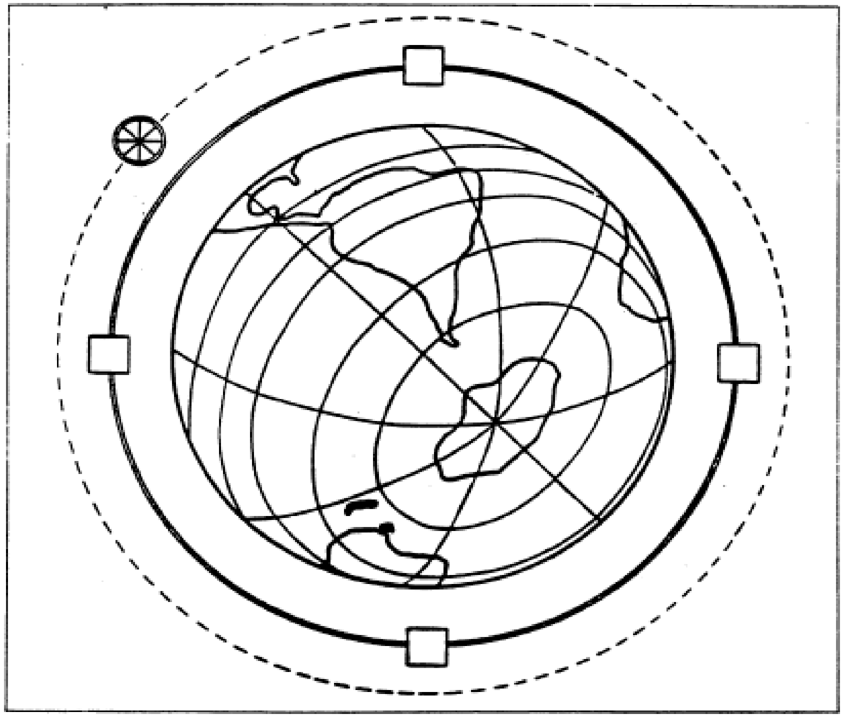
Toward the Next Energy Frontier



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

Summary of the VLHC design study

Dmitri Denisov

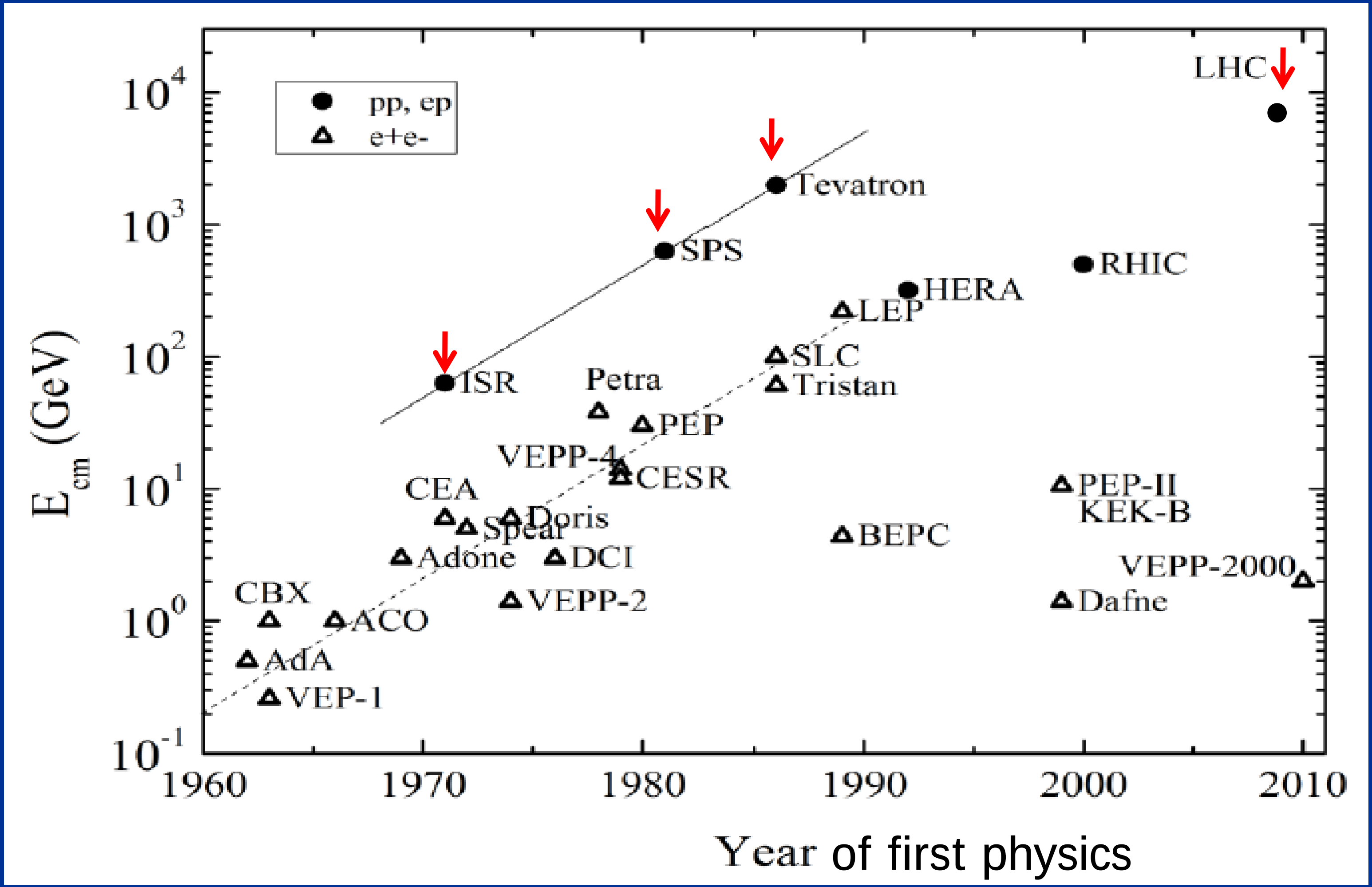
Workshop Next Steps in the Energy Frontier - Hadron Colliders

Fermilab, August 26, 2014

Talk Outline

- Brief history of hadron colliders
- Why higher energy – fundamental properties of space-time
- Very Large Hadron Collider design study – Fermilab 2001
- Are detectors feasible?
- Main challenges for the next generation of colliders
- Summary

Hadron pp and $p\bar{p}$ Colliders



- First hadron collider (storage ring) started in 1971 with completion of ISR
- Highest among all accelerators center of mass energy by over an order of magnitude
- Relatively few machines with ~10 years intervals, two laboratories: CERN and Fermilab

Early 70's – First Hadron Collider

- Collider center of mass energy is $2E_{beam}$ instead of $\sqrt{(2mE_{beam})}$ for fixed target
  - Use existing proton beams from the Proton Synchrotron
- Intersecting Storage Rings - ISR - was the first hadron collider

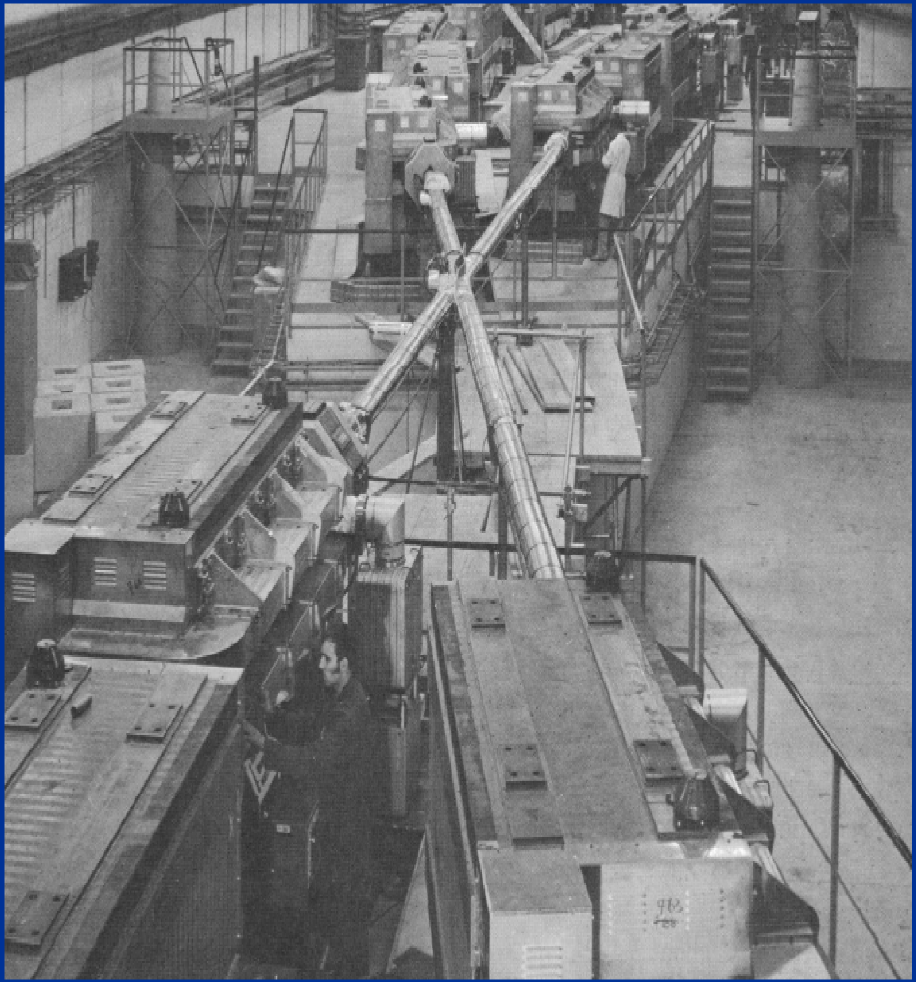
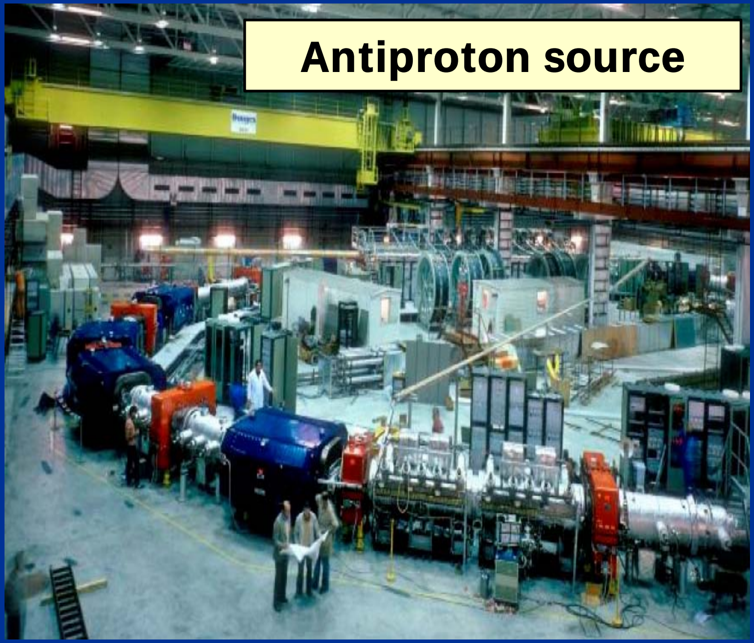
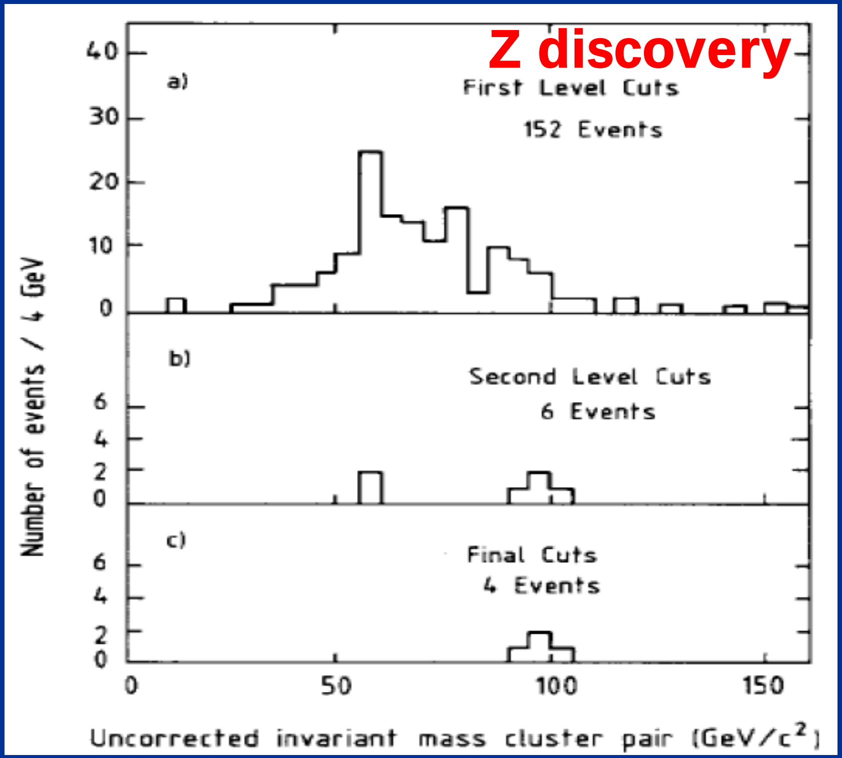


TABLE 1. *Main parameters of the ISR*

Number of rings	2
Circumference of rings	942.66 m
Number of intersections	8
Length of long straight section	16.8 m
Intersection angle at crossing points	14.7885°
Maximum energy of each beam	28 GeV
Hoped for luminosity (per intersection)	4×10^{30} cm^{-2} s^{-1}
Magnet (one ring)	
Maximum field at equilibrium orbit	12 kG
Maximum current to magnet coils	3750 A
Maximum power dissipation	7.04 MW
Number of magnet periods	48
Number of superperiods	4
Total weight of steel	5000 tons
Total weight of copper	560 tons

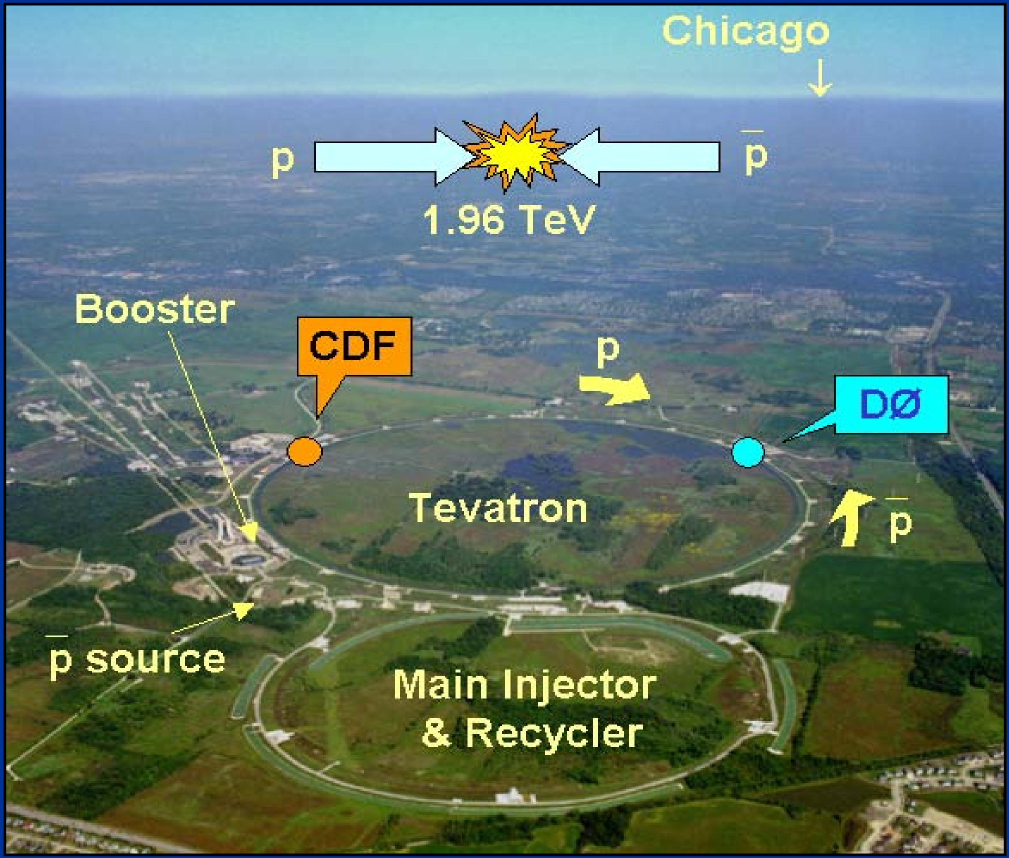
SppS Collider



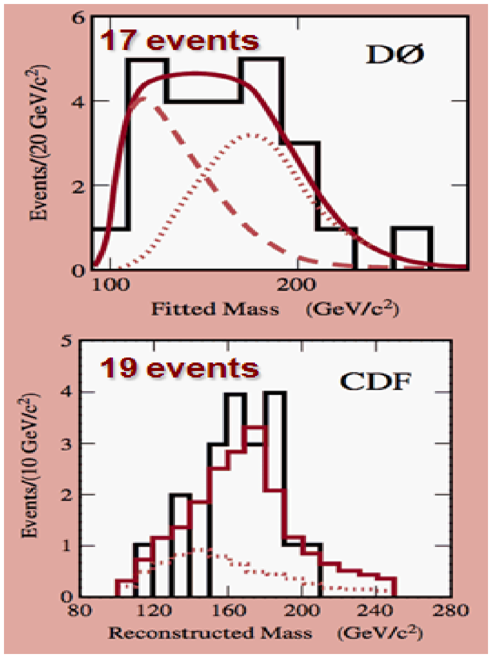


- **Use of antiprotons in the existing fixed target machine**
- **Provided next step in the understanding of the Standard Model**
  - **W/Z bosons discovered**

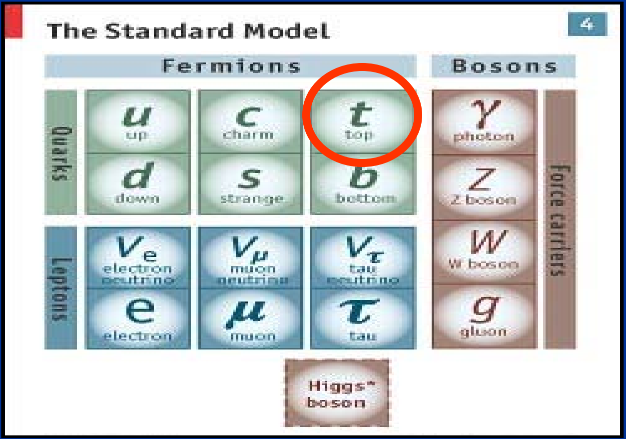
The Tevatron



Top Quark Discovery



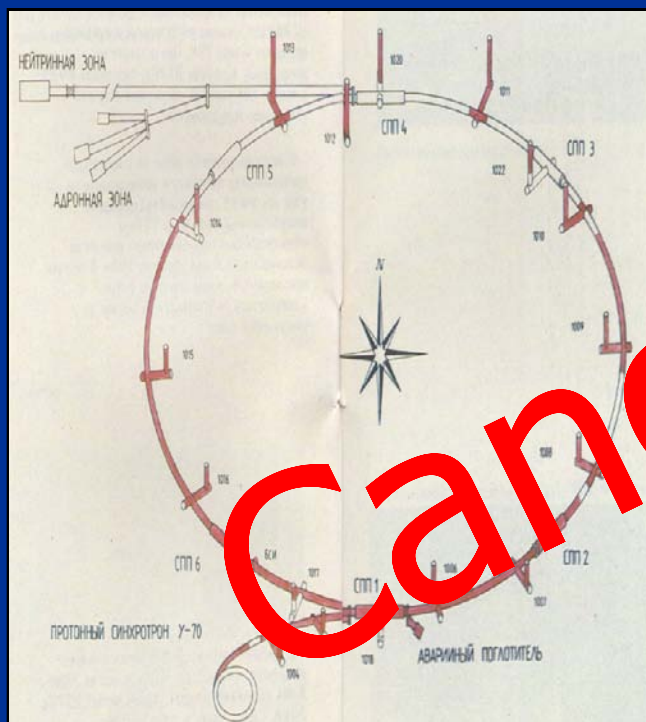
1995, CDF and DØ experiments, Fermilab



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

Attempts to Reach Higher Energies: 90's

- For higher energy machines, as partonic cross sections decrease with energy, higher luminosities are required
  - Challenges producing large number of anti-protons
  - Proton-proton colliding beams for dedicated hadron collider
- Larger rings and higher field superconducting magnets to achieve beam energies well above 1 TeV

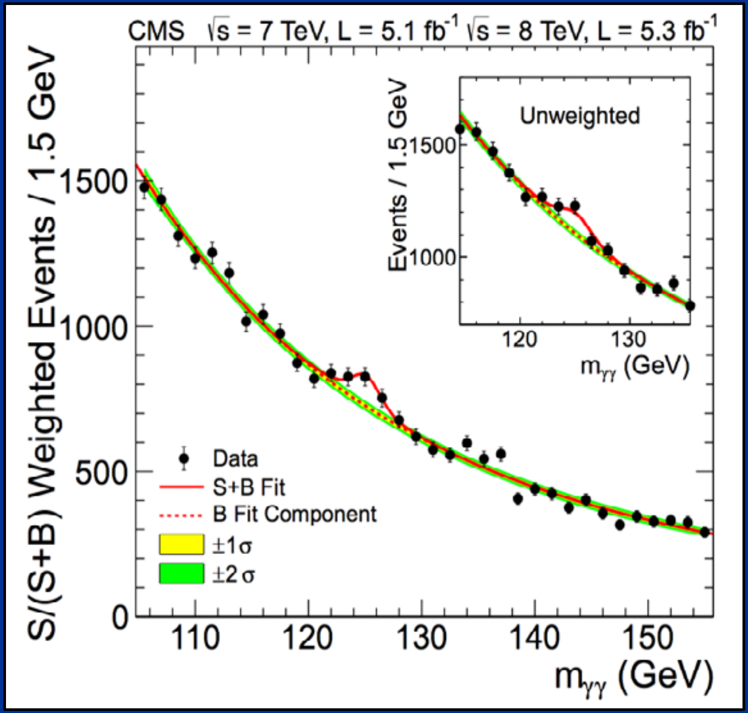


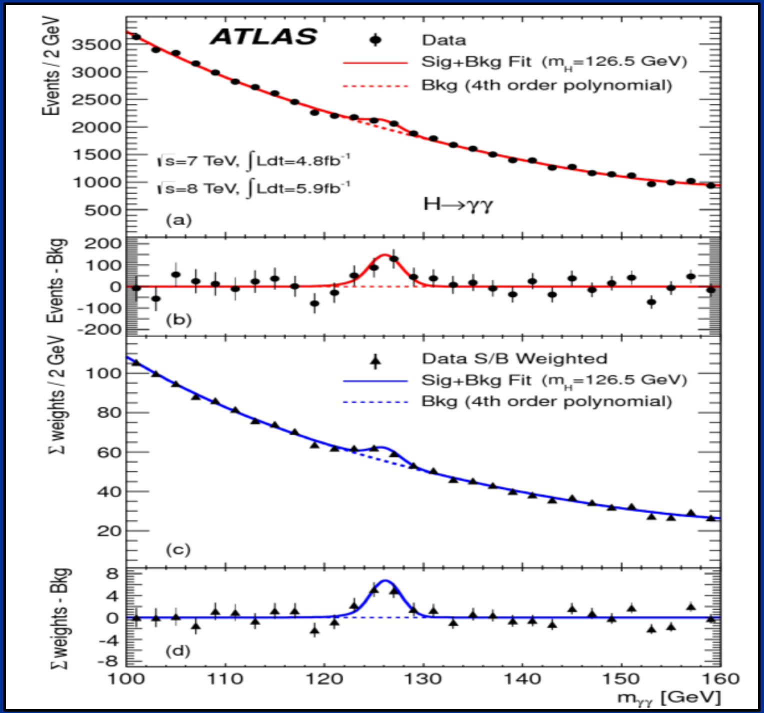
3x3 TeV, UNK

Cancelled

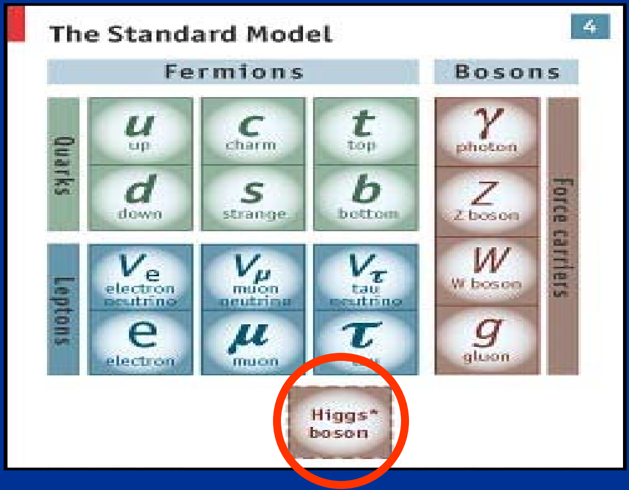
20x20 TeV, SSC

The LHC – the History in the Making

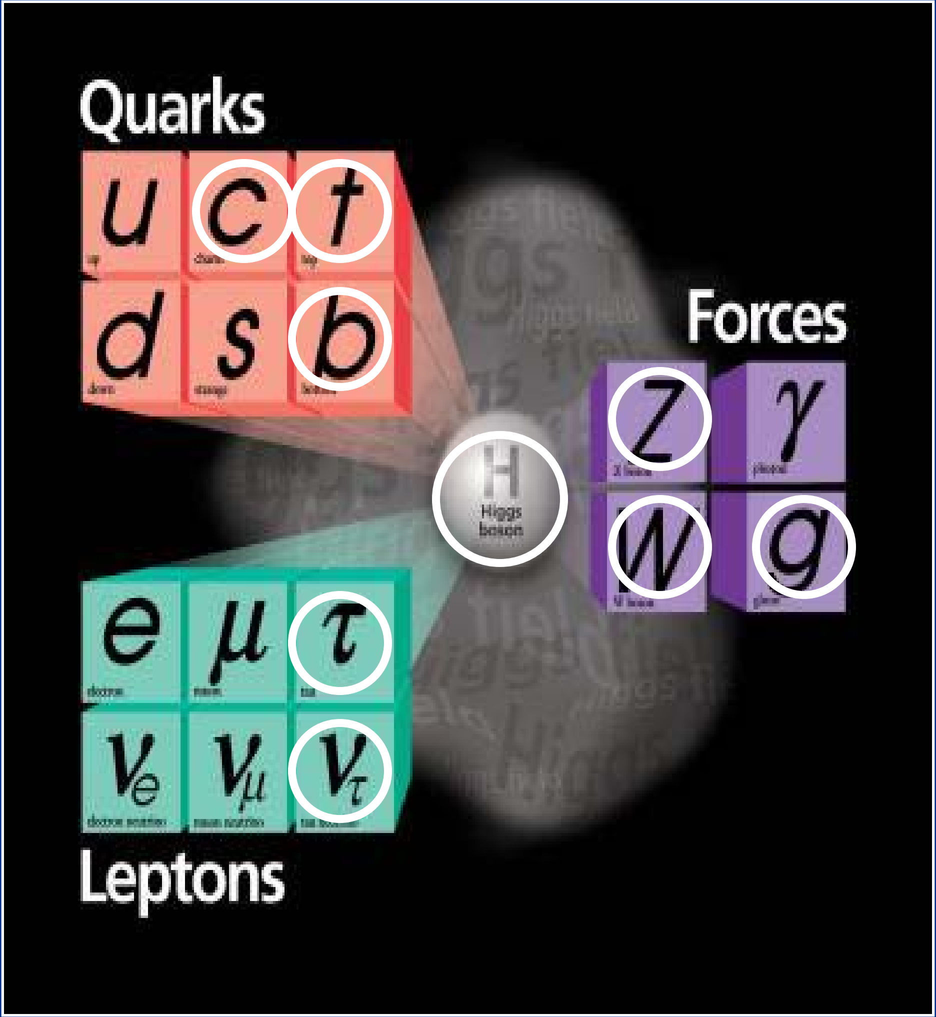




- **Re-use of LEP tunnel**
- **Discovered missing piece of the Standard Model - the Higgs boson**
- **Extensive searches for physics beyond Standard Model**
- **Many more exciting results expected**



Accelerators and the Standard Model



- Elementary particles discoveries over past 40 years were closely related to the new accelerator ideas
  - Strong focusing
    - c and b quarks
  - Colliders
    - Tau lepton, gluon
  - Use of antiprotons in the same ring as protons
    - W and Z bosons
  - Superconducting magnets
    - Top quark, tau neutrino, and the Higgs boson

At every step new accelerator ideas provided less expensive way to get to higher beams energies

Why Higher Energies

- Accelerators are built to study nature smallest objects

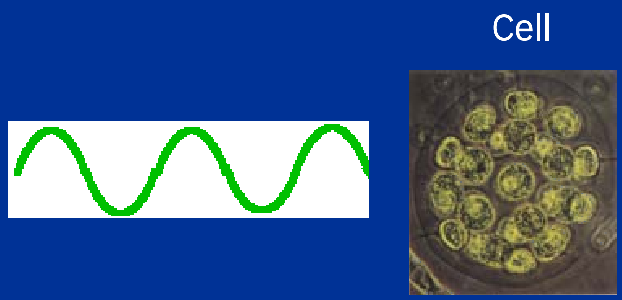
Wavelength = h / E

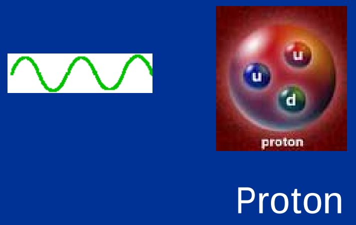
~2 ·10^{-18} cm for LHC

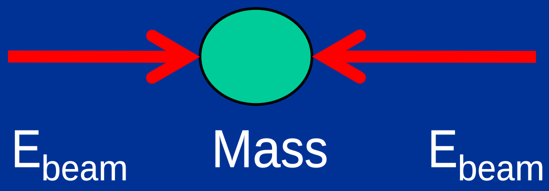
- Accelerators converter energy into mass

$$E = mc^2$$

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

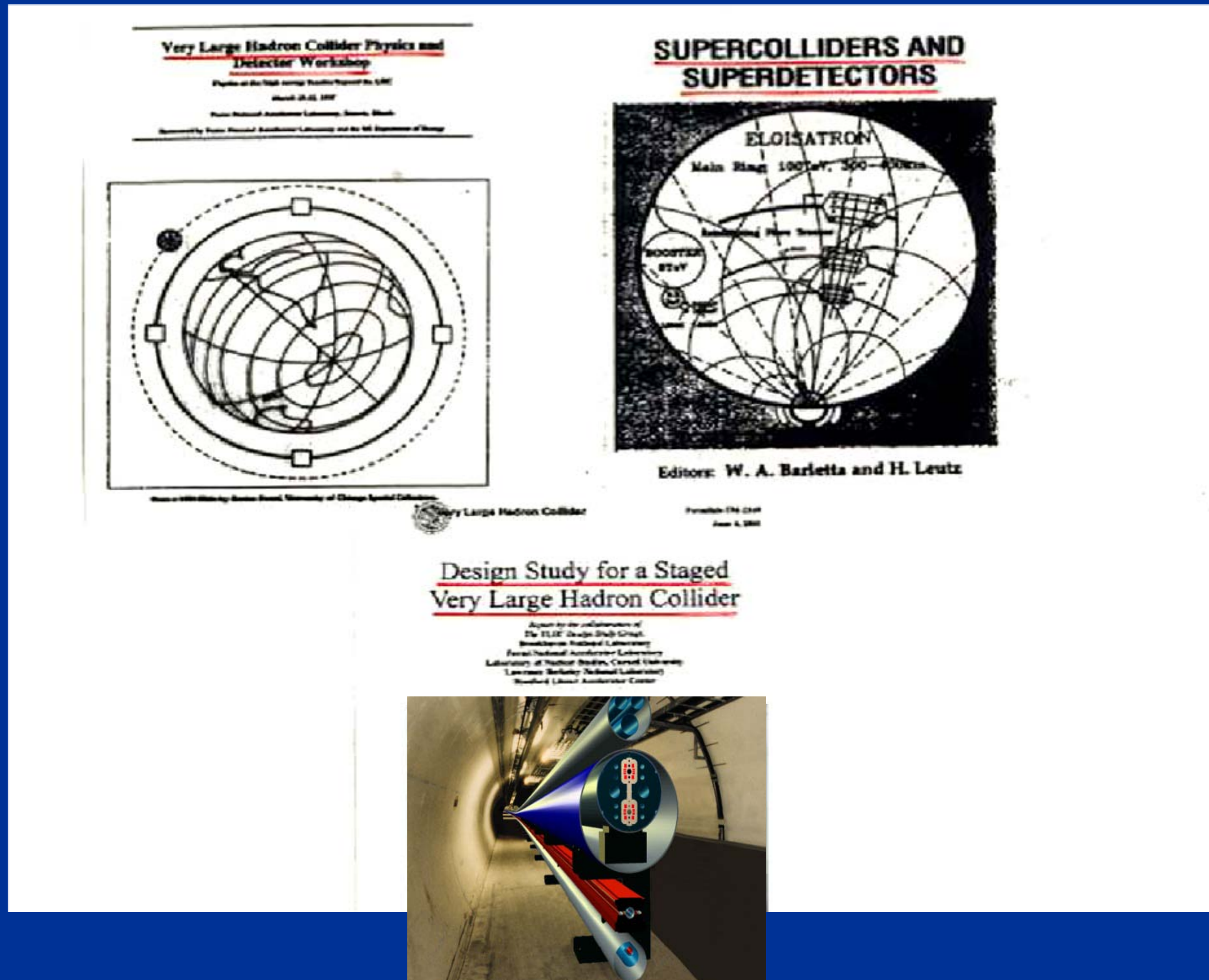






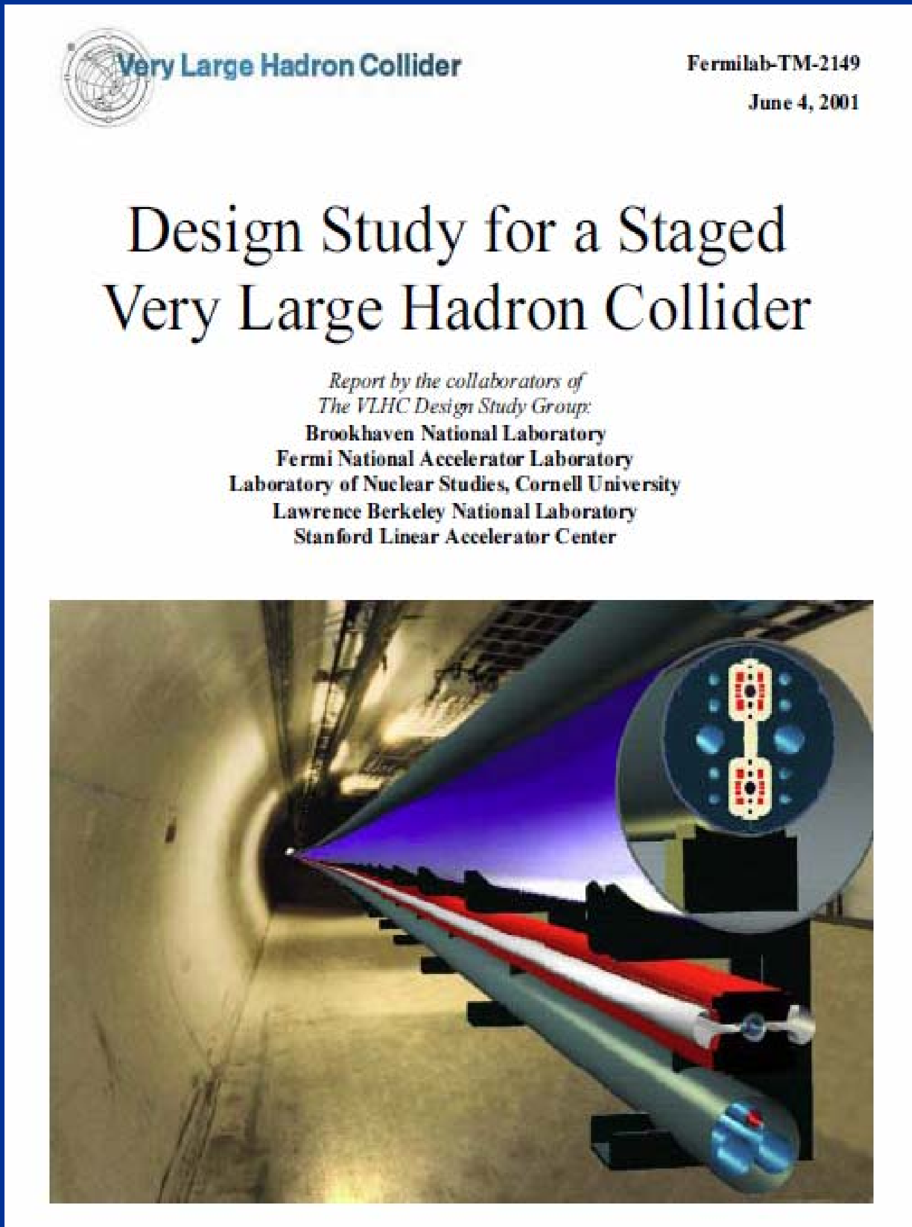
To get to the next step in Nature studies - at both smaller distances and higher masses - higher energy is the only way to succeed

Many Studies for ~100 TeV Accelerators/Detectors Exist



SppS, UNK, SSC, LHC studies/proposals/experiences are invaluable

Design Study for a Staged Very Large Hadron Collider


Very Large Hadron Collider

Fermilab-TM-2149

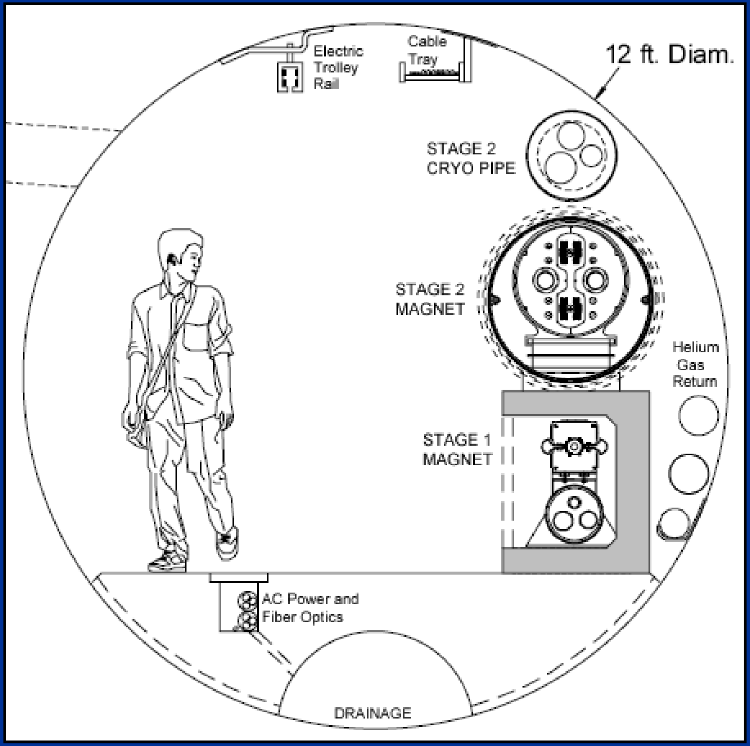
June 4, 2001

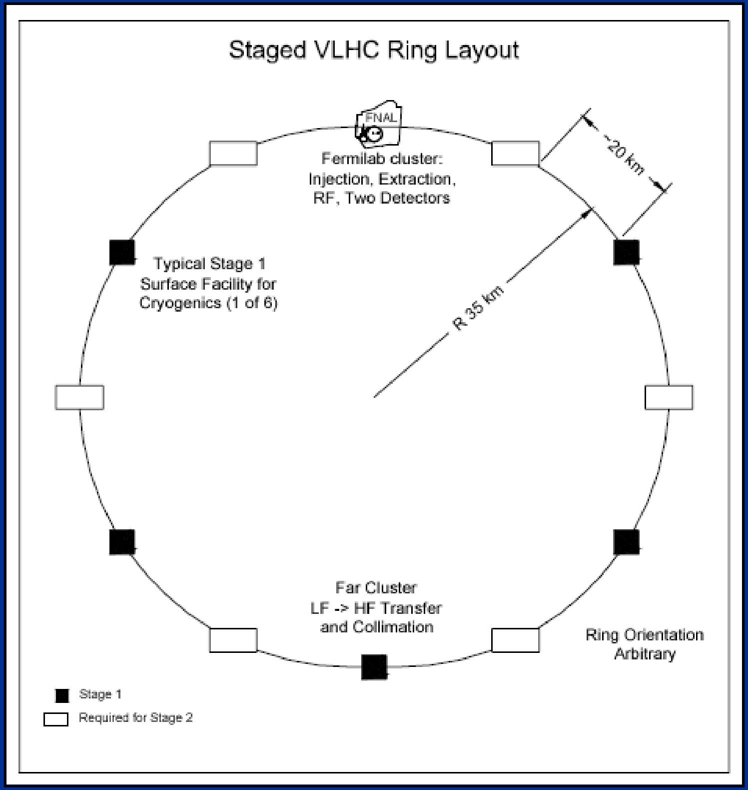
Design Study for a Staged Very Large Hadron Collider

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 for 2001 Snowmass**
- **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**

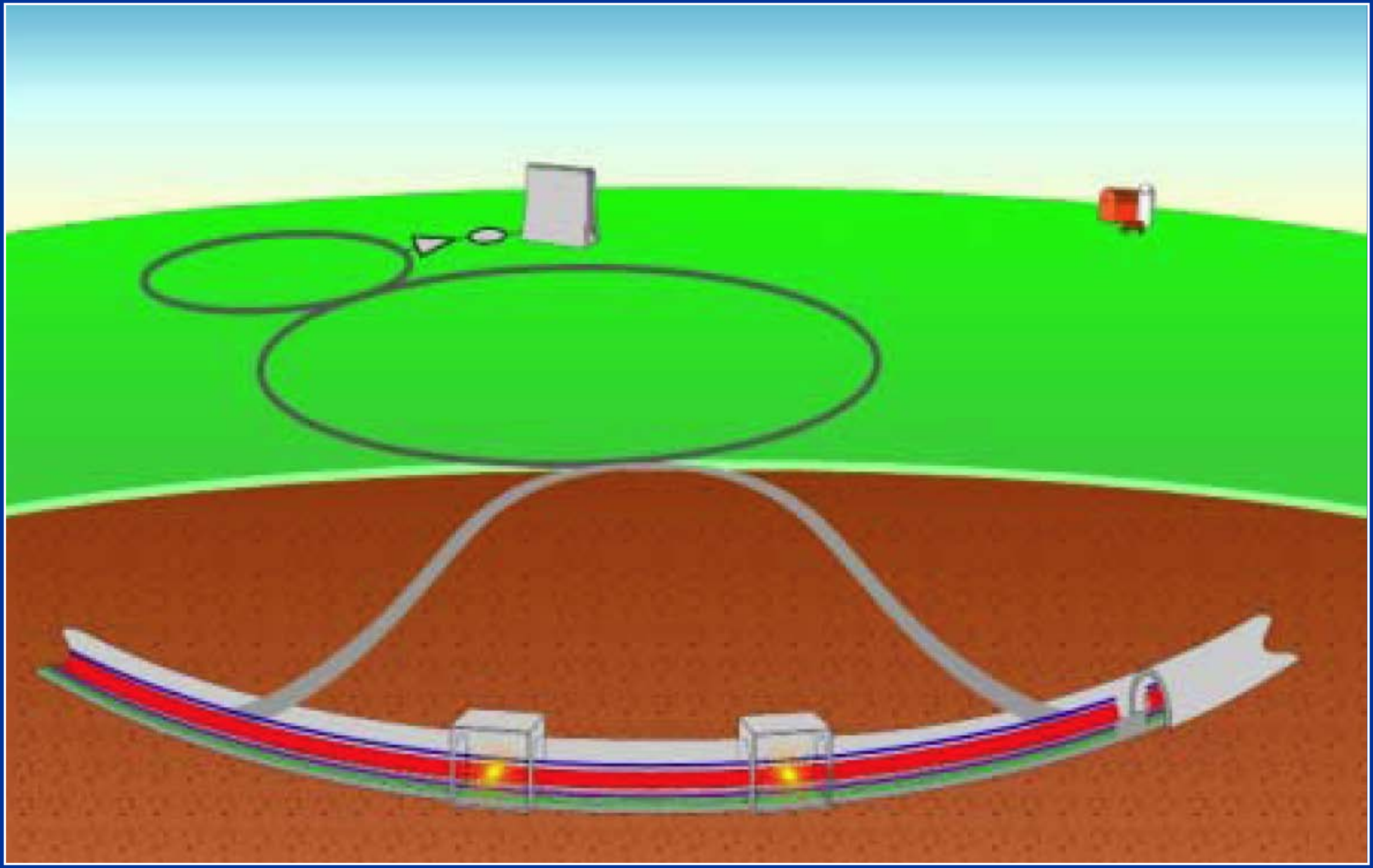
Main Idea: Long Tunnel vs Highest Field Magnets





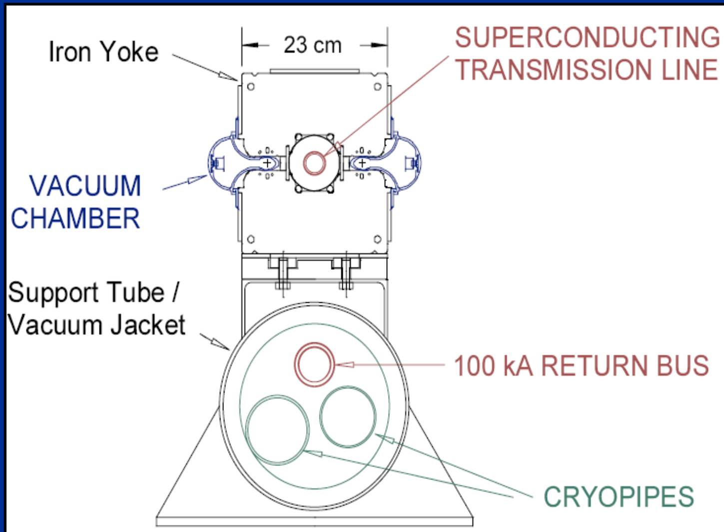
- **Tunnel length proposed is 233 km, small diameter, deep underground, only few shafts**
- **Two stages: “stage 1” is 2 Tesla warm steel magnet at 40 TeV, “stage 2” is 10 Tesla dual core magnet at 175 TeV**
- **Over last ~20 years long and deep tunnels technology was greatly advanced**

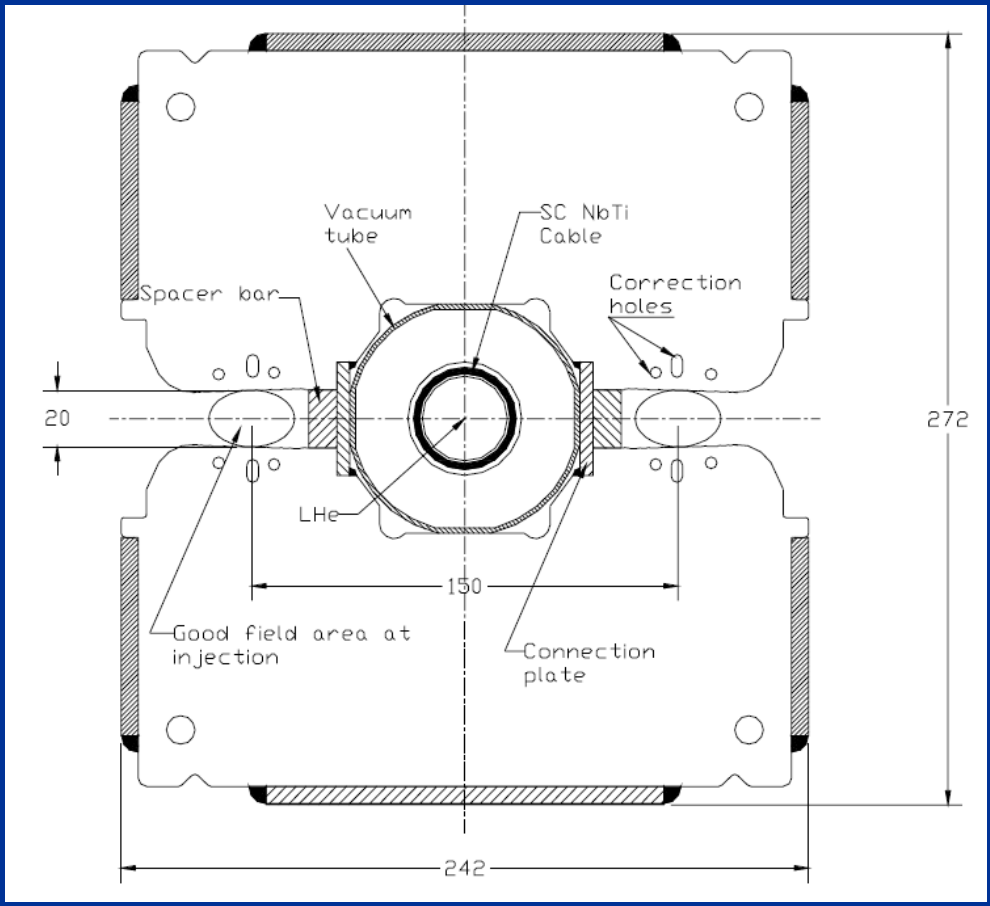
Fermilab’s Complex as Injector

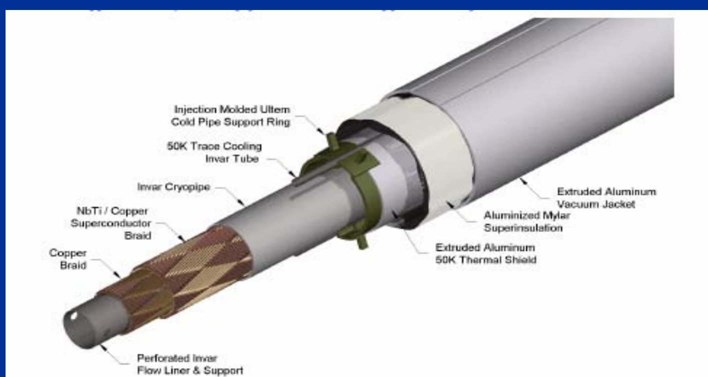


Fermilab’s accelerator complex is used as an injector with two main collision points located under Fermilab’s site

Idea of "one turn" Magnet







- **The idea is to use warm iron (means 2 Tesla) 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**

Stage 1 Magnets Parameters

Table 5.2. Main parameters of the dipole magnets.

		Main Arc Dipole	*Dispersion Suppressor*
Magnet air gap in the orbit center		20 mm	22.26 mm
Beam Pipe Inner Dimensions		18 mm x 28 mm (elliptical)	
Separation Between Beams		150 mm	
Magnet length		65.75 m	48.81 m
Half-cell length		135.5 m	101.6 m
Sagitta in Magnet		1.6 cm	0.6 cm
Gradient		± 4.73 %/cm	± 9.449 %/cm
Magnetic field:	injection	0.1 T	0.09 T
	maximum	1.966 T	1.766 T
Good field diameter (< 0.02%):	injection	20 mm	
	maximum	10 mm	
Transmission Line Design Current		100 kA	
Current at 20 TeV		87.5 kA	
Magnetic field energy @100 kA		790 kJ (12 kJ/m)	473 kJ (10 kJ/m)
Superconducting cable		braided NbTi with braided Cu stabilizer	
Specified Max. Temp of Conductor		6.5-6.7 K	
Nominal Max Temp of Cryo System		6.0 K	
Iron Core		1-mm laminated low carbon steel (AISI 1008 or better)	

High Energy Stage 2 Design

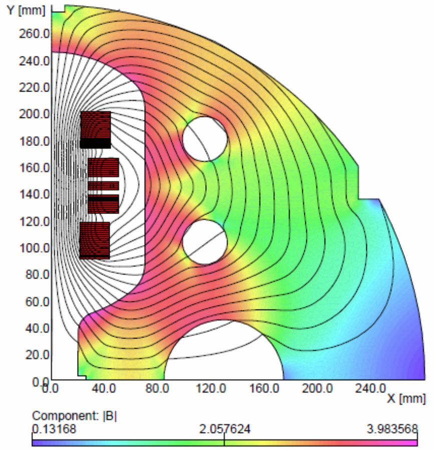


Figure 6.1. Magnetic design of the arc dipole.

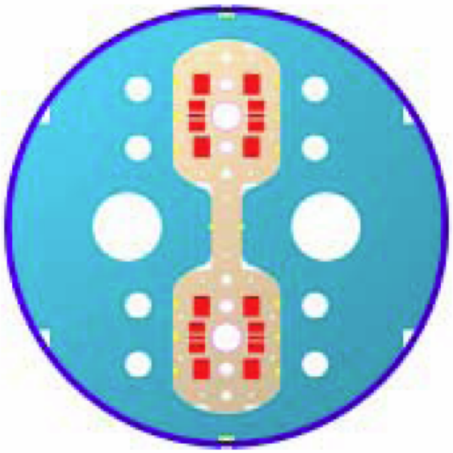


Figure 6.2. Cross-section of the arc dipole.

Table 6.1. Arc dipole parameters.

B_{nom}, T	10
I_{nom}, kA	23.5
Aperture, mm	40
Aperture separation, mm	290
Magnetic length, m	16.15
Iron yoke OD, mm	560
Stored energy @10T, kJ/m	2×414
Inductance @10T, mH/m	2×1.5

- **Design has two beam pipes with vertical orientation**
- **Maximum field is 10 Tesla providing 175 TeV in 233 km tunnel**

Parameters of 40-175 TeV Collider

Table 1.1. The high-level parameters of both stages of the VLHC. 2001 Proposal

	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

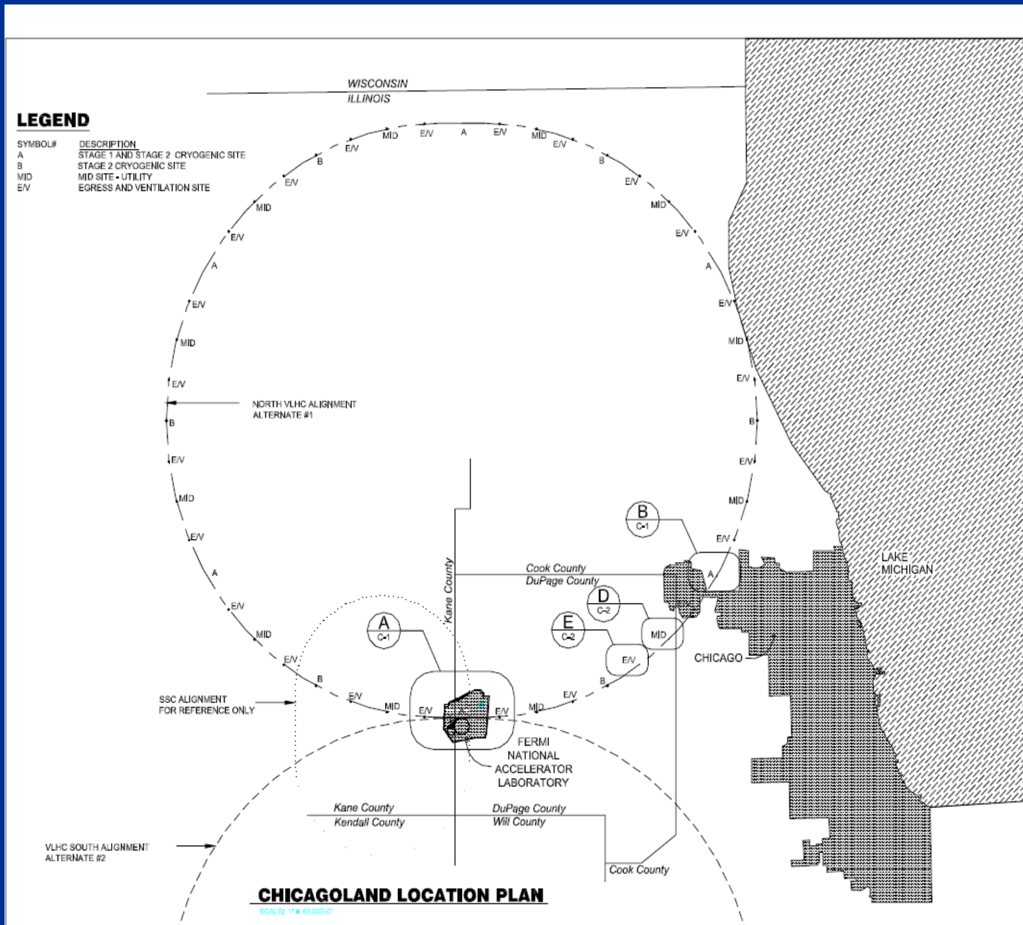
Cost Estimates

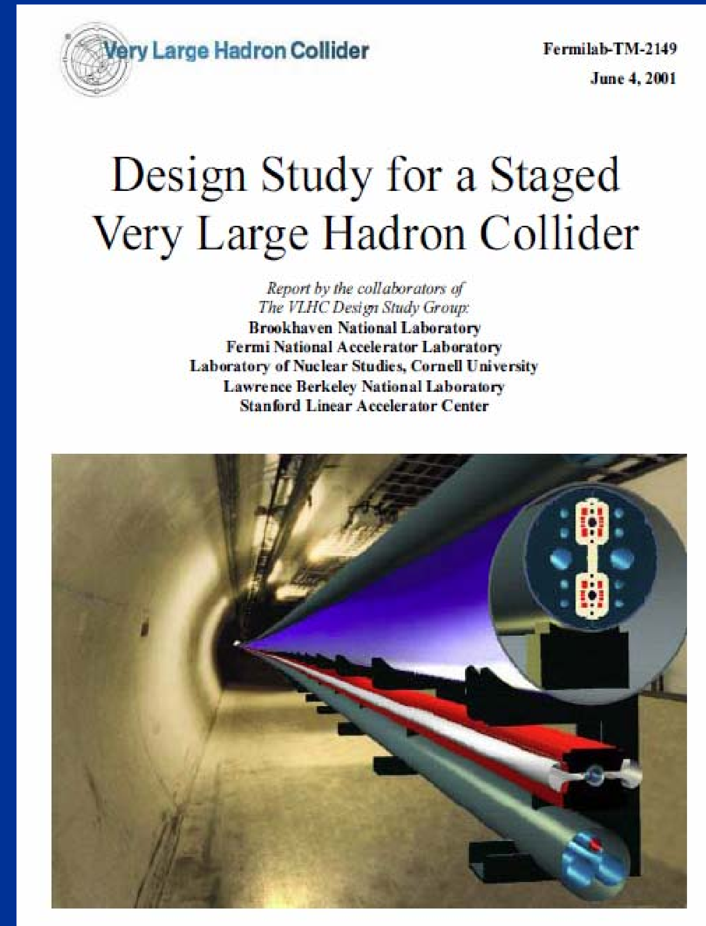
Table 9.2. The estimated costs of the major cost drivers for Stage-1 VLHC.

Stage-1 VLHC Cost Driver	Cost Estimate (in FY2001 M$)	Fraction of Total Stage-1 Cost
Total Cost	**4,138**	**100 %**
Construction – Below Ground*	2,125	51.4 %
Construction – Above Ground	310	7.5 %
Main Arc Magnets	792	19.1 %
Correctors & Special Magnets	112	2.7 %
Refrigerators	95	2.3 %
Other Cryogenic Systems	22	0.5 %
Installation	232	5.6 %
Vacuum System	154	3.7 %
Interaction Regions	26	0.6 %
Other Accelerator Systems	270	6.5 %

- Only Stage 1 (40 TeV) cost estimate was performed
- Estimate is in "2001 dollars" and has no contingency, escalation, etc.
  - Stage 1 cost "in the same units" is close to 40 TeV SSC
  - But… it provides the path to 175 TeV by building long tunnel

273 Pages VLHC Technical Proposal

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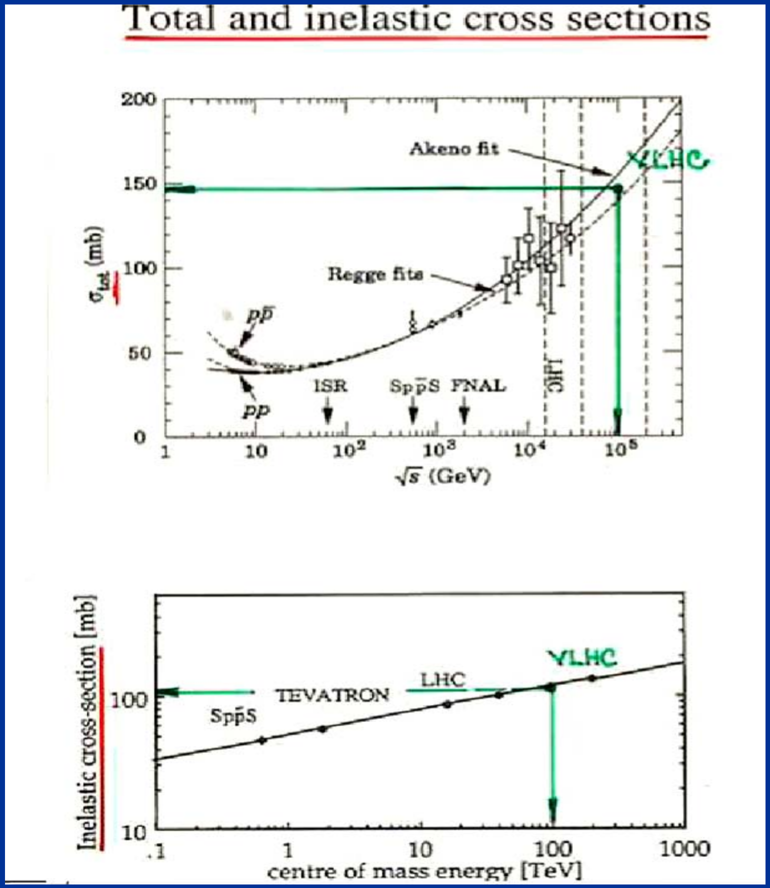
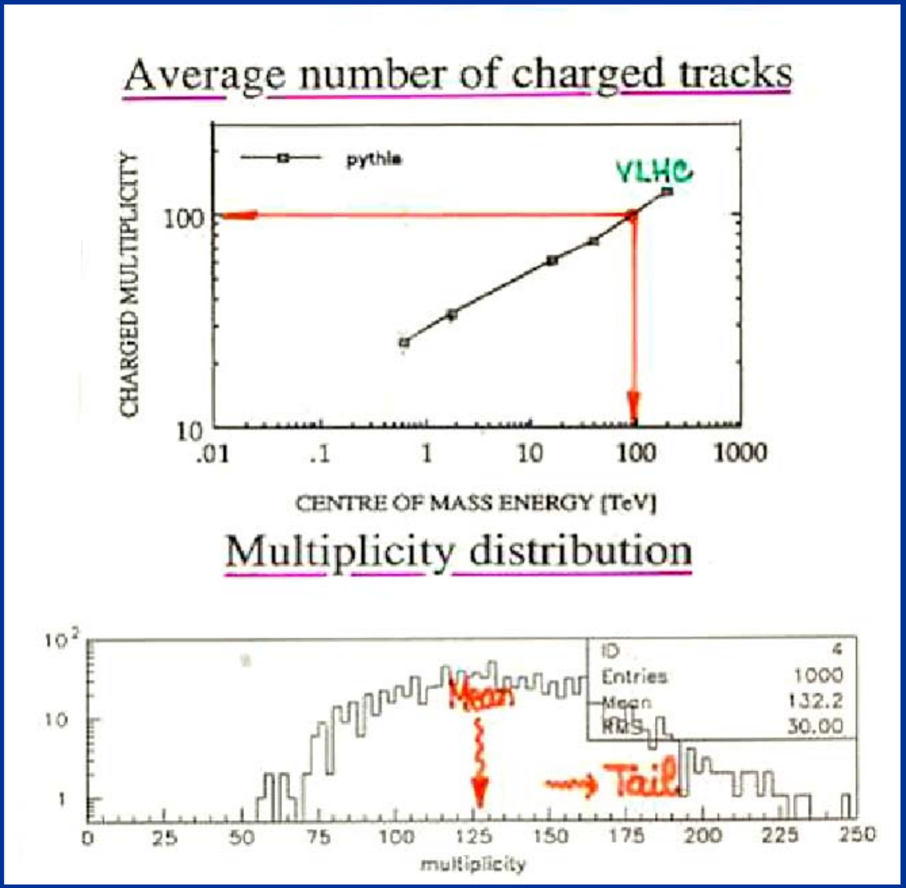
- **The VLHC proposal was well developed with all major technical solutions documented, including many details on the tunneling**
- **Very important outcome was that there are no technical “show stoppers” in building 175 TeV pp collider**

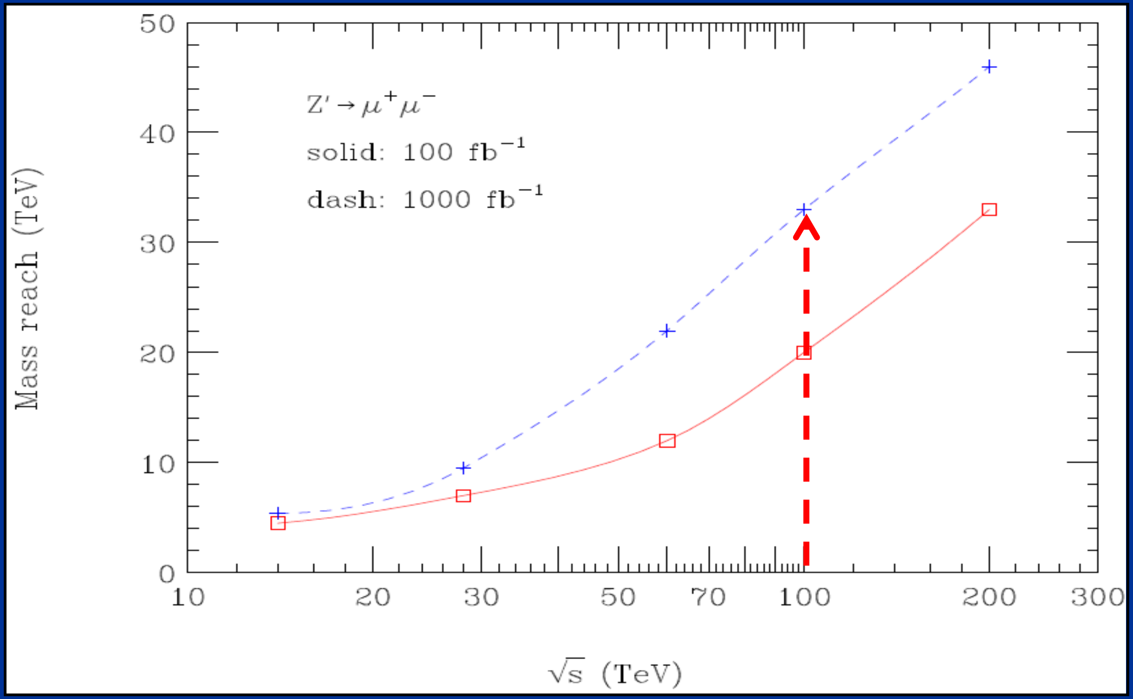
VLHC Design Studies on Experiments and Detectors





- VLHC design study provided important information on experiments and detectors
- Properties of soft pp interactions at 100 TeV are very similar to Tevatron and LHC
  - Radiation doses and pile-up are functions of luminosity, not energy
  - Detectors “similar” to Tevatron and LHC could be used to study collisions
-

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**
- **There is no well defined "energy needed" for VLHC yet**
  - **20 TeV machine could be about twice less expensive than 40 TeV (could saved SSC?)**
  - **But don't want to miss major discovery due to a few % lower energy (LEP)**

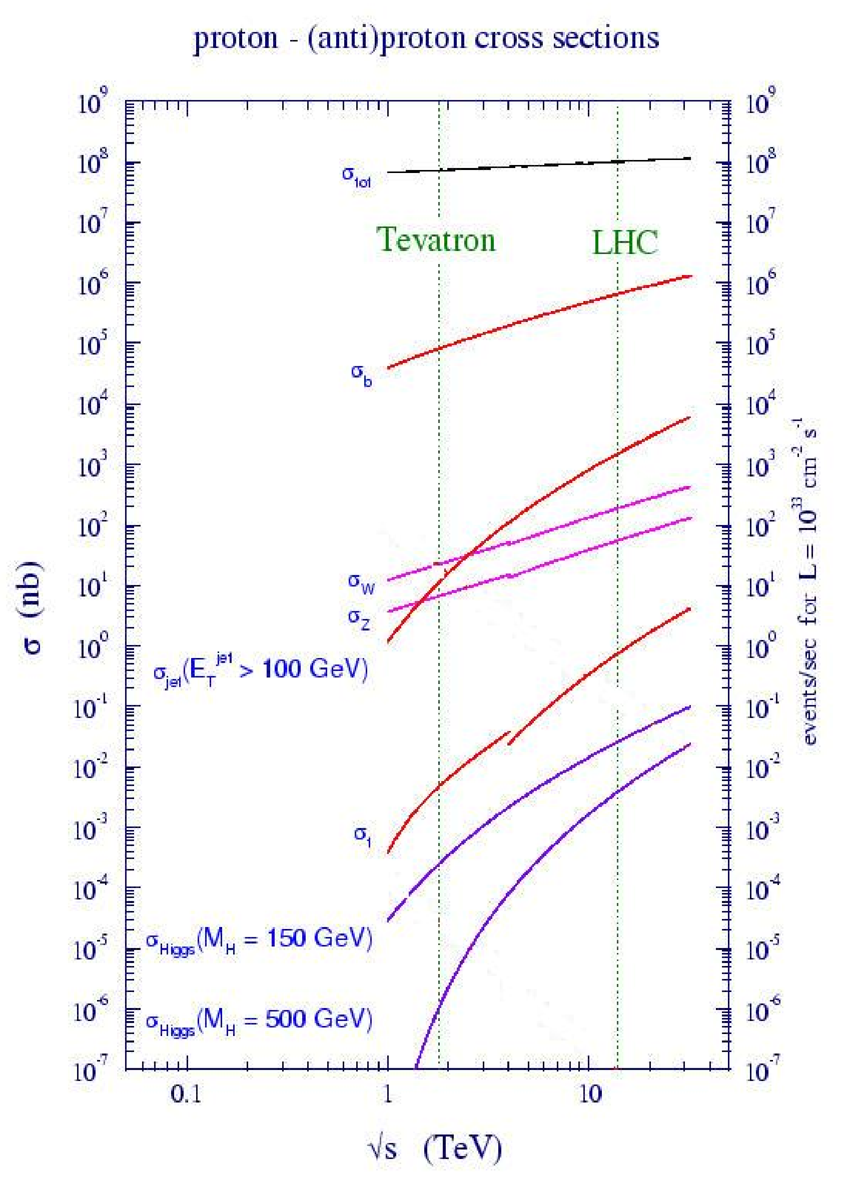
Where is the Problem?...

- With such excellent past, present, and exciting future, why we are not building hadron colliders now?
  - The answer is simple – cost is very high
- There are many ways to estimate costs, many speculations. An interesting study by experts is presented in
  - http://www-ad.fnal.gov/ADSeminars/SeminarsArchieve/APTSeminars-2013.html (July 2, 2013)
  - Based on past experience and reasonable extrapolations cost of 100 TeV pp collider expected to be in excess of $30 billion
- Hard to convince (any) government to spend such money
  - Reduction in cost is critical
    - Detectors are not driving the cost (~10%)
    - No widely accepted ways for substantial reduction
- Reasons to build such machine beyond particle physics and science are important
- Re-developing proposals and concentrating R&D on cost reduction is prudent way to proceed: HEPAP sub-panel on accelerator R&D – Wednesday and Thursday at Fermilab this week - http://www.usparticlephysics.org/p5/ards

VLHC Design Study and Beyond

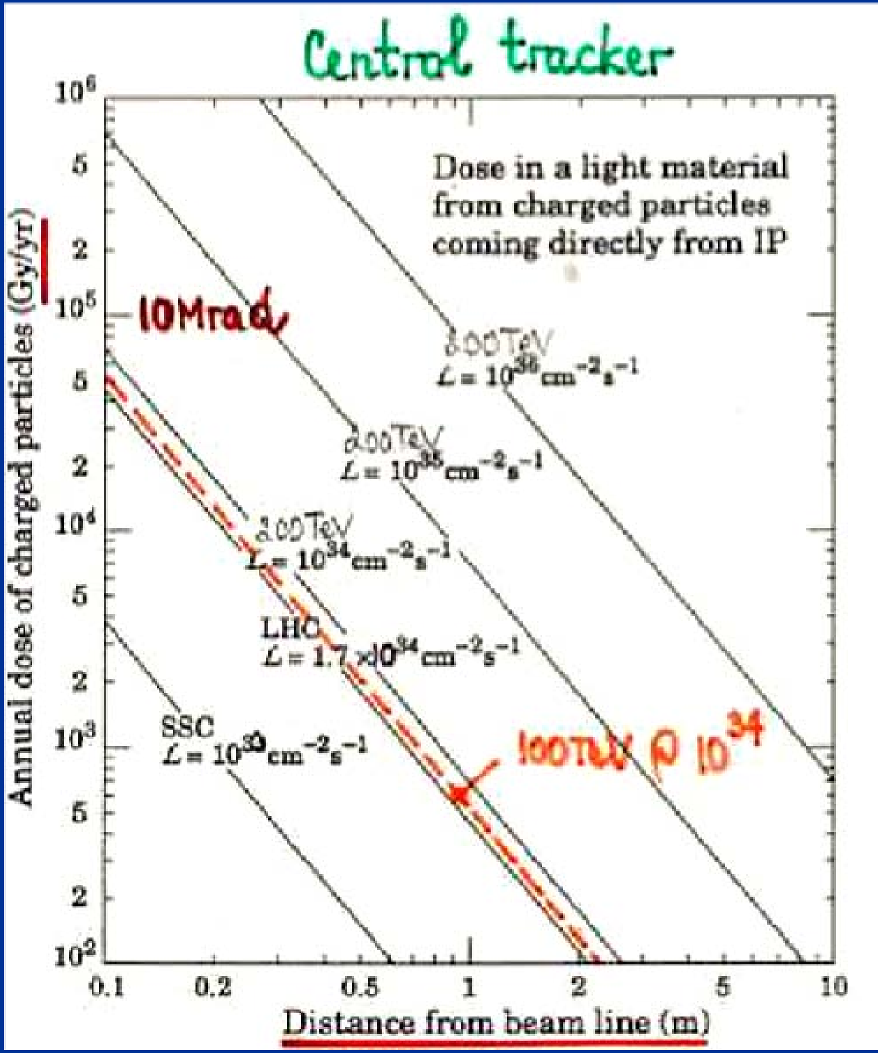
- For ~35 years energy frontier hadron colliders are leading progress in high energy physics with discoveries of
  - W/Z bosons, top quark and the Higgs boson
- The path to 40 TeV (Stage 1) and 175 TeV (Stage 2) colliders is technically feasible
  - Requires large ring and higher field magnets
  - VLHC technical proposal exists
- ~100 TeV hadron collider will provide direct way to
  - Study distances of ~10^{-19} cm
  - Create objects with ~50 TeV mass
- Detectors for ~100 TeV collider are feasible
  - While many improvements are needed
- Cost is the main issue
  - Reduction in cost is important via new ideas and R&D

Experiments at 100 TeV



- Main features of pp collisions
  - Very slow raise of total cross sections with energy
  - Very fast raise of "interesting" cross sections with energy
- "Energy is better than luminosity"
  - For physics reach
  - For detectors performance

What about Radiation Doses?



Radiation in the center region scales with luminosity, not energy

Detectors for 100 TeV collider are challenging, but no fundamental issues

Bending Magnets and Tunnels

- 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
- There are two options to increase energy of a hadron collider
  - Increase magnetic field in the bending magnets
    - Not easy beyond ~10-12 Tesla
  - Increase radius of the tunnel
    - New underground tunneling methods

Detectors for 100 TeV Collider

- We would like to detect all "well know" stable particles which 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 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 10^{35} cm^{-2} sec^{-1} looks reasonable, challenging for above both due to pileup and radiation aging