Fermilab

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Future Colliders

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Fermilab Users Meeting

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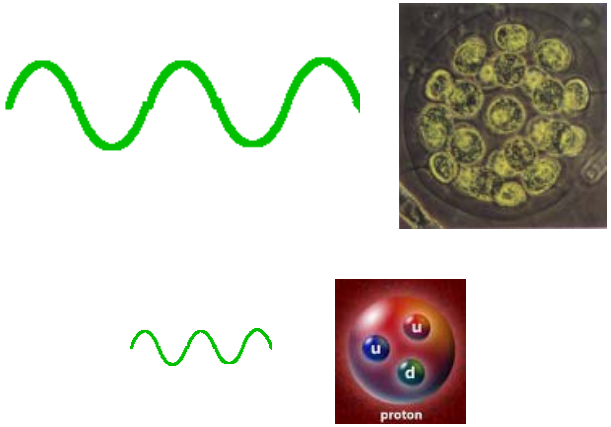
Why High Energy and Why Colliders

- Accelerators are built to study the Nature smallest objects

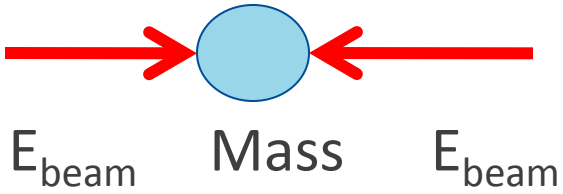


Wavelength = h/E

~2 ·10^{-18} cm for LHC

- Accelerators convert energy into mass

$E = mc^2$

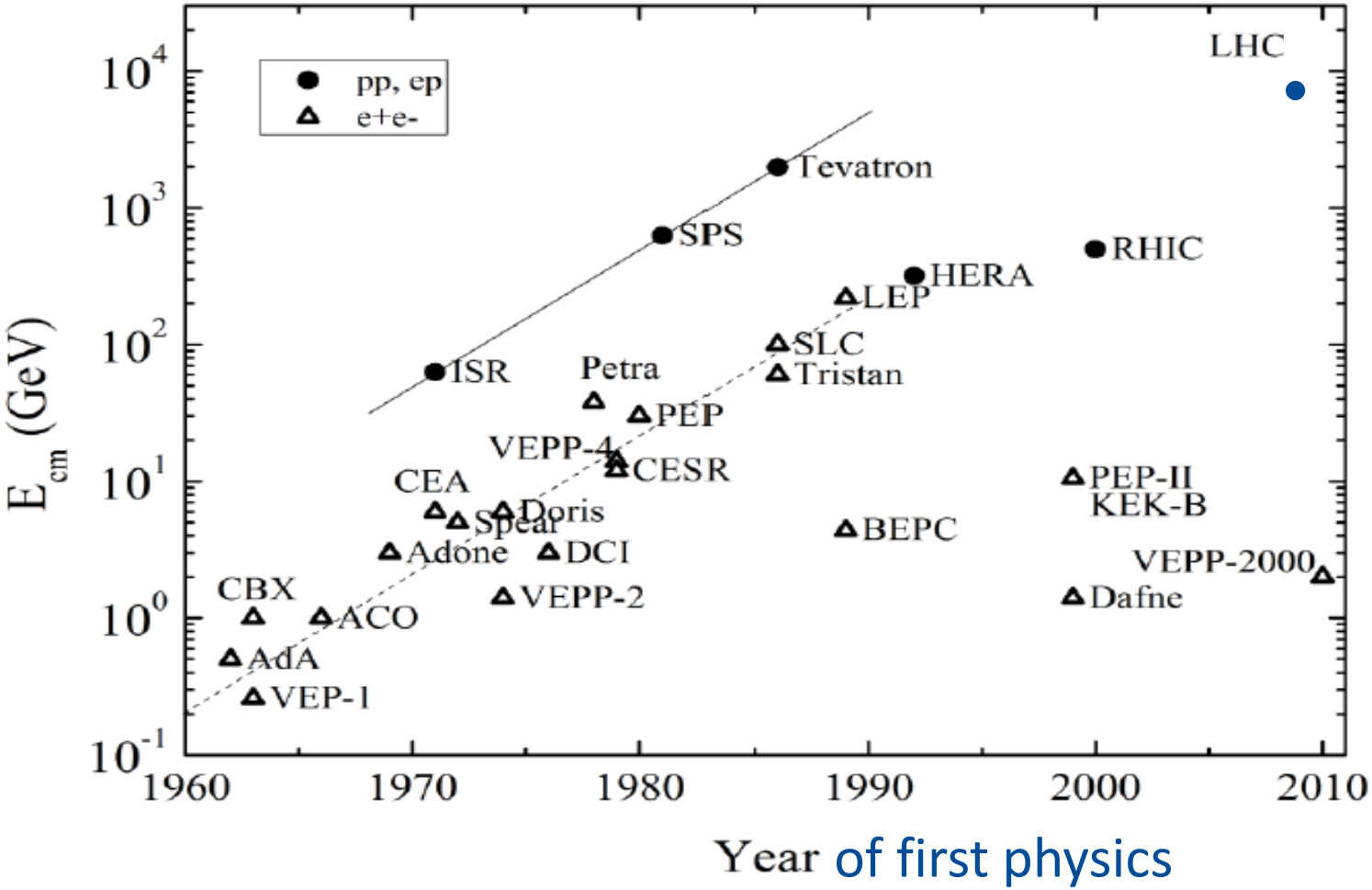


Objects with masses up to
Mass = $2E_{beam}$ could be created

Collider center of mass energy is $2E_{beam}$ instead of $\sqrt{(2mE_{beam})}$ for fixed target

To get to the next step in understanding of Nature - at both smaller distances and higher masses - higher energy is the only way to succeed

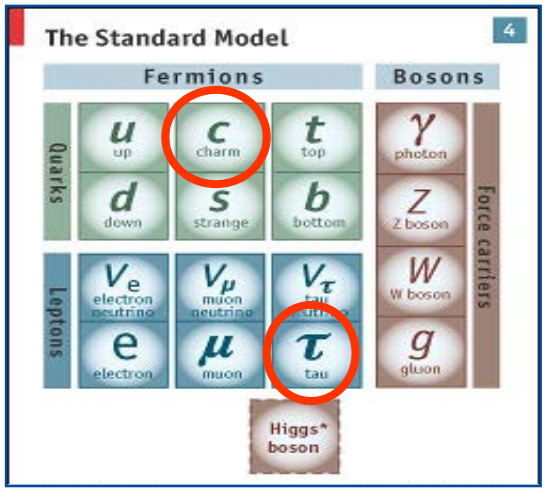
Colliders



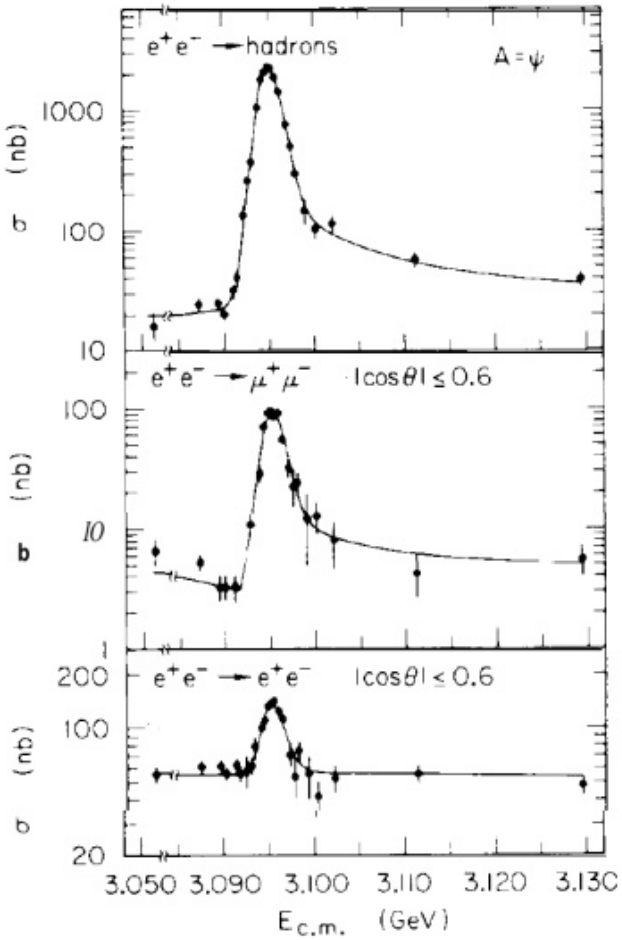
- First e^+e^- colliders started operation in early 1960's with hadron colliders (storage ring) first collisions in 1971 with the completion of the ISR
- Large number of e^+e^- colliders, while few hadron colliders
- Hadron colliders provide higher center of mass energy, while colliding "composite" particles

SPEAR e^+e^- Collider at SLAC: start 1972

SPEAR construction



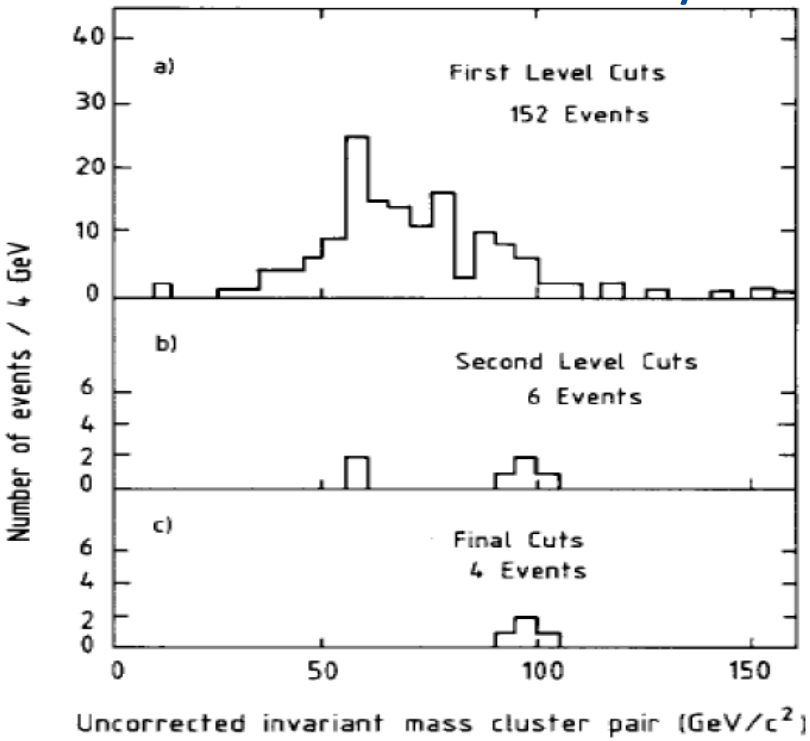
J/Psi discovery



- Started in 1972 with ~3 GeV center of mass energy
- Opened extremely productive energy range
  - Co-discovery of c-quark (J/Psi meson) in 1974
  - Discovery of τ-lepton in 1975
- One of the most productive colliders in the world

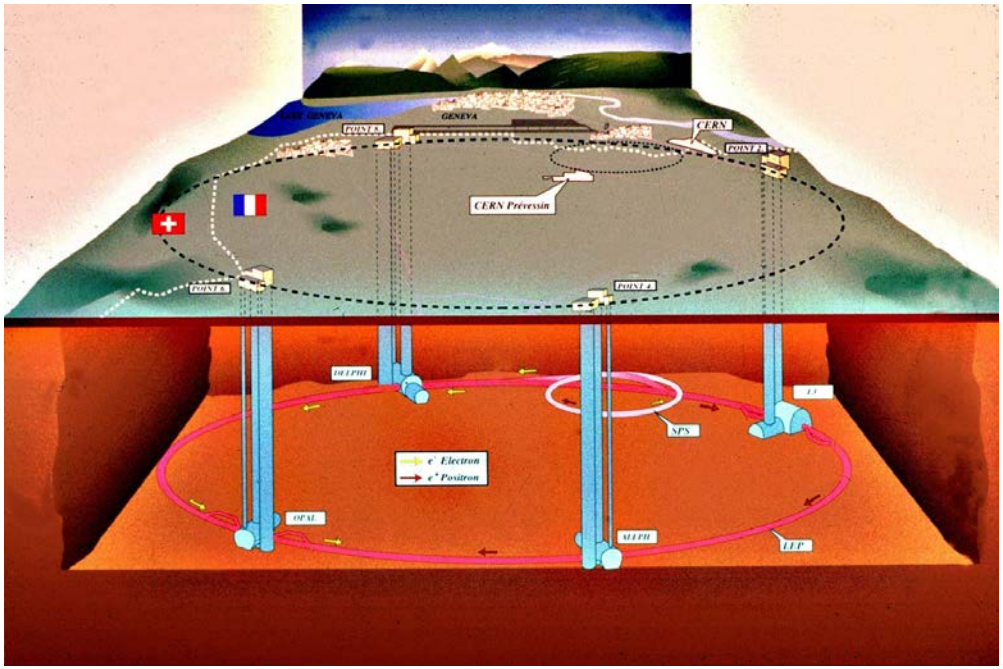
SppS Collider at CERN: start 1981

Z boson discovery

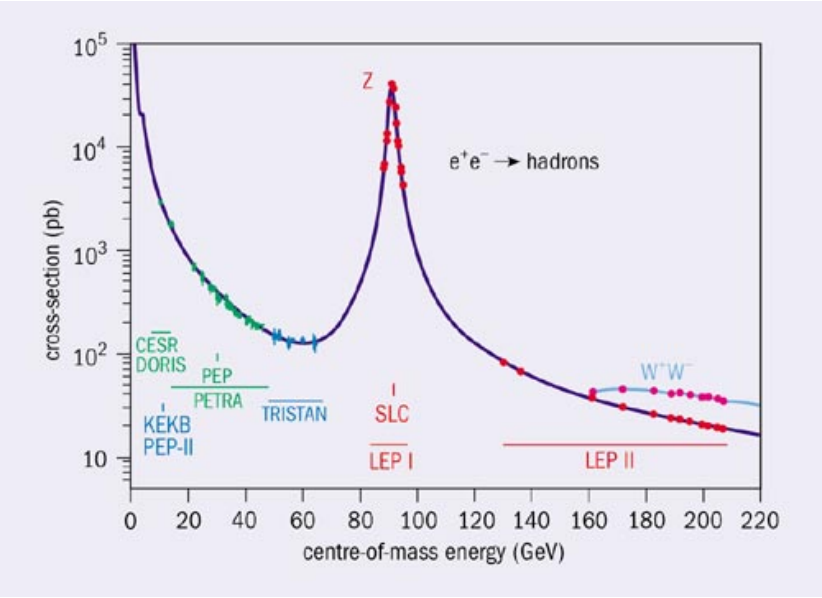


- Use of antiprotons in the existing fixed target accelerator
- Provided next step in the understanding of the standard model
  - W/Z bosons discovered

LEP e^+e^- collider at CERN: start 1989

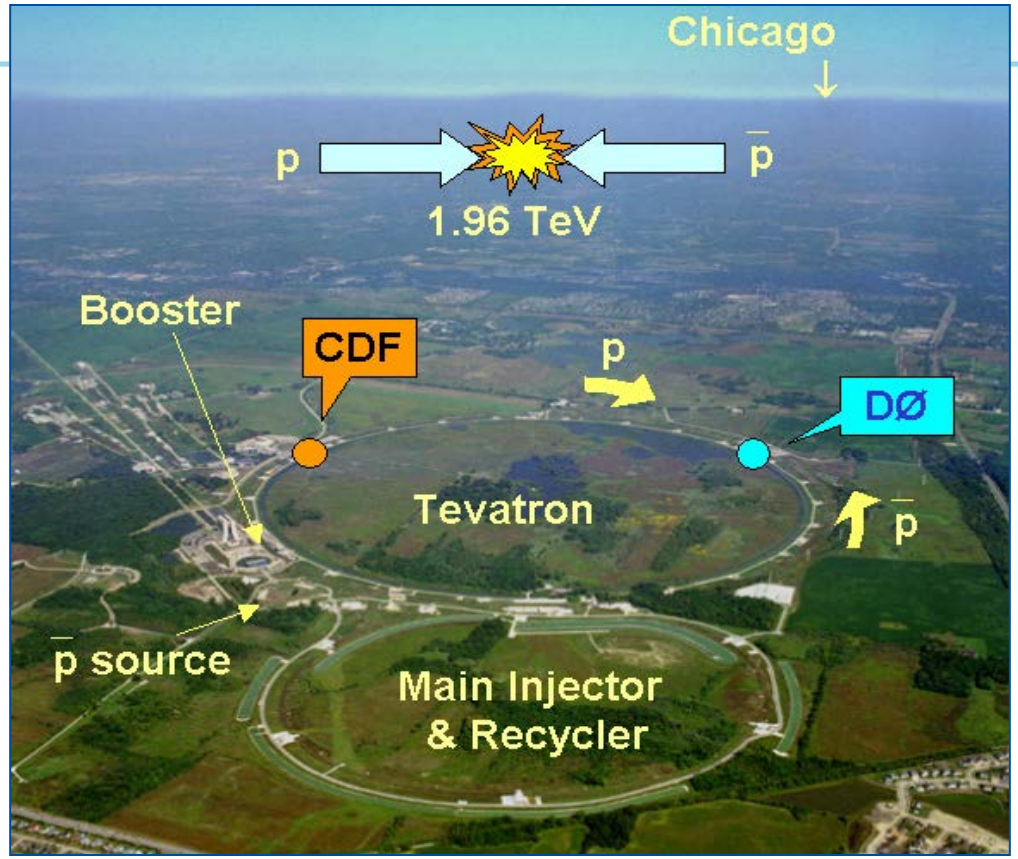


Z boson factory

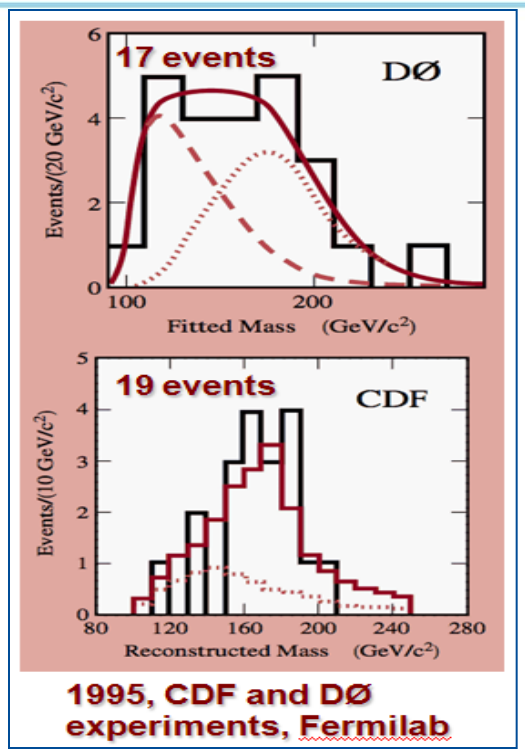


- 27 km long tunnel for up to ~200 GeV center of mass energy
  - Started operation in 1989 as “Z factory”
  - Wide range of extremely precise measurements, including Z boson mass measurement and determination of the number of neutrino generations
- SLC linear collider Z factory at SLAC operated at about the same time
- LEP needed less than 5% extra center of mass energy to discover the Higgs…

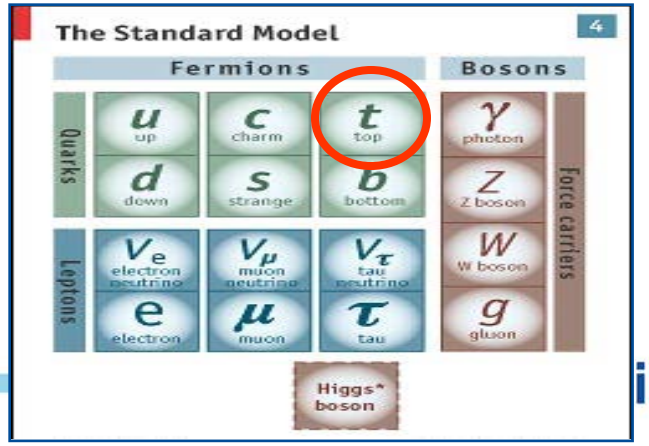
The Tevatron



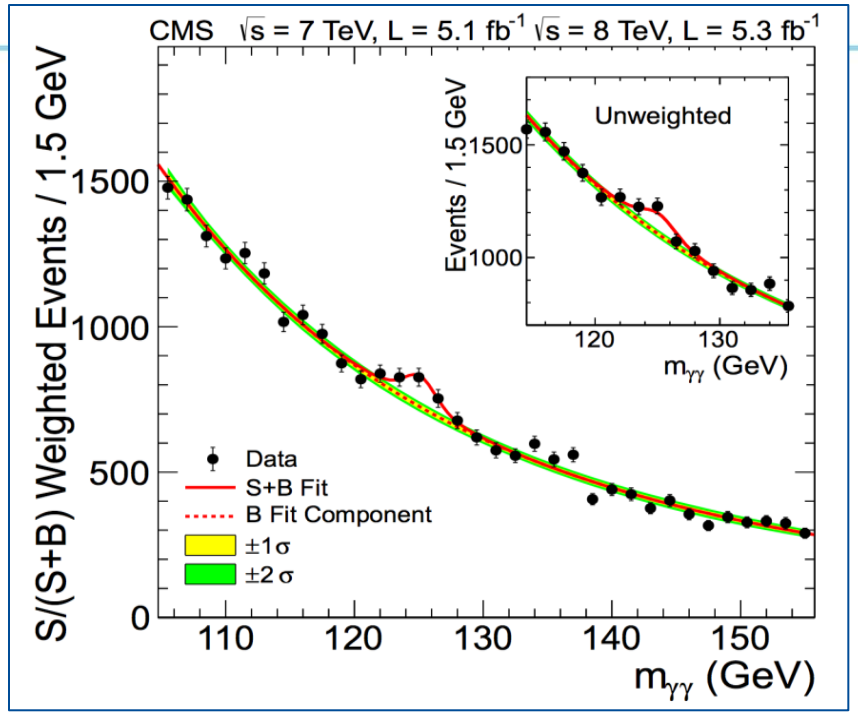
Top quark discovery



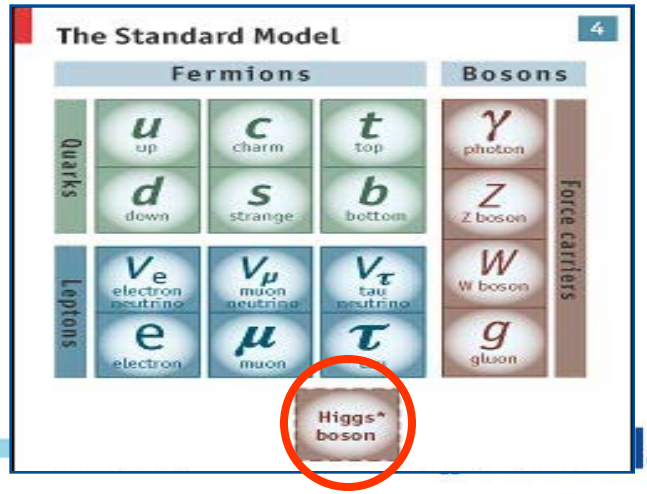
- First superconducting accelerator with 2 TeV center of mass energy
- Discovered last standard model quark – the top quark



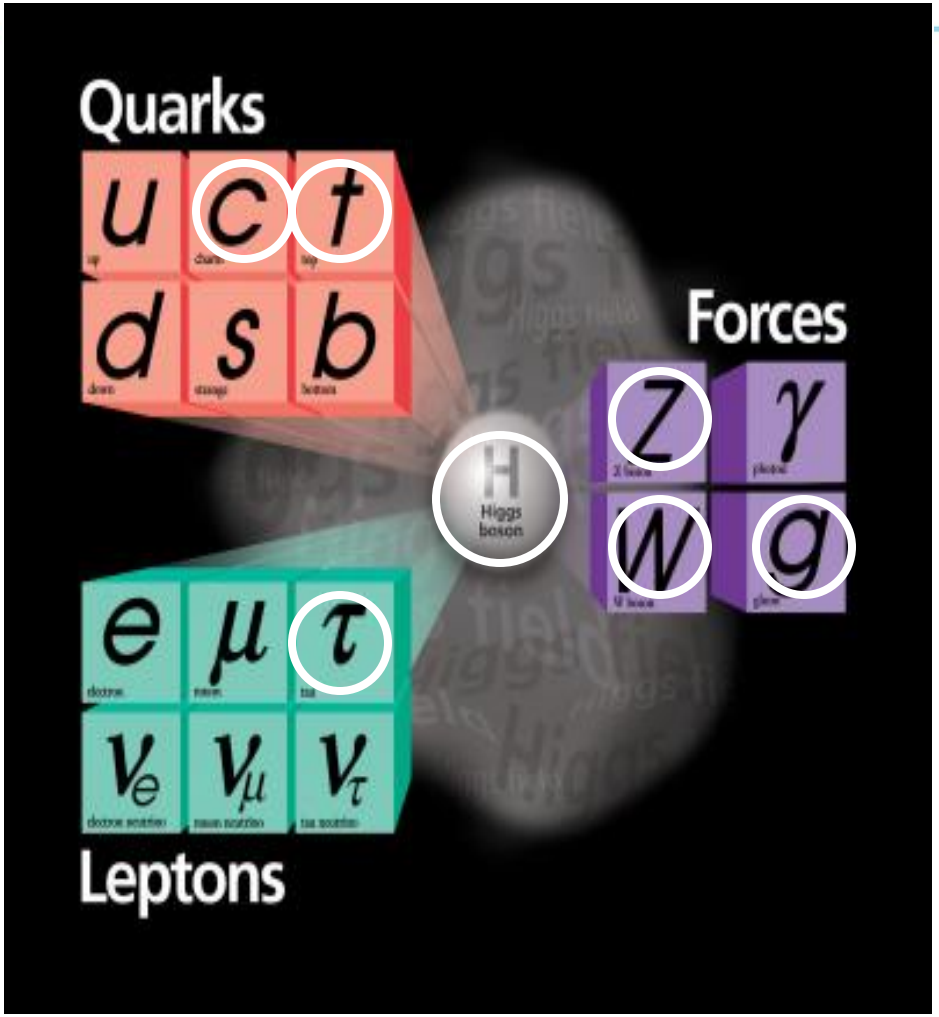
The LHC – the History in the Making



- Re-use of the LEP tunnel
  - With superconducting magnets
- Discovered last missing piece of the standard model - the Higgs boson
- Extensive searches for physics beyond the standard model
- Many more exciting results expected



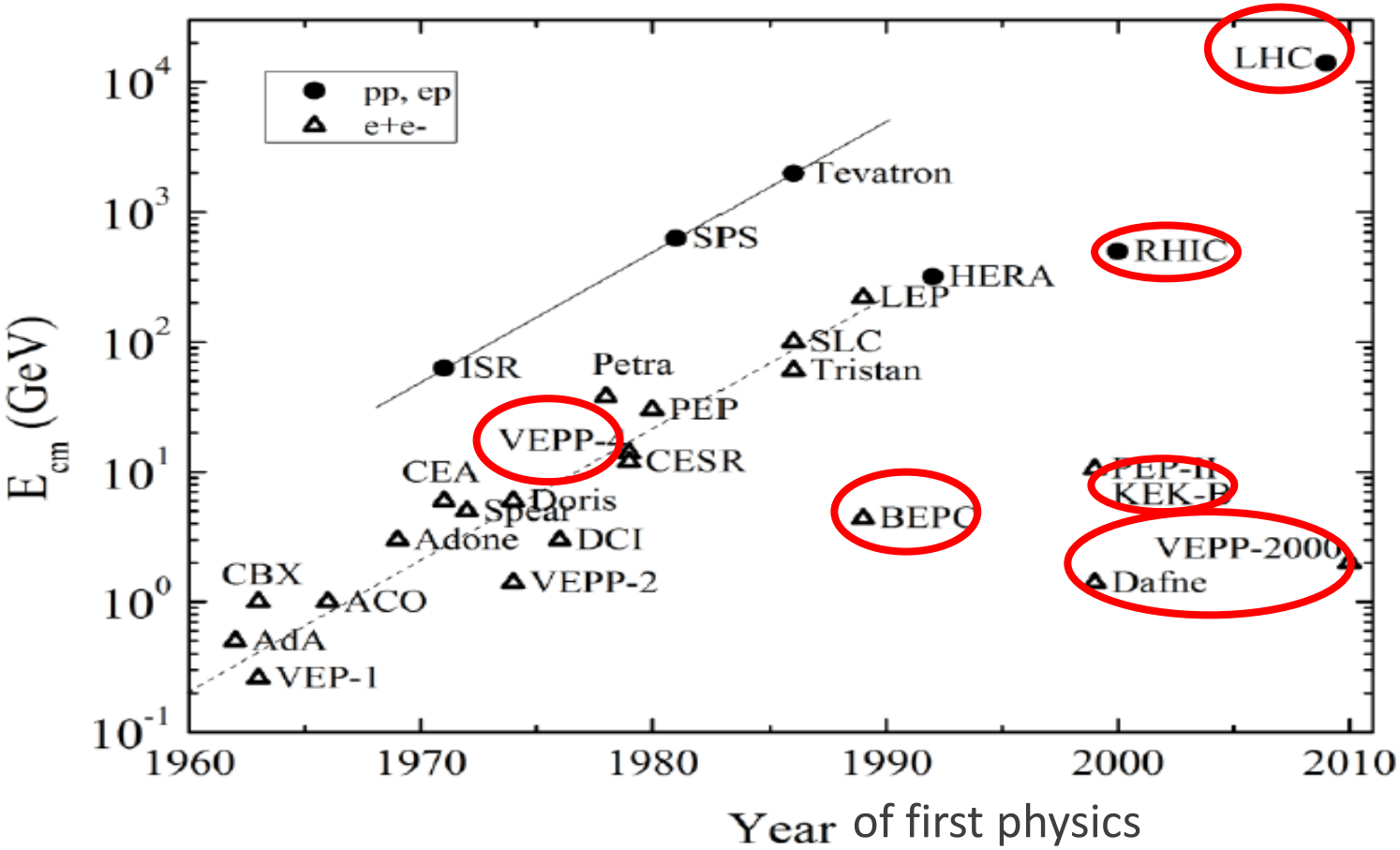
Accelerators and the Standard Model



- Progress in particle physics over past 40 years was closely related to discoveries at ever more powerful colliders
  - e^+e^- colliders
    - c quark, tau lepton, gluon
  - Use of antiprotons in the same ring as protons
    - W and Z bosons
  - Superconducting magnets
    - Top quark and the Higgs boson
- All expected standard model elementary particles have been discovered at colliders
  - Tau neutrino in fixed target experiment at Fermilab

At every step new accelerator ideas provided less expensive ways to get to higher beams energies and higher luminosities

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

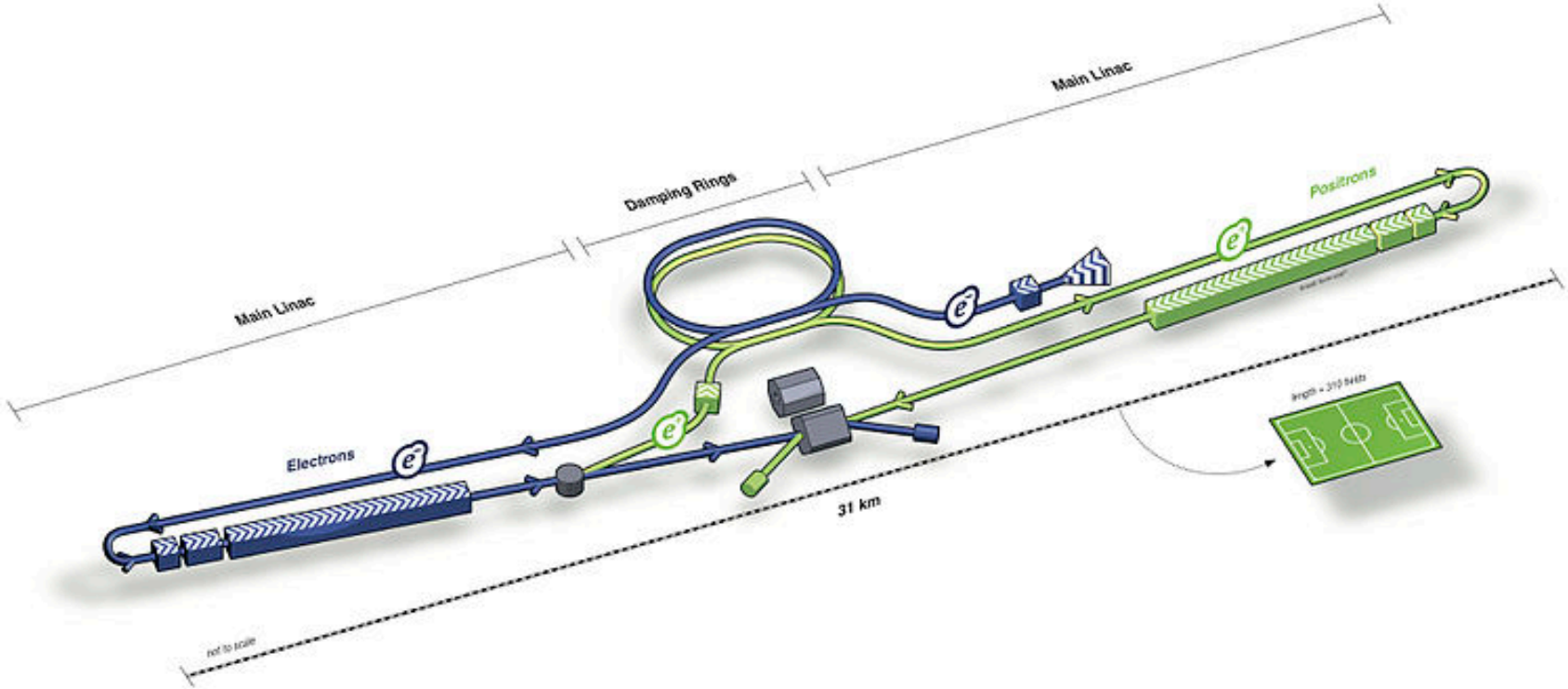
Physics Goals and Challenges of the Future Colliders

- Physics interests often 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
    - Study distances up to ~10^{-19} cm and particles masses up to ~50 TeV
- Both options highlighted by the recent P5 panel report
- What are challenges in building next generation of colliders
  - Progress in new acceleration methods aimed to reduce cost of the colliders was relatively slow over last ~20 years
  - Colliders are becoming rather expensive and require long time to build

Medium Term Future Colliders Projects

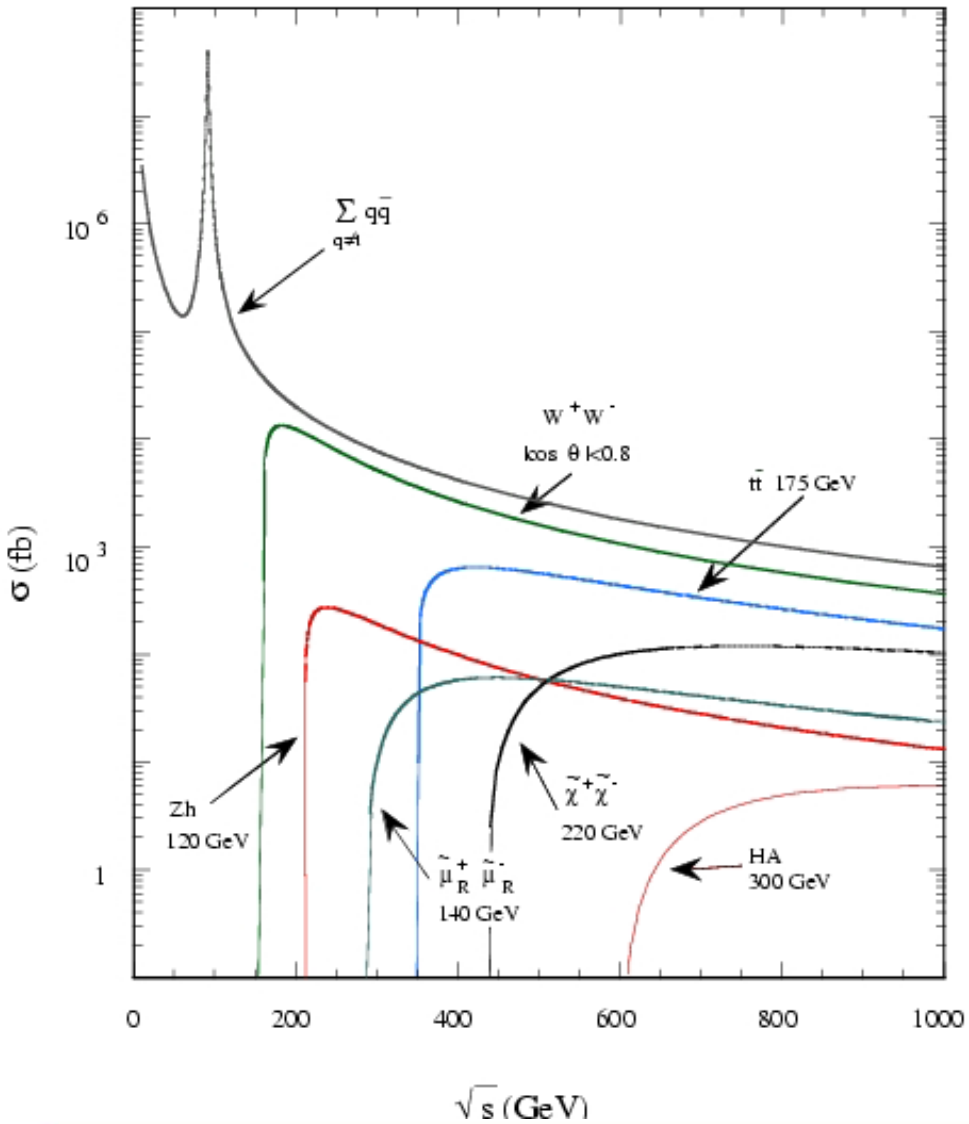
- **ILC - International Linear Collider**
  - 500 GeV linear e^+e^- collider (upgradable to 1 TeV)
  - Higgs factory (and top quark factory)
  - Location – Japan
  - Start of construction ~2019
  - Estimated cost ~$10B
- **CEPC – Circular Electron Positron Collider**
  - ~250 GeV circular e^+e^- collider (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 - ?

International Linear Collider



- ILC or International Linear Collider is e^+e^- linear collider with the following main parameters
  - Center of mass energy ~500 GeV
  - Luminosity $>10^{34}$ $cm^{-2}s^{-1}$
- No synchrotron radiation, but long tunnel to accelerate to ~250 GeV/beam
  - Colliding point-like particles
  - Excellent Higgs factory with many Higgs production and decay channels accessible
- Strongly endorsed by P5

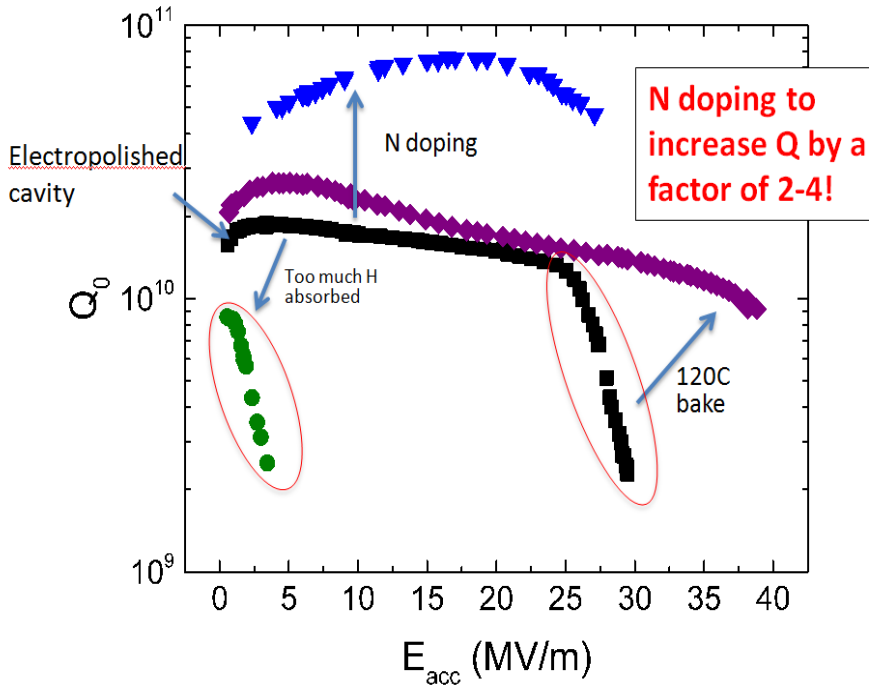
ILC Physics and Experiments

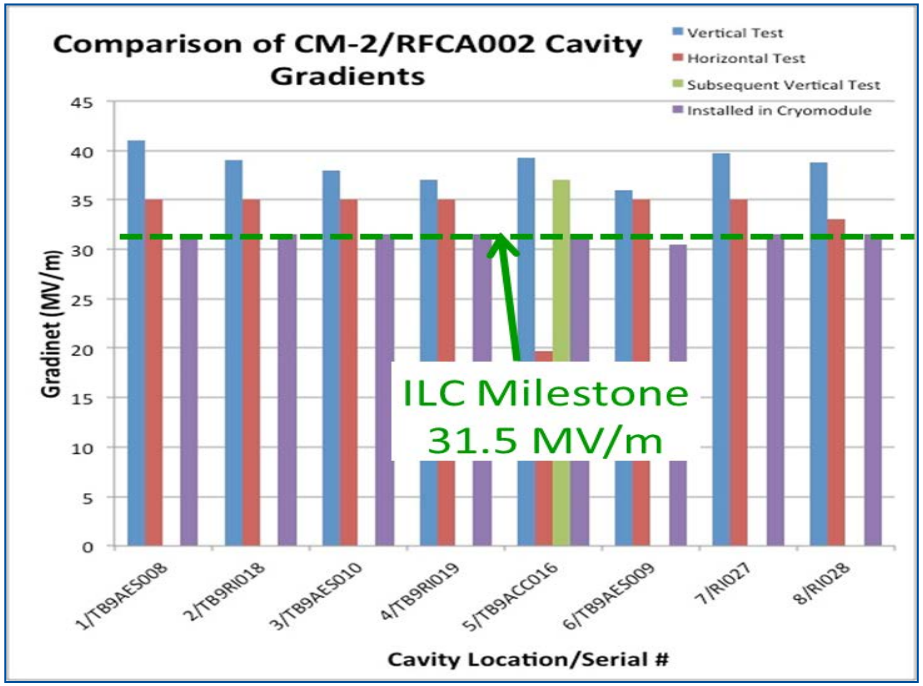


- Low cross sections
  - High luminosity needed
- Low rate of interactions
  - Collect all events
  - High efficiency needed
- Point like particles colliding
  - Sharp thresholds
  - Can be used for precision measurements including top mass
- Large number of different production/decay channels
  - Have to detect all “standard objects” well
  - Jets/photons, leptons, charged tracks, missing energy

Fermilab's Potential ILC Contributions

- SCRF accelerating cavities
  - Synergy with PIP-II and LCLS accelerating cryomodules
- R&D in accelerator systems, including controls
- Design of the ILC detectors





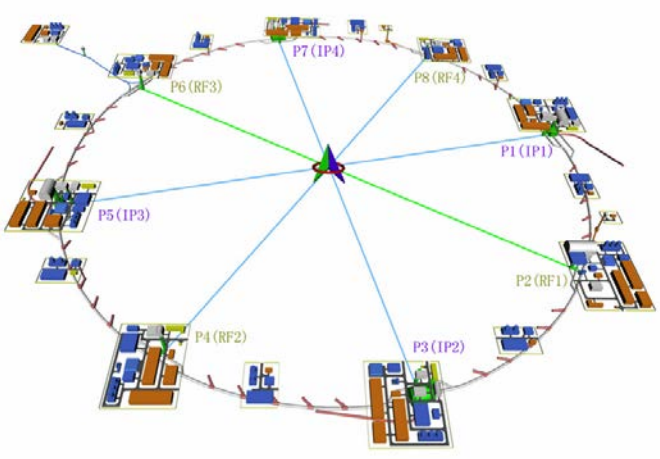
- Two excellent results for SCRF cavities obtained at Fermilab recently
  - Substantial Q factor increase of the cavities with nitrogen doping
  - Fermilab's cryomodule reached ILC specification of 31.5 MV/m

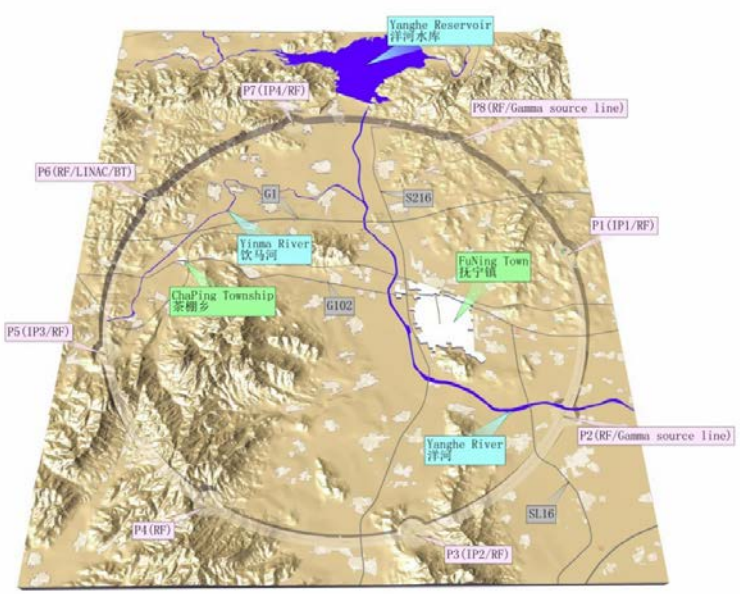
ILC Status and Plans

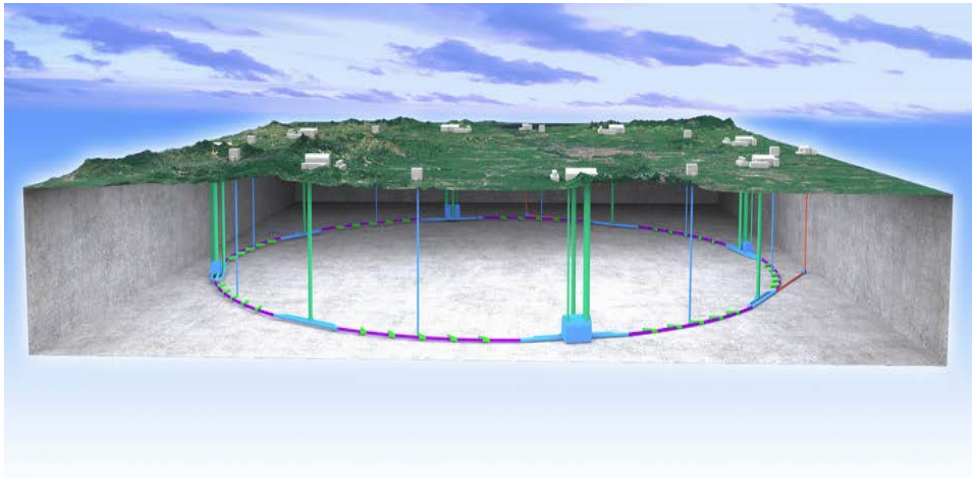
- After success of SLAC's linear e^+e^- collider in 1990's (SLC) various proposals developed to go to even higher colliding energy
  - Among them NLC(SLAC), TESLA(DESY), "ILC at Fermilab"
- Starting in 2008 Global Design Effort (GDE) progressed developing
  - Technical design of the ILC
  - Cost estimate and international cooperation plan
- GDE concluded in 2012
  - Including TDRs for the accelerator and detectors
  - Physics case strengthened with a Higgs discovery
- In 2012 Japan expressed strong interest to host the ILC
- Over last two years
  - Substantial progress in technical developments
  - Development of cooperation between participants on "Governments level"
- All involved agree that ILC project should be international project with Japan as the host country
  - Challenges in establishing high level agreements between countries are substantial
  - Funding for this international project, including in Japan, is expected to be "in addition to the existing particle physics funding"

Proposals for 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

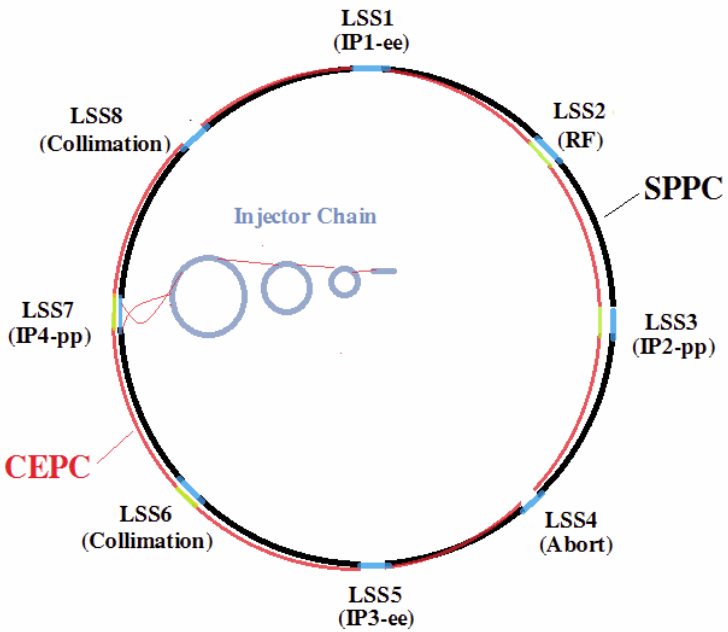






Future Colliders in China

- Very active progress with the CEPC and SPPC design over last two years
  - International reviews (positive) of the conceptual proposals in Spring of 2015
- Plan is to get funding for detailed technical design report by later this year
  - ~$50 million per year effort
  - Completed by 2020
- Construction of CEPC to start in 2021
  - Completed in 2027
  - Data collection 2028-2035
- SPPC time line
  - Design 2020-2030
  - Construction 2035-2042
  - Physics at ~70 TeV starting in 2043
- The proposal is based on
  - Experience with BEPC e^+e^- collider
  - Relatively inexpensive tunneling in China
  - Strong Government interest in scientific leadership – both CEPC and SPPC are "national projects with international participation"
  - Setting realistic goals based on the expected availability of resources



FCC – Future Circular Colliders

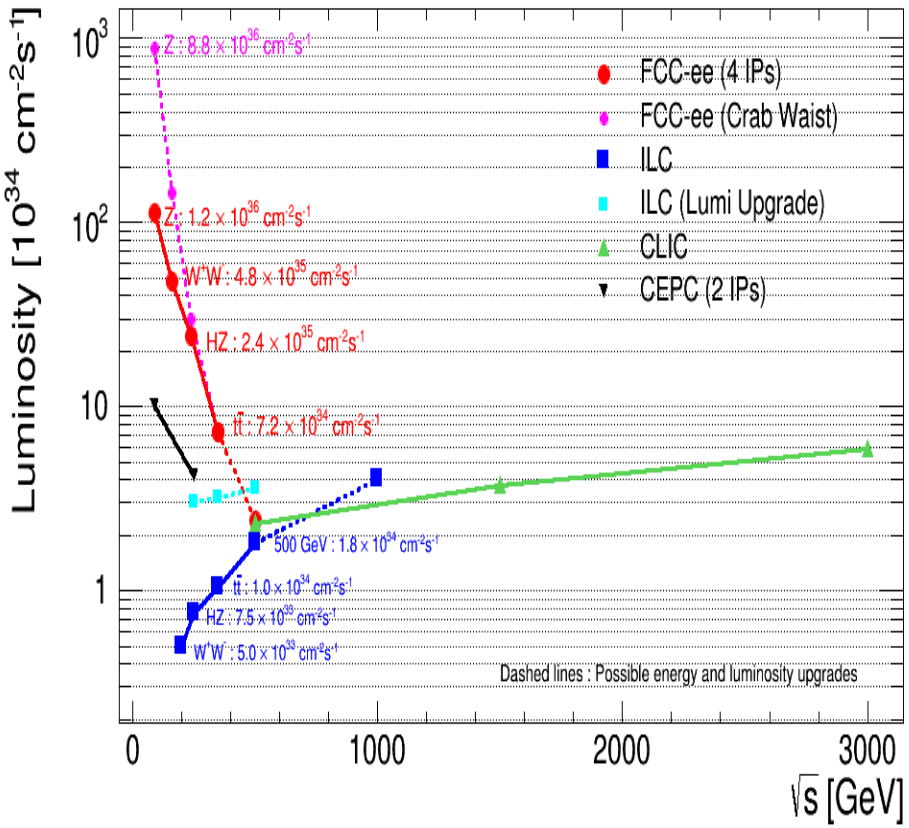
- FCC activity follows European particle physics strategy recommendation to develop future energy frontier colliders at CERN
  - "…to propose an ambitious post-LHC accelerator project….., CERN should undertake design studies for accelerator projects in a global context,…with emphasis on proton-proton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

FCC pp 100 TeV collider

Parameter	FCC-pp	LHC
Energy [TeV]	100 c.m.	14 c.m.
Dipole field [T]	16	8.33
# IP	2 main, +2	4
Luminosity/IP_{main} [$cm^{-2}s^{-1}$]	5 - 25 x 10^{34}	1 x 10^{34}
Stored energy/beam [GJ]	8.4	0.39
Synchrotron rad. [W/m/aperture]	28.4	0.17
Bunch spacing [ns]	25 (5)	25

- Main challenges
  - Long tunnel
  - High field magnets
  - High synchrotron radiation load
- Tevatron and LHC experience demonstrate feasibility of such a collider

FCC e^+e^- Collider



Parameter	FCC-ee			LEP2
Energy/beam [GeV]	45	120	175	105
Bunches/beam	13000-60000	500-1400	51- 98	4
Beam current [mA]	1450	30	6.6	3
Luminosity/IP x 10^{34} cm^{-2}s^{-1}	**21 - 280**	**5 - 11**	**1.5 - 2.6**	0.0012
Energy loss/turn [GeV]	0.03	1.67	7.55	3.34
Synchrotron Power [MW]	100			22
RF Voltage [GV]	0.3-2.5	3.6-5.5	11	3.5

- Circular e^+e^- collider has substantially higher luminosity at lower energies vs linear collider
- Main challenges: long tunnel and high synchrotron losses requiring demanding superconducting RF system and high electricity consumption

FCC study is expected to take ~4 years and to provide technical proposals and cost estimates for all three options: pp, ee and ep

Future Colliders - Summary

- Colliders played major role in establishing and understanding the standard model
  - Discovered all expected standard model particles!
- Future proposed colliders are of two types
  - e^+e^- colliders as “Higgs factory”
  - pp colliders at the next energy frontier
- Three proposals are under active discussion
  - ILC (Japan)
  - CEPC and SPPC (China)
  - FCC (CERN)
- Many exciting opportunities are not discussed in the talk
  - VLHC, electron-ion colliders, muon collider, CLIC, etc.
- Key for the future colliders is to reduce cost dramatically
- Fermilab is actively engaged in the future colliders efforts with our strength in the accelerators design, high field magnets, SCRF and physics/detectors
  - If interested, come, talk to us to participate!