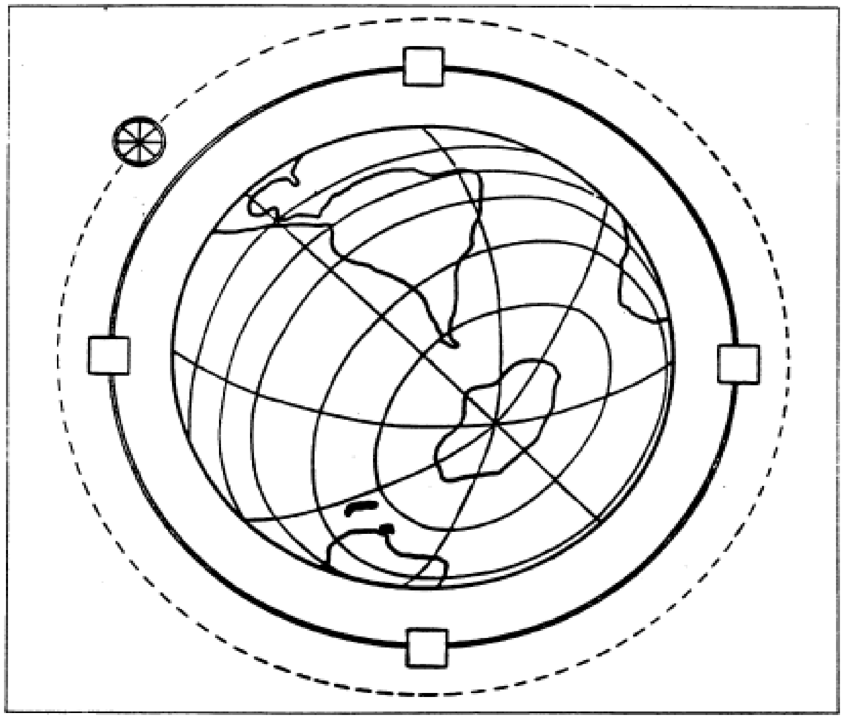
Experience with VLHC Detectors Design



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

Summary of the VLHC design study

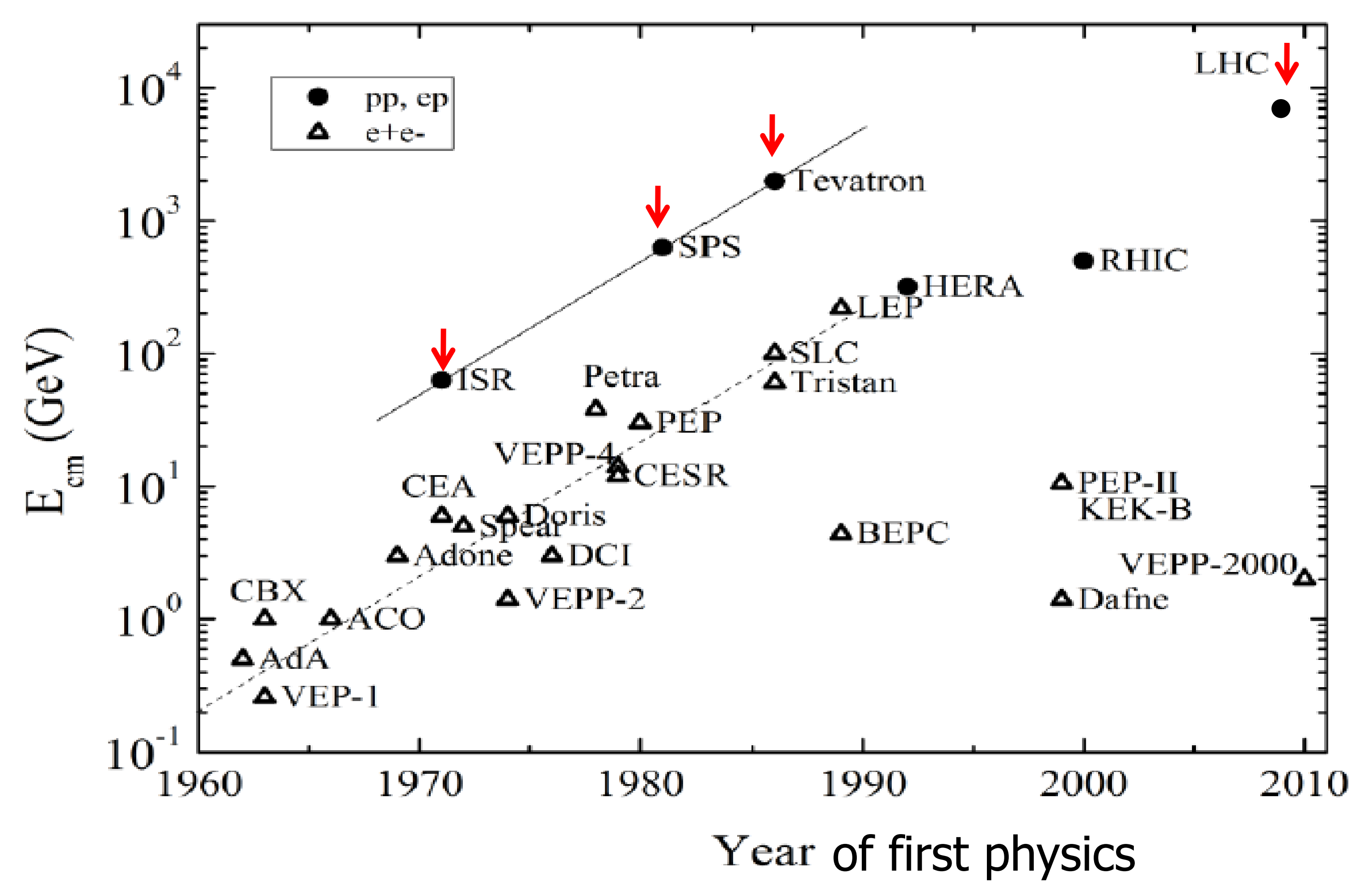
Dmitri Denisov

FCC Workshop
Washington DC, March 25, 2015

Talk Outline

- Brief history of hadron colliders
- Very Large Hadron Collider design study – Fermilab 2001
- Are detectors feasible?
- Main challenges for the future collider detectors
- Summary

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



- First hadron collider (storage ring) started in 1971 with the completion of the 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
  - Used existing proton beams from the Proton Synchrotron
- Intersecting Storage Rings - ISR - was the first hadron collider

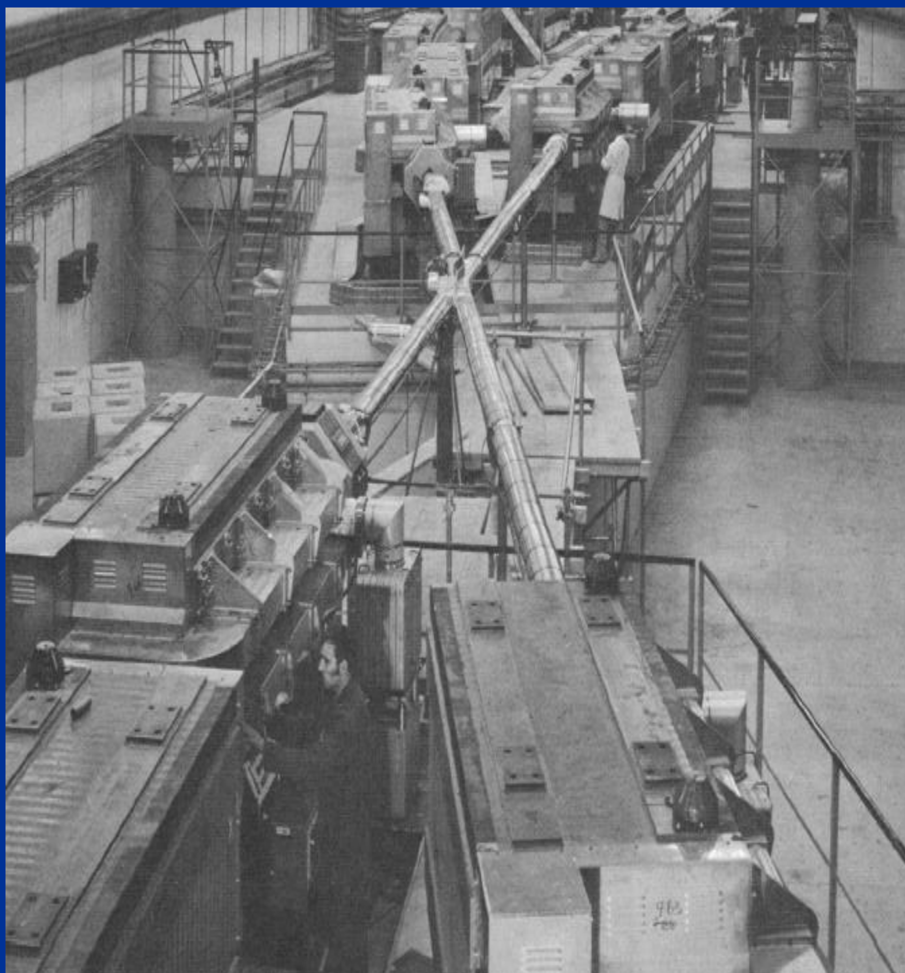
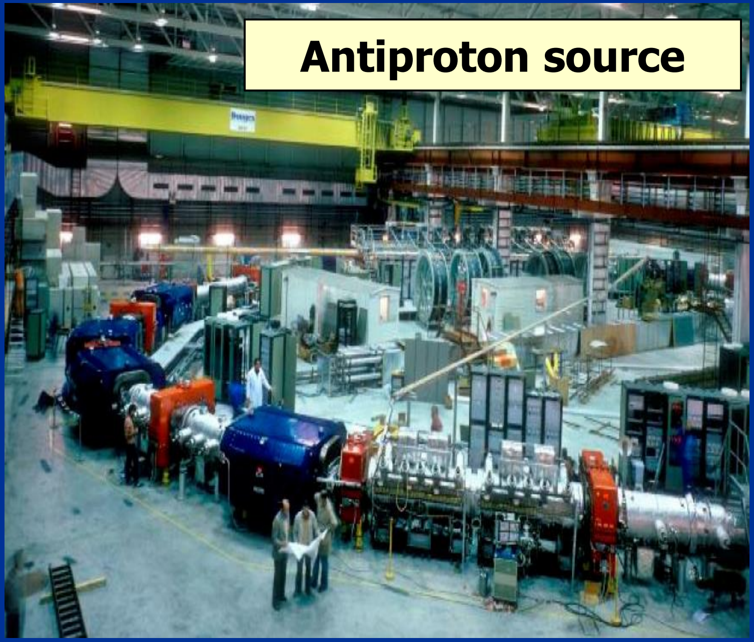
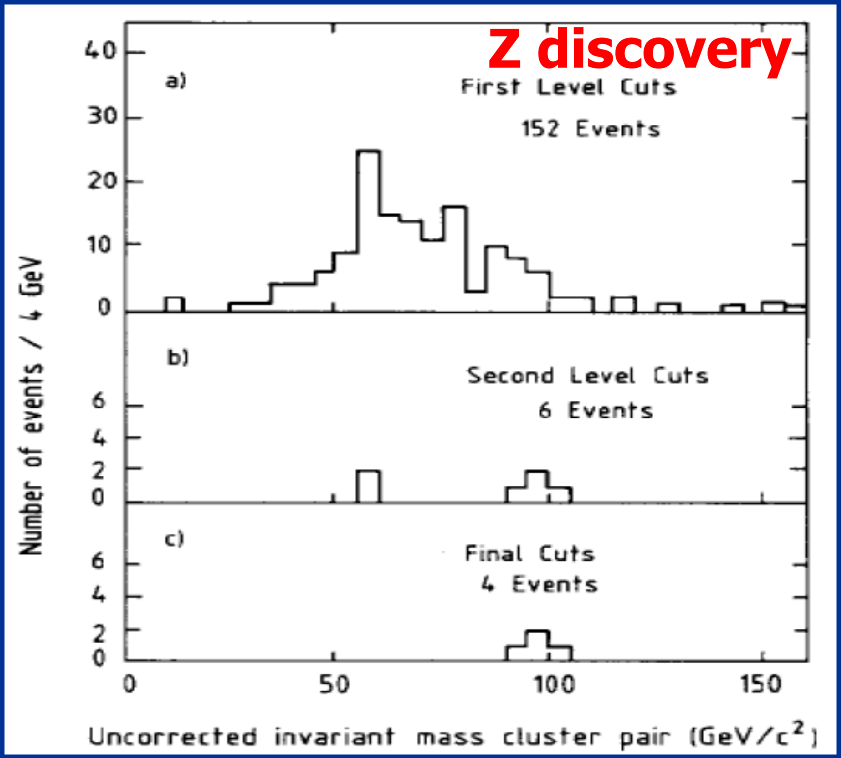


TABLE 1. *Main parameters of the ISR*

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

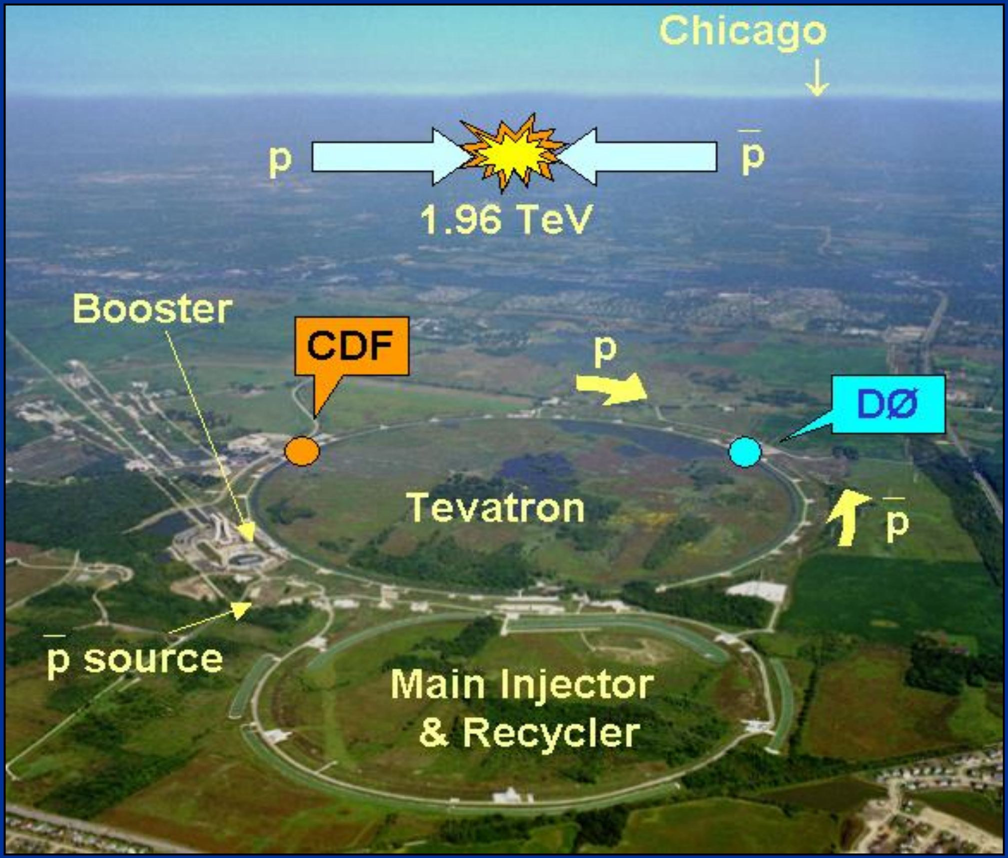
SppS Collider



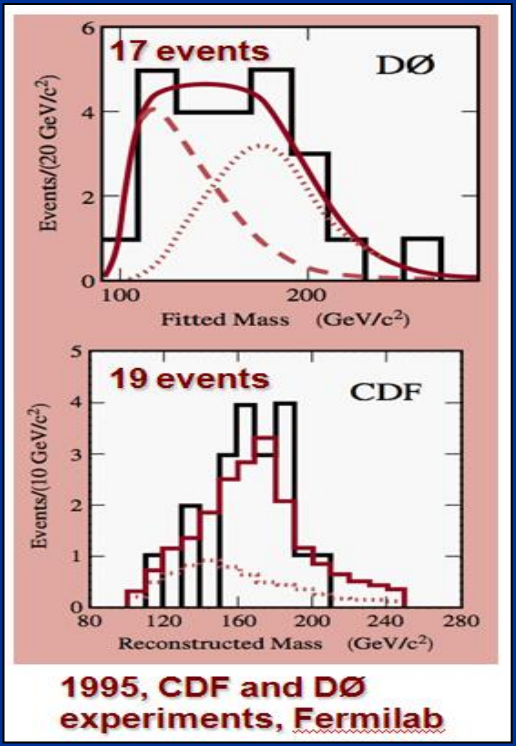


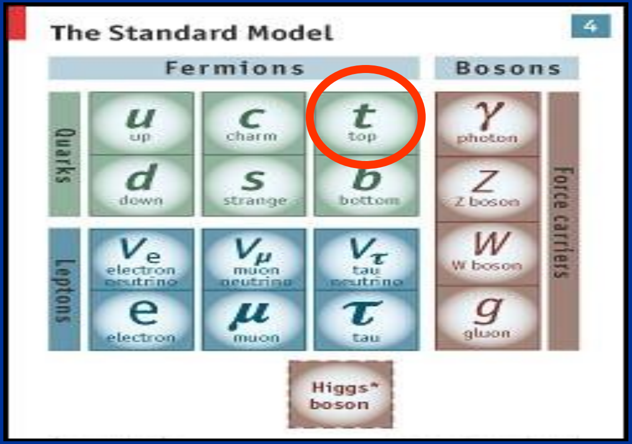
- **Use of antiprotons in the existing fixed target machine**
- **Provided next step in the understanding of the Standard Model**
  - **W/Z bosons discovered**

The Tevatron



Top Quark Discovery

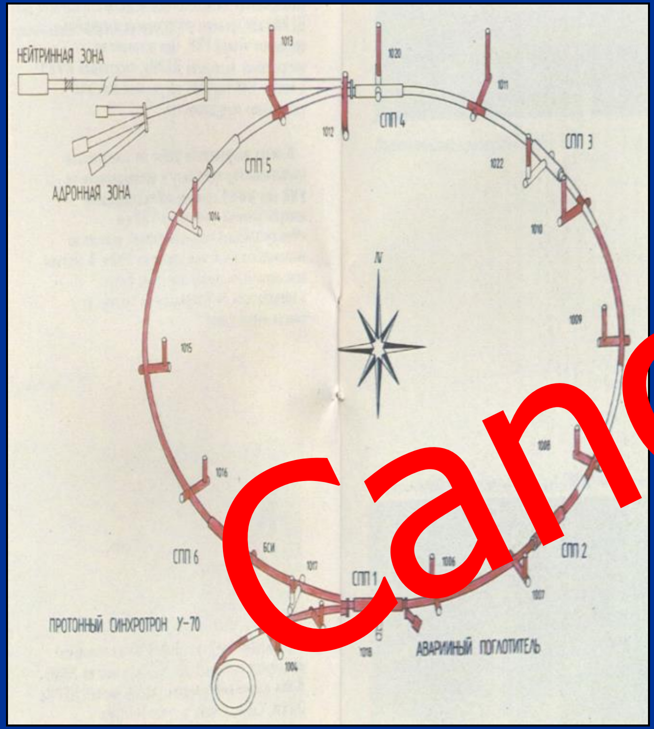




- **First superconducting accelerator with 2 TeV center of mass energy**
- **Discovered last Standard Model quark – the top quark**

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 used in the dedicated hadron collider
- Larger rings and higher field superconducting magnets to achieve beam energies well above 1 TeV

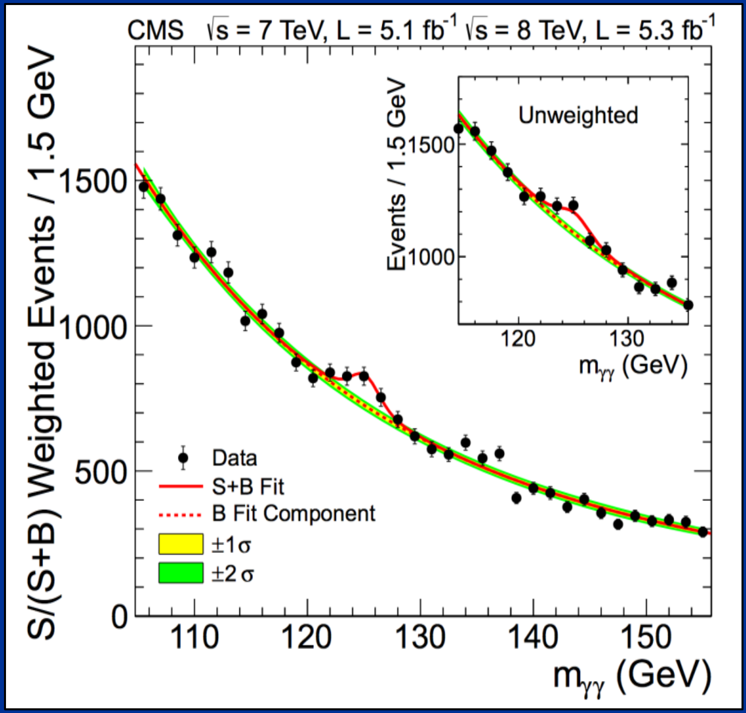


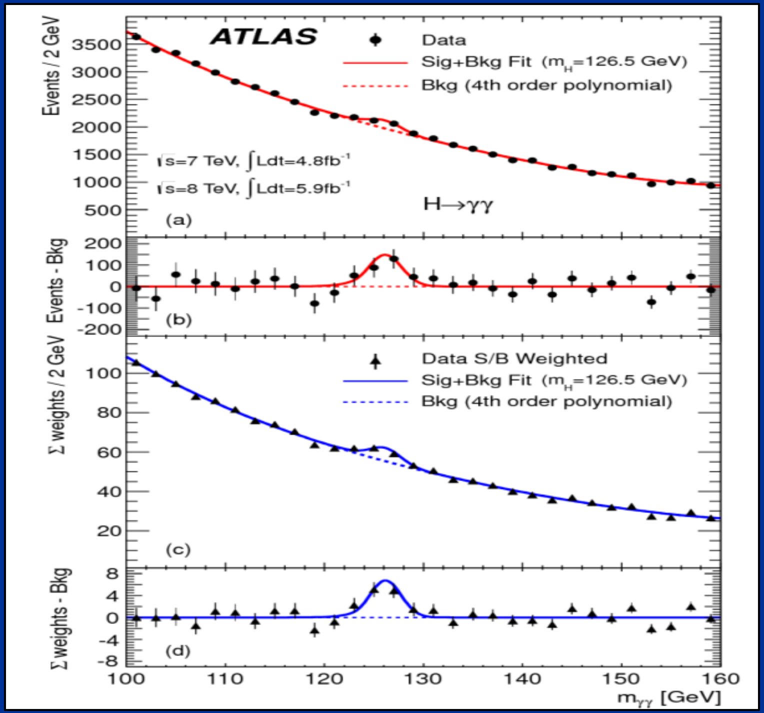
Cancelled

3x3 TeV, UNK

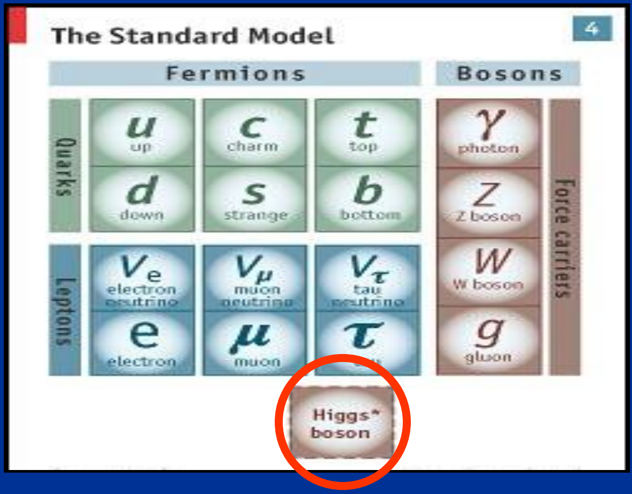
20x20 TeV, SSC

The LHC – the History in the Making

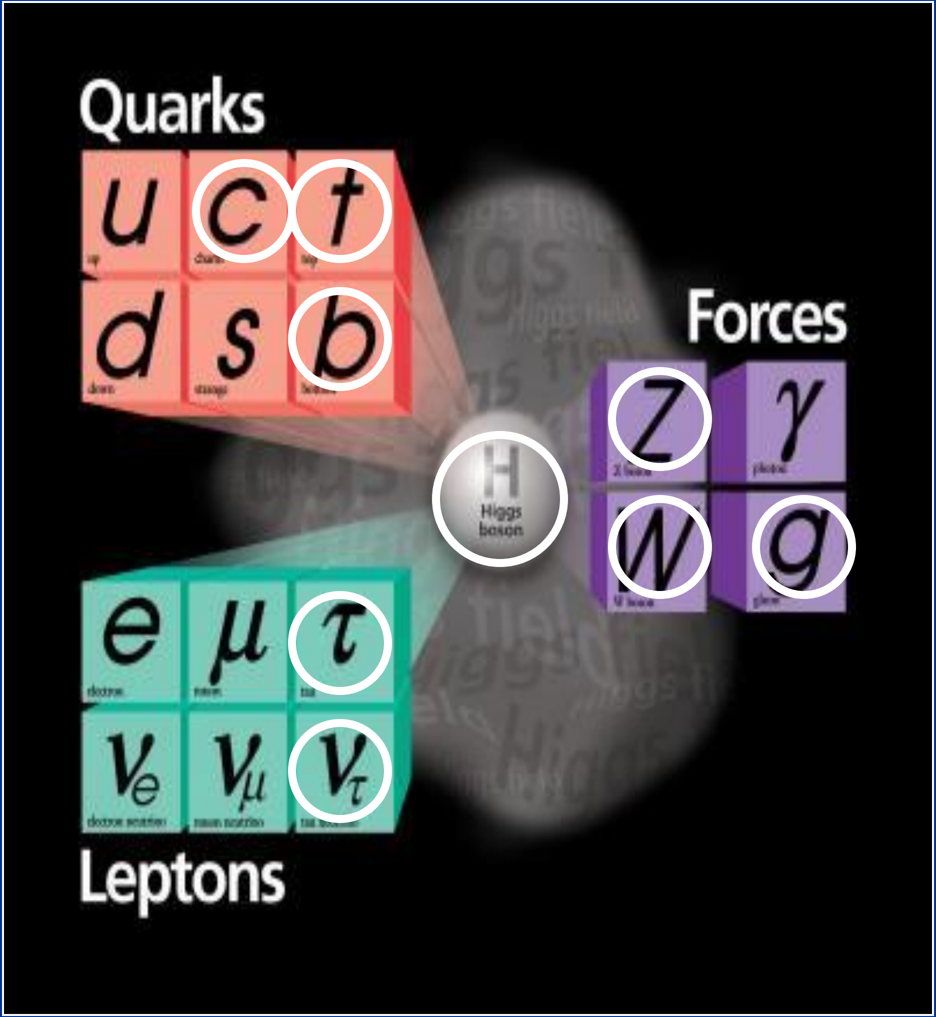




- **Re-use of LEP tunnel**
- **Discovered missing piece of the Standard Model - the Higgs boson**
- **Extensive searches for physics beyond Standard Model**
- **Many more exciting results expected**



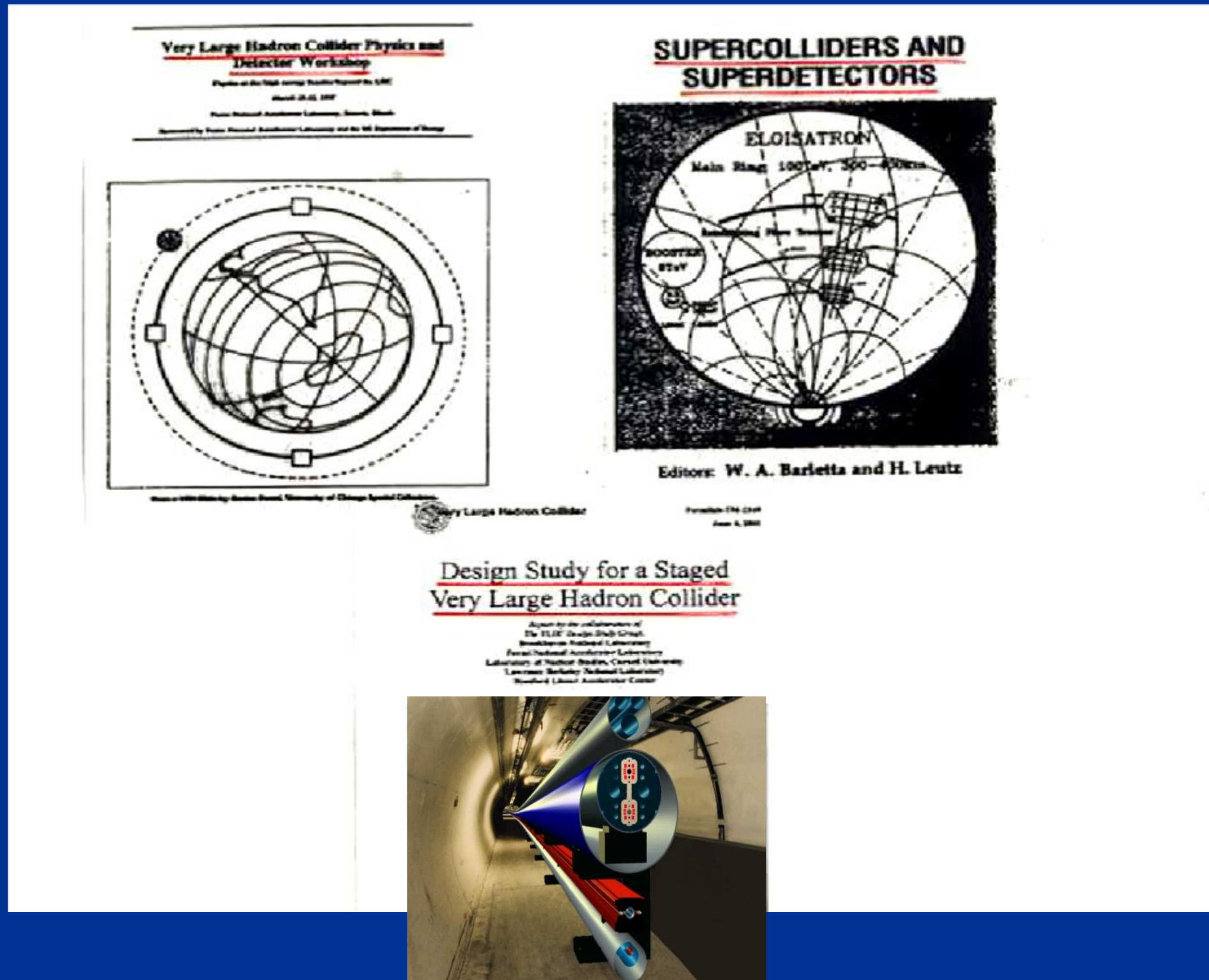
Accelerators and the Standard Model



- **Progress in particle physics over past 40 years was 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**

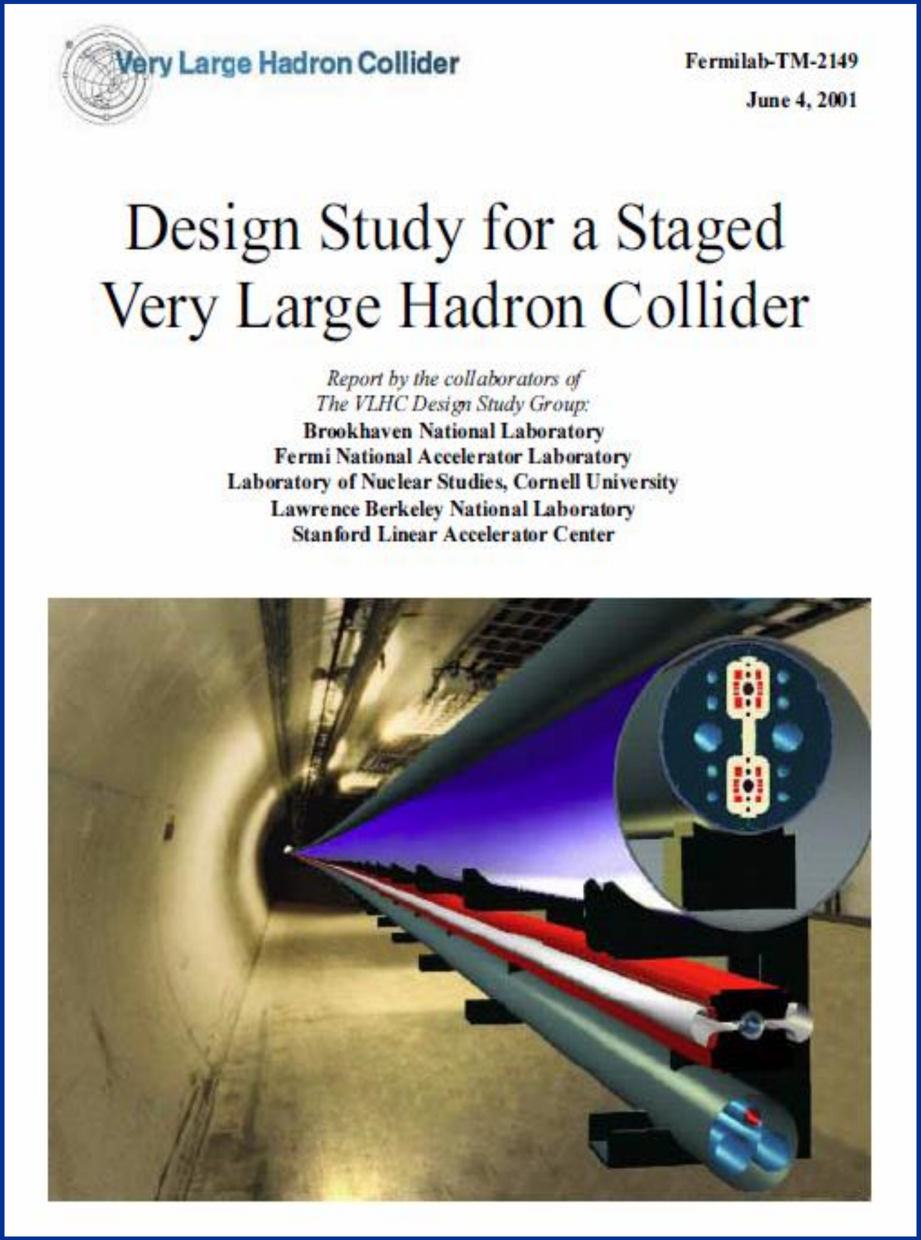
At every step new accelerator ideas provided less expensive ways to get to higher beams energies

Many Studies for ~100 TeV Accelerators/Detectors Exist



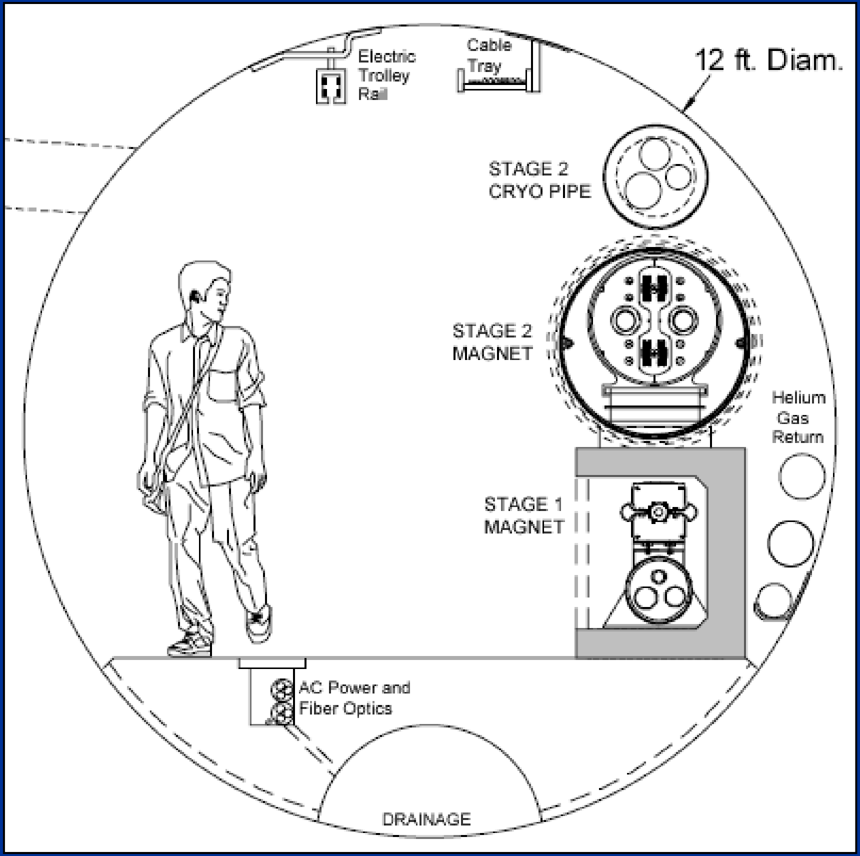
SppS, Tevatron, UNK, SSC, LHC studies/proposals/experiences are invaluable

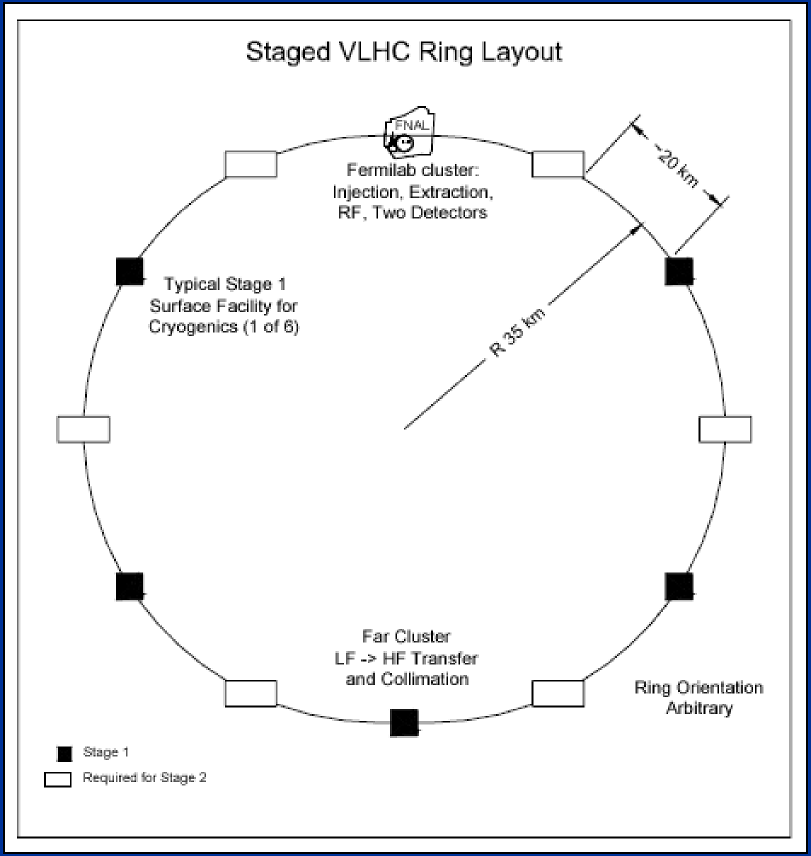
Design Study for a Staged Very Large Hadron Collider



- Study performed for 2001 Snowmass meeting
- 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

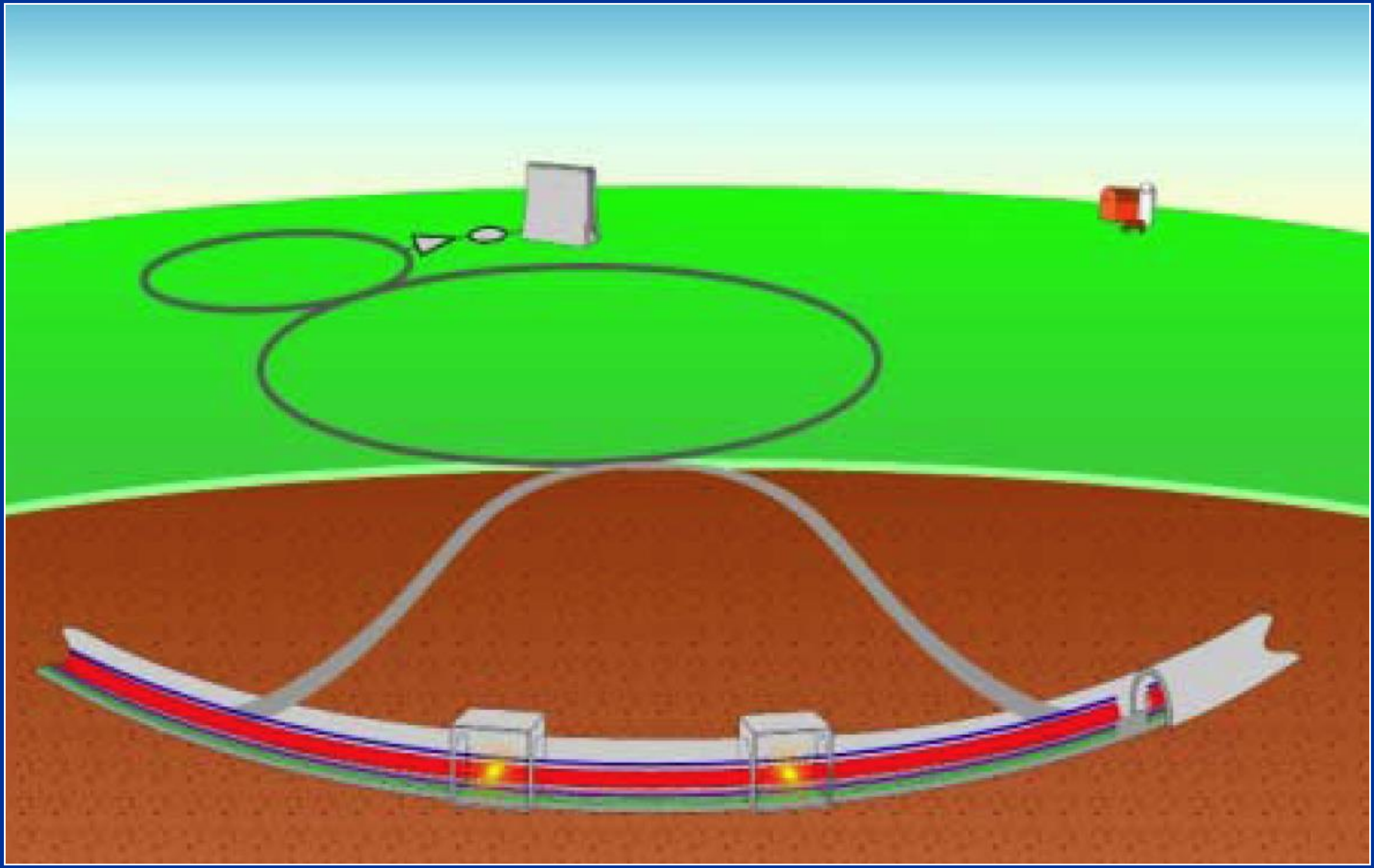
Main VLHC Idea: Long Tunnel vs Highest Field Magnets





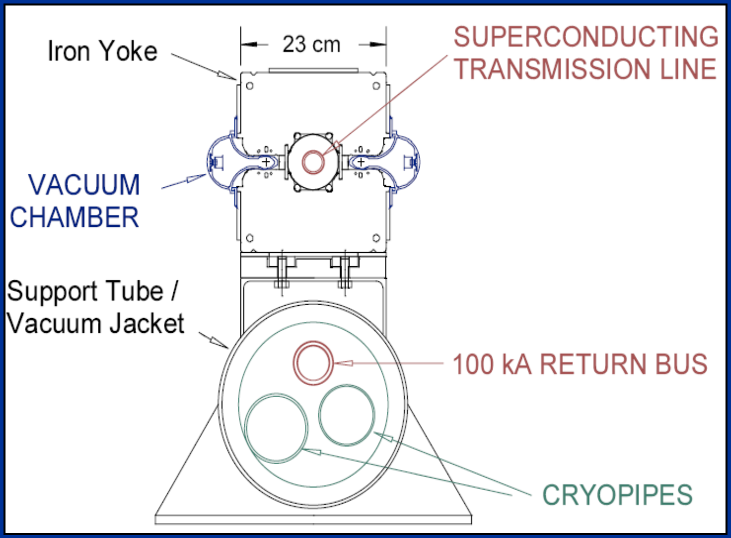
- **Tunnel length proposed is 233 km, small diameter, deep underground, only few shafts**
- **Two stages: "stage 1" is 2 Tesla warm steel magnet at 40 TeV, "stage 2" is 10 Tesla dual core magnet at 175 TeV**
- **Over last ~20 years long and deep tunnels technology was greatly advanced**

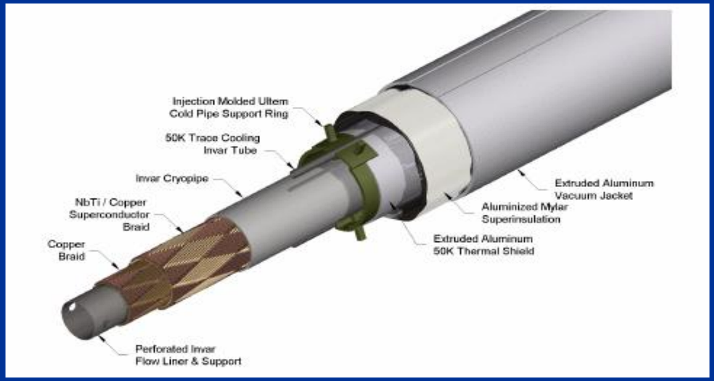
Fermilab’s Complex as an Injector

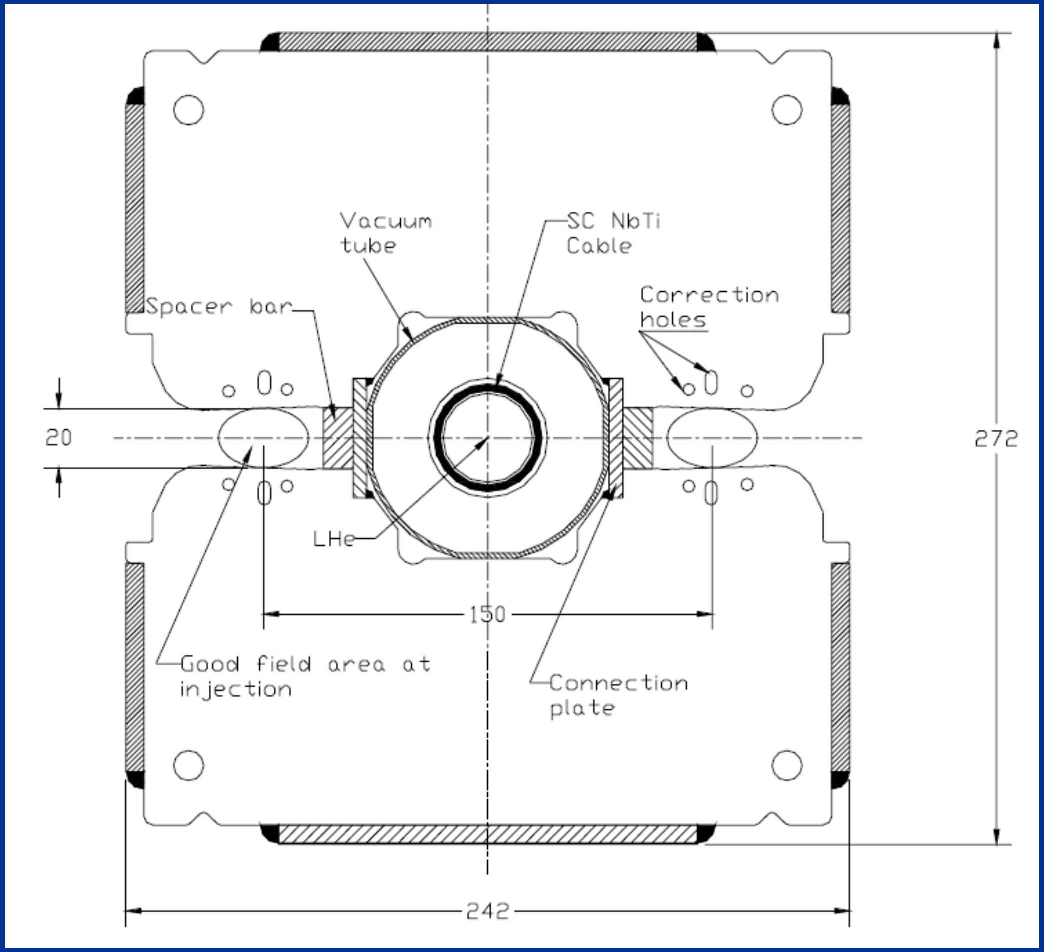


Fermilab’s accelerator complex is used as an injector with two main collision points located under Fermilab’s site

The Idea of "one turn" Magnet







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

High Energy Stage 2 Design

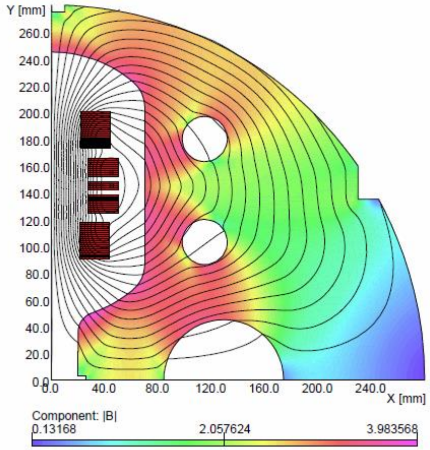


Figure 6.1. Magnetic design of the arc dipole.

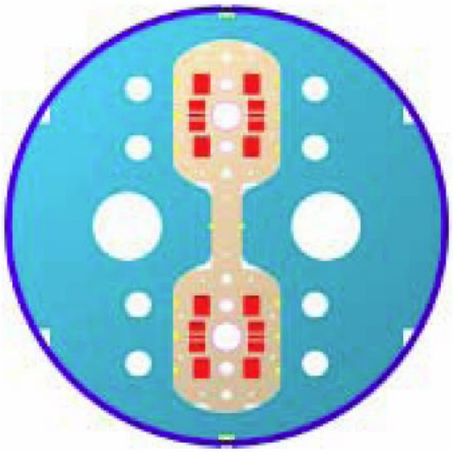


Figure 6.2. Cross-section of the arc dipole.

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

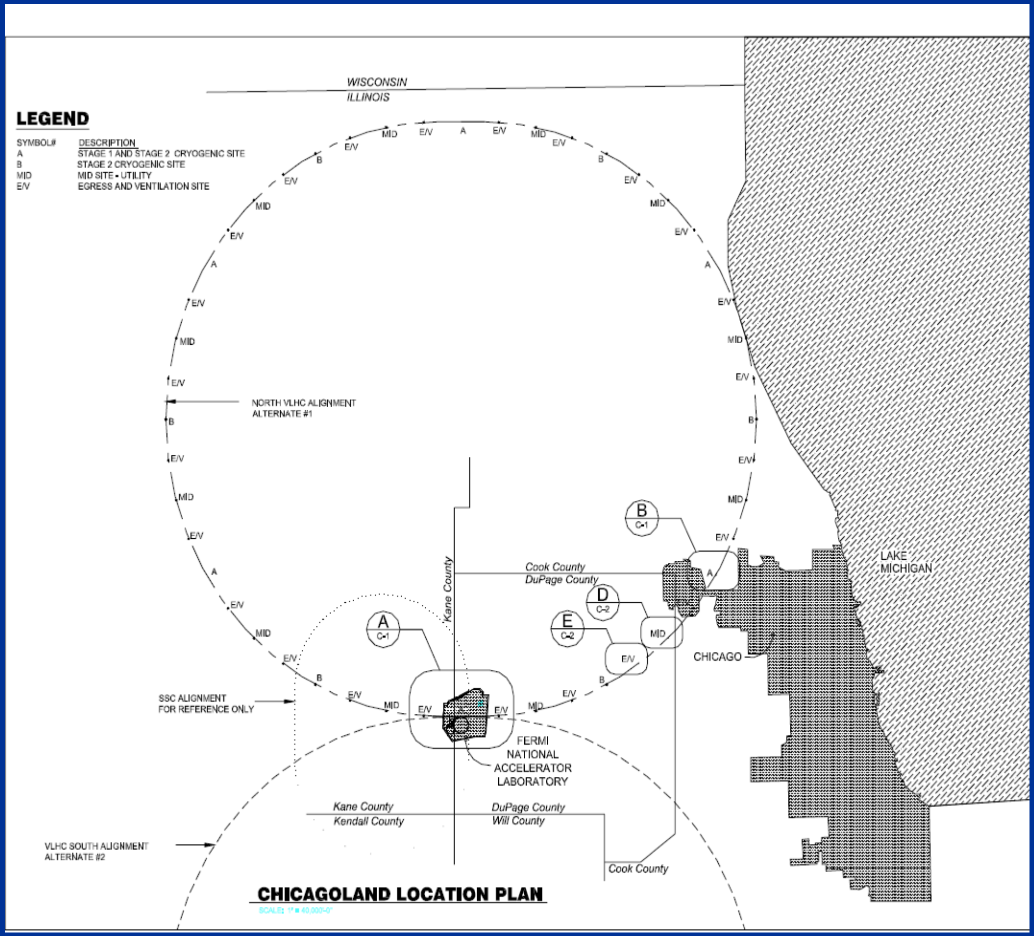
- **Design has two beam pipes with vertical orientation**
- **Maximum field is 10 Tesla providing 175 TeV in 233 km tunnel**

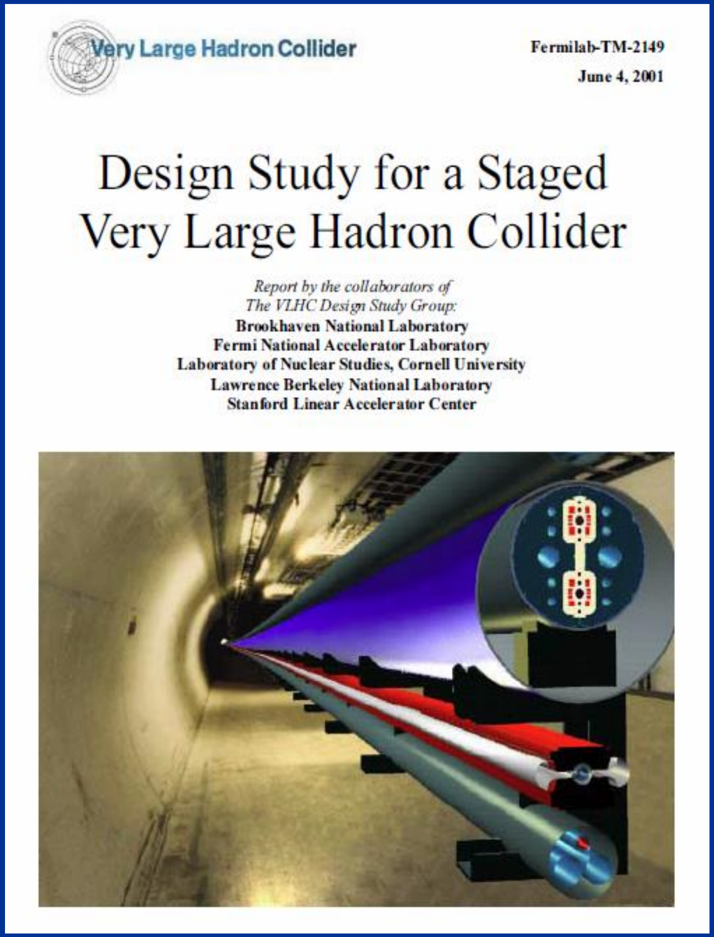
Parameters of 40 and 175 TeV Colliders

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

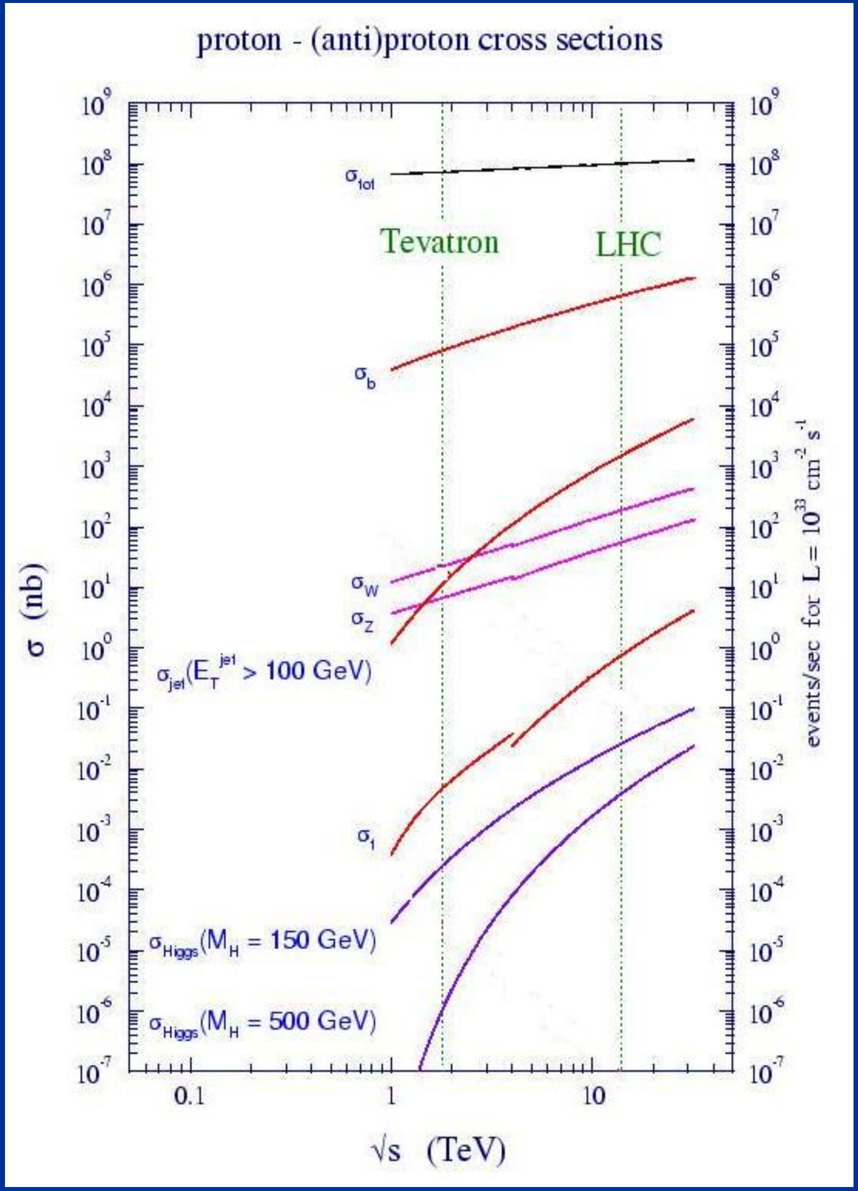
273 Pages VLHC Technical Proposal





- **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**

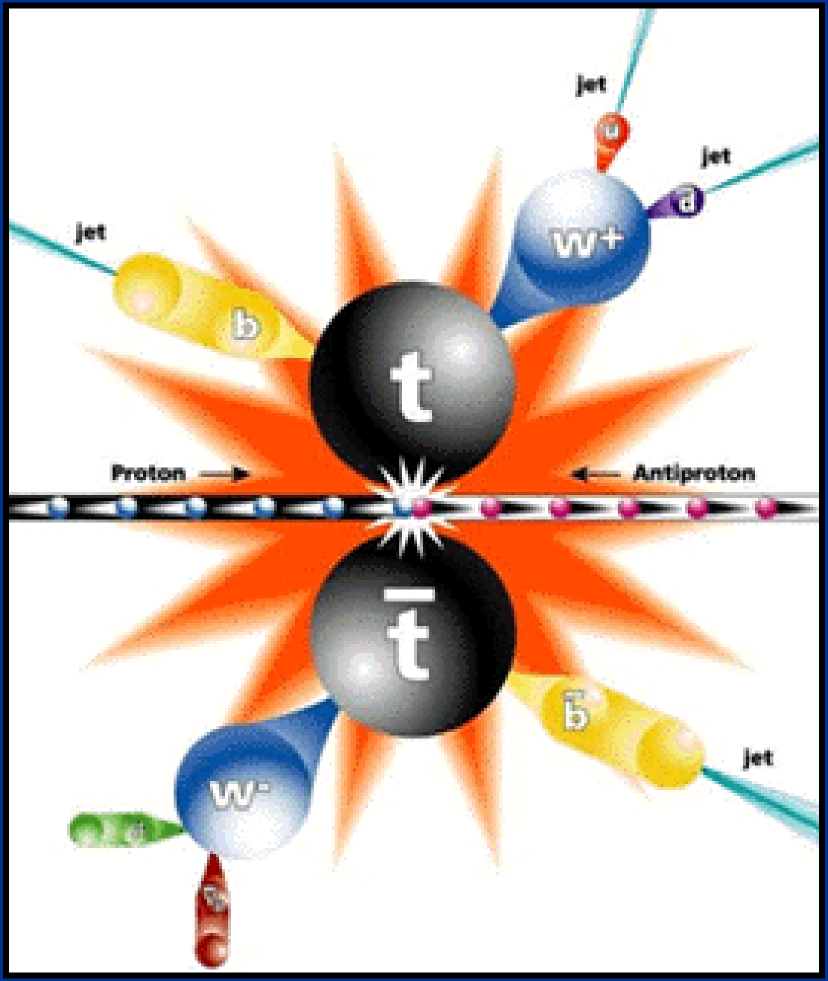
Experiments at ~100 TeV



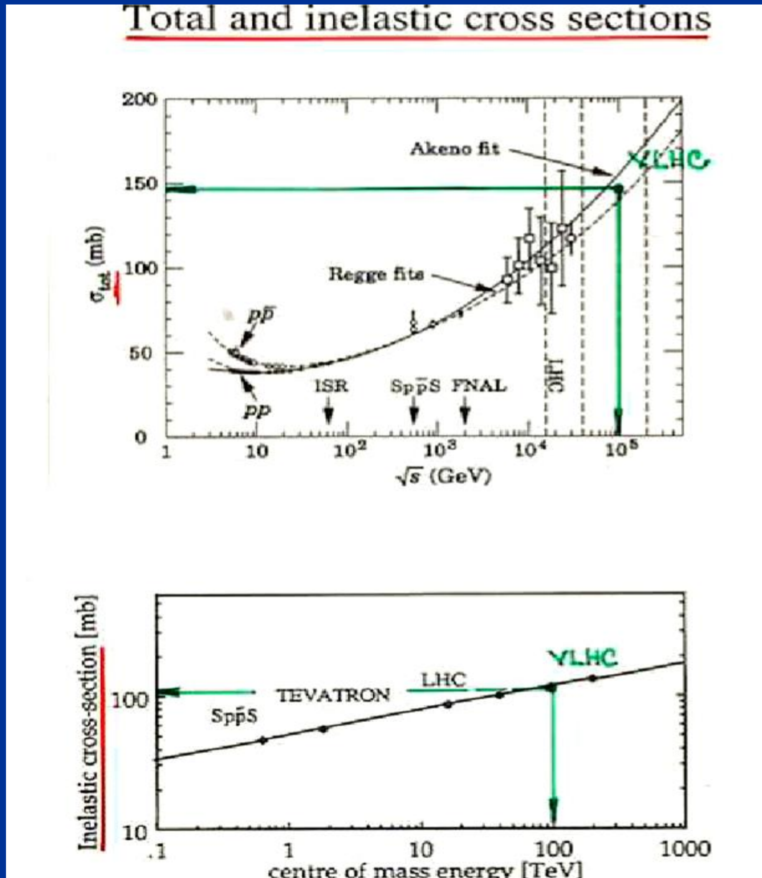
- **Main features of pp collisions**
  - **Very slow raise of total cross sections with energy**
  - **Very fast raise of "interesting" cross sections with energy**
- **"Energy is better than luminosity"**
  - **For physics reach**
  - **For detectors performance**

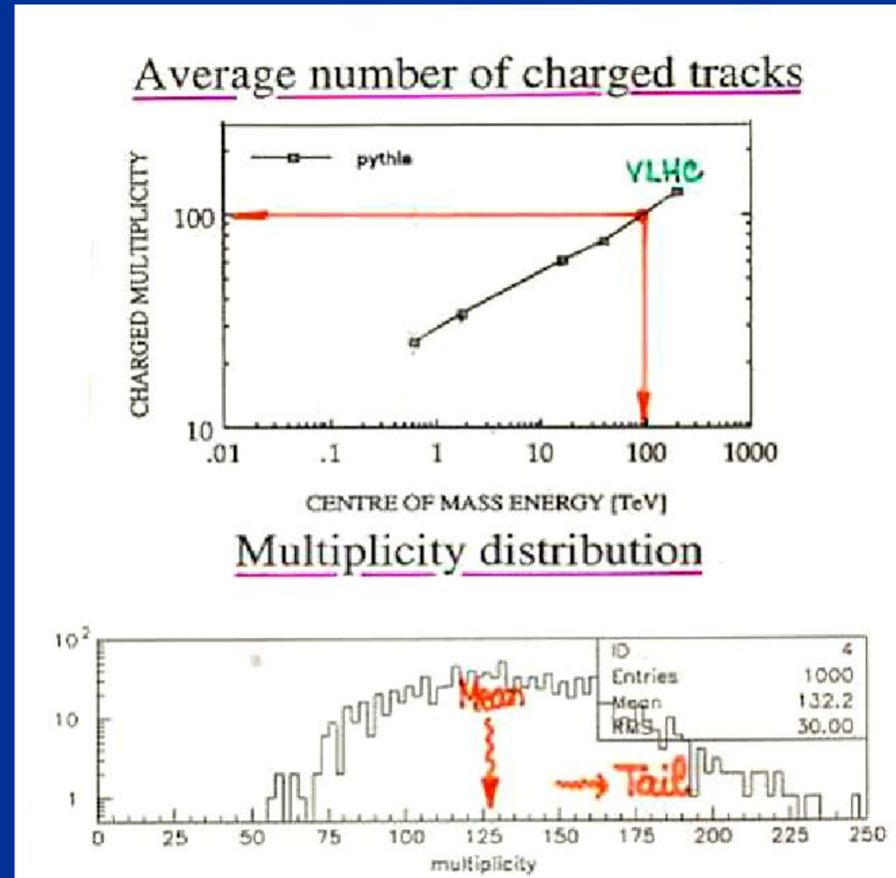
What We Would Like to Measure?

- In order to discover the top quark both CDF and D0 had to detect
  - Leptons (e/μ)
  - Jets
  - Tag b-quarks (associated lepton, displaced vertex)
  - Neutrinos (missing E_t)
- We need
  - Tracker (e/μ, vertex)
  - Calorimeter (jets, missing E_t)
  - Muon system
- Basically we are measuring all stable (lifetime more than a few mm) known particles



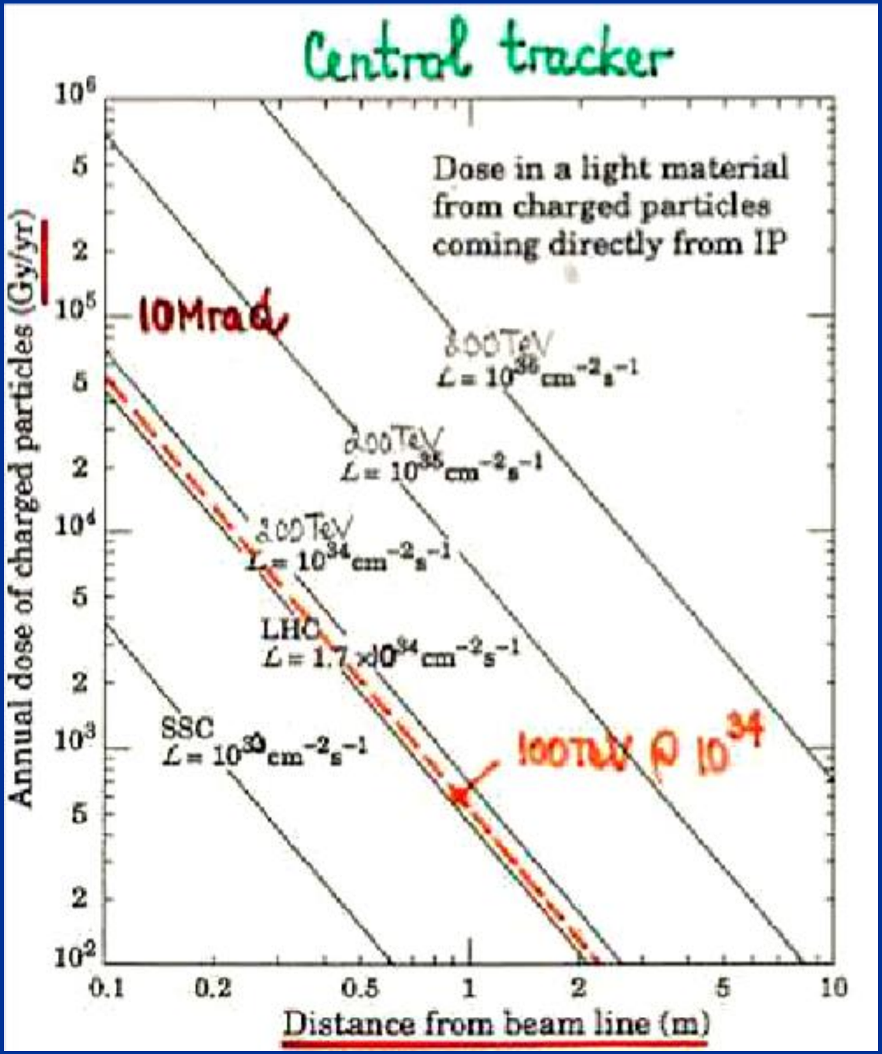
VLHC Design Study on Experiments





- VLHC design study provided important information on experiments and detectors
- Properties of soft pp interactions at 100 TeV are 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 the collisions
-

What about Radiation Doses?



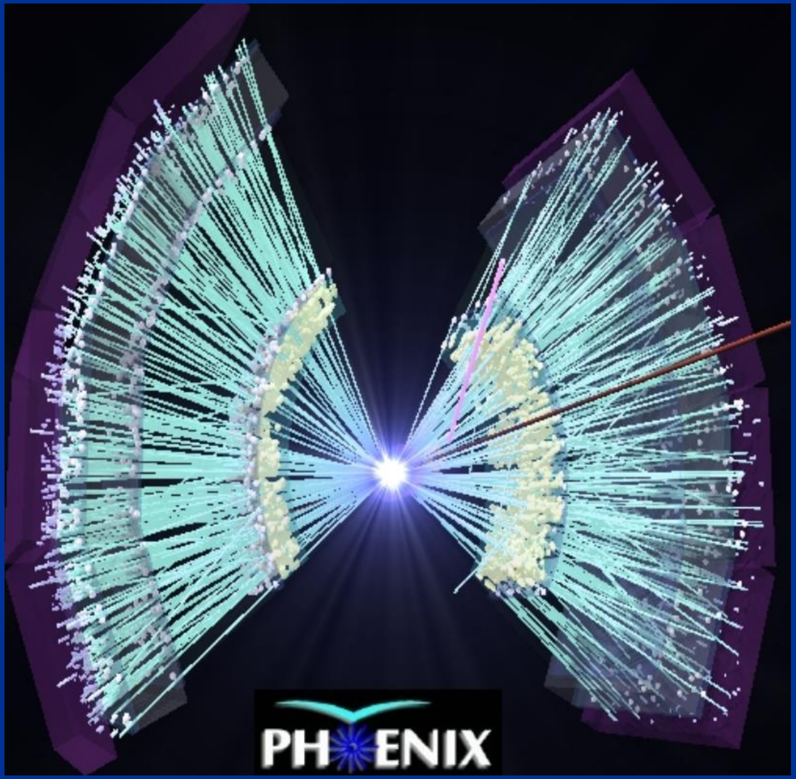
Radiation in the center region scales with luminosity, not energy

Accelerator-Detector Interface Parameters

- Interaction region sizes
  - Transverse plane
    - A few microns in diameter beam spot
      - As a point for a precision tracking
      - For short lived particles detection
  - Longitudinal dimension
    - Longer
      - Easier to separate multiple interactions
      - Lower local occupancies and radiation doses
    - Shorter
      - Smaller (cheaper) detectors
      - Better missing E_t resolution
- From Snowmass and other studies longitudinal size of $\sigma \sim 10$ cm came as the baseline number
  - Reasonable for the accelerator design

Accelerator-Detector Interface

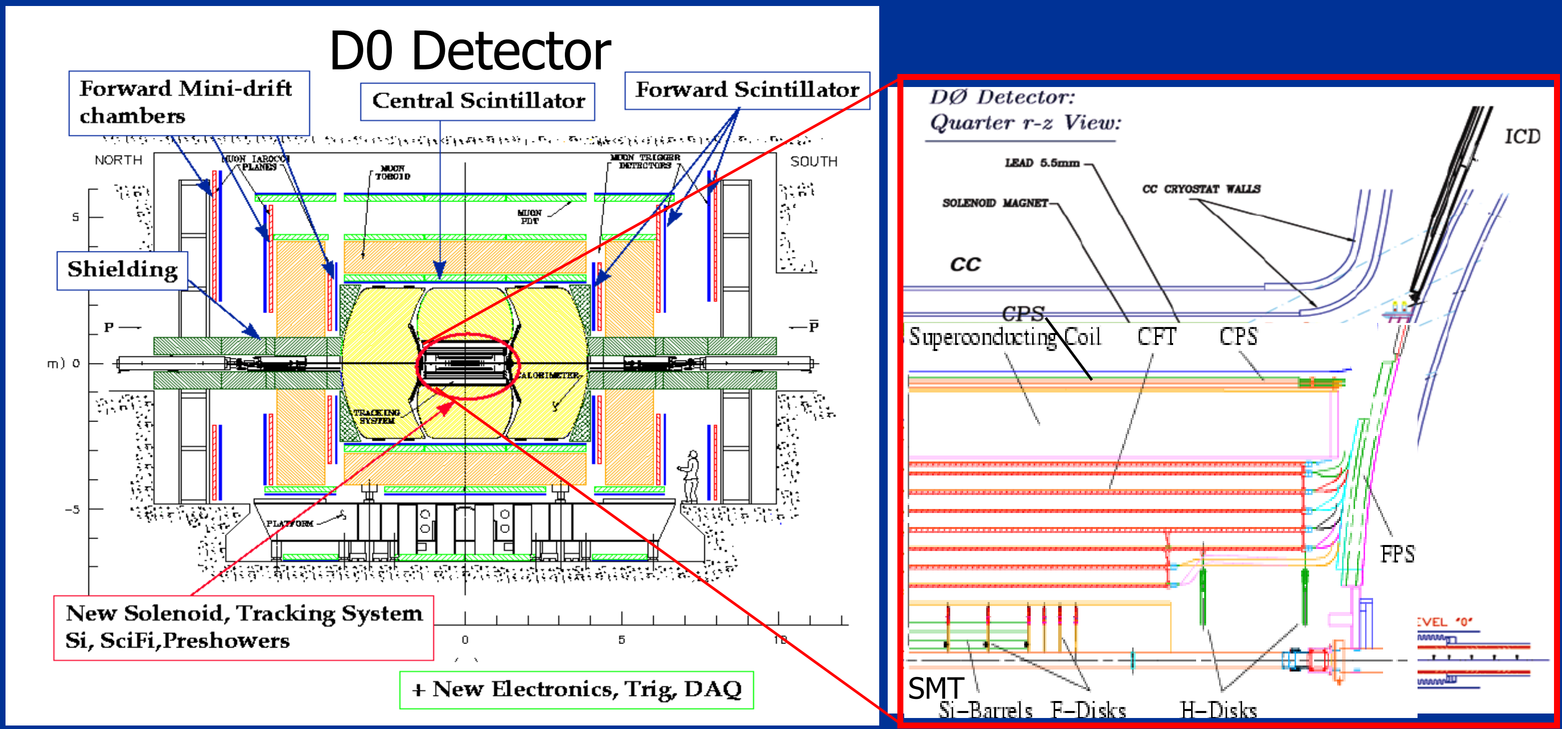
- Bunch spacing time
  - Shorter bunch spacing reduce number of interactions per crossing
    - Events pileup reduction
    - Complicates detectors and electronics
  - Natural limit
    - (detector size)/c
    - ~20ns (LHC's choice)
  - DC beam?
- Very important
  - Beam halo
  - Other accelerator induced "backgrounds"
    - Beam aborts



"Simulation" of a large multiplicity crossing…

General Purpose Detector

- General purpose colliding detector design has been pretty stable over last ~30 years
  - Tracking in the central solenoid field with precision vertexing
  - Hermetic electromagnetic and hadron calorimetry with fine segmentation and good rapidity coverage
  - Large acceptance muon system with good triggering and tracking capabilities



Central Tracker

- **Tracker momentum resolution deteriorates with momentum**

$$\sigma_p/p \sim p \cdot \frac{\sigma_{det}}{B \cdot L^2}$$

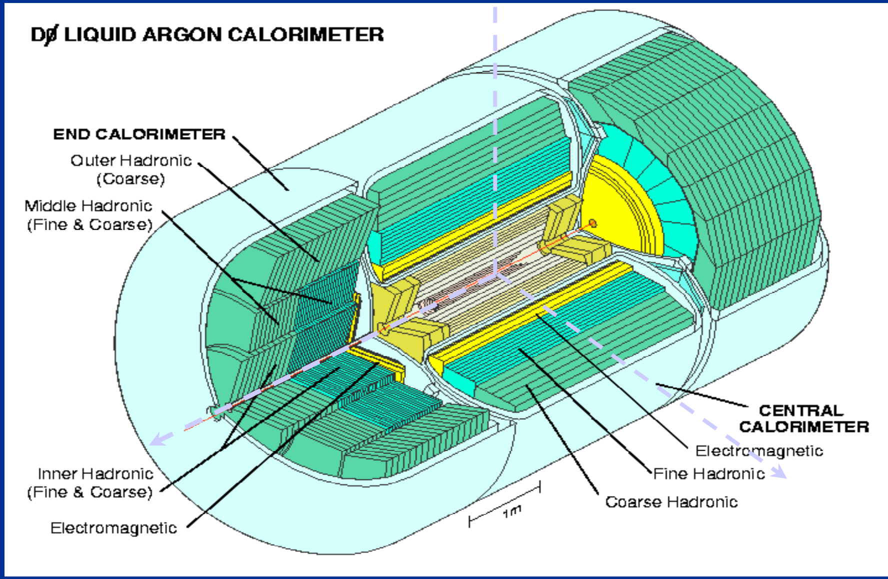
- **To keep resolution reasonable with increase in momentum scale**
  - **Increase detector lever arm (L) – cost increase**
  - **Increase magnetic field (B) – at the limit**
  - **Improve coordinate accuracy of detectors σ_{det} to a few micron level**

- **Serious issue for VLHC tracker is to keep momentum resolution at reasonable level for high p_t tracks**
  - **Give up momentum measurement a'la Run I Tevatron D0 detector?**

D0 silicon tracker

Calorimetry

- Shower depth is ~ln(E)
  - Minor size increase in comparison with LHC
- Energy resolution:
  - Electromagnetic: $\sim 15\%/\sqrt{E}$, 0.5% at 1 TeV
  - Hadron $\sim 50\%/\sqrt{E}$, 2% at 1 TeV
- Calorimetry gets very precise at high energy!
- Issues
  - Events pile up
    - ~50GeV/jet cone at $L=10^{34}\ cm^{-2}sec^{-1}$
    - Background energy fluctuates and luminosity dependent
  - Large dynamic range



Calorimetry

- **Main specifications for VLHC calorimetry**
  - **Radiation hard**
  - **Small constant term, stable, easy to calibrate**
  - **Thick – missing E_t, energy resolution**
  - **Fast – signal collection time below bunch spacing**

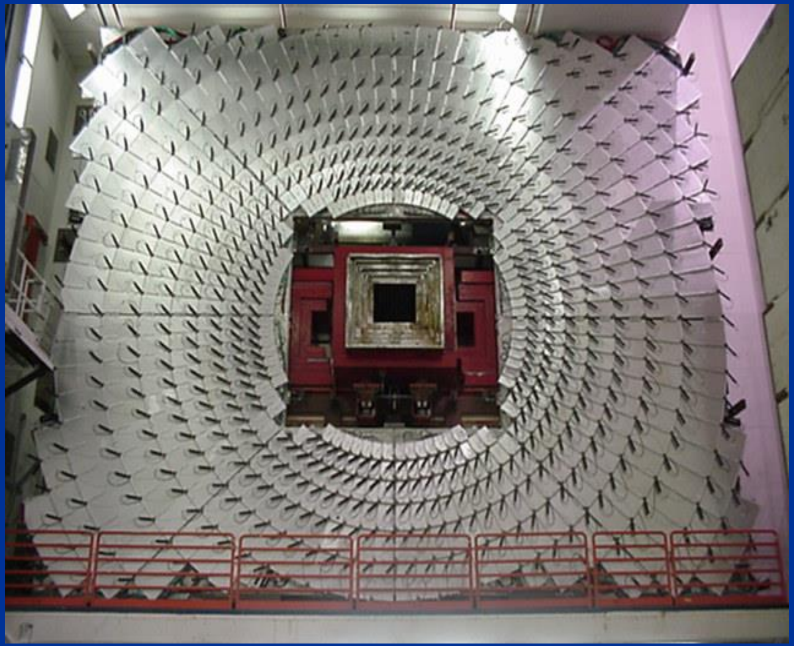
- **Multiple options available**
  - **Scintillation based calorimetry**
  - **LAr**
  - **Crystals**
  - **High density gas calorimetry**

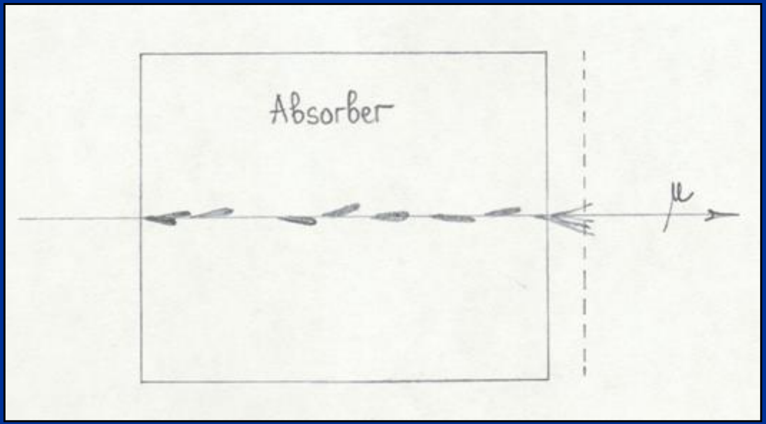
Calorimetry looks feasible for luminosity up to ~10^{35} cm^{-2} sec^{-1}, but not many choices for above 10^{35} cm^{-2} sec^{-1}

Detection of Muons

- *High* energy muons are important for search of heavy objects and *low* energy muons for t, b quarks and Higgs tagging
- Muon detectors are BIG!
- Radiation damage is less of a problem for muon detectors
  - but fluxes from accelerator and neutrons have to be carefully estimated
- High energy muons start to irradiate γ (em showers) and loose more energy due to radiation losses then due to ionization at a few hundred GeV
  - Creates backgrounds in the muon tracking detectors and requires corrections for momentum measurements

10x10 m² D0 muon system





Detection of Muons

SDC/SSC Proposal

- **Momentum resolution is limited by factors similar to the central tracker**

$\sigma_p/p \sim$ $p \cdot \frac{\sigma_{det}}{B \cdot L^2} \oplus$ multiple scattering

  - **Design SDC (SSC) muon system resolution is ~ 10% at p_t ~ 1TeV/c**

- **Precision measurement of very high energy muons is a challenging task**

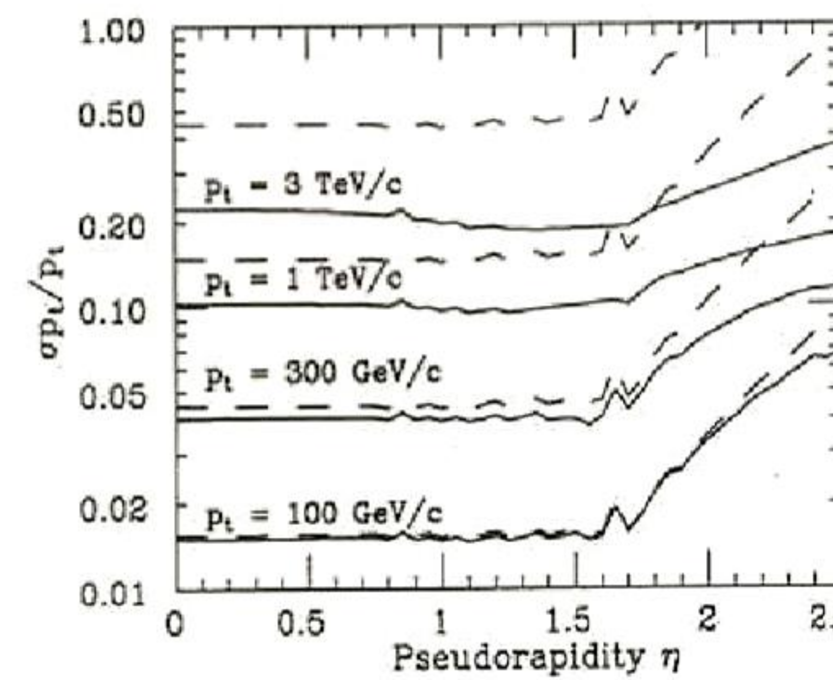
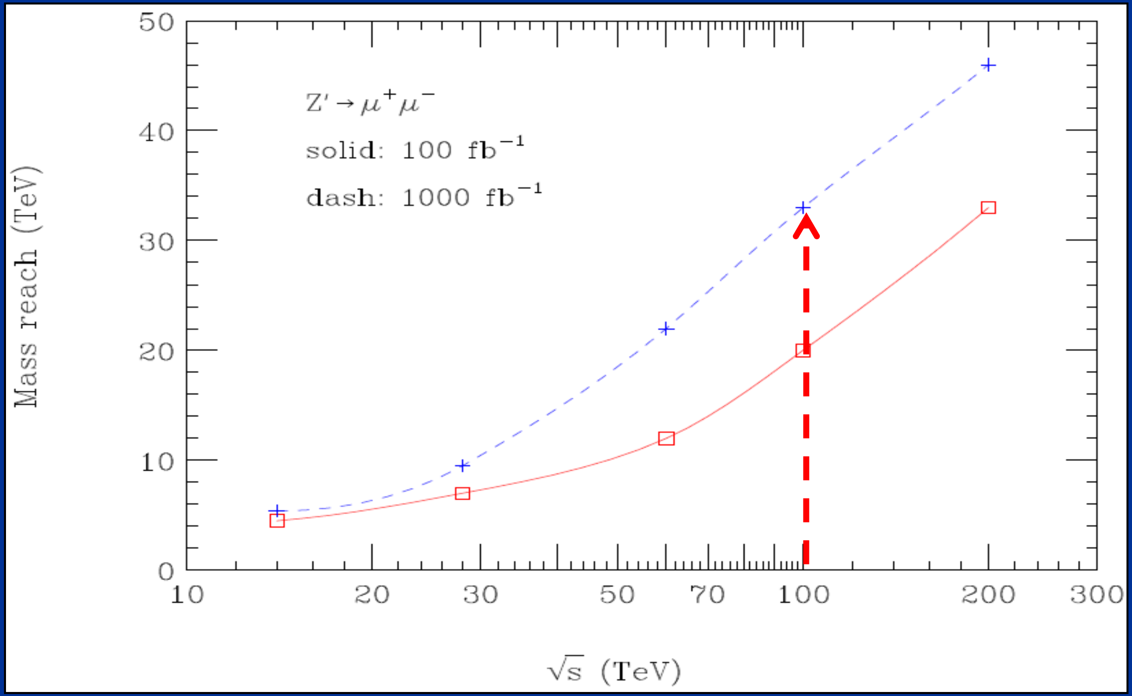


FIG. 7-4. Momentum resolution for muons using combined measurements from the inner tracker and the muon system (solid lines) and from the inner tracker alone (dashed lines).

Collider Energy and Mass Reach



- **Many studies have been 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 would be about twice less expensive than 40 TeV (could saved SSC?)**
  - **But don't want to miss a discovery due to a few % lower energy (LEP)**

VLHC Study: Detectors for ~100 TeV Collider

- We would like to detect all "well known" 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 vs LHC
- Calorimetry
  - Getting better with energy: hadronic energy resolution ~50%/$\sqrt{E}$, 2% at 1 TeV
  - Length of shower increase has ln(E) dependence – limit detectors sizes
- 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 above both due to pileup and radiation aging

Stage 1 VLHC 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)	

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

Issues/Studies of the VLHC Detectors

- Radiation hard detectors
  - Central tracking and calorimetry
- Very high precision tracking to measure muon momentum in the range 1TeV to 10 TeV with a few % resolution
  - Field? Size? Accuracy?
- Effect of events overlap on final states recognition
  - Handling 5 TeV per trigger tower from min_bias overlaps?
- The only way to reduce number of events per crossing is smaller bunch spacing. Can we build detectors/electronics which will resolve collisions a few ns apart
  - Begining of one shower is in the em calorimeter while hadron calorimeter still sees remnants of the shower from previous collision?
- Reduction in cost of the detectors, trigger and DAQ systems
  - Can we design detectors with slightly worse parameters, but cheaper with less construction time?
- For many years we did not see new principles of particle detection
  - Need reasonable level of R&D for the new methods of particles detection, however strange they look from the first glance