC pre-Lab proposal being released by ILC-IDT

- provides Organizational Framework and work plan
- all technical development and engineering work needed for ILC construction to be completed
- Intergovernmental discussion of governance and sharing of responsibilities and cost.

America in the International Development Team * FNAL

IDT Executive Board

Andy Lankford (UCI) – Americas rep

Hitoshi Murayama (UCB/Tokyo) – WG3 chair

IDT WG1 – Pre-lab organization (includes EB)

Bruce Dunham (SLAC)

Reiner Krueken (TRIUMF)

Stuart Henderson (TJNAF)

Joe Lykken (FNAL) *

IDT WG2 – Accelerator

SRF

Sergey Belomestnykh (FNAL) *

Rongli Geng (ORNL)

Bob Laxdal (TRIUMF)

Matthias Liepe (Cornell)

Sam Posen (FNAL) *

Bob Rimmer (TJNAF)

Marc Ross (SLAC)

DR/BDS/Dump

Tom Markiewicz (SLAC)

Brett Parker (BNL)

David Rubin (Cornell)

Nikolai Solyak (FNAL) *

Glen White (SLAC)

Sources

Joe Grames (TJNAF)

IDT WG3 – Physics & Detector

Hitoshi Murayama (UCB/Tokyo) – WG3 chair

Steering Group

Jim Brau (Oregon)

Dmitri Denisov (BNL)

Patty McBride (FNAL) *

Tim Nelson (SLAC)

Andy White (UT Arlington)

Speakers Bureau

Alain Bellerive (Carleton)

Detector & Technology R&D conveners

Petra Merkel (FNAL) *

David Miller (Chicago)

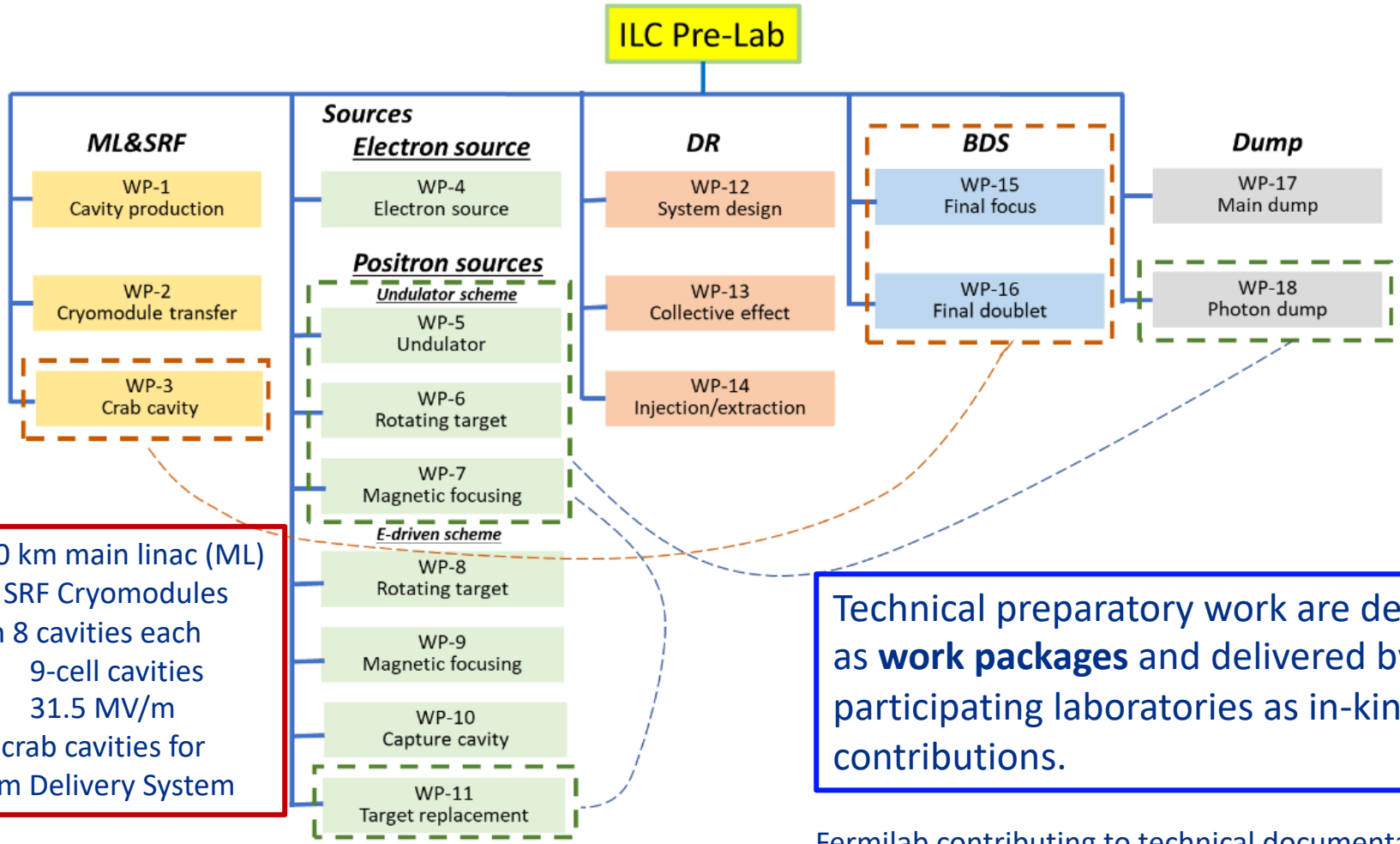
Software & Computing conveners

Jan Strube (Oregon)

Physics Potential & Opportunities conveners

Michael Peskin (SLAC)

Pre-lab machine work packages



2x10 km main linac (ML)
900 SRF Cryomodules
with 8 cavities each
9-cell cavities
31.5 MV/m
SRF crab cavities for
Beam Delivery System

Technical preparatory work are defined as **work packages** and delivered by the participating laboratories as in-kind contributions.

Fermilab contributing to technical documentation, WBS and cost estimates, and many work packages. Will coordinate North America's effort on SRF.

ILC pre-Lab Work Packages & SRF R&D

SRF Work Packages for the ILC Main Linac (Contact: S. Belomestnykh)

- **WP-1**: Cavity Industrial-Production Readiness (Prepare for mass production)
  - 120 cavities to be produced (40 x 3 regions) using cost-effective methods while maintaining performance above baseline (US-Japan efforts since 2017 on performance, cost-reduction)
- **WP-2**: Cryomodule (CM) Global Transfer and Performance Assurance
  - Demonstrate cryomodule transport from abroad to Japan with no performance degradation
  - CM must satisfy high-pressure-gas safety regulations; design to be fixed if needed
- **WP-3**: Crab Cavity (CC) for BDS
  - Produce and test a prototype two-cavity cryomodule (pCM)

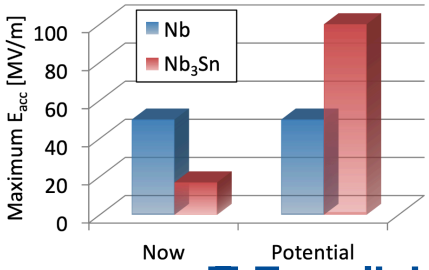
Polarized Positron Source and Damping Ring (Contact: S. Nagaitsev)

- Discussions for US engagement underway, coordinated by Andy Lankford
- Information gathering underway: Interest in US national labs; Status of designs, studies and plans
  - (Fermilab scientists: B. Zwaska, G. Velev, A. Valishev, N. Solyak, R. Ainsworth, …)

SRF R&D for ILC++ (Contact: S. Posen)

Significant progress in SRF technology since ILC-TDR with new innovative cavity treatments

- The ILC TDR design spec 31.5 MV/m.
- Aiming for 38 MV/m, Q>10^{10} ; stretch goal ~ 40 MV/m
- Nb cavities have reached ~ 48-50 MV/m
- Nb_3Sn cavities could potentially provide (>100 MV/m) in the future
  - Possible use in future energy upgrades



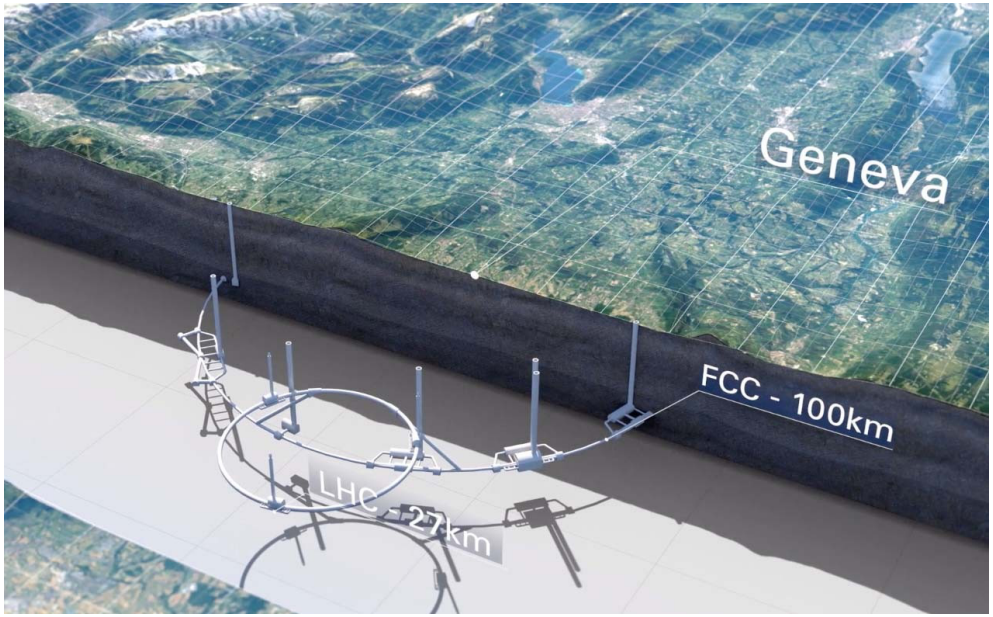
Physics and Detectors

- ILC physics is of great interest even at 250 GeV
  - Precision studies of the Higgs properties; Higgs as a tool for discoveries
- Great potential for engagement in detector R&D and physics
  - Active and extensive work for CMS upgrades and generic detector R&D at Fermilab
  - Precision tracking, High granularity calorimeters, timing detectors
  - Detector R&D in the context of ILC or EIC could be beneficial for other future collider experiments (Petra Merkel, Artur Apresyan, Zoltan Gecse)
  - Workshop on ILC experiments (ILCX 2021), Oct. 26-29 in Tsukuba
    - Opportunity for coordination and planning
- Also exploring participation in software & computing
- Serious engagement/progress in these areas require and benefit from direct ILC-related funding.

(WPs for accelerators also assume separate ILC funding with pre-Lab approval.)

Engagement in Global Projects

Future Circular Colliders



Future Circular Colliders @CERN

- As per the 2020 European Strategy update, the FCC Study is now focused on investigating the technical and financial feasibility of a ~100 TeV pp collider at CERN in a 100 km ring, with an e+e- Higgs and electroweak factory as a first stage
  - FCC(ee) followed by FCC(hh)
- Highest priority studies:

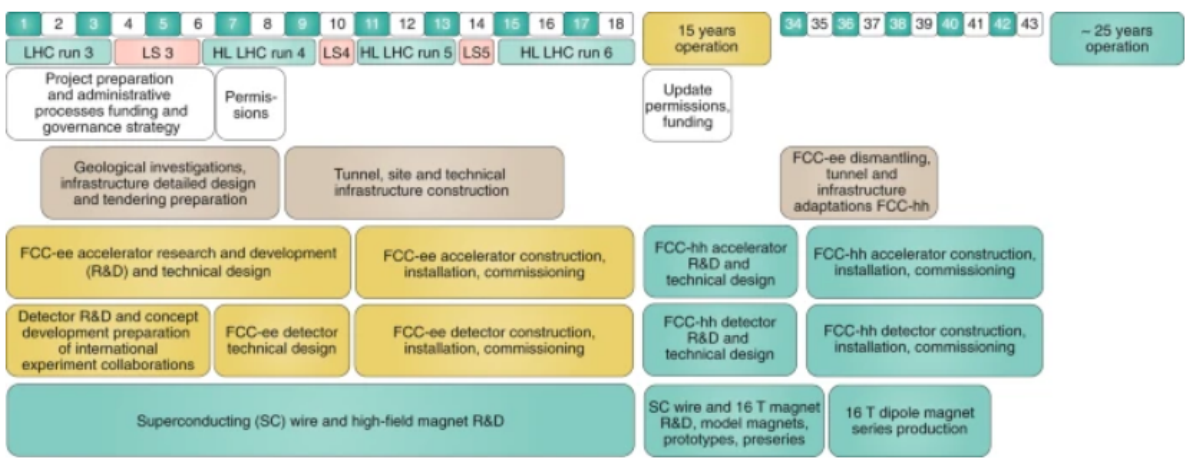
❑ tunnel: high-risk zones, surface areas, administrative processes, environment

❑ machines: R&D (e.g. superconducting RF for FCC-ee; magnets for FCC-hh); design

→ Goal is CDR++ with results of feasibility studies by ~ 2026.

~ 70 years timeframe

Fig. 1: Technical schedule of the FCC integrated project.

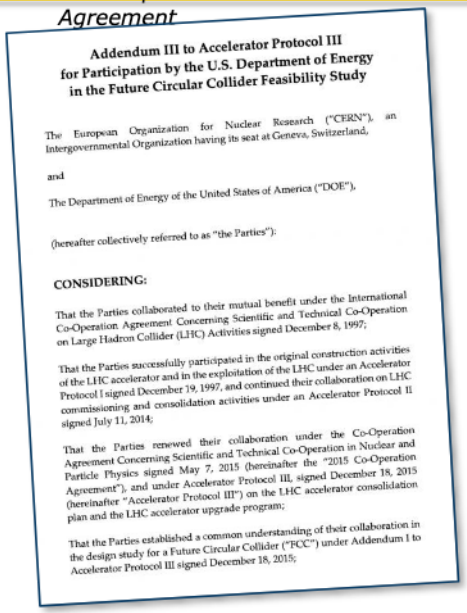


Future Circular Colliders (FCC)

DOE-CERN Future Circular Collider Cooperation

- **DOE coordinating with CERN to update the 2015 DOE-CERN FCC agreement to continue future R&D topics**
  - Framework to advance the next stage of FCC feasibility studies as emphasized in the 2020 update of the European Strategy for Particle Physics
- **Cooperative activities include**
  - Overall FCC concept optimization, including civil engineering and technical infrastructure designs
  - Beam physics studies
  - Accelerator R&D and key technology developments in view of either the FCC-ee and FCC-hh collider
  - Longer-term activities towards the development of concepts of time- and cost-effective FCC tunneling techniques
- **Framework continues to allow DOE national labs to undertake topic-specific activities with CERN that are to be identified through subsequent MOUs**
  - For additional guidance, interested DOE labs may contact Abid Patwa and L.K. Len at abid.patwa@science.doe.gov and lk.len@science.doe.gov
- **DOE and CERN aiming to sign the new FCC agreement by end of calendar year 2020**

2020: *Proposed DOE-CERN FCC Agreement*



Addendum III to Accelerator Protocol III for Participation by the U.S. Department of Energy in the Future Circular Collider Feasibility Study

The European Organization for Nuclear Research ("CERN"), an Intergovernmental Organization having its seat at Geneva, Switzerland,

and

The Department of Energy of the United States of America ("DOE"),

(hereafter collectively referred to as "the Parties"):

CONSIDERING:

That the Parties collaborated to their mutual benefit under the International Co-Operation Agreement Concerning Scientific and Technical Co-Operation on Large Hadron Collider (LHC) Activities signed December 8, 1997;

That the Parties successfully participated in the original construction activities of the LHC accelerator and in the exploitation of the LHC under an Accelerator Protocol I signed December 19, 1997, and continued their collaboration on LHC commissioning and consolidation activities under an Accelerator Protocol II signed July 11, 2014;

That the Parties renewed their collaboration under the Co-Operation Agreement Concerning Scientific and Technical Co-Operation in Nuclear and Particle Physics signed May 7, 2015 (hereinafter the "2015 Co-Operation Agreement"), and under Accelerator Protocol III, signed December 18, 2015 (hereinafter "Accelerator Protocol III") on the LHC accelerator consolidation plan and the LHC accelerator upgrade program;

That the Parties established a common understanding of their collaboration in the design study for a Future Circular Collider ("FCC") under Addendum I to Accelerator Protocol III signed December 18, 2015;

Jim Siegrist at HEPAP mtg. Dec. 2020

Future Circular Colliders (FCC)

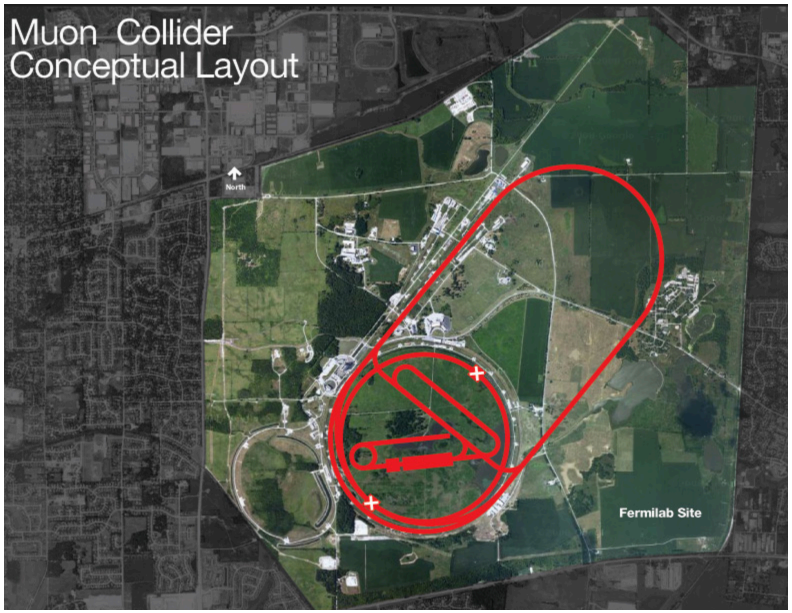
- CERN-DOE agreement on FCC signed in Dec. 2020
- We are advised to identify synergistic activities with FCC at the Lab in order to advance R&D on those topics
- Examples:
  - Space charge effects; Beam polarization studies; Collimation and Machine-detector interface; High Q_0 SRF R&D; rapid cycling HTS magnets
- MOU with LBNL (including other labs) on magnet development
- Fermilab's magnet R&D under US Magnet Development Program
    - G. Velev, A. Zlobin, G. Apollinari, ..
  - Now: ~12T Nb3Sn magnets for HL-LHC; demo model: 14.5 T record Goal: ~20T hybrid magnet model [~15T Nb_3Sn, ~5T HTS insert] by around 2025;
    20-25 T possible with LTS/HTS
  - Some conductor R&D on Iron-based superconductors (as Lab LDRD; T. Spina)
    - Promising for >20T; cost-effective and better mechanical properties

FCC Physics and Detectors

- A significant amount of work and studies has already been performed for European Strategy update for FCC-ee and FCC-hh, and additional studies continue for Snowmass.
- Fermilab is the hub for the US hadron collider community. Therefore, more focus has been on post-LHC hadron collider studies.
  - LOIs for Snowmass: Higgs couplings, Higgs self-coupling, multi-Higgs production, vector boson scattering, BSM physics, resonance searches (some studies include e+e- and μ+μ-, more info in back-up)
- Detector requirements for FCC-ee and FCC-hh somewhat different
  - FCC-hh: radiation-hard tracking and calorimetry, large bore solenoid, high granularity and precision timing (~5 ps) for pile-up rejection, novel trigger/DAQ
  - FCC-ee: high precision (low mass) Si tracking, 3D imaging and/or dual readout calorimetry, control of systematics
- Fermilab group engaged in development of technologies such as 3D sensor/readout integration for 4D tracking, FastML, etc., which will be useful for FCC detectors.

Engagement in Global Projects

Renewed Enthusiasm for Muon Colliders



An explosion of interest!

Touted as a precision and discovery machine

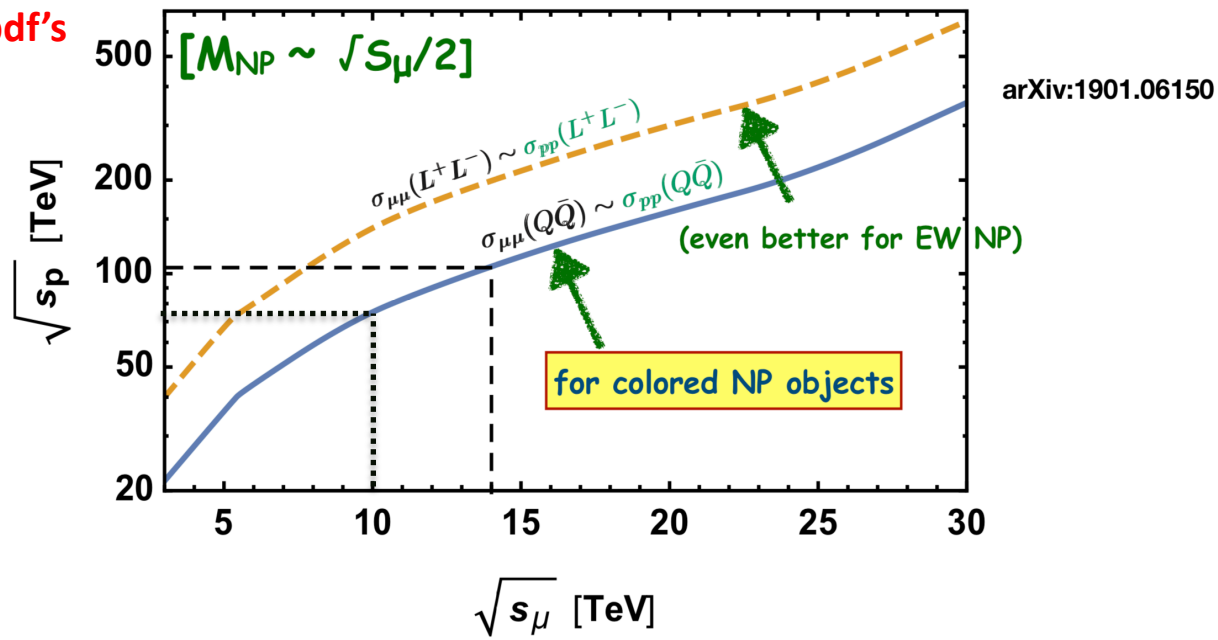
Technologically challenging and hence exciting

Unique opportunities for innovation

Physics at the Muon Collider

Precision and Discovery Machine

Equivalent reach in pp after rescaling for pdf's



- Direct New Physics Reach: for colored particles 10 TeV $\mu\mu \sim$ 70 TeV pp. For colorless particles 10 TeV $\mu\mu \sim$ 150 TeV pp
- A high energy Muon Collider (~10 TeV) can give excellent precision for Higgs couplings measurements and allow to probe trilinear Higgs coupling (also quartic coupling at higher energies)

"The Muon Smasher's Guide"
https://arxiv.org/abs/2103.14043

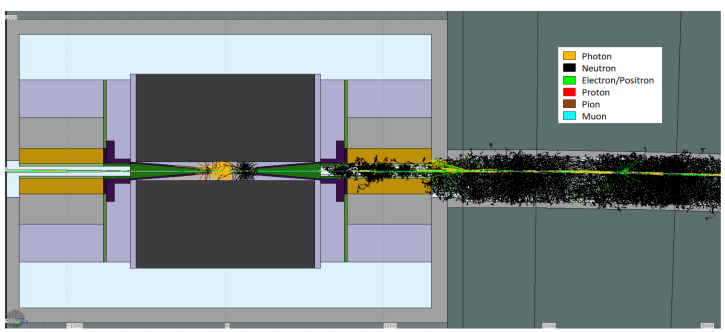
International Muon Collider Collaboration

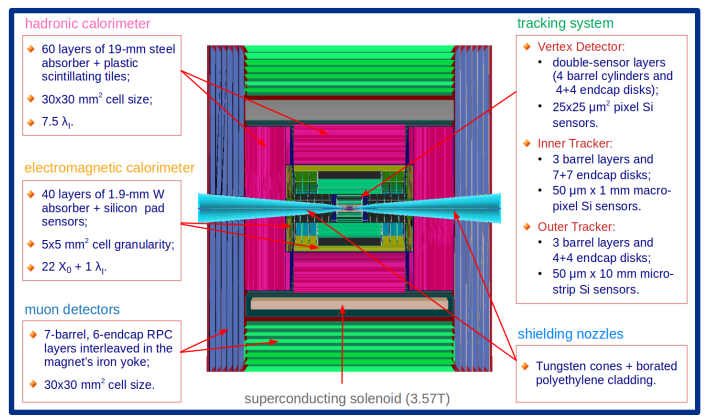
- Many activities ongoing in the context of the International Muon Collider Collaboration (MCC), initiated by CERN and European Lab Directors' Group (LDG) and also in the context of Snowmass.
- MCC is working on the following plans
  - A demonstration facility ready for construction in 4-5 years (total cost ~500M)
  - Collider facility ready for construction in ~20 years.
  - A staged approach for a Muon Collider from 3 TeV to 10+ TeV
  - A preliminary costing of demonstration & collider facilities on the timescale of ~ 1 year. (Requested by CERN DG)
- The MCC is open to discussions of various siting options for the demonstration facility, including tests and R&D elsewhere e.g., Fermilab.
- Muon Collider Community mtg. May 20-21. Goal: identify key challenges, R&D needed. Next mtg. in July, report to LDG and Council later this year.
- Active participation of Fermilab scientists in the meeting, in particular, in the areas of Magnets, High-Energy Complex, Muon Cooling, Radiation Protection, and Machine-Detector Interface.

Working-group co-conveners from Fermilab, organizing MCC community meetings: Sasha Zlobin, Eliana Gianfelice-Wendt, Diktys Stratakis, Vladimir Shiltsev, Nikolai Mokhov, Sergo Jindariani

Detectors at the Muon Collider

- Beam-induced background is one of the main challenges
  - At 1.5 TeV $\lambda = 9.3\times10^{6}$m, with $2\times10^{12}\mu$/bunch $\Rightarrow 2\times10^{5}$decays per meter of lattice.
- Developed detailed Beam-Induced Background simulations with both FLUKA and MARS packages
- Cutting-edge detector technologies needed to mitigate effects of the Beam Induced Background
  - Smart trackers with high granularity and timing capabilities (+shielding)
  - PF Calorimetry with good timing capabilities
  - Innovative event reconstruction strategies exploiting time correlations between different subdetectors
- Simulation Framework exists, performance studies ongoing; need design optimization, and new ideas

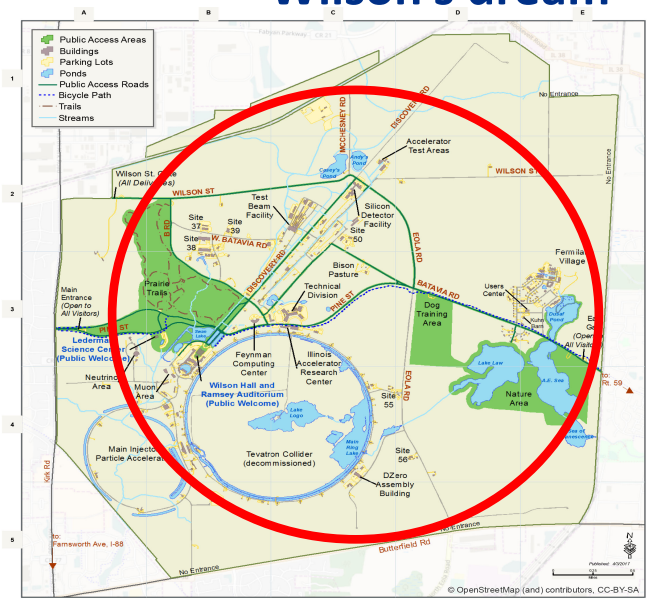




Other Collider Options

- Given the planned development of the accelerator complex for LBNF/DUNE program, Fermilab will have a robust infrastructure for a future muon collider or a hadron collider
  - Multi-MW proton beam with PIP-II linac and Booster replacement
  - A lot of expertise in all relevant areas
- A Site Filler for a Muon Collider or a Compact Hadron Collider?
- Muon accelerator complex at Fermilab
  - Muon Collider R&D facility with muon and neutrino programs
  - Multi-TeV (5 -10 TeV) Muon Collider
  - Work ongoing within MCC and Snowmass
  - (D. Neuffer, A. Bross, V. Shiltsev,..)
- A Compact Hadron Collider at Fermilab
  - Site Filler (16 km, 24-28 TeV); need > 20 T LTS/HTS magnets
  - IBS magnet research promising for >20T but early days
  - Intermediate step to FCC and test bed for high field magnet use
  - Efforts in the group looking at preliminary designs (Snowmass)
  - (T. Sen, M. Syphers, J. Johnstone, PB)
- An Advanced Linear Collider (ALC?) > 10TeV

Wilson's dream



Summary

- **The Future Colliders** group will develop plans to facilitate Fermilab's engagement in future collider projects, synergize efforts on future accelerator/colliders of interest to Fermilab, and develop a longer-term roadmap for further studies and R&D.
- Members of the group are currently engaged with ILC-IDT, FCC and CERN-based MCC working groups.
- In the near term, we will continue to work within the context of Snowmass, and work with the US university community, other national labs and the international community.
- Fermilab has unique facilities where R&D for future accelerators and detectors can be carried out.
- The development of the accelerator complex for LBNF/DUNE provides impetus and infrastructure for planning future facilities.
- The Future Colliders organization will ensure/strengthen Fermilab's leadership role at the energy frontier.

Extra Slides

Energy Frontier LoIs for Snowmass

(Led by Fermilab scientists)

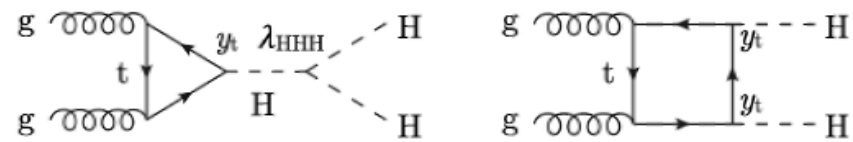
- A significant body of work has been produced for the ESPPU
  - Objective here is to carry out selected studies with updated machine parameters for hadron colliders and ILC, a systematic evaluation of physics case for the muon collider, and explore future collider options for Fermilab

1. Higgs self-couplings: Measurements at future proton-proton colliders
2. Probing extended scalar sectors in multi-Higgs Channels: Prospects at future proton-proton colliders
3. Prospects of Vector Boson Scattering at future colliders
4. Using pMSSM scans to elucidate SUSY sensitivity and complementarity of future colliders
5. Dark Matter Searches
6. Sensitivity to dijet resonances at future proton-proton colliders
7. Muon Collider: Solidifying the physics case
8. Muon Collider: Higgs and electroweak physics
9. Muon Collider: A window on new physics
10. Future collider options for the U.S.

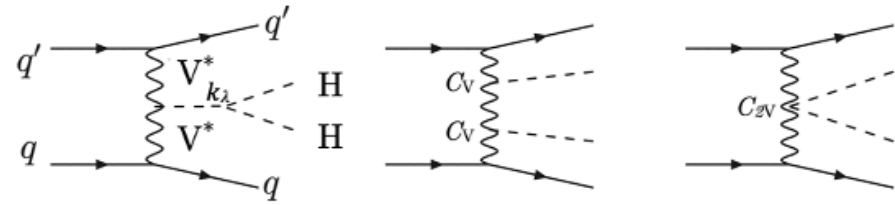
THE HIGGS BOSON AS A TOOL FOR DISCOVERY

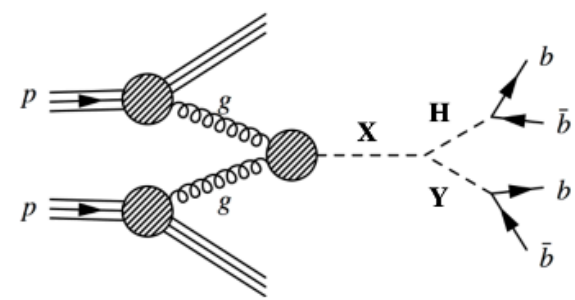
- **Higgs Self Couplings: Measurements at Future proton-proton Colliders**
  - *P. C. Bhat, A. Canepa, M. Carena, C. Gao , P. Merkel, F. Ravera*
  - The measurement of the Higgs trilinear and quartic self-couplings provide invaluable information on the electroweak symmetry breaking and the electroweak phase transition.
  - Plan to explore the HH vector boson fusion production process via the hhVV quartic coupling at various pp colliders using Deep Neural Networks to maximize sensitivity
- **Probing extended scalar sectors in multi-Higgs channels: Prospects at Future proton-proton Colliders**
  - *P. C. Bhat, A. Canepa, M. Carena, C. Gao , P. Merkel, F. Ravera (EF2_EF0-198)*
  - Many BSM theories (e.g. NMSSM) predict the existence of extended Higgs sector
  - Sensitivity of future pp colliders under study

High cross section ggHH production



High sensitivity VBF HH production

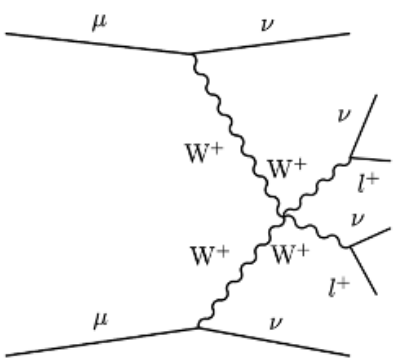


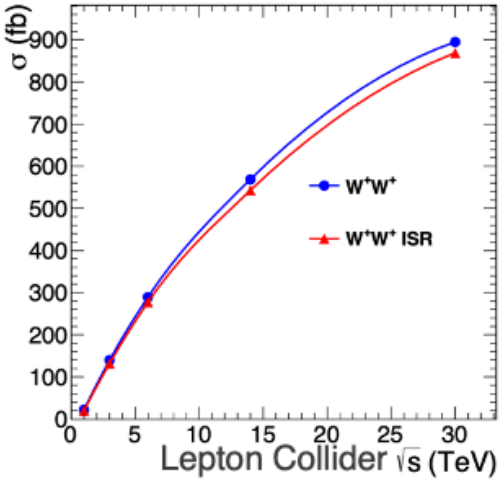


Current activity: Generation of samples

SEARCHES IN EWK SECTOR

- **The Prospects of Vector boson scattering at future colliders**
  - *A. Apyan, J. Berryhill (EF4_EF0)*
  - VBS processes provide key insights into the quartic gauge couplings as well as the Higgs sector.
  - Plan a comparative study of sensitivity at future high-energy hadron colliders as well as circular multi-TeV $\mu^+\mu^-$ and linear e^+e^- machines





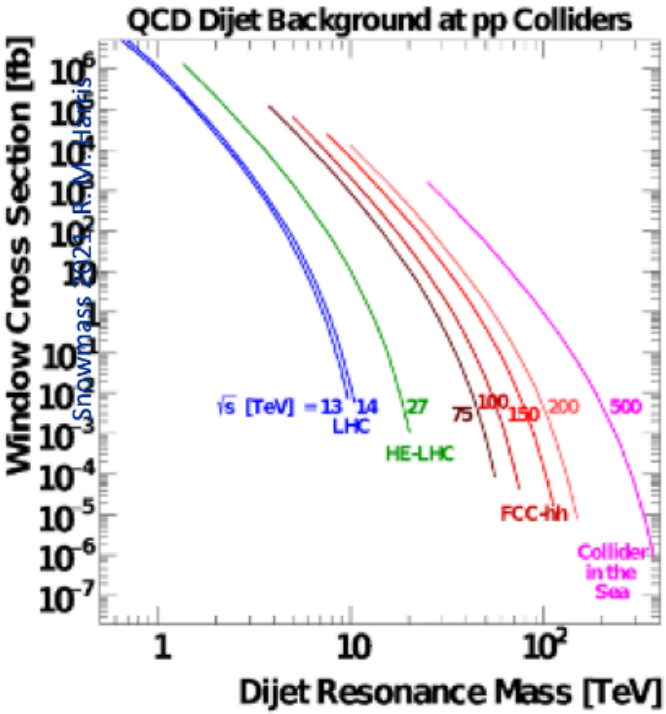
Current activity: Development of MuC simulation

- **Using pMSSM scans to elucidate SUSY sensitivity and complementarity of future colliders**
  - *J. Dickinson, Jim Hirschauer*
  - Use the 19-parameter phenomenological minimal supersymmetric standard model to quantify individual sensitivity to SUSY from a variety of current and future experiments
    - Markov chain Monte Carlo (McMC) "grand scan" populating all relevant regions of parameter space
    - Likelihood including measurements from external packages to steer scan towards un-excluded regions.

Central McMC code development nearly completed

DIRECT SEARCHES FOR BSM

- **Sensitivity to Dijet Resonances at Proton-Proton Colliders**
  - *R. Harris (EF9_EF8)*
  - Sensitivity to a dijet resonance X is a classic benchmark for discovery at a proton-proton collider
    - X(jj) predicted by a variety of BSM models (including excited quarks, axigluons/colorons, scalar diquarks, Z', W', gravitons)
  - Assessing sensitivity for 27 (HE-LHC), 75, 100 and 150 TeV (FCC-hh) and 500 TeV (Collider in the sea!)



Background calculations complete

Good progress on signals (6 models calculated: q*, Z', W', Graviton, Coloron, Diquark)

Signal shape simulations begun

PHYSICS STUDIES AT MUON COLLIDER

- 3 LoIs:
  - *Performance Studies, Higgs/SM Physics, and BSM*
  - *A. Apresyan, D. Berry, A. Canepa, M. Cremonesi, K. Di Petrillo, Z. Gecse, A. Hall, C. Herwig, J. Hirschauer, B. Jayatilaka, S. Jindariani, R. Lipton. N. Mokhov, K. Pedro, H.Weber*
- Significant progress with the framework:
  - Tracking performance shown to be excellent
  - Fermilab scientists have done assisting studies, such as measuring the occupancies in the tracker from backgrounds to inform the decision on the size and time resolution of the active readout devices (pixels).
- So far, the focus has been on tracking, (b-) jets and muons. Recently started looking into the reconstruction of electrons.
- Discussed strategy for MDI studies at high energies
- First meeting of the Cross-Frontier Muon Collider Forum (S. Jindariani and D.Stratakis are co-leaders)
- The informal LPC working group that had formed last summer decided to slow down activities (but not halt). Hold regular meetings on a monthly instead of biweekly schedule.

P5 (2013) Recommendations

- Recommendation 1: Pursue the most important opportunities wherever they are, and host unique, world-class facilities that engage the global scientific community.

ILC:

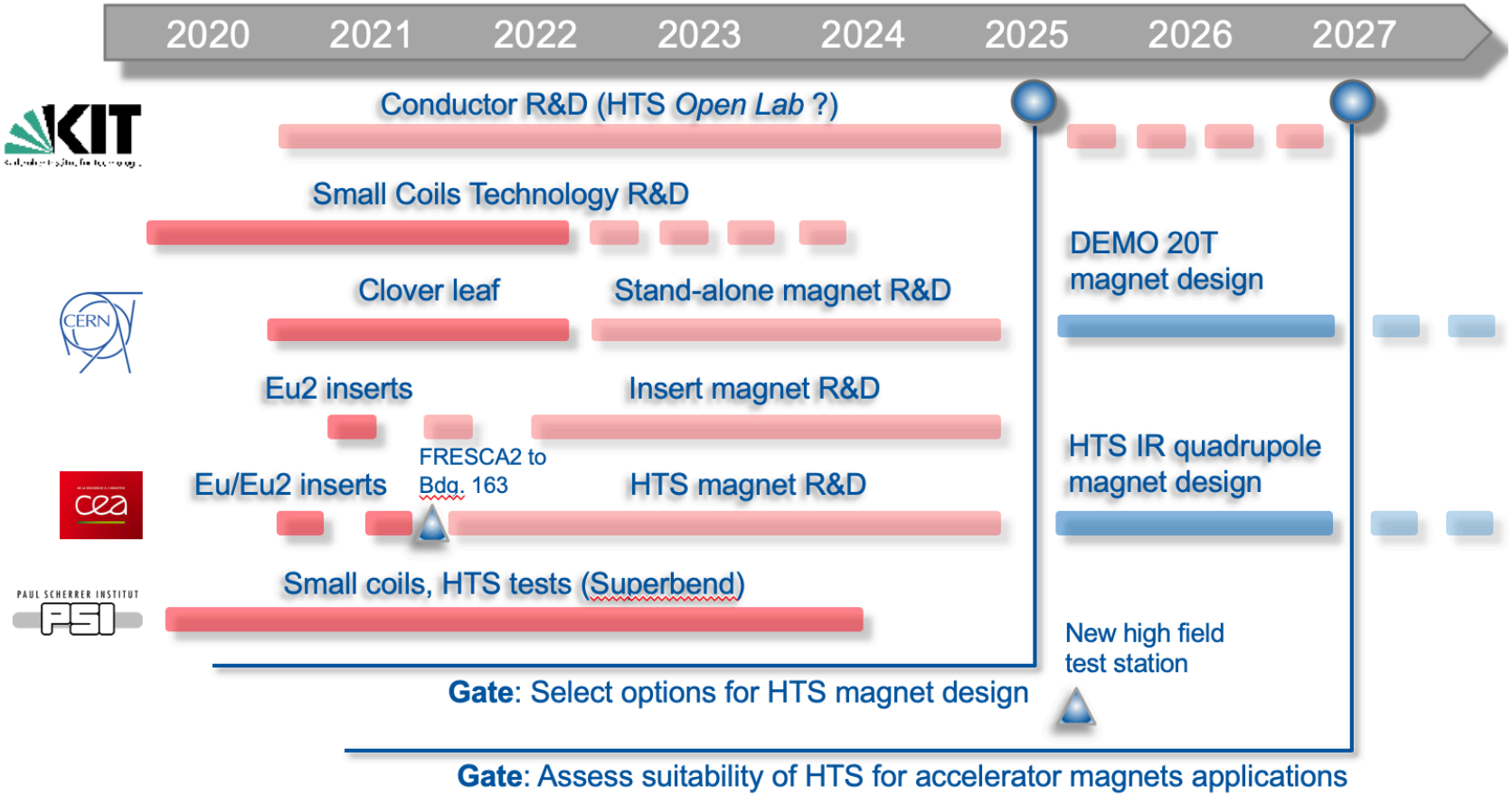
- Recommendation 11: Motivated by the strong scientific importance of the ILC and the recent initiative in Japan to host it, the U.S. should engage in modest and appropriate levels of ILC accelerator and detector design in areas where the U.S. can contribute critical expertise. Consider higher levels of collaboration if ILC proceeds.

FCC:

- Recommendation 24: Participate in global conceptual design studies and critical path R&D for future very high-energy proton-proton colliders. Continue to play a leadership role in superconducting magnet technology focused on the dual goals of increasing performance and decreasing costs.

High Field Magnet R&D for pp Collider

CERN plan:



Muon Collider Studies/Activities

- Fermilab scientists are engaged/leading in Muon Collider studies in the context of Snowmass and in the Muon Collider Collaboration
  - Accelerator Design Studies
  - Physics Studies
  - Detector simulation and event reconstruction
  - BIB Simulations and MDI optimization
- Unique expertise at Fermilab in many other key areas:
  - Overall system design
  - RF and high field magnets
  - Ionization cooling
  - Targets
  - Advanced detector design
  - Neutrino radiation issues and mitigation
- Exploring synergies with Intensity and Precision Frontiers.
- Understand the evolving interest within the US community, identify key R&D needs and outline path forward
- Several meetings held by the US HEP community; an LPC Forum, coordinators: Sergo and Kevin Black (U Wisconsin) + Snowmass MC forum