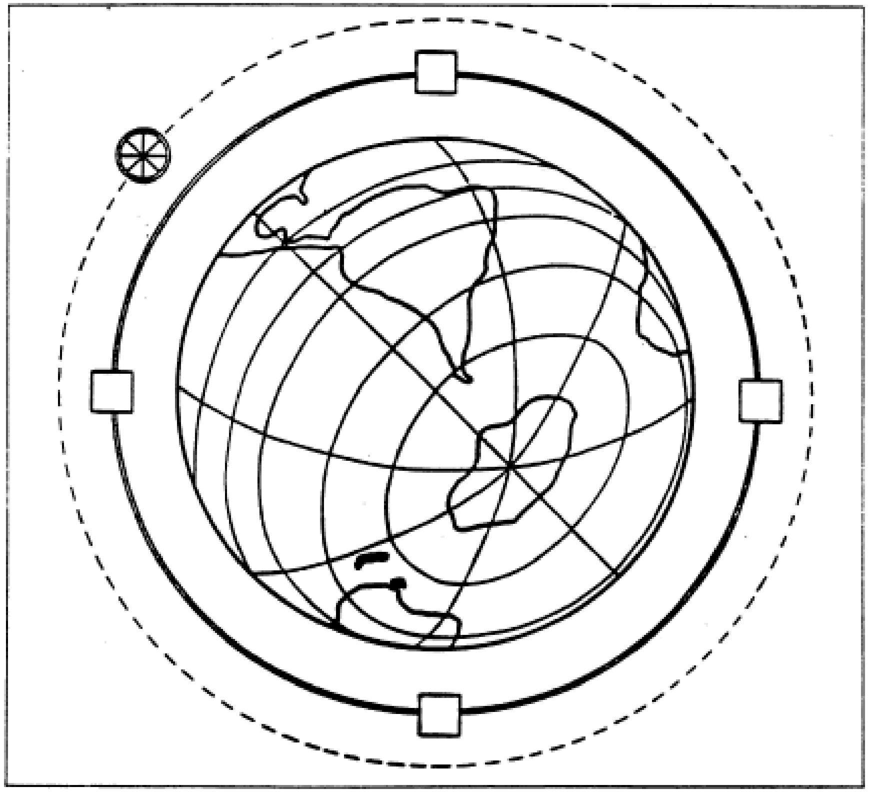
Future Particle Colliders



From a 1954 Slide by Enrico Fermi, University of Chicago Special Collections.

Dmitri Denisov, Fermilab

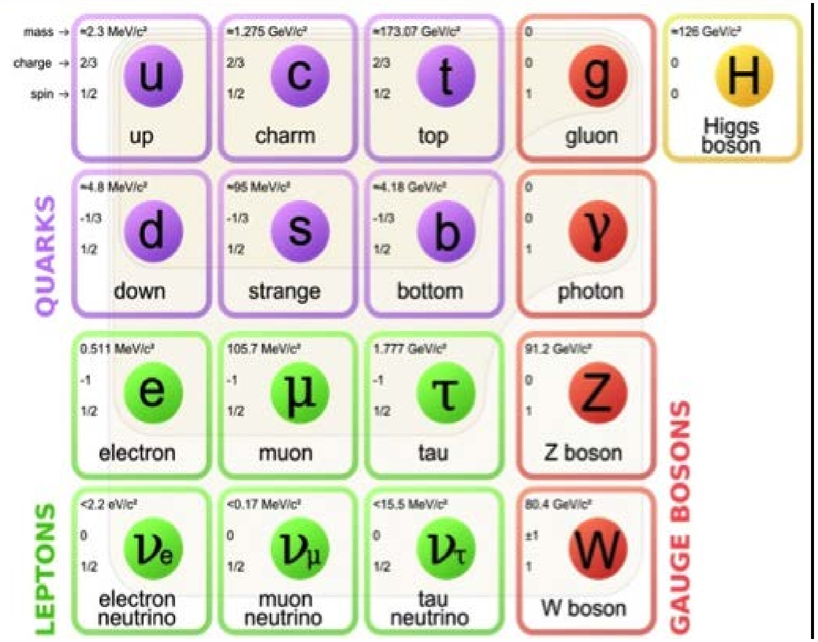
Hadron Collider Physics Summer School, August 15 2016

Outline

- Why colliders?
- Overview of colliders
- Future colliders options and challenges
  - e^+e^-, $\mu^+\mu^-$, pp colliders
- 100 TeV pp collider design
- Medium term future colliders proposals
- Next steps

Particle Physics

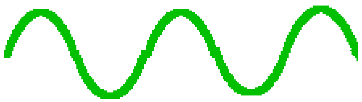
- Standard Model is the theory of elementary particles and interactions
  - Describes majority of phenomena in Nature
  - Makes everything of a small number of objects
    - Quarks and leptons
  - Forces are carried by
    - photon - electromagnetic
    - gluons - strong
    - W/Z bosons - weak
  - Higgs boson provides mass
  - Accurate to a very high precision
    - Better than 10^{-10}
- Addresses 1000's of years hunt of mankind to understand
  - What everything around us is made of



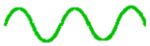
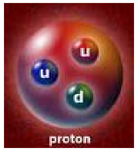
- But our current understanding is incomplete
  - Can't explain observed number of quarks/leptons
  - Model parameters can't be predicted
- Nothing is "wrong" with the Standard Model
  - The goal is to define limits of applicability and find what lies beyond

Why High Energy and Why Colliders

- Accelerators are built to study the Nature smallest objects



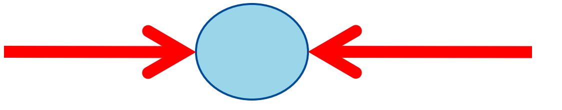

Wavelength = h/E

~2 $\cdot 10^{-18}$ cm for LHC

- Accelerators convert energy into mass

$E = mc^2$



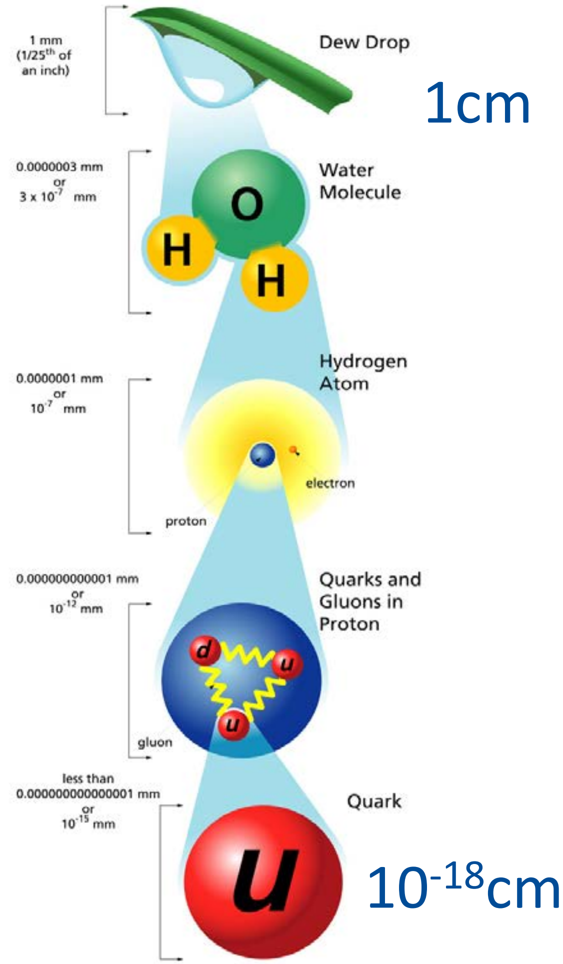
Objects with masses up to
Mass = $2E_{beam}$ could be created

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

Accelerator are “Telescopes for Sub-atomic world”

Fermi National Accelerator Laboratory Accelerator Complex near Chicago



What is next?

Basics of Accelerators

- The only practical way to accelerate elementary particles is to use electric field
  - Can only accelerate charged particles
  - 1 Volt potential provides 1 eV energy to a particle with electron/proton charge
- What types of charged particles?
  - Protons, electrons, muons
  - The rest are either live for a very short time or have no electric charge
  - Up to now all high energy accelerators used electrons or protons/antiprotons as beams
- There are two main types of the accelerators: circular and linear
- Circular accelerators
  - Small area of accelerating electrical field (a few meters) and then particles bended with magnets around circle to pass through the accelerating field many times (millions)
  - Every turn bunch of particles gets more and more energy with each turn
  - Limit in the energy: maximum magnetic field in the magnets for proton accelerators and synchrotron radiation for electron accelerators, length of the tunnel
- Linear accelerators
  - Long straight line with electrical accelerating structures
  - Limited in energy by maximum electric field we can create without sparks and length of the tunnel

Progress in Accelerators Sizes: 4 orders of Magnitude!

First ~12 cm cyclotron by Lawrence – 1930's

Tevatron near Chicago – 1990's

Circular Accelerators

- To keep charged particles rotating around the ring when energy of the beams is increasing bending magnets are needed
  - The key element of a high energy circular accelerator

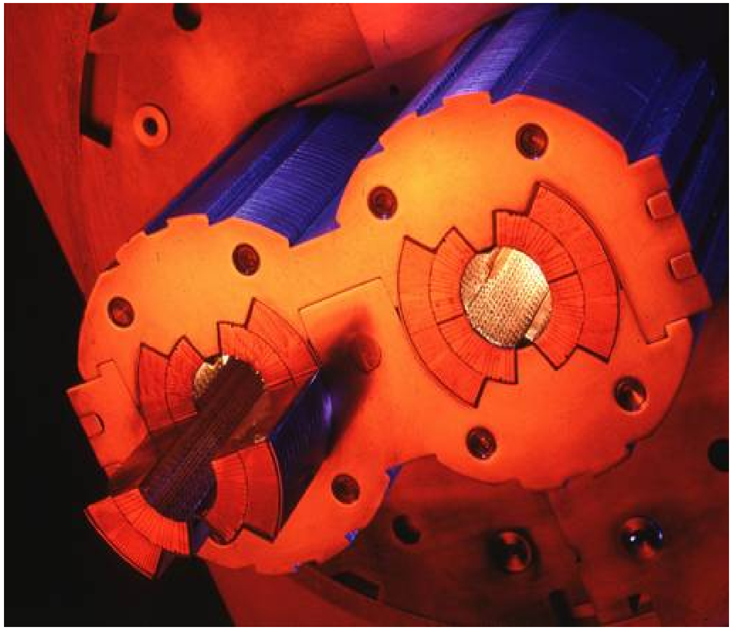
- Radius of the accelerator is

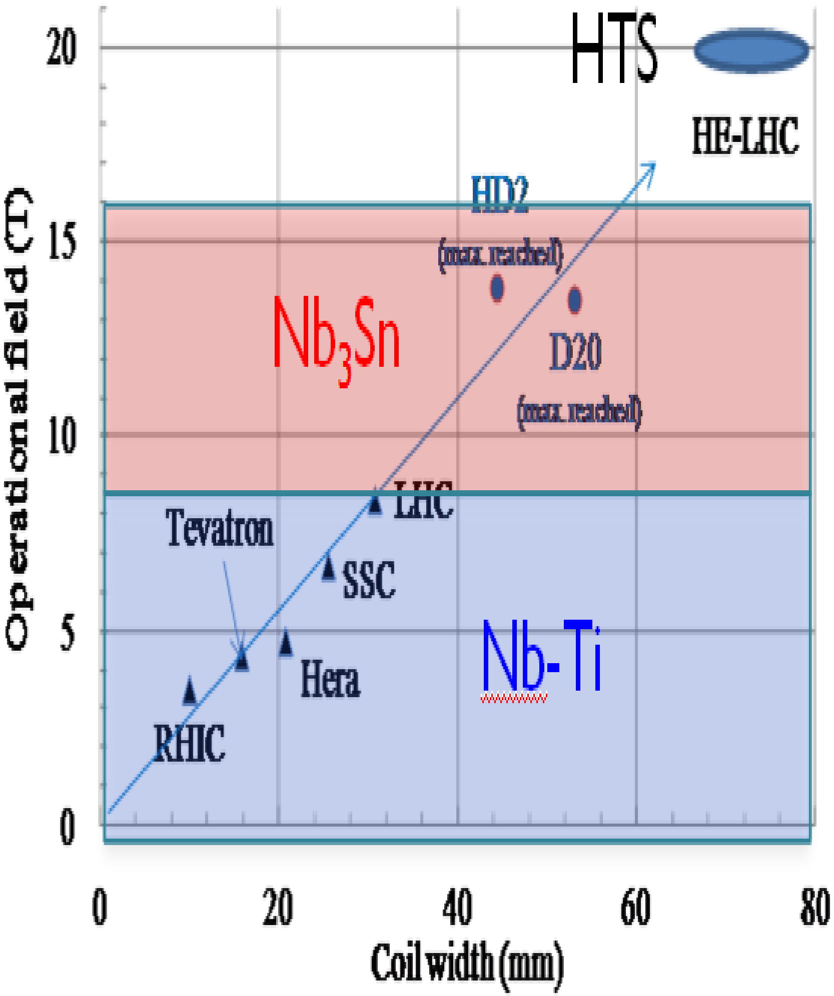
  - $R \sim E_{beam}/B$ where B is magnetic field and E_{beam} is beam energy

- First Fermilab accelerator had energy of ~450 GeV with bending field of ~2 Tesla (room temperature iron magnets)
  - Superconducting magnets increased field to ~4.5 Tesla bringing energy of the beam to ~1 TeV (Tevatron!)
  - At such energy mass of the proton is 1000 times more than it rest mass (of about 1 GeV)
- There are two options to increase energy of a hadron collider
  - Increase magnetic field in the bending magnets
  - Increase radius of the tunnel
  - For e+e- colliders synchrotron radiation is the limiting factor

Bending Magnets Developments

- Two main issues to reach high field
  - Critical superconducting current
  - Mechanical forces acting on coils
- LHC magnets are ~9 Tesla
- Current practical limit is ~16 Tesla

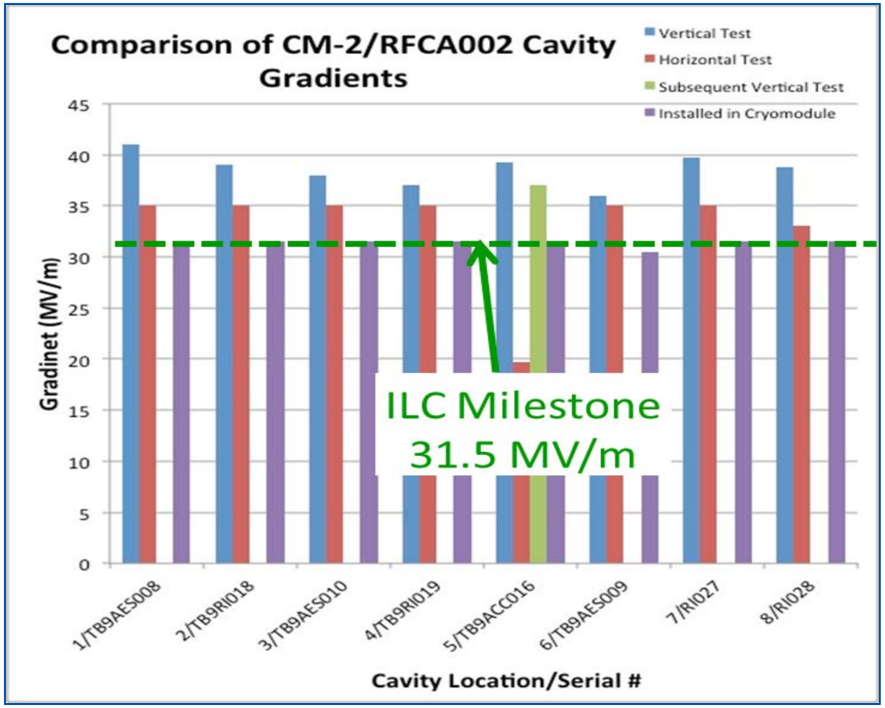




Fermilab

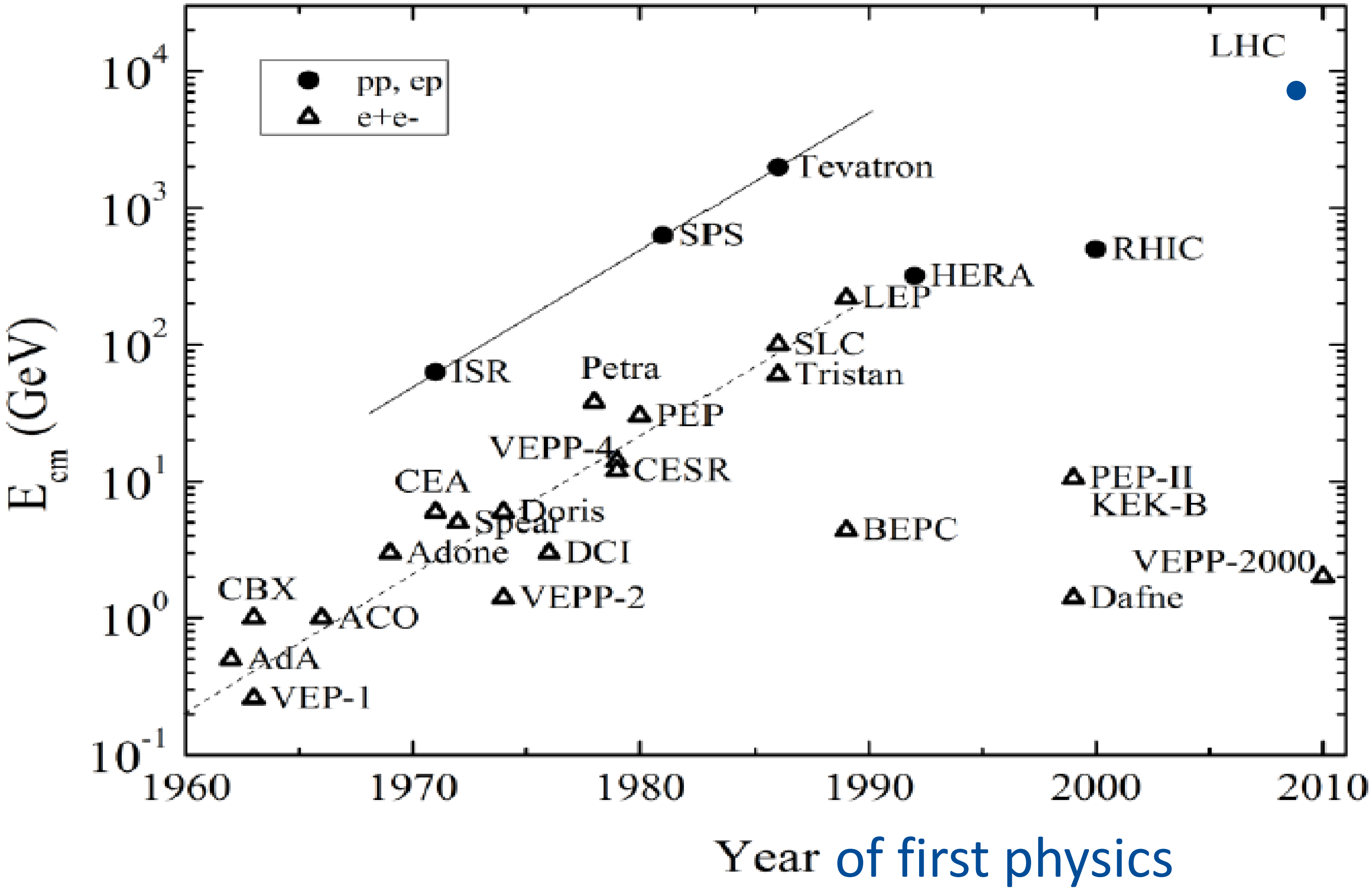
Linear Accelerators

- Major challenge is to create high electric field without sparks
- Usually superconducting "cavities" are used for the acceleration
  - To reduce energy losses
- Oscillating electric field is created along beam line which accelerates particles bunches



- Current maximum field is ~30 million Volts per meter
- To accelerate particle to 1 GeV we need ~30 meters, to 1 TeV, 30 kilometers…

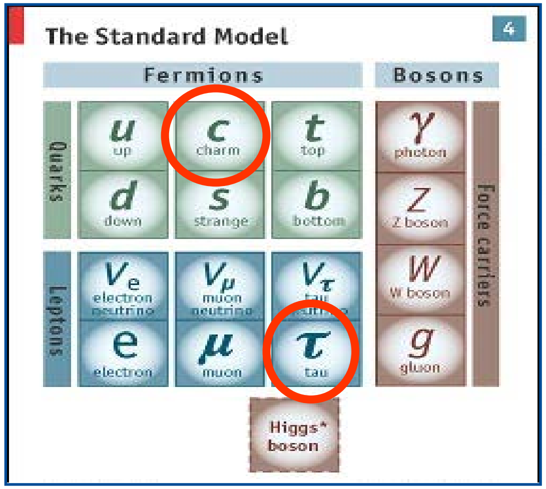
Colliders



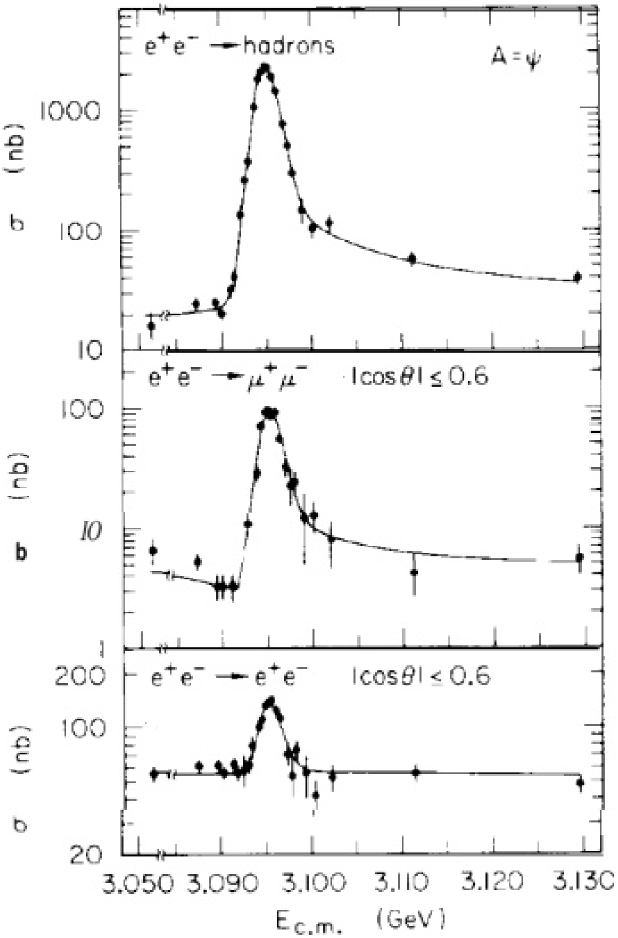
- First e^+e^- colliders started operation in early 1960's with hadron colliders (storage ring) first collisions in 1971 with the completion of the ISR
- Large number of e^+e^- colliders, while few hadron colliders
- Hadron colliders provide higher center of mass energy, while colliding "composite" particles

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

SPEAR construction

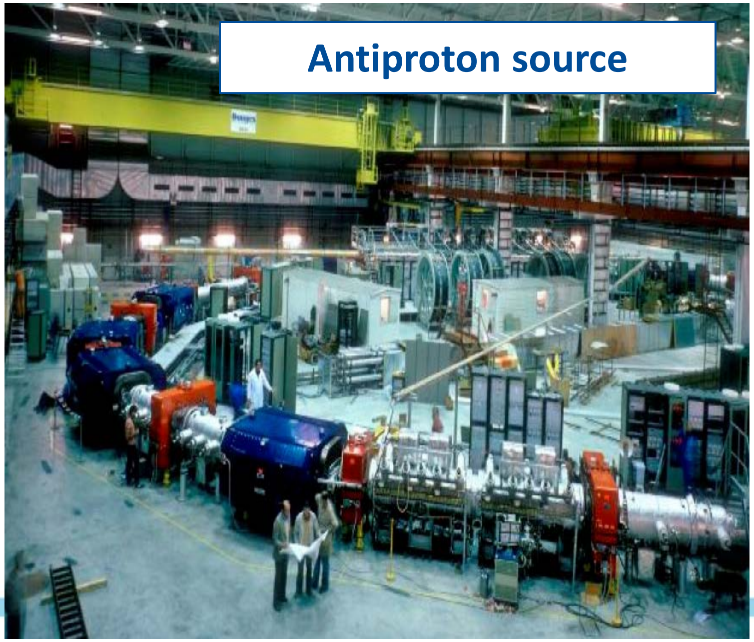


J/Psi discovery

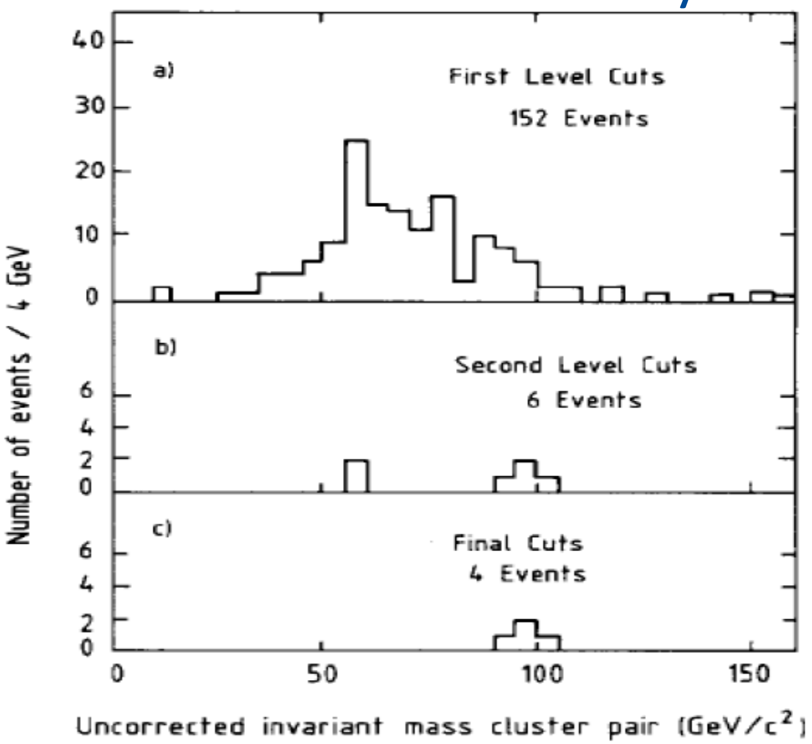


- Started in 1972 with ~3 GeV center of mass energy
- Opened extremely productive energy range
  - Co-discovery of c-quark (J/Psi meson) in 1974
  - Discovery of τ-lepton in 1975
- One of the most productive colliders in the world

SppS Collider at CERN: start 1981

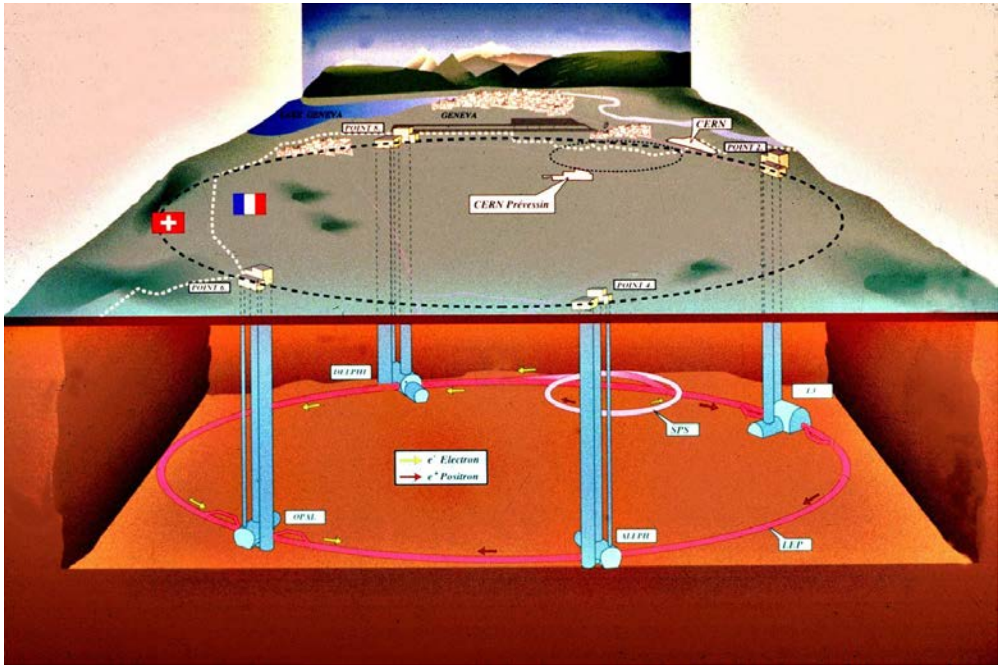


Z boson discovery

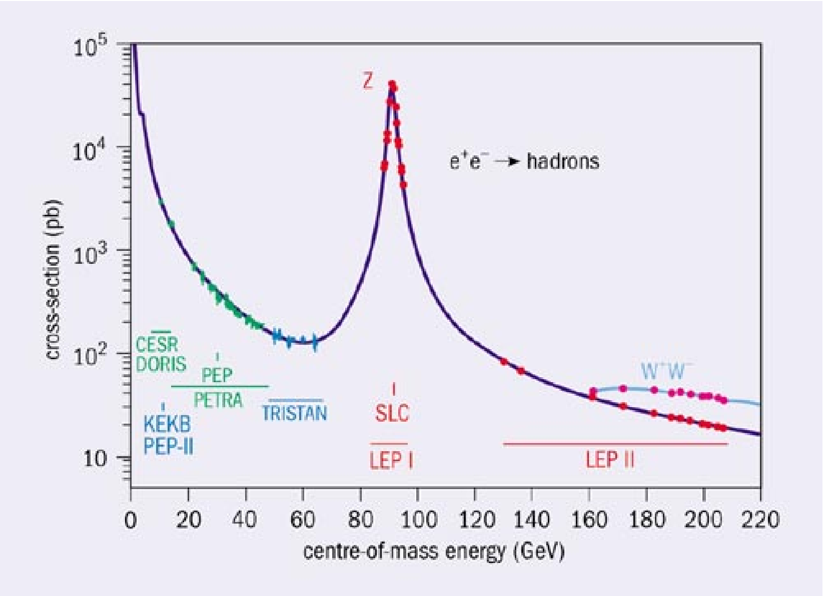


- Use of antiprotons in the existing fixed target accelerator
- Provided next step in the understanding of the standard model
  - W/Z bosons discovered

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

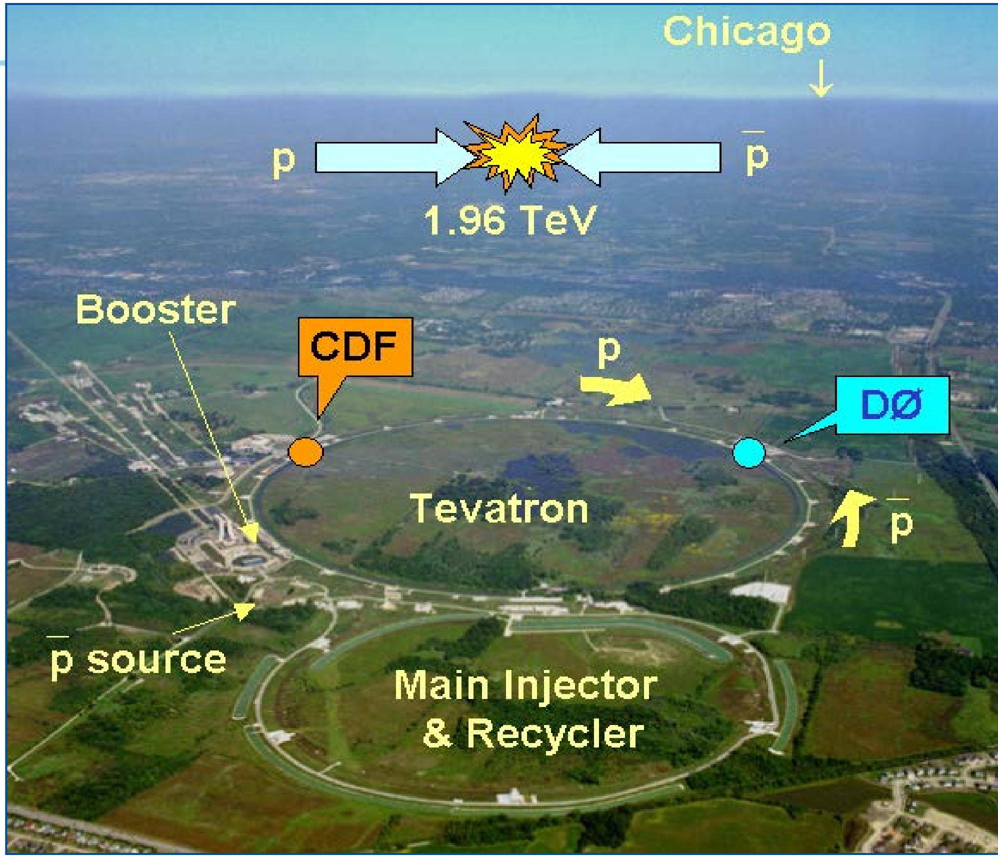


Z boson factory

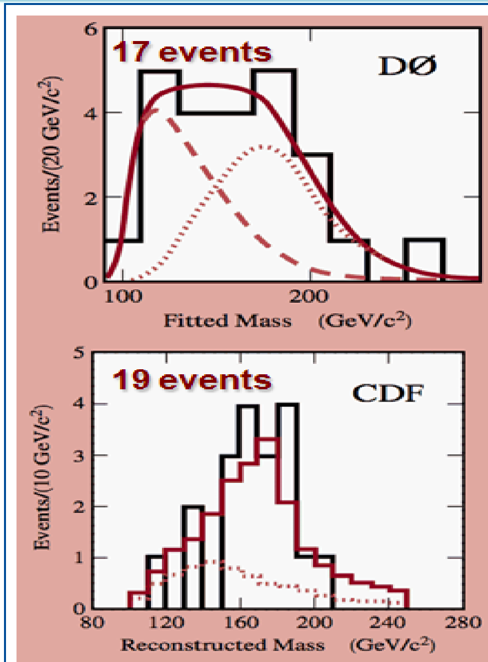


- 27 km long tunnel for up to ~200 GeV center of mass energy
  - Started operation in 1989 as “Z factory”
  - Wide range of extremely precise measurements, including Z boson mass measurement and determination of the number of neutrino generations
- Linear collider Z factory at SLAC operated at about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

The Tevatron: start 1985

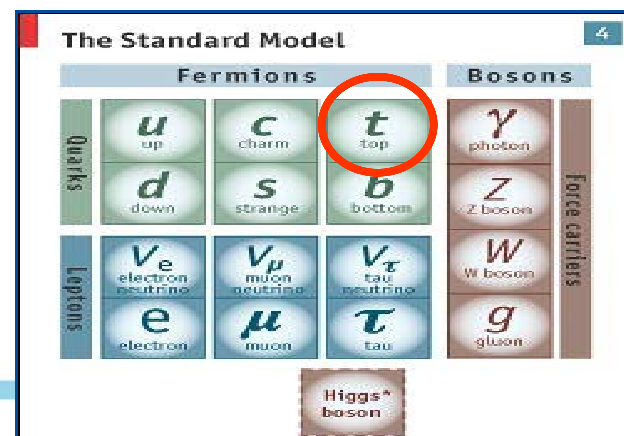


Top quark discovery



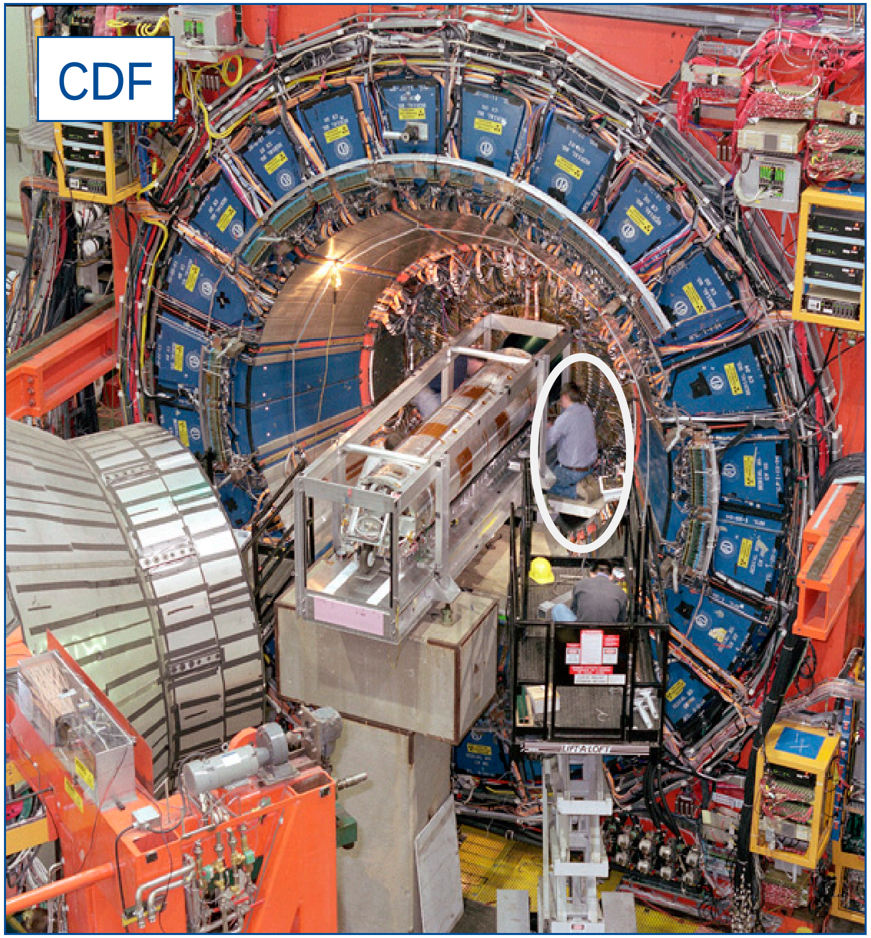
1995, CDF and DØ experiments, Fermilab

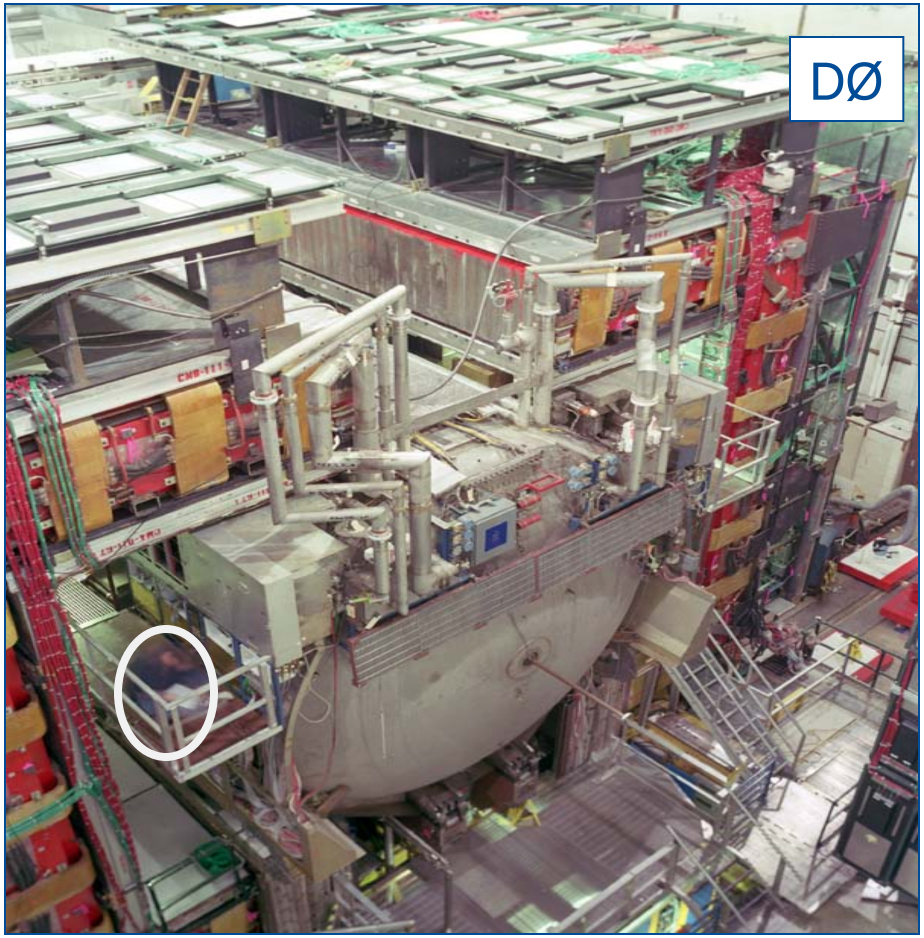
- First superconducting accelerator with 2 TeV center of mass energy
- Discovered last standard model quark – the top quark



CDF and DØ Detectors

In order to analyze millions of interactions per second with particles carrying kinetic energies 100's times above their rest mass two complex detectors have been built at Fermilab

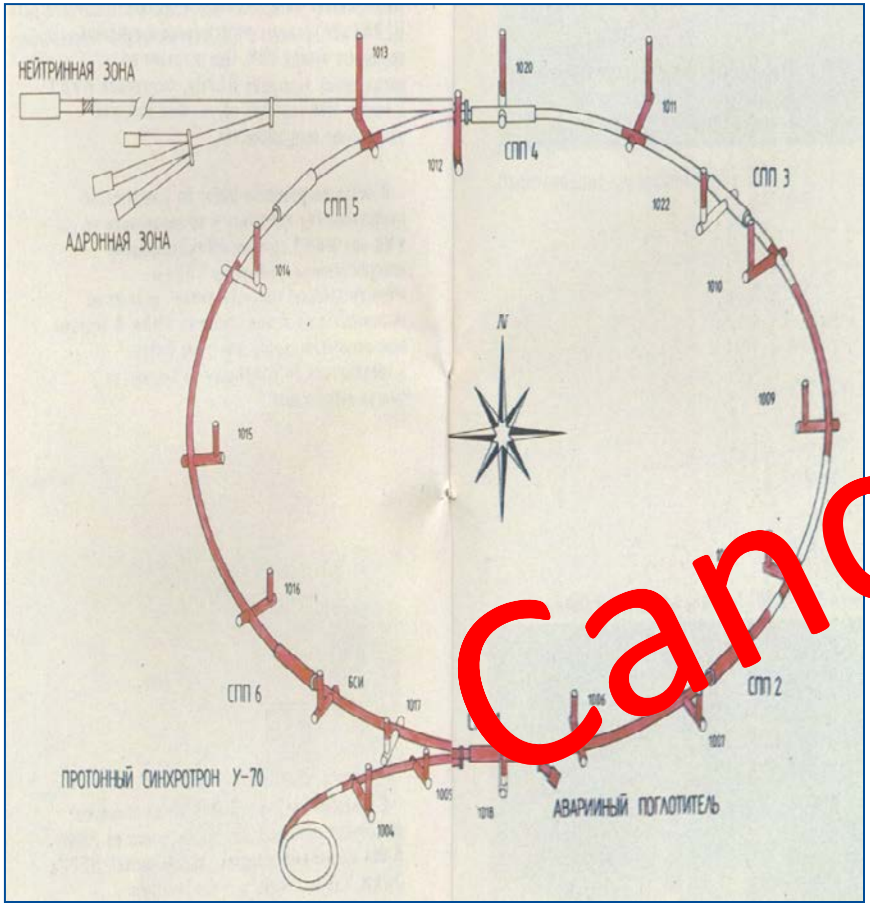


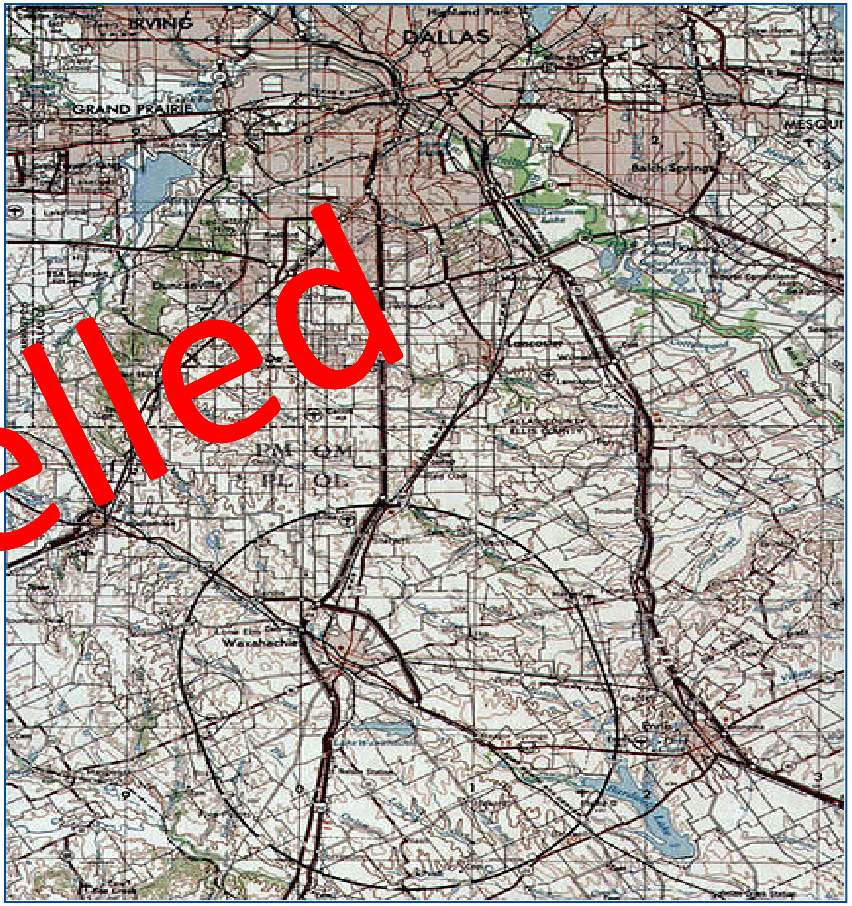


Attempts to Reach Higher Energies: 80'-90's

USSR

USA



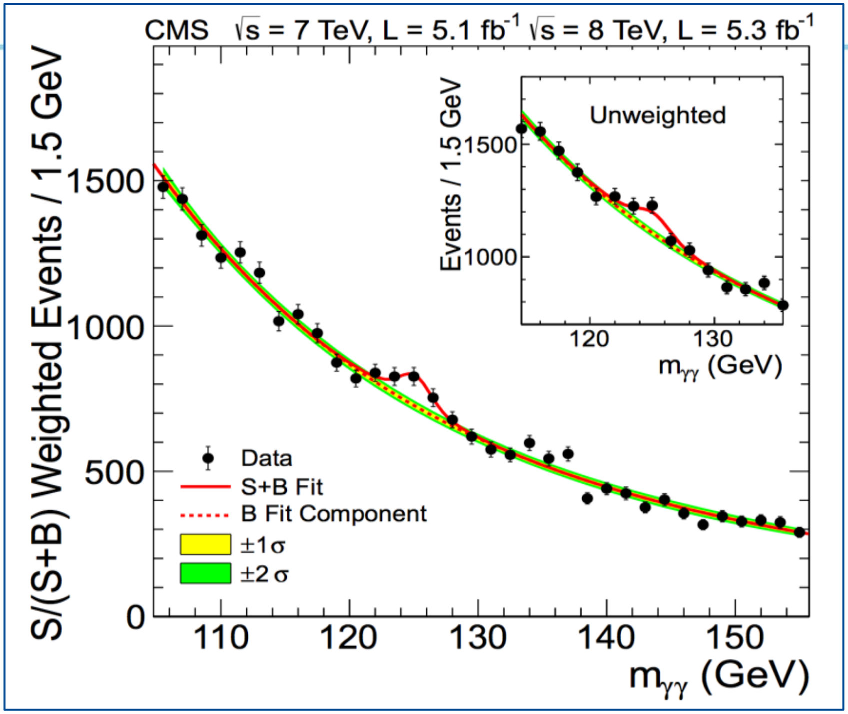


Cancelled

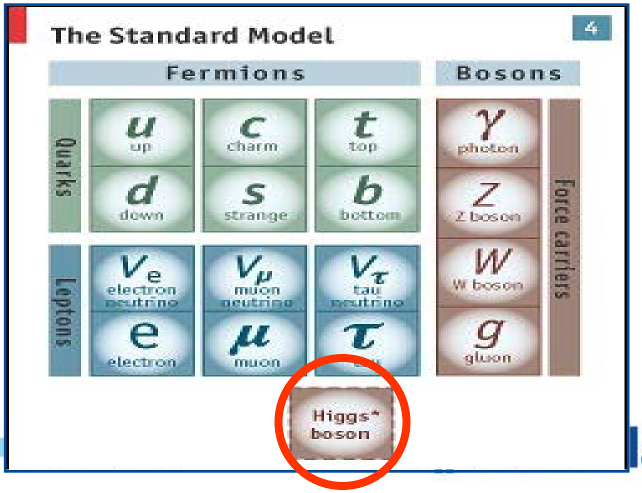
3x3 TeV, UNK

20x20 TeV, SSC

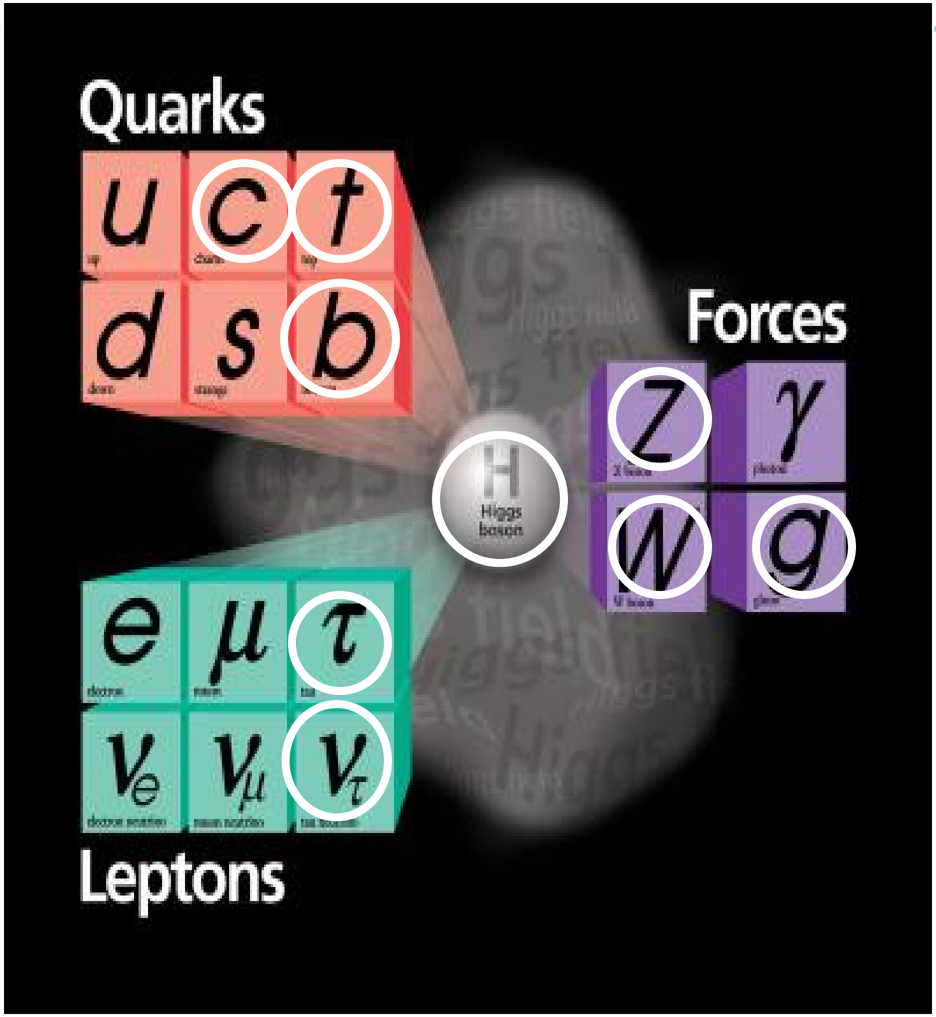
The LHC – the History in the Making



- 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



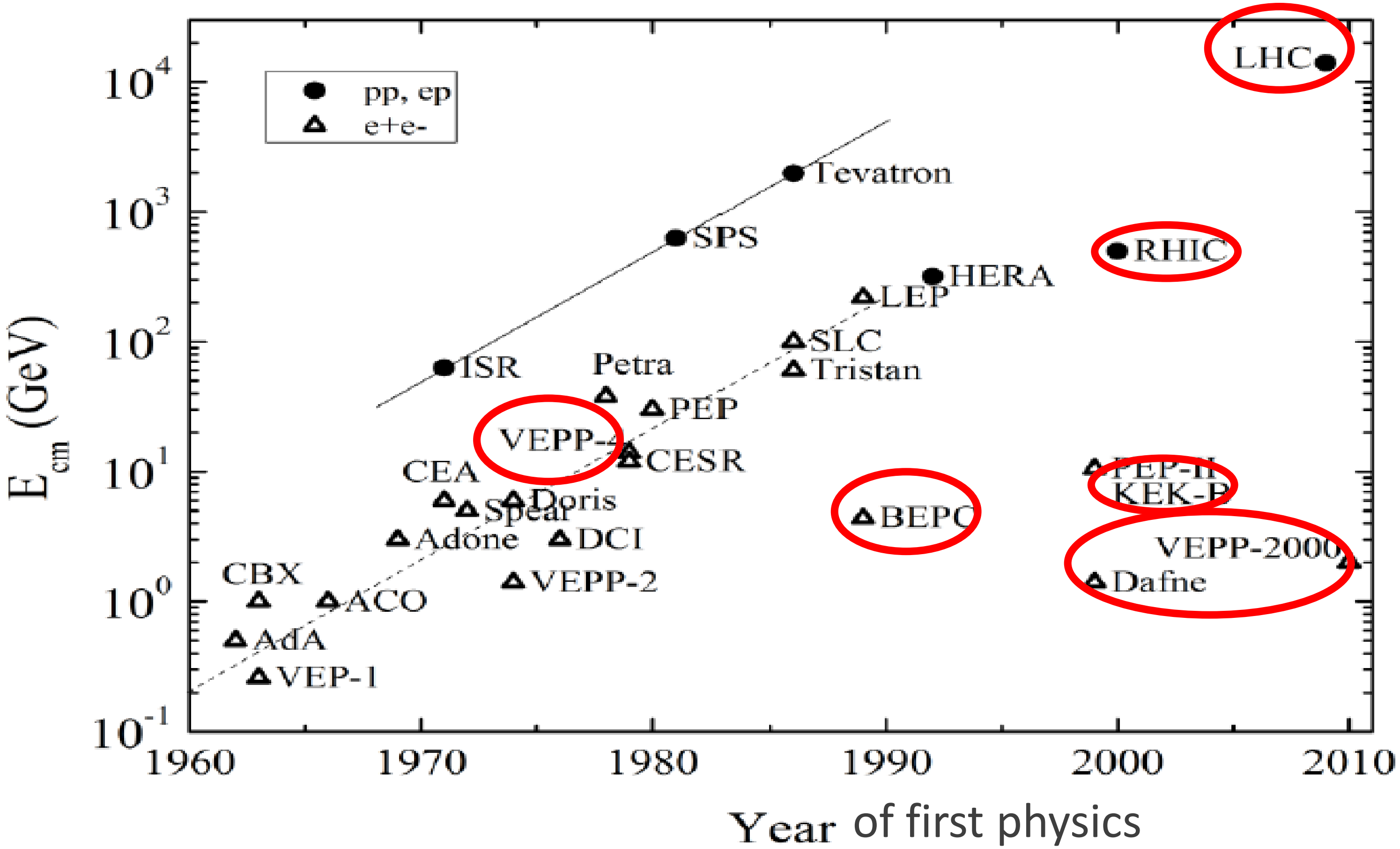
Accelerators and the Standard Model



- 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 and b quark 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



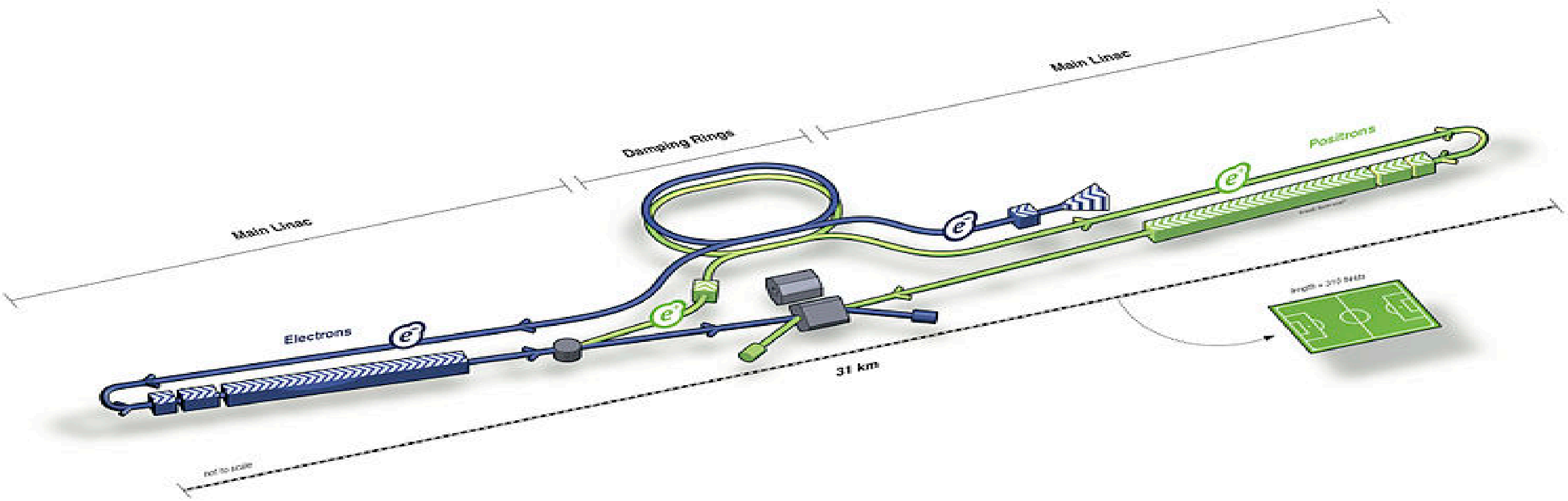
- Single high energy hadron collider – the LHC, now at 13 TeV
  - RHIC at BNL – nuclear studies
- DAFNE (Frascati), VEPP (Novosibirsk), BEPC (Beijing) – low energy e^+e^- colliders
- SuperKEK-B – b-factory at KEK restarted in 2016 with ~40 times higher luminosity
  - Studies of particle containing b-quarks

Physics Goals and Challenges of the Future Colliders

- Physics interests drive colliders development
  - Like colliding antiprotons in the already existing ring 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
- 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

e^+e^- Colliders

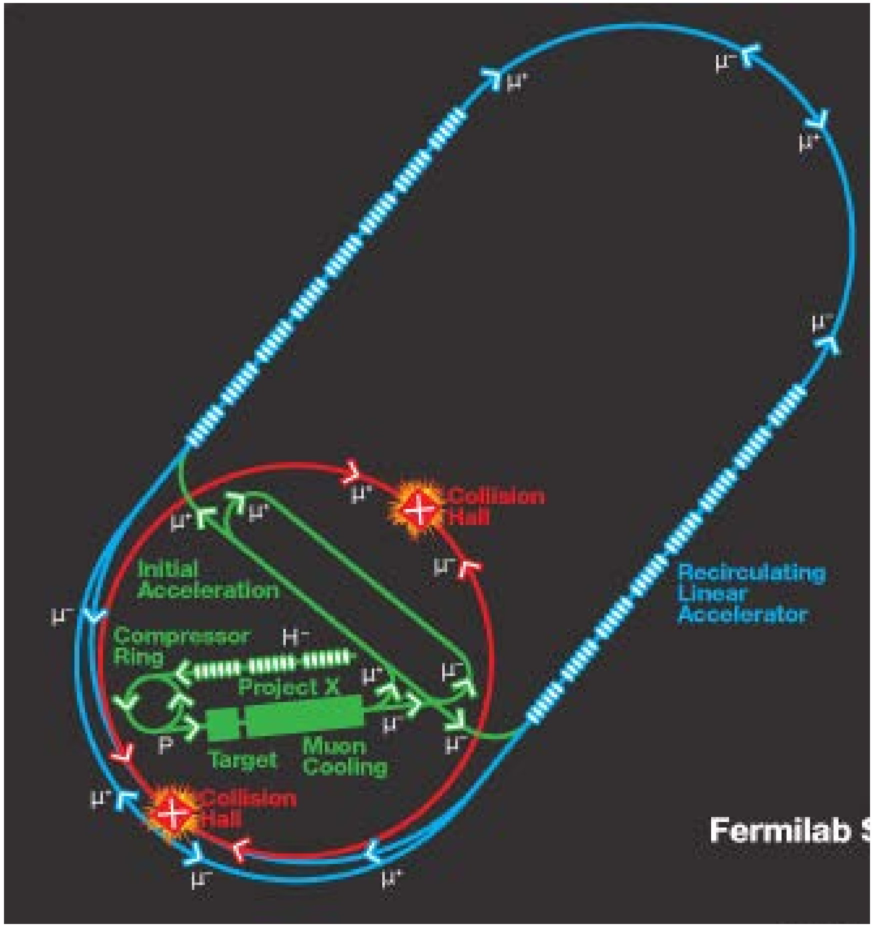
- Circular and linear
  - Large Electron Positron (LEP) collider
  - International Linear Collider (ILC) and SLAC linear collider
- Major limitations of circular e^+e^- colliders
  - Synchrotron radiation causes electrons to constantly loose energy
    - Energy loss is proportional to γ^4 (~3% per turn for LEP)
    - Power consumption is 100's MW
  - Limit energy to ~0.5 TeV even for ~100 km long ring
- Major limitation of linear colliders
  - Need to add energy to electron in "one path"
  - Rate of adding energy is limited to ~30 MeV/meter, requires ~30 km long tunnel to reach ~1 TeV energy



$\mu^+\mu^-$ Colliders

- Muons are “heavy electrons”, they do not have high synchrotron radiation making circular accelerator viable for multi TeV energies
  – γ factor at the same energy is ~200 times less than for the electrons
- Muons are unstable with life-time of 2.2 micro seconds
  – Decay to an electron and a pair of neutrinos
  – With γ factor of 1000, 2.2 milli seconds lifetime in the lab system -1000 km flight at a speed of light
- Main accelerator challenge
  – To make large number of muons quickly and then “cool” them to focus into small diameter beam to collide
- Another issue are decays and irradiation by electrons from muon decays
  – and neutrinos irradiation!

2x2 TeV



Fermilab

Hadron Colliders

- What particles to collide: pp or ppbar ?
  - Using antiprotons in the first high energy colliders was “quick” way to get to higher center of mass energy by using existing(!) rings designed for fixed target accelerators:
    - If accelerator complex is designed from the start as a collider, it is better to have proton-proton collisions
    - An order of magnitude or more higher luminosity
    - No complex antiproton sources

- All hadron colliders designed since early 1980’s are proton-proton colliders
  - Two separate beam pipes

- Point-like vs not point-like colliding particles
  - Only fraction of the beam energy is utilized in the collision: up to ~50%
  - Lack of precision knowledge about event kinematics is a challenge

Design Study for Very Large Hadron Collider

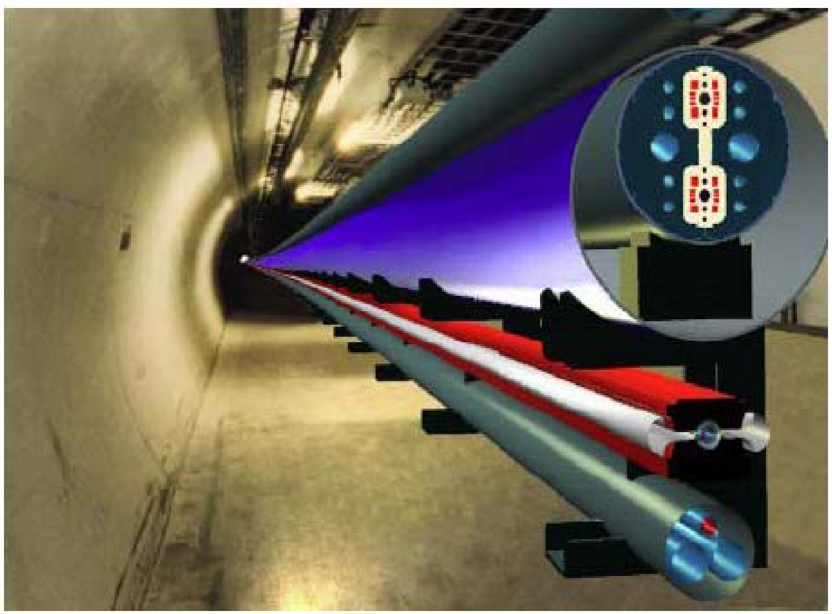
Very Large Hadron Collider

Fermilab-TM-2149

June 4, 2001

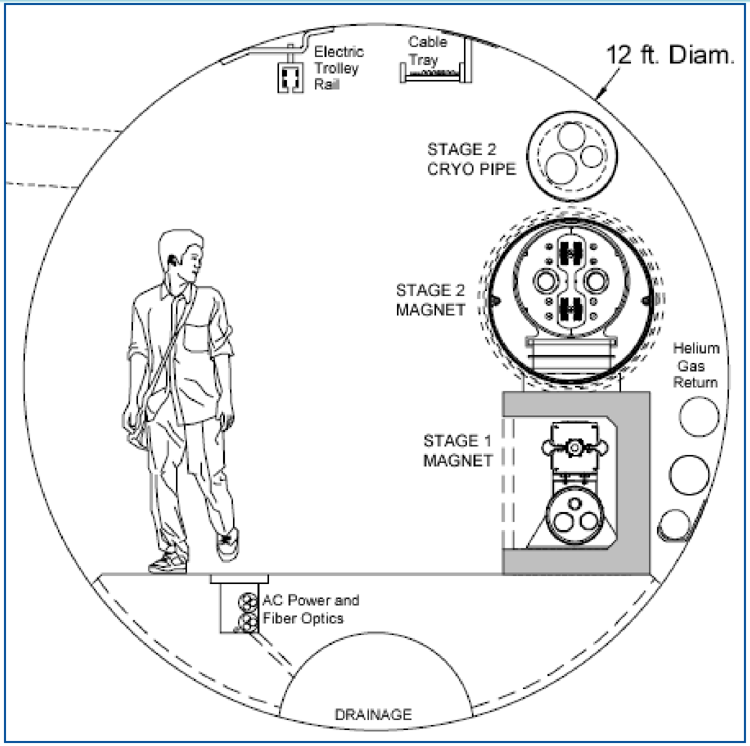
Design Study for a Staged Very Large Hadron Collider

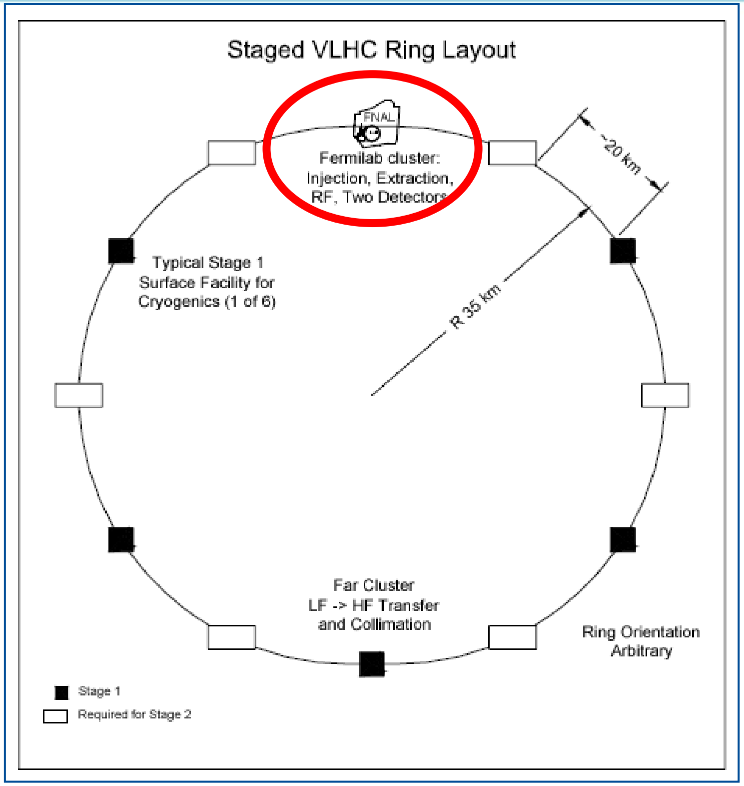
Report by the collaborators of
The VLHC Design Study Group:
Brookhaven National Laboratory
Fermi National Accelerator Laboratory
Laboratory of Nuclear Studies, Cornell University
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center



- Study performed by international design group
- Main goals were
  - New ideas
  - Technical design and feasibility
  - Cost estimate
- "Staged" means first stage of 40 TeV and second stage of 175 TeV

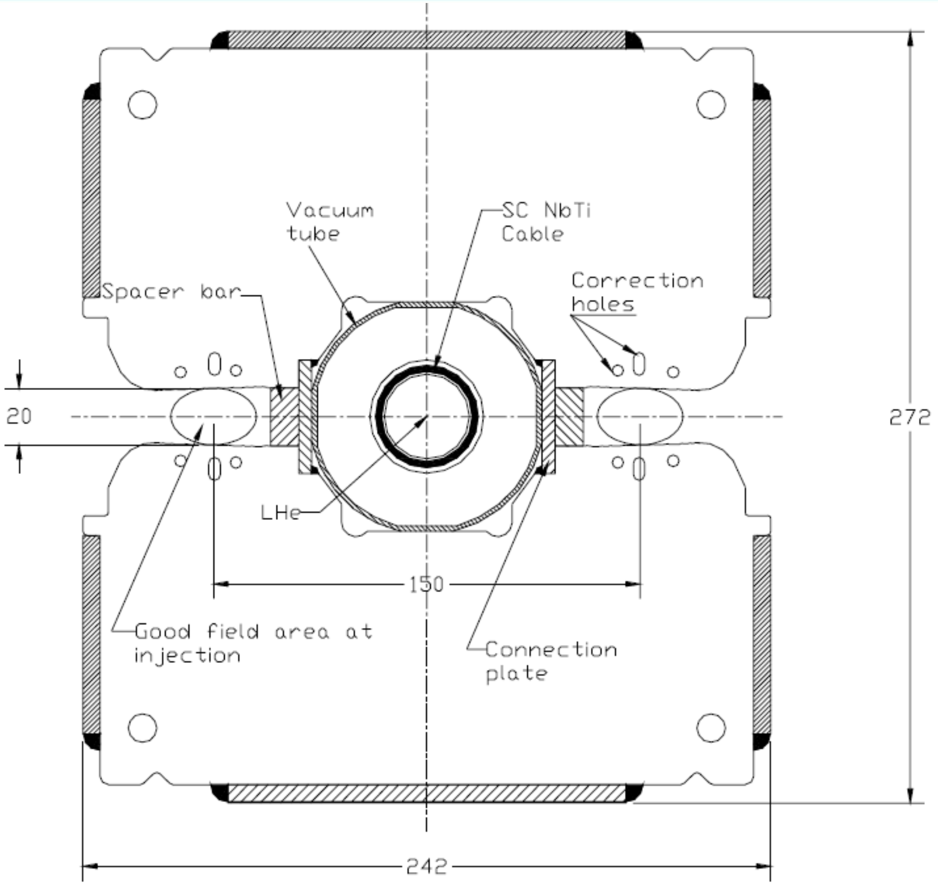
Main Idea: Long Tunnel vs Highest Field Magnets





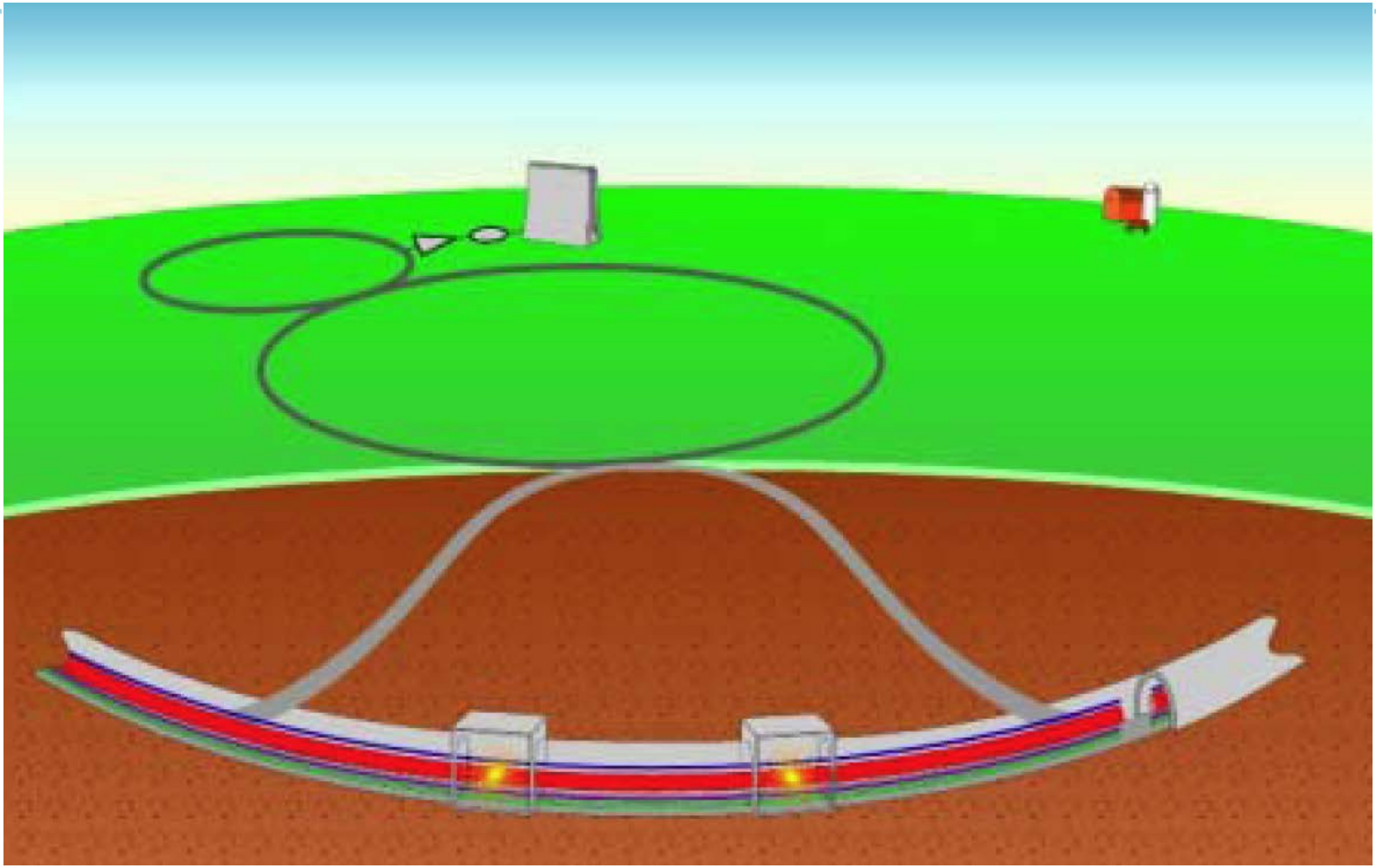
- Tunnel length proposed is 233 km, small diameter, deep underground, only few shafts
- Two stages: “stage 1” is 2 Tesla warm steel magnet at 40 TeV energy, “stage 2” is 10 Tesla dual core magnet at 175 TeV energy
- Over last ~20 years long and deep tunnels technology was greatly advanced

Idea of “one turn” Magnet



- The idea is to use warm iron (means 2 Tesla max field) with “single turn” coil
- All parts of the magnet are “very simple”, like extruded vacuum chamber
- Number of “parts” in cross section is ~10, vs ~100 for high field magnets

Fermilab's Complex as Injector



Fermilab's accelerator complex is used as an injector with two main collision points located under Fermilab's site

Parameters of 40-175 TeV Collider

Table 1.1. The high-level parameters of both stages of the VLHC.

	Stage 1	Stage 2
Total Circumference (km)	233	233
Center-of-Mass Energy (TeV)	40	175
Number of interaction regions	2	2
Peak luminosity ($cm^{-2}s^{-1}$)	1×10^{34}	2.0×10^{34}
Luminosity lifetime (hrs)	24	8
Injection energy (TeV)	0.9	10.0
Dipole field at collision energy (T)	2	9.8
Average arc bend radius (km)	35.0	35.0
Initial number of protons per bunch	2.6×10^{10}	7.5×10^{9}
Bunch spacing (ns)	18.8	18.8
β^* at collision (m)	0.3	0.71
Free space in the interaction region (m)	± 20	± 30
Inelastic cross section (mb)	100	130
Interactions per bunch crossing at L_{peak}	21	54
Synchrotron radiation power per meter (W/m/beam)	0.03	4.7
Average power use (MW) for collider ring	25	100
Total installed power (MW) for collider ring	35	250

Detectors for 100 TeV pp Collider

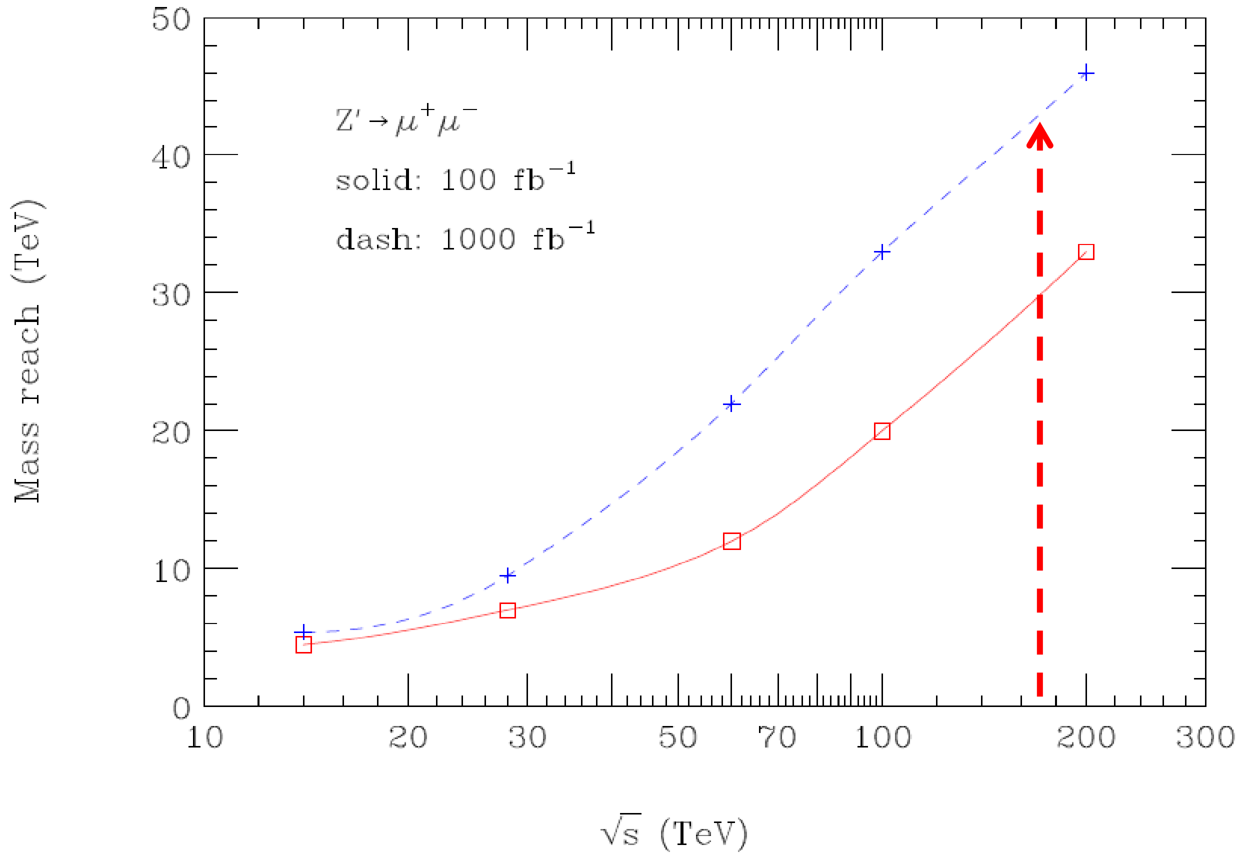
- We would like to detect all “well know” stable particles including products of short lived objects decays: pions, kaons, muons, etc.
  - Need 4π detector with layers of tracking, calorimetery and muon system
- Central tracker
  - Most challenging is to preserve momentum resolution for ~10 times higher momentum tracks
- Calorimetry
  - Getting better with energy: hadronic energy resolution ~50%/$\sqrt{E}$, 2% at 1TeV
  - Length of shower increase has log(E) dependence – not a major issue
- Muon system
  - Main challenge is momentum resolution and showering of muons as they are becoming “electrons” due to large γ factor
- Occupancies and radiation doses
  - Up to luminosity 10^{35} cm^{-2} sec^{-1} looks reasonable, challenging for above both due to pileup and radiation aging

Detectors are “doable”, main challenge is the accelerator size/cost

Medium Term Colliders Projects Under Design

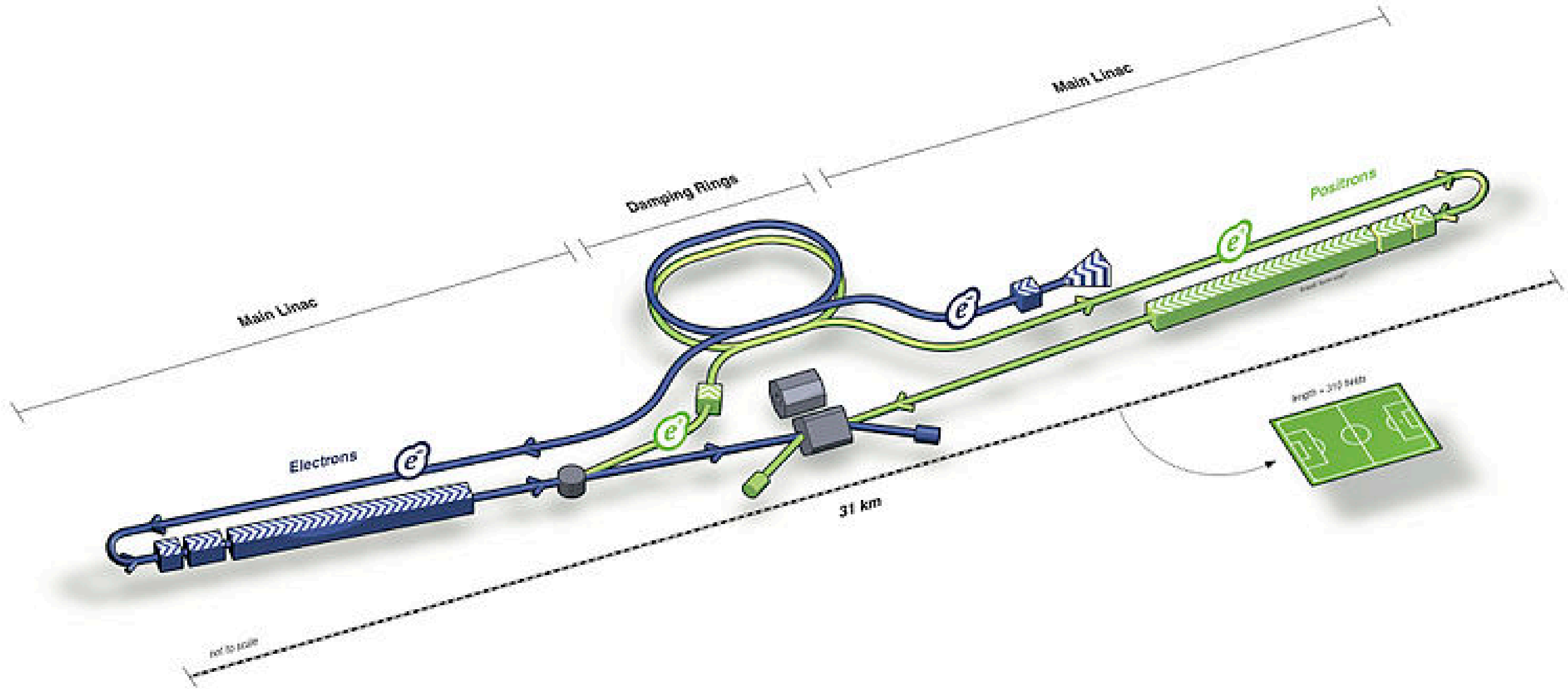
- **ILC - International Linear Collider**
  - 500 GeV linear e^+e^- collider (upgradable to 1 TeV)
  - Higgs factory (and top quark factory)
  - Location – Japan
  - Start of construction ~2019
  - Estimated cost ~$10B
- **CepC – Circular Electron Positron Collider**
  - ~250 GeV circular e^+e^- collider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

Collider Energy and Mass Reach



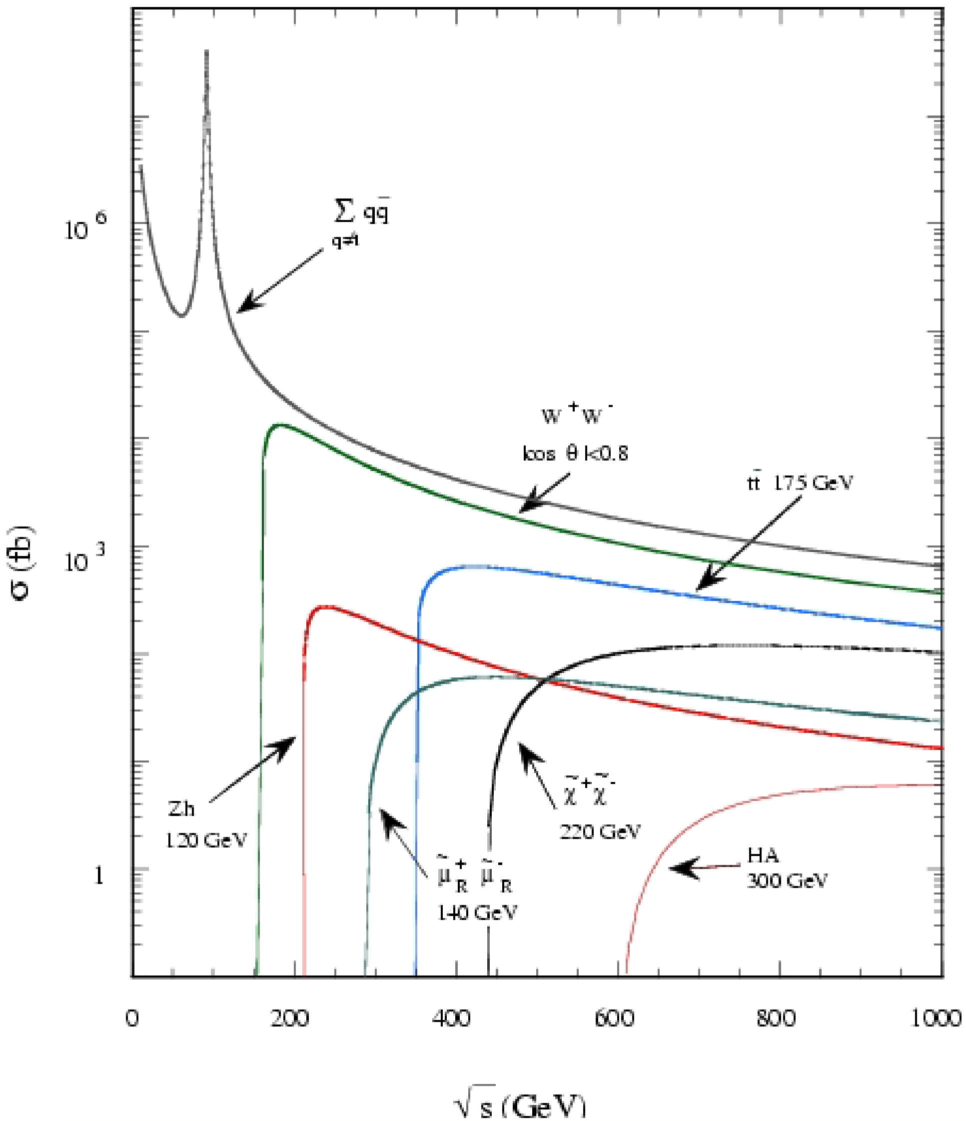
- Many studies done on the reach of high energy hadron colliders
- With reasonable luminosity mass reach for direct searches of ~1/2 of the full collider energy is achievable

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

ILC Physics and Experiments



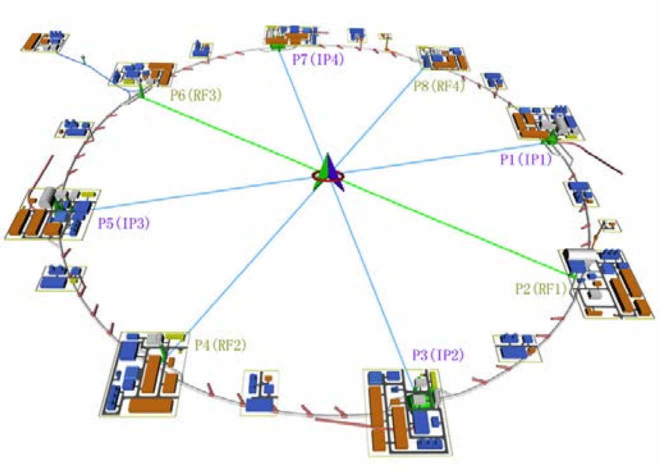
- Low cross sections
  - High luminosity needed
- Low rate of interactions
  - Collect all events
  - High efficiency needed
- Point like particles colliding
  - Sharp thresholds
  - Can be used for precision measurements including top quark mass
- Large number of different production/decay channels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

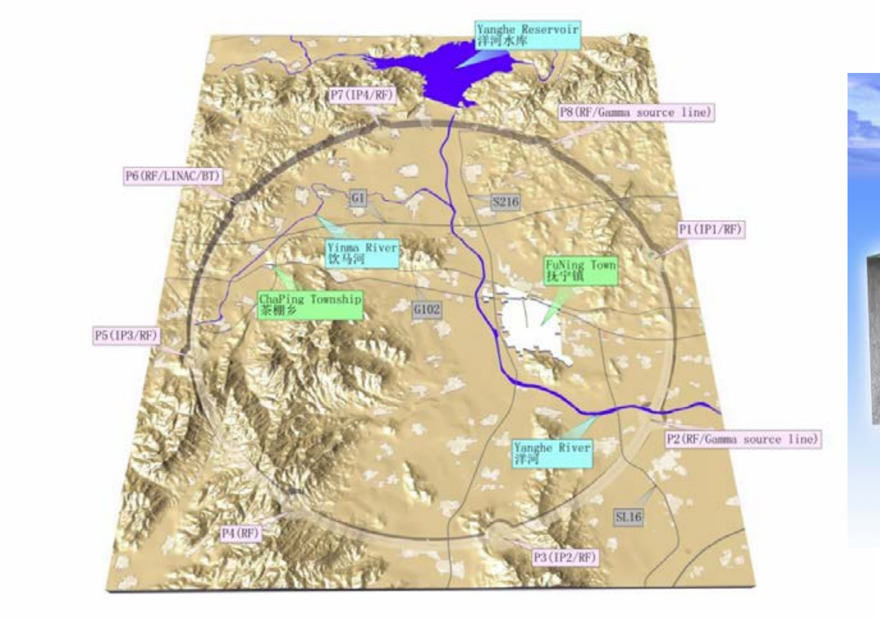
ILC Status and Plans

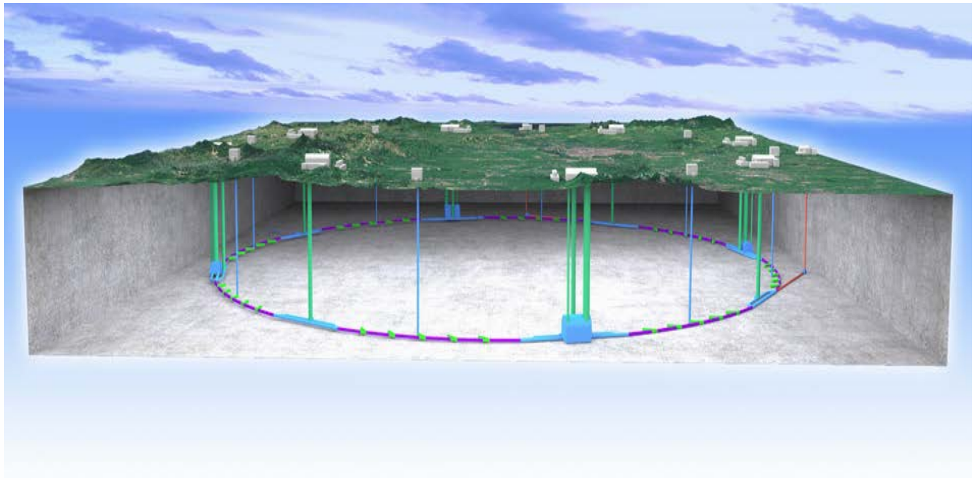
- Starting in 2008 Global Design Effort (GDE) progressed developing
  - Technical design of the ILC
  - Cost estimate and international cooperation plan
- GDE concluded in 2012
  - Including designs for the accelerator and detectors
  - Physics case strengthened with a Higgs discovery
- In 2012 Japan expressed strong interest to host the ILC
- Over last four years
  - Substantial progress in technical developments
  - Development of cooperation between Governments
- 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

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

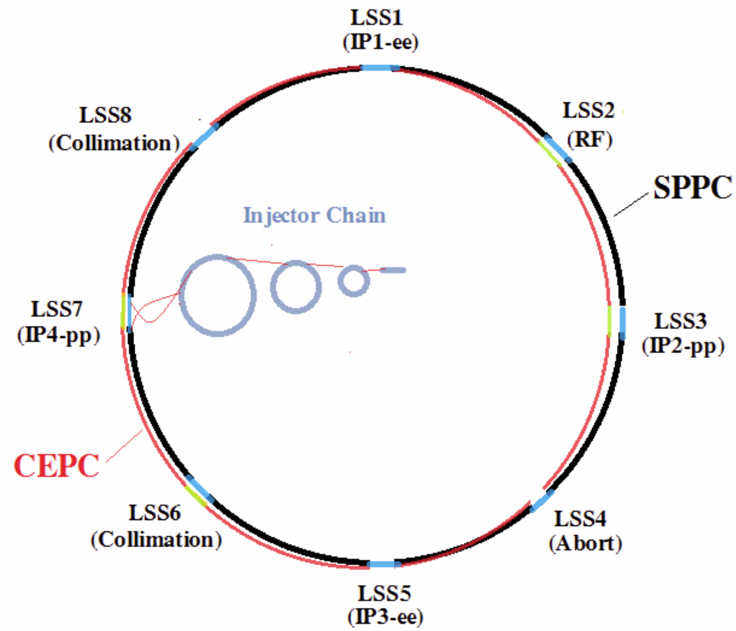






Future Colliders in China

- Very active progress with 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
  - Completed by 2020
- Construction for e^+e^- to start in 2021
  - Completed in 2027
  - Data collection 2028-2035
- Proton-proton collider time line
  - Design 2020-2030
  - Construction 2035-2042
  - Physics at ~70 TeV starting in 2043
- The proposal is based on
  - Experience with existing e^+e^- collider in China
  - Relatively inexpensive tunneling in China
  - Strong Chinese Government interest in scientific leadership



FCC – Future Circular Colliders at CERN

- 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 starting from 350 GeV e^+e^- collider and later going to 100 TeV pp collider is considered
  - But in no way decided

Fermilab

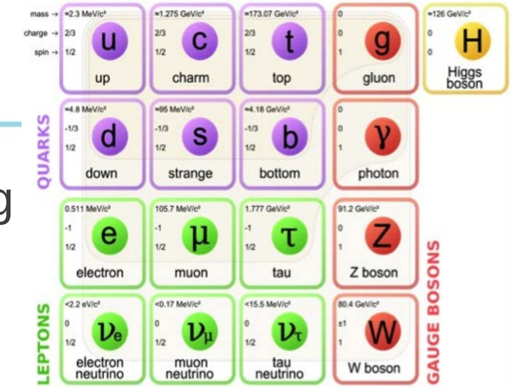
CERN's pp 100 TeV collider

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}	5 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

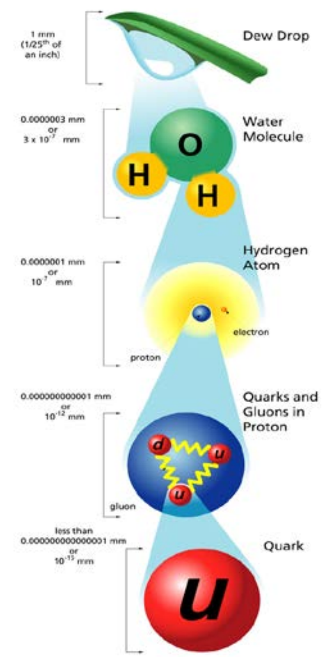
- Main challenges
  - Long tunnel
  - High field magnets
  - High synchrotron radiation load – for protons!
- Tevatron and LHC experience demonstrate feasibility of such a collider

FCC study is expected to take ~3 years and to provide technical proposals and cost estimates for all three options: pp, ee and ep

Future Colliders - Summary



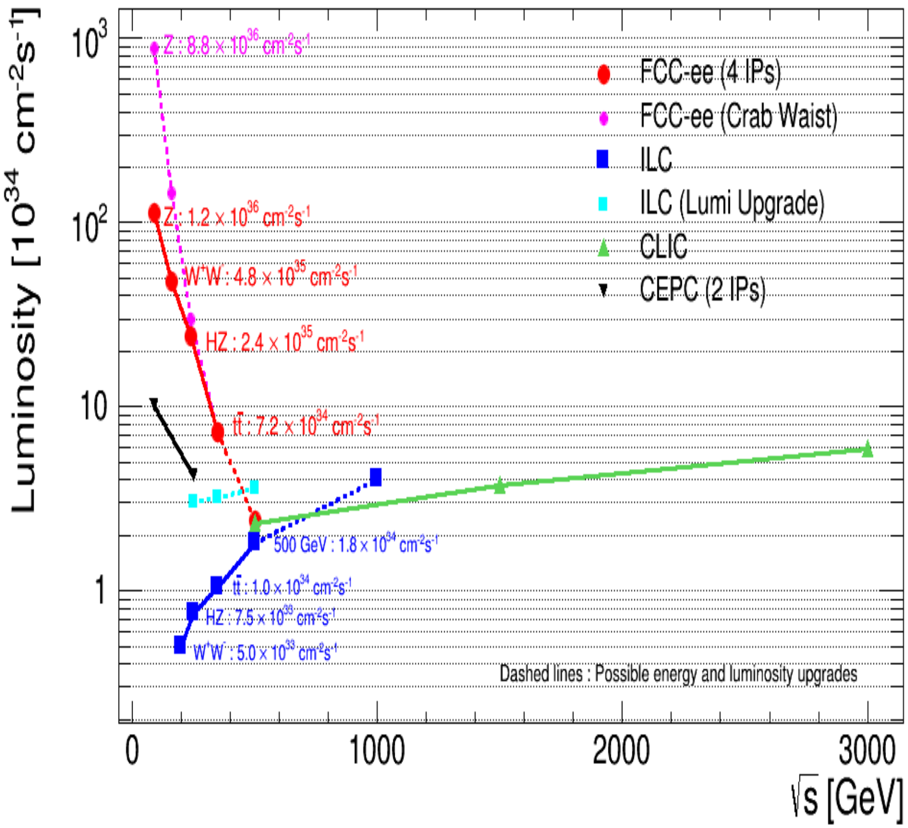
- Colliders played major role in establishing and understanding the standard model
  - Discovered all expected standard model particles!
- Developing colliders and detectors provided many technological breakthroughs
- Future proposed colliders are of two types
  - e^+e^- colliders as “Higgs factory”
  - pp colliders at “the next energy frontier”
- There are many interesting ideas under studies
  - Muon colliders, electron-proton colliders, plasma based accelerators and others
- Sooner of later mankind will find options to built higher energy colliders
  - As this is the only way to progress toward understanding nature on even smaller distances and higher mass scales!



What is next?

Fermilab

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

Large International Collaborations

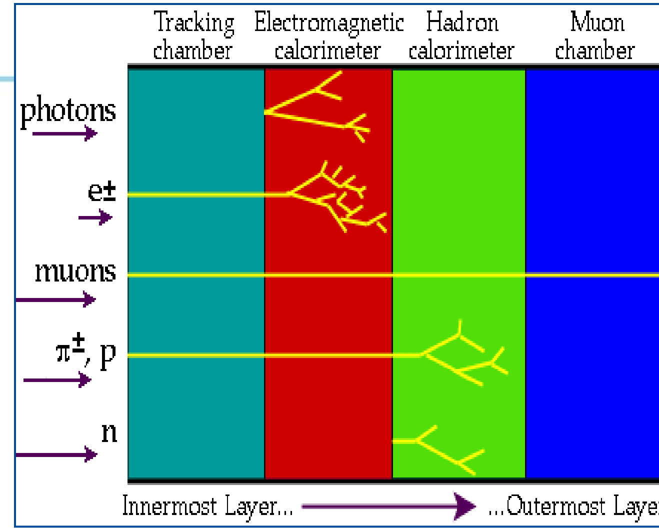
Behind all technical complexity there are 100's of excellent scientists from all over the world working closely together excited by the challenge of pushing limits of knowledge and discovering unknown

CDF : ~600 physicists, 15 countries, 63 institutions

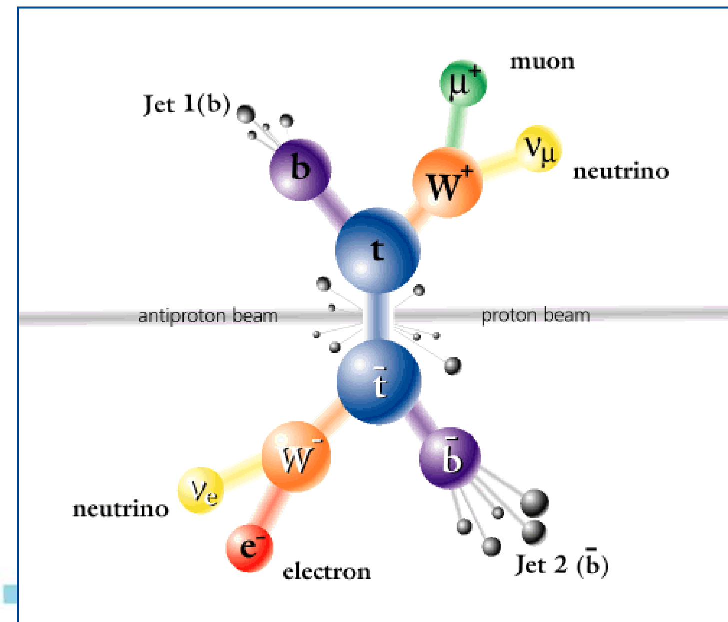
DØ : ~550 physicists, 18 countries, 90 institutions

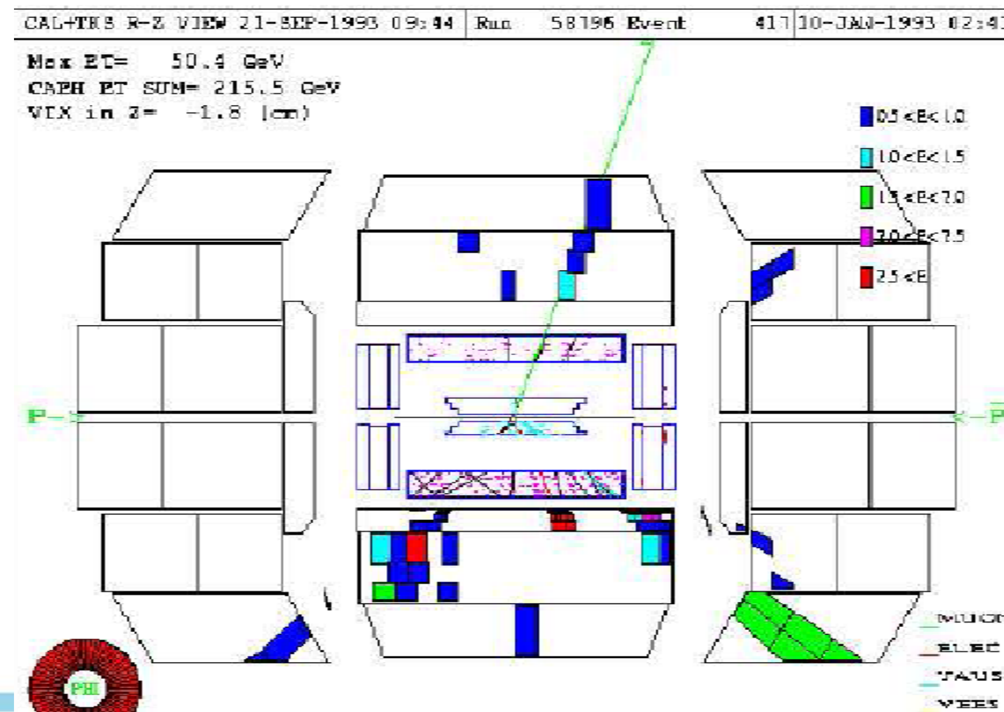
How Physicists Detect Particles

- Majority of particles decays into other particles almost immediately
  - Detectors surround interaction region
  - Many layers to detect different species
- Particles we study have very high energies large detectors are needed to absorb them
- We are taking millions of “pictures” per second to analyze collected data “off-line”



Top quark pair production





Top quark pair production event display

Technology Breakthroughs Now Used in Many Applications

1980's

2000's

Development of supeconducting magnets for the first superconducting accelerator in 1970's and 1980's paved the way for use of supeconducting coils for medical imaging via MRI