High energy colliders were critical for the progress of the particle physics over last 50 years:
- Discoveries of c and t quarks, gluons, W/Z bosons and recently the Higgs boson
- 1000’s of high precision measurements which helped to develop the standard model
- Going to higher energies is the only way to study even smaller distances (~10^{-18} cm at the LHC) and particles with even higher masses
Operating or Soon to be Operating Colliders

- Single high energy hadron collider – the LHC, now at 13 TeV
  - RHIC at BNL – nuclear studies
- DAFNE (Frascati), VEPP (Novosibirsk), BEPC (Beijing) – low energy e⁺e⁻ colliders
- SuperKEK-B – b-factory at KEK to restart in 2016 with ~40 times higher luminosity
  - Studies of particle containing b-quarks
Physics Goals of the Future Colliders

• Physics interests drive colliders development
  – Like colliding antiprotons in the already existing ring of SpS at CERN to discover W and Z bosons

• Today there are two areas where new colliders are especially important
  – “Higgs factory” – a collider (most probably $e^+e^-$) with a center of mass energy 250 GeV and above and high luminosity to study the Higgs boson properties
  – “~100 TeV” pp collider to get to the “next energy frontier” an order of magnitude above LHC

• Both options highlighted by the recent P5 report
Fermilab’s Program is Based on P5 Recommendations

**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.

**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.

- Fermilab’s future colliders program is based on P5 recommendations and implemented in close cooperation with other US laboratories and Universities
  - Taking into account changing situation in the field, including proposals of new collider projects
Muon Collider

- Muon collider provides point like particles collisions with up to ~10 TeV energy on Fermilab’s site

- Challenging due to short muon lifetime

- Considerable efforts at Fermilab in 2012-2013 to support muon accelerator program
  - Development of physics program
  - Detector design
  - Optimization of the interaction region

- With P5 recommendation to terminate muon collider activities, efforts in this area were quickly ramped down
  - Vast amount of information is available in the published papers and Fermilab’s Technical Memos
Medium Term Future Colliders Projects

- **ILC - International Linear Collider**
  - 500 GeV linear $e^+e^-$ collider (upgradable to 1 TeV)
  - Higgs factory (and top quark factory)
  - Location – Japan
  - Start of construction ~2019
  - Estimated cost ~$10B

- **CepC – Circular Electron Positron Collider**
  - ~250 GeV circular $e^+e^-$ collider (the tunnel could be later used for pp collider)
  - Higgs factory
  - Location – China
  - Start of construction ~2021
  - Estimated cost ~$3B

- **FCC – Future Circular Colliders**
  - 350 GeV $e^+e^-$ and/or ~100 TeV pp
  - Higgs factory and/or next energy frontier
  - Location - CERN
  - Start of construction - ?
  - Estimated cost - ?
ILC Activities at Fermilab

Cooper, Denisov, Fisk, Lipton, Mazzacane

TDRs for the ILC accelerator design and two detectors were completed in 2012 by the Global Design Effort group.

Fermilab scientists have been involved in the design of the ILC detectors and continuing improvements and optimizations based on the recent detectors developments.

Important role is played by close cooperation with expertise available at Fermilab:
- Shielding of the detectors and accelerator components
- Superconducting RF developments

Fermilab organized Linear Colliders Workshop in 2014 and our scientists serve on main ILC organization bodies, including representing Americas on physics and detectors executive committee.
100 TeV Collider Activities at Fermilab

Anderson, Bhat, Denisov, Lipton, Kotwal

2001 Study

- We are cooperating with FCC activities
  - Participating in FCC workshops
  - Sharing experience obtained during 2001 VLHC collider study at Fermilab
- Cooperating with LPC CMS center at Fermilab where young scientists are interested to contribute and performed many studies for Snowmass 2013
- Organizing workshops and series of weekly seminars on 100 TeV colliders
  - With main goal to explore physics potential of such a collider
- Working on developing specifications for the detectors
  - Based on basic detection principles and newly available technologies
- Working closely with accelerator and high field magnets GARD programs

Excited quark studies at 100 TeV Collider
Colliders in China: CepC and SppC

• CepC – Circular Electron Positron Collider
  – ~50 km long ring
  – 90-250 GeV in the center of mass
  – Z boson and Higgs factory
• SppC – Super Proton Proton Collider
  – In the same ring as CepC
  – ~50 TeV with 12 T magnets, ~70 TeV with 20 T

• Fermilab activities in this area started in early 2015
• We are helping with reviews of the LoIs for accelerator, physics and detector
• Participating in the workshops to discuss areas of mutual interest
  – Based on Fermilab’s expertize
• Working closely with the University of Chicago and ANL

Denisov, Future Colliders Program

July 29 2015
Future Collider Program Plans

- Plans are based on ~3 FTE planned to be involved in the future colliders activities
- ILC activities
  - Help to establish ILC international support and sharing mechanism
  - Organize and participate in ILC workshops
  - Serve on ILC organization committees and coordinate US ILC physics and detectors activities
  - Continue modest work on the optimization of ILC detectors design and development of physics program
- 100 TeV pp collider
  - Participate in FCC design activities
  - Continue series of seminars at Fermilab on 100 TeV colliders physics
  - Organize workshops and meetings to develop physics program for the 100 TeV collider
  - Perform modest scale detectors R&D starting from establishing main specifications for detector elements at 100 TeV collider
- CepC
  - Continue to help with reviews of the accelerators, detectors and physics programs
  - Establish areas of mutual interest assuming modest Fermilab efforts
  - Participation in modest detectors R&D efforts, utilizing Fermilab test beam, is among potential areas of cooperation
Future Colliders Conclusions

• Based on P5 recommendations Fermilab is contributing modest resources to activities on ILC, CepC and 100 TeV pp colliders
  – Current and planned level of activities is ~ 3 FTEs
  – Based on major experience in colliders physics and detectors at Fermilab

• Major challenge is to create “critical mass” team to make substantial contributions with relatively small number of Fermilab scientists involved
  – Involve CMS community at Fermilab
  – Invite and support key experts from US Universities
  – Develop G&V program for accelerator, physics and detectors developments
  – Work with Fermilab Accelerator and Technical Divisions on accelerators and high field magnets designs
  – Concentrate on critical areas where Fermilab has extensive expertise
  – Assume leadership positions in the international programs

High energy colliders are critical for the progress in particle physics and we have to invest in their developments
FCC – Future Circular Colliders

• FCC activity follows European particle physics strategy recommendation to develop future energy frontier colliders at CERN
  – “…to propose an ambitious post-LHC accelerator project….., CERN should undertake design studies for accelerator projects in a global context,…with emphasis on proton-proton and electron-positron high-energy frontier machines…..”

• There are three options in ~100 km long tunnel
  – pp collider with energy of ~100 TeV
  – e⁺e⁻ collider with energy of ~350 GeV
  – ep collider

• Similar to “LEP then LHC” option of starting from 350 GeV e⁺e⁻ collider and later going to 100 TeV pp collider is considered
  – But in no way decided