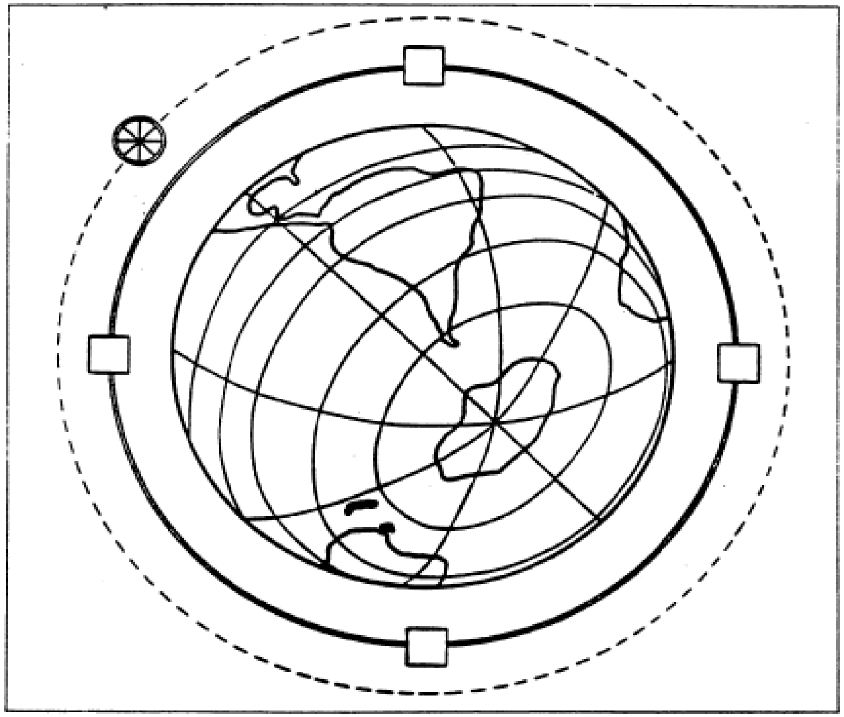
Toward the Next Energy Frontier



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

100 TeV proton-proton Collider

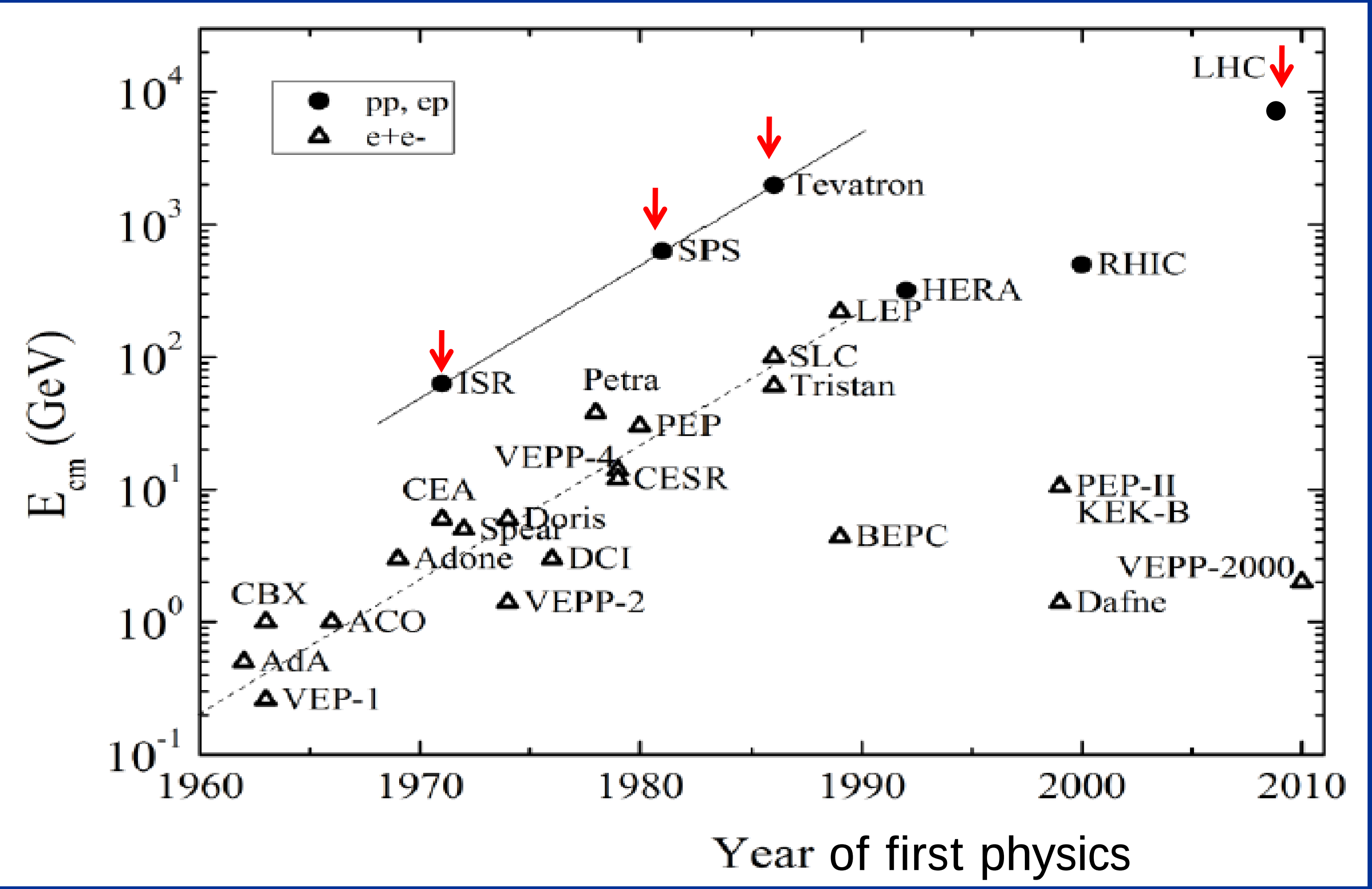
Dmitri Denisov

LPC Meeting on Future 100 TeV Proton Collider, January 31, 2014

Talk Outline

- Brief history of hadron colliders
- Why higher energy - quantum mechanics and relativity
- Available designs of very high energy colliders
- Are detectors feasible?
- Why we are not building higher energy hadron collider now?
- Comments

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 Proton Synchrotron
- Intersecting Storage Rings - ISR - was the first hadron collider

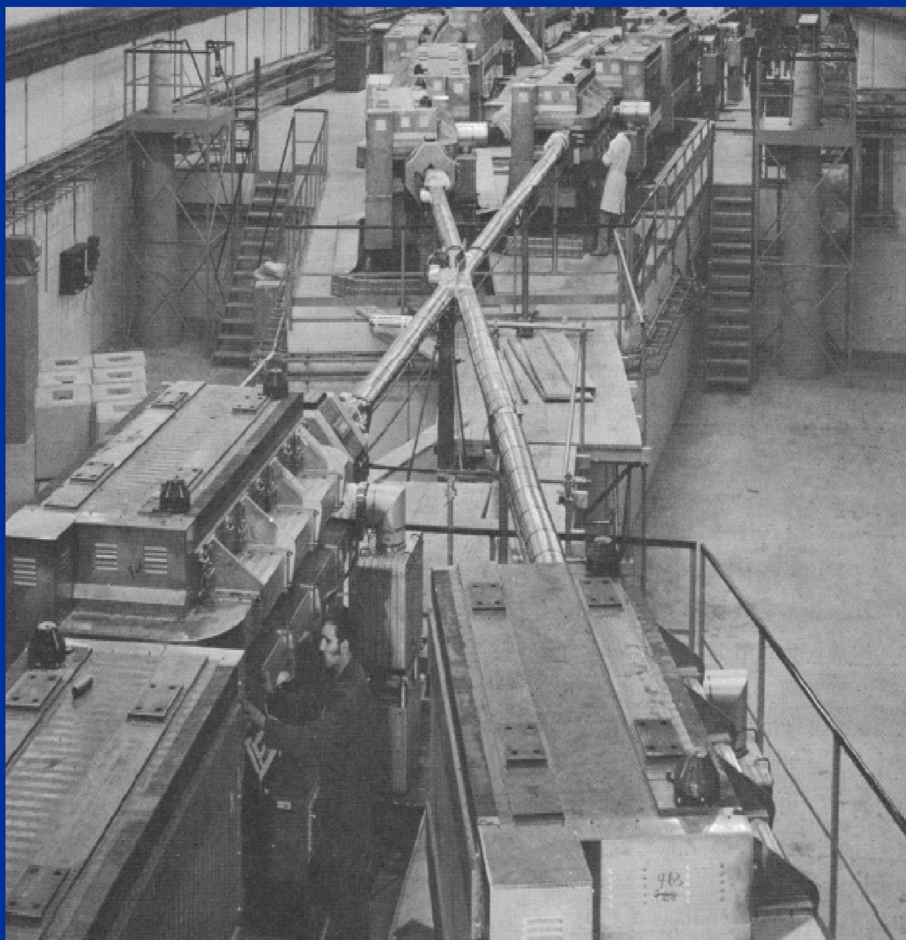
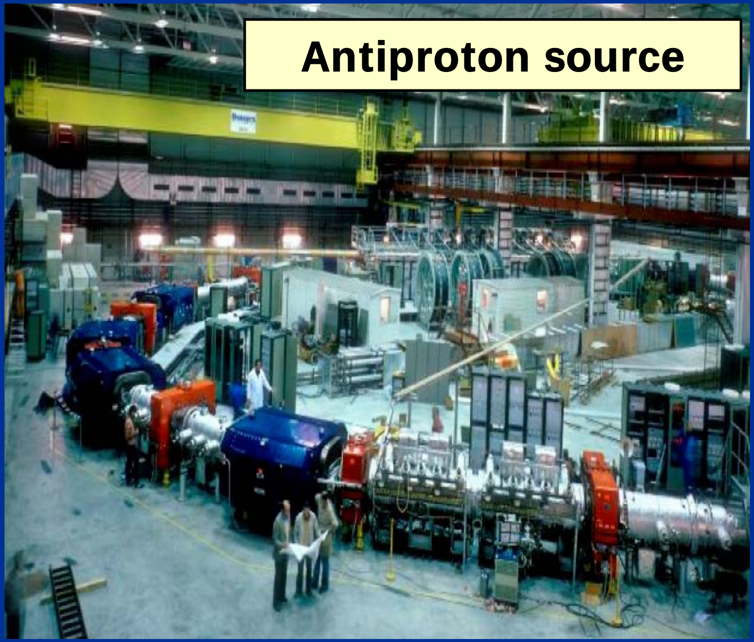
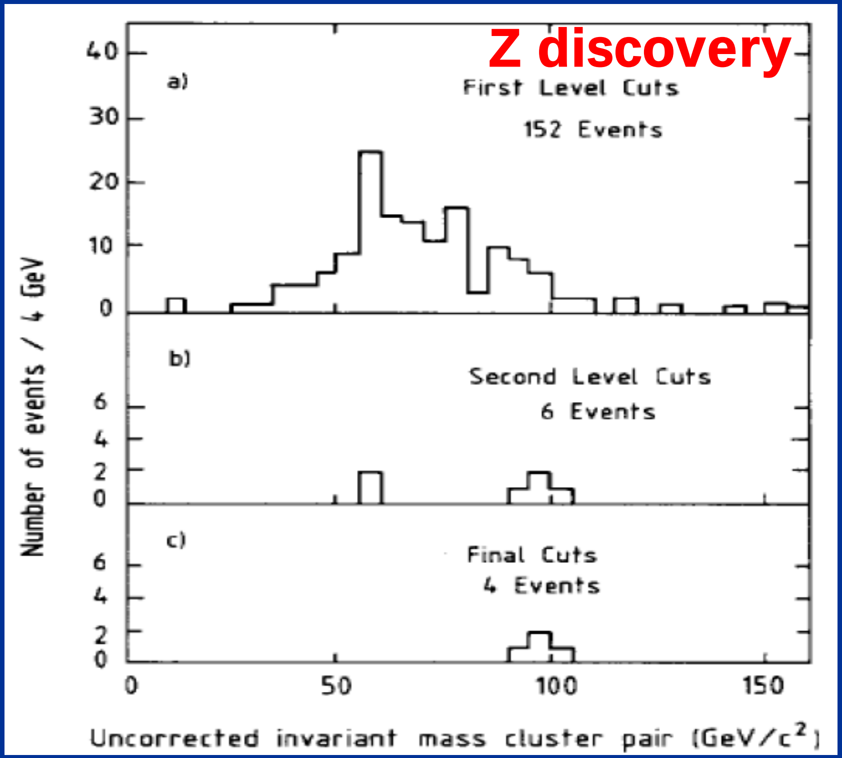


TABLE 1. *Main parameters of the ISR*

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

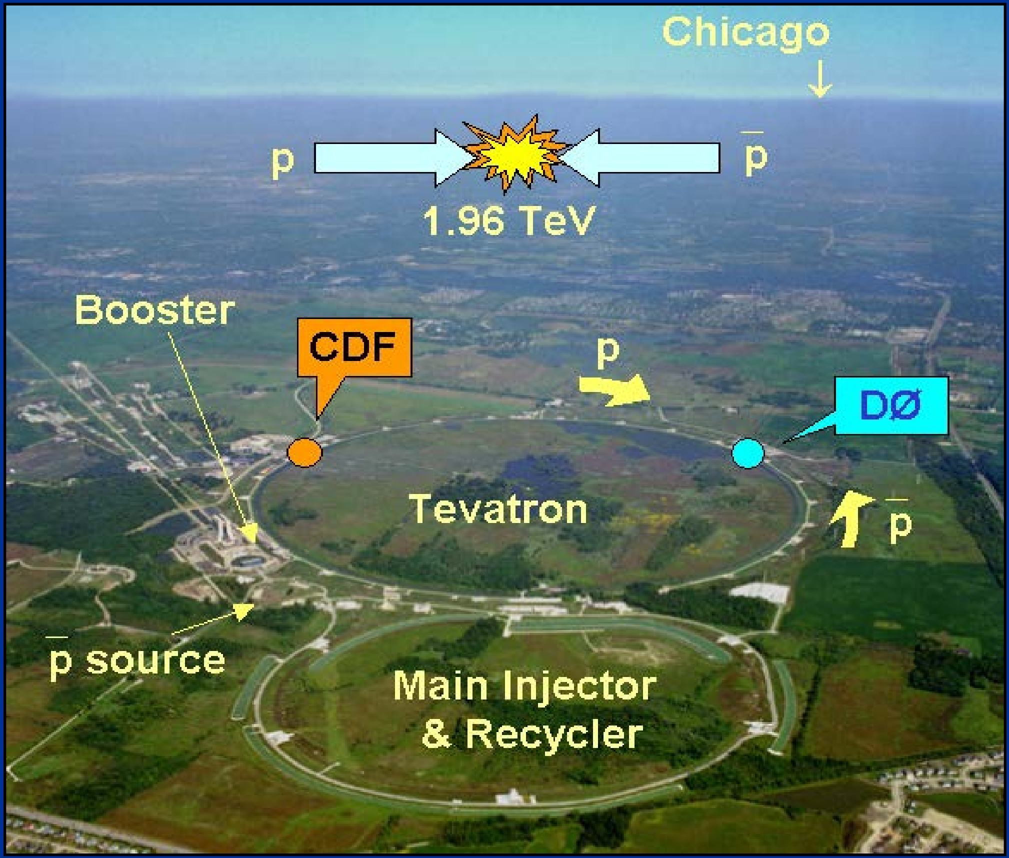
SppS Collider



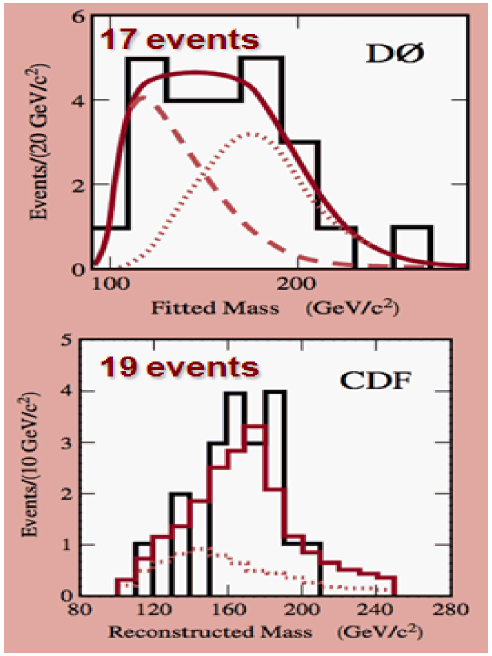


- **Use of antiprotons in the existing fixed target machine**
- **Provided next step in the understanding of the Standard Model**
  - **W/Z bosons discovered**

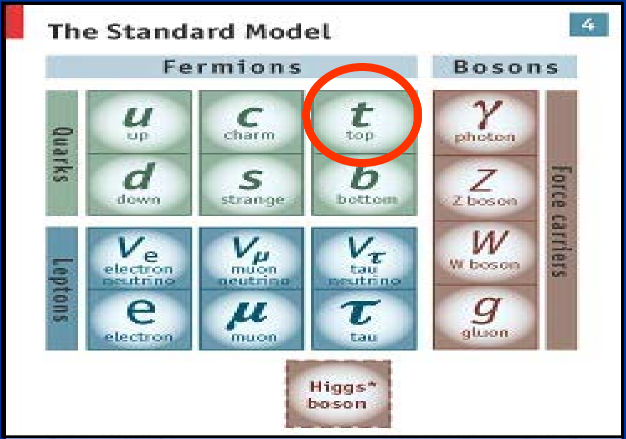
The Tevatron



Top Quark Discovery



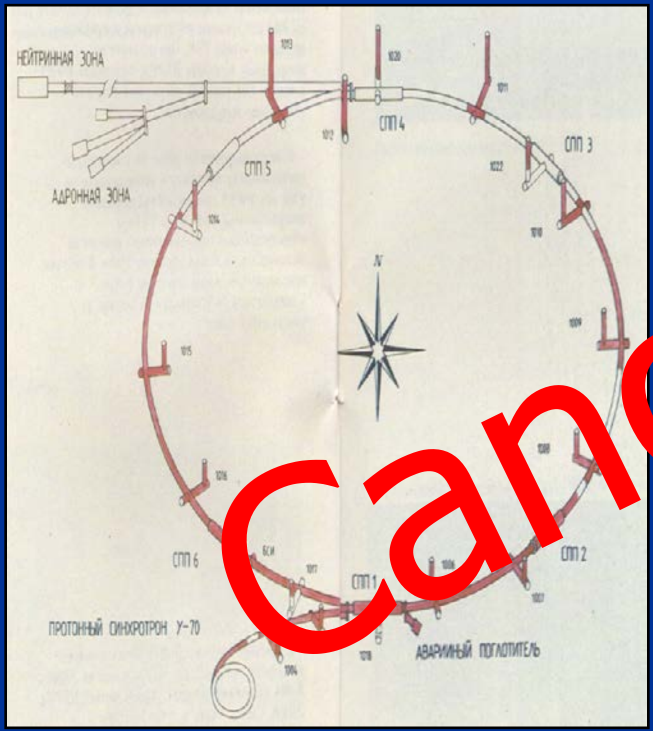
1995, CDF and DØ experiments, Fermilab



- **First superconducting accelerator 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, high luminosities are required
  - Challenges producing large number of anti-protons
  - Proton colliding beams for dedicated hadron collider
- Larger rings and higher field superconducting magnets to achieve beam energies well above 1 TeV

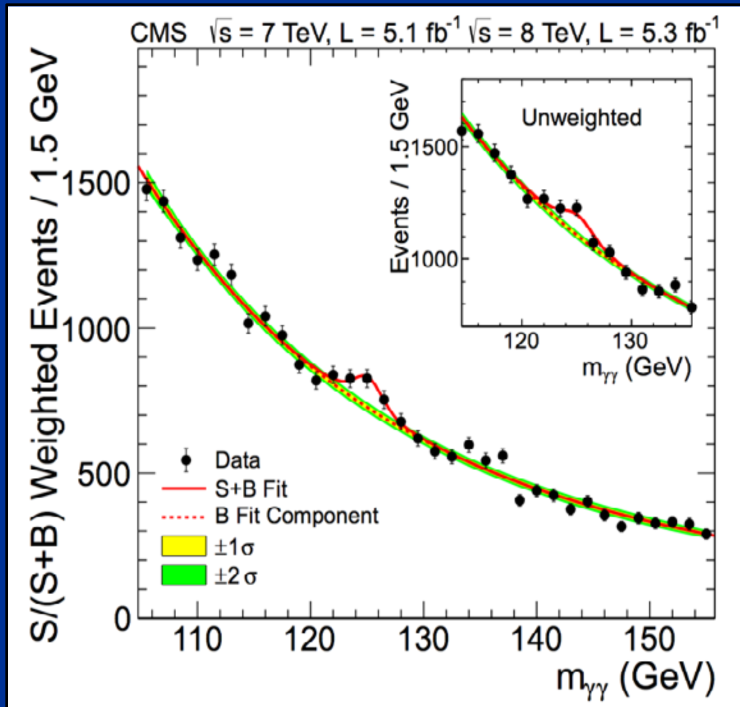


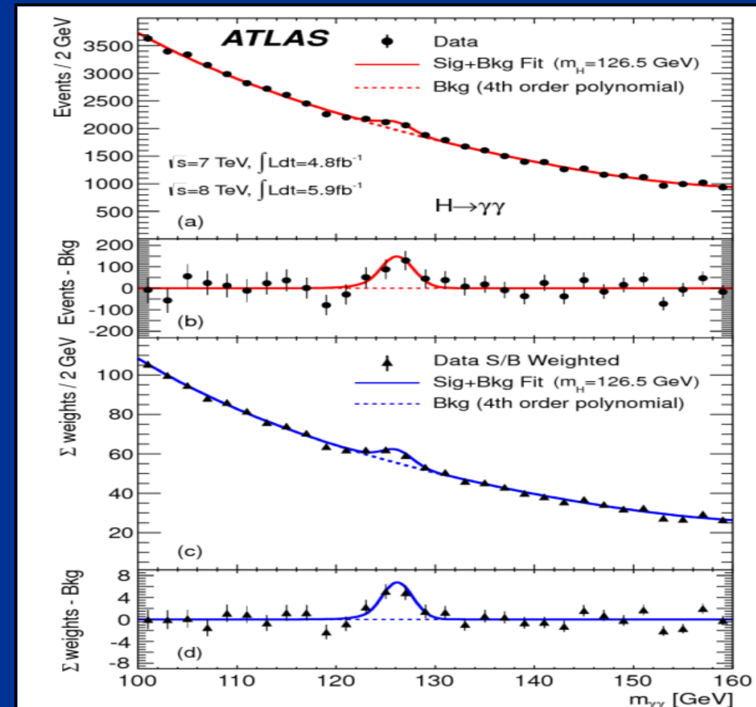
3x3 TeV, UNK

20x20 TeV, SSC

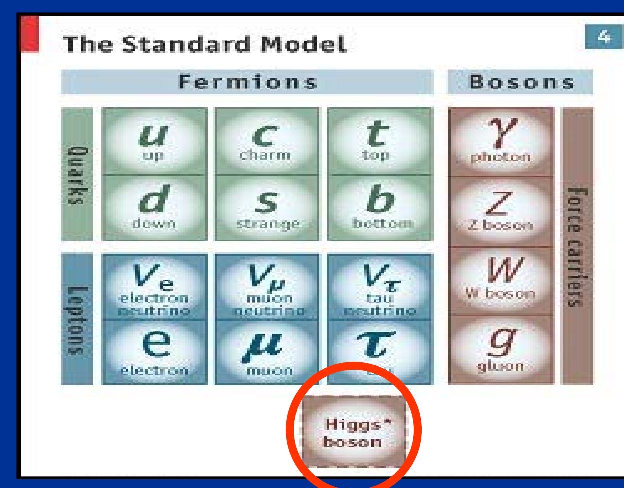
Cancelled

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**



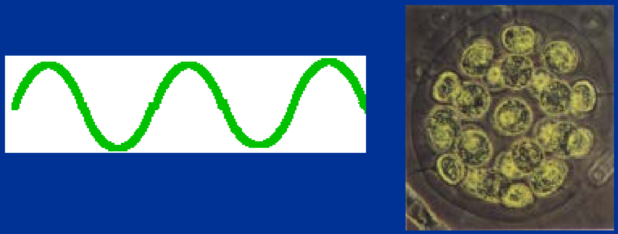
Why Higher Energies are Needed

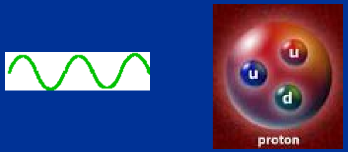
- **Accelerators are built to study nature smallest objects**

Wavelength = h / E

~2 ·10^{-18} cm for LHC

Cell



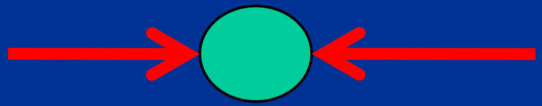


Proton

- **Accelerators converter energy into mass**

E = mc^2

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



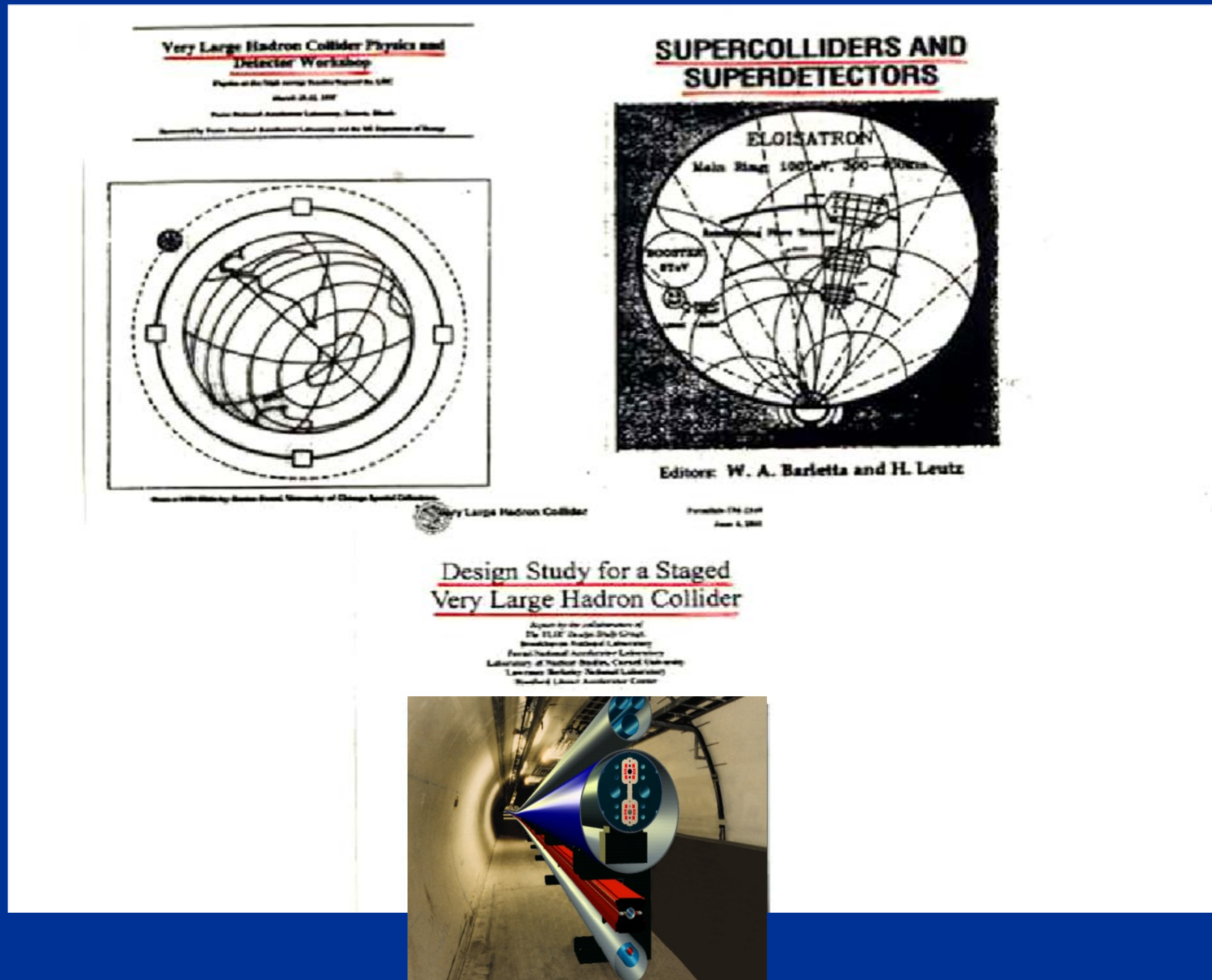
E_{beam} Mass E_{beam}

Accelerators are required for research due to fundamental principles of quantum mechanics and relativity

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 developed

A lot of Studies for 100 TeV Accelerators/Detectors Exist



- LHC and especially SSC studies/proposals/experiences are invaluable
- We can make quite a few predictions/estimates based on available information

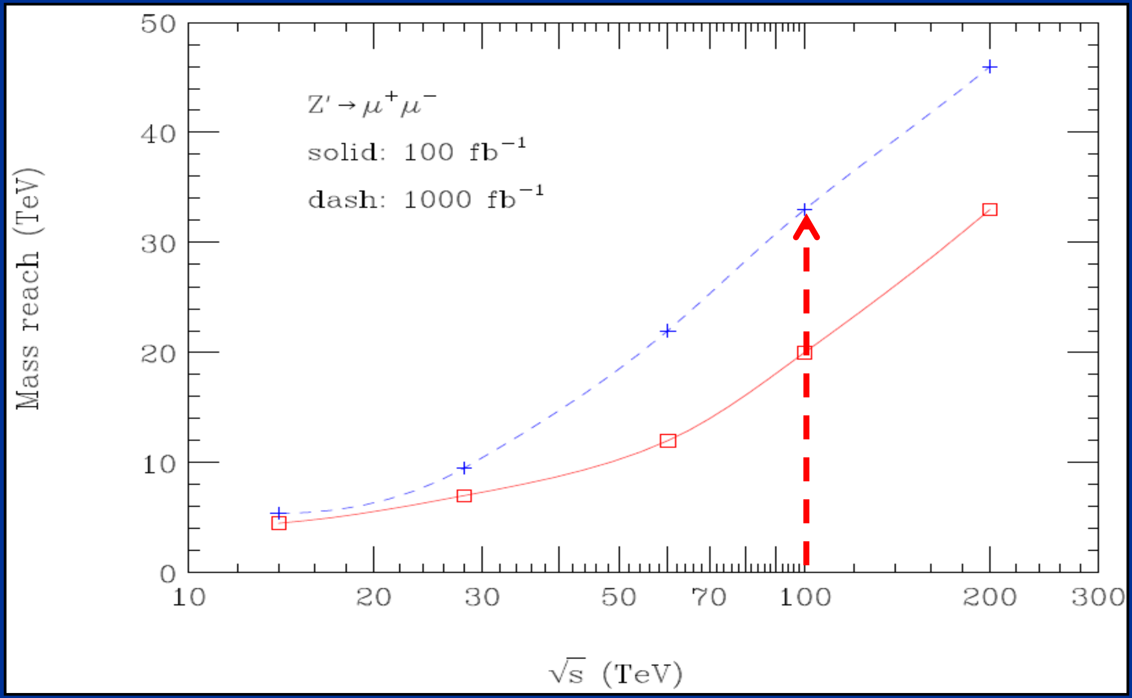
Parameters of 100+ TeV Collider

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

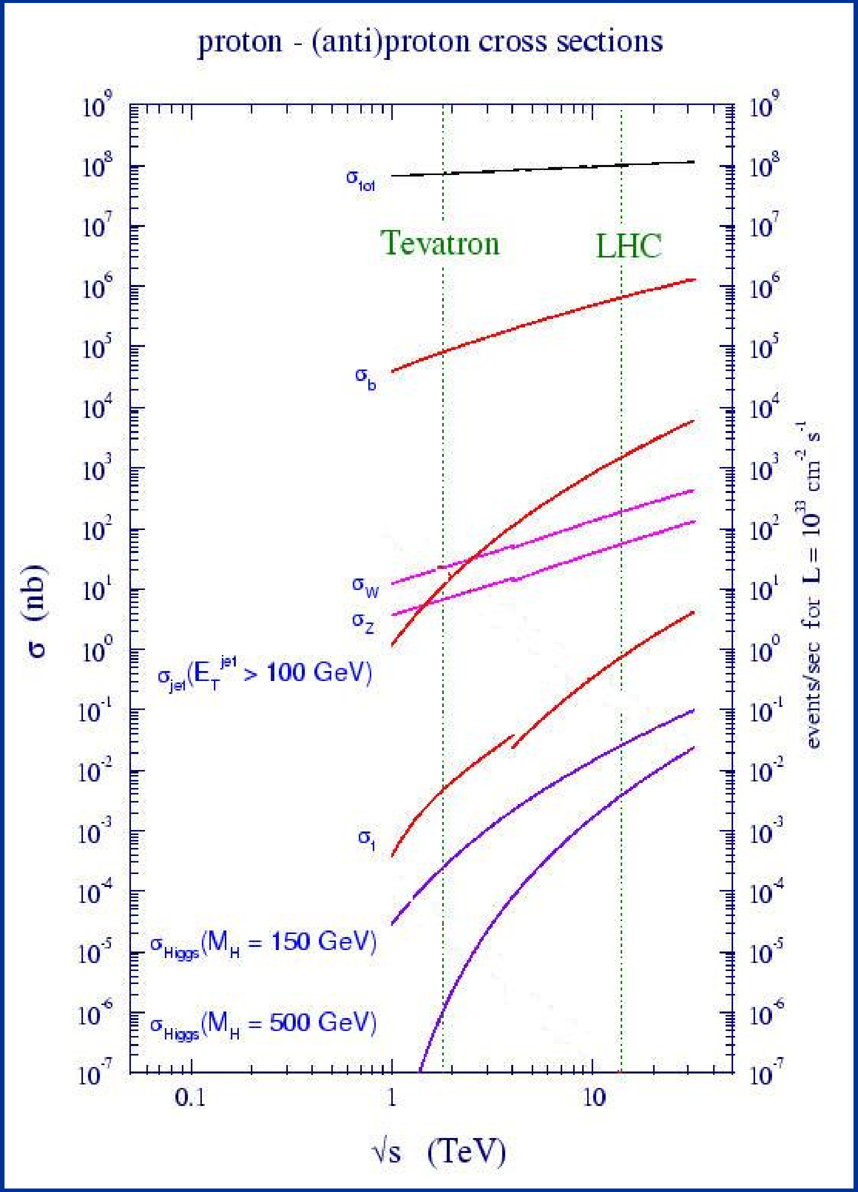
There are developed technical ways to get to 100-200 TeV energies

Collider Energy and Mass Reach



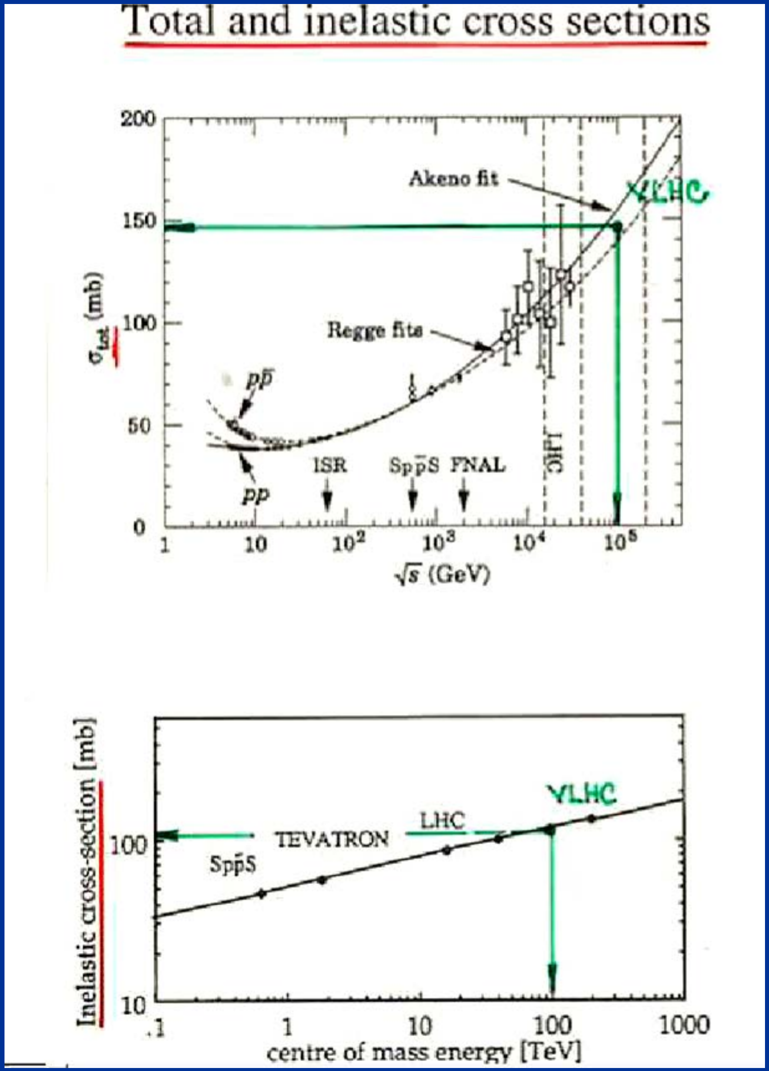
- Many detailed studies done on the reach of high energy hadron colliders
- With reasonable luminosity mass reach for direct searches of ~1/2 of the full collider energy is achievable
- There is no well defined "energy needed" for VLHC yet
  - 50 TeV machine could be about twice less expensive than 100 TeV (could saved SSC?)
  - But don't want to miss discovery due to a few % lower energy (LEP)

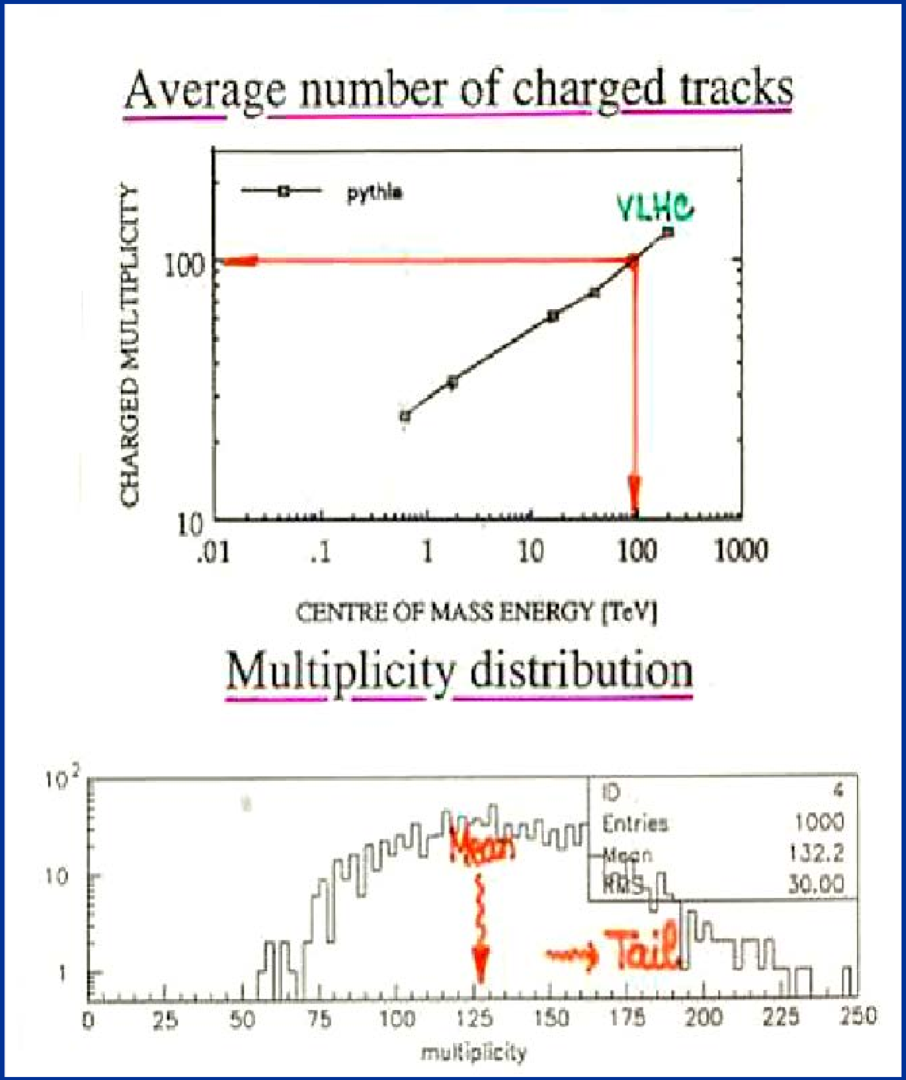
Experiments at 100 TeV



- 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

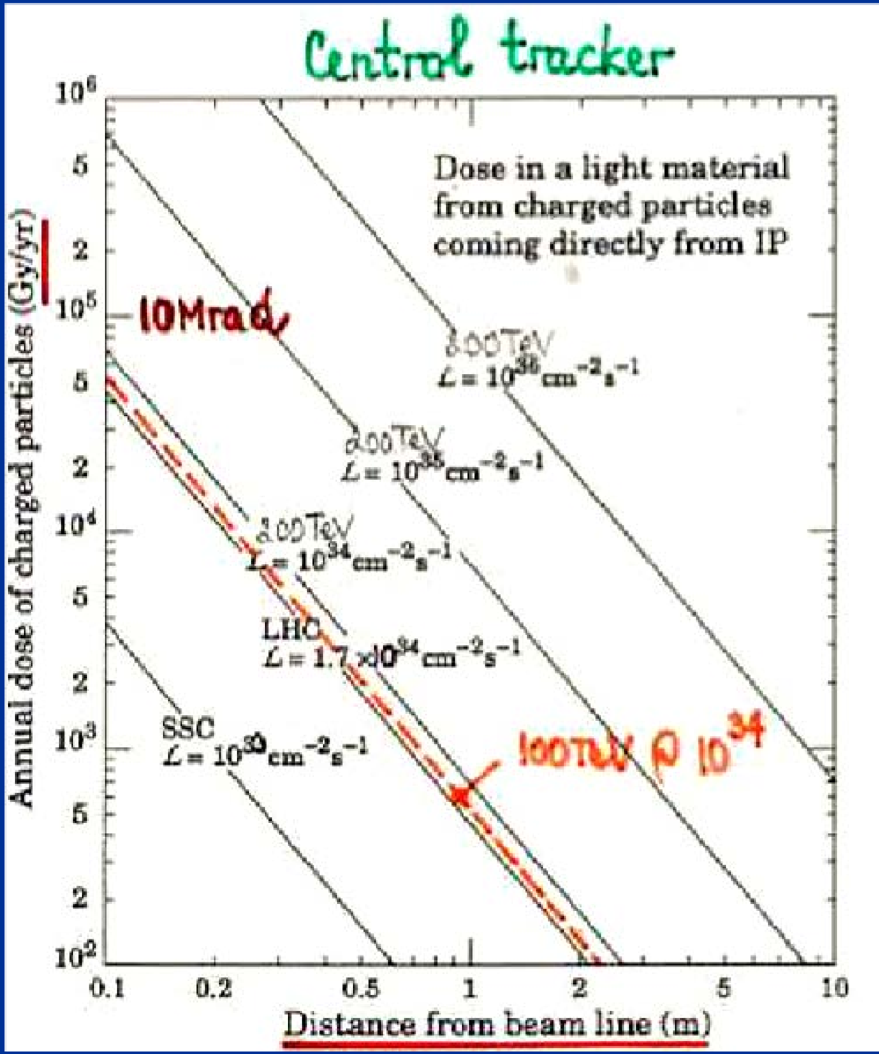
Properties of 100 TeV pp Collisions





Properties of soft pp interactions at 100 TeV are very similar to Tevatron and LHC

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

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

Where is the Problem?...

- With such excellent past, present, and exciting future, why we are not building hadron colliders now?

- 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 needed

- Re-developing proposals and concentrating R&D on cost reduction is prudent way to proceed

100 TeV pp Collider

- For ~35 years energy frontier hadron colliders are leading progress in high energy physics with discoveries of
  - W/Z bosons, top quark and Higgs boson
- The path to 100 TeV collider is technically feasible
  - Requires larger ring and higher field magnets
  - Proposals exist
- 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 required
  - Reasons for construction beyond pure science are important