Particle Physics at the Energy Frontier

- The Standard Model of particle physics
- The relationship between the
  - $W^{\pm}$ boson, t quark and Higgs boson
- The Fermilab accelerator complex
- The CDF-II experiment
- Measuring the $W^{\pm}$ and t masses
  - Implications for the Higgs boson mass
- The future of the high energy frontier
  - The ATLAS experiment at CERN

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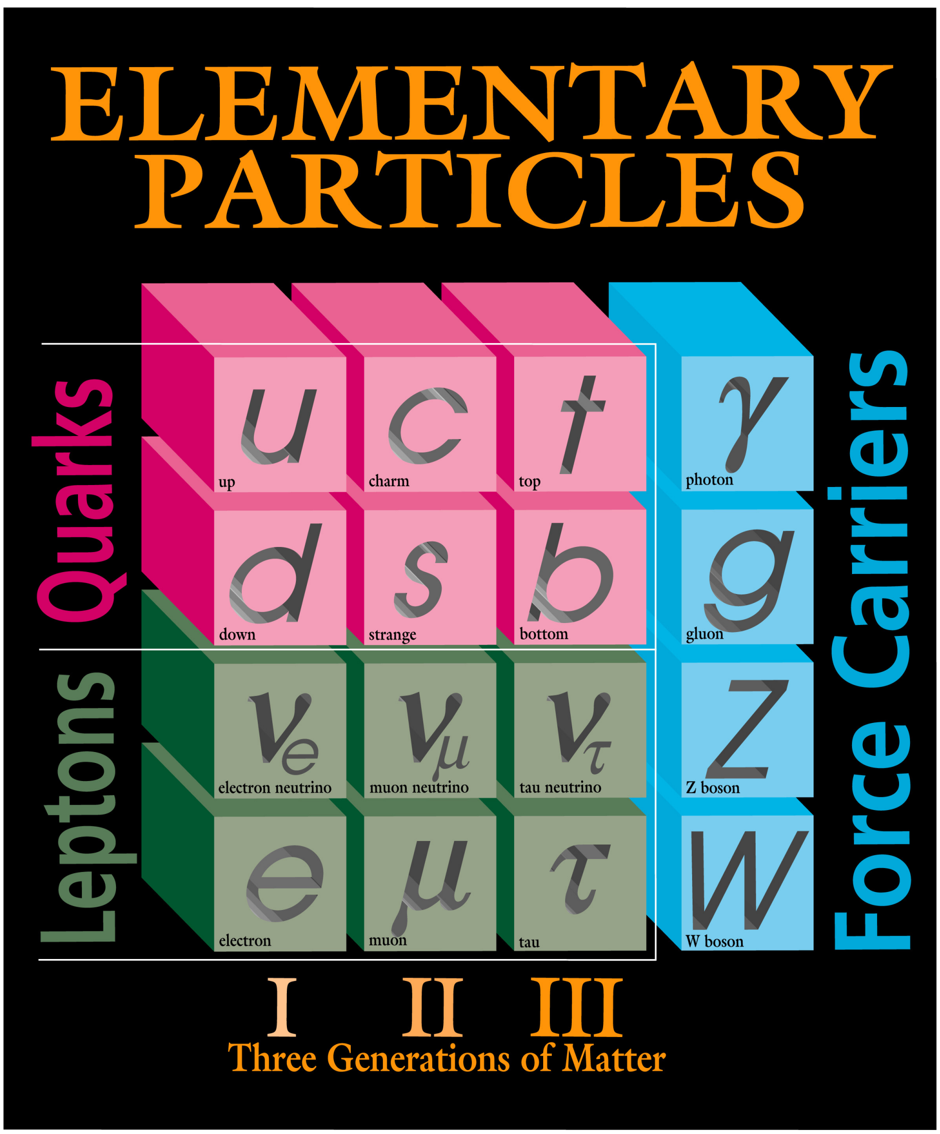
November 2004

Building Blocks of the Standard Model

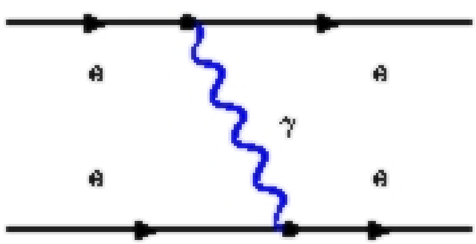
- We think the world can be described by:

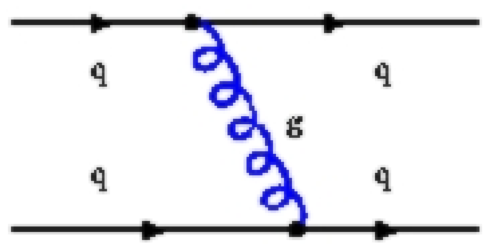


Fermilab 95-759

Forces on Elementary Particles

- At their most fundamental level
  - Forces are the exchange of gauge bosons





Electrons interact by exchanging

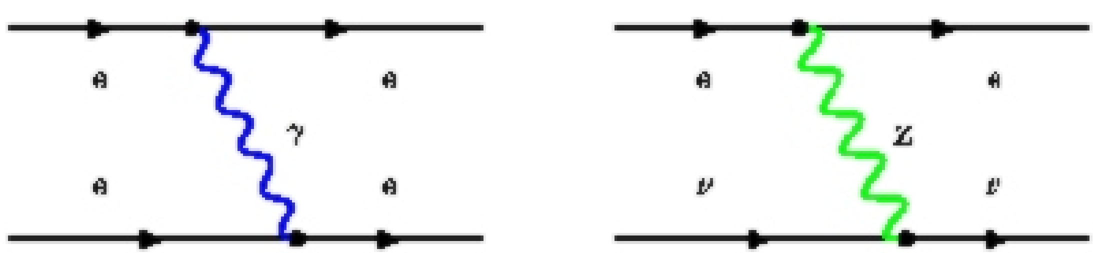
Virtual Photons

Quarks interact by exchanging

Virtual Gluons

The Weak Force

- Weak force behaves like electromagnetism
  - Interacts with electrons and neutrinos
  - Responsible for all nuclear reactions



- Glashow, Weinberg and Salam suggested in 1960s
  - The $W^{\pm}$, Z^0 and γ are Electroweak bosons
- Different strengths arise from boson masses

$$F_{\text{em}} \propto \frac{e^2}{q^2} \qquad F_{\text{weak}} \propto \frac{e^2}{q^2 + m_Z^2}$$

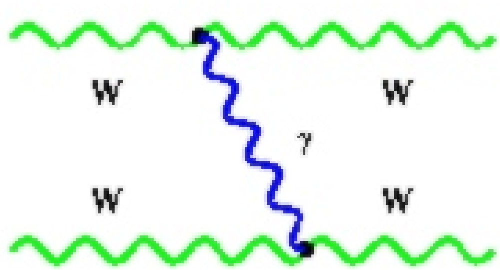
- Precision weak measurements predicted

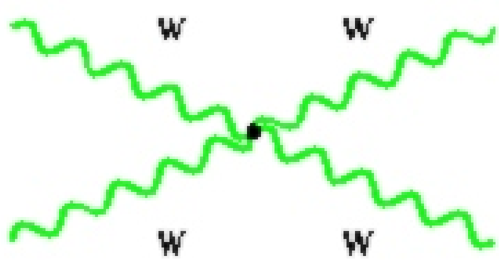
$$m_{W,Z} \approx 50 - 100\text{GeV}/\text{c}^2$$

  - Confirmed with W and Z discovery in 1980s

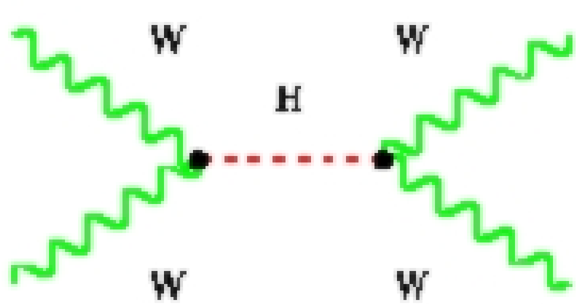
The Higgs Boson

- Theory describes electroweak interactions
  - With frightening accuracy (parts in 10^{10})
- Unified Electroweak theory predicts interactions:



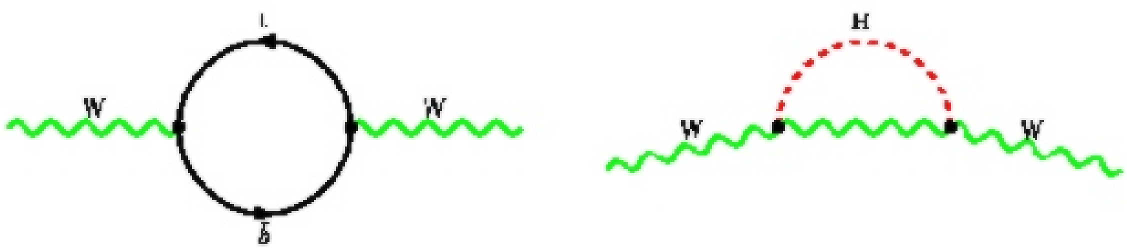


  - Predicted to have infinitely large rates
- Controlled by introducing a new particle



Corrections to the $W^{\pm}$ and t Mass

- Virtual production of t quarks and H bosons
  - Can alter the observed mass of the $W^{\pm}$ bosons
- Electroweak theory predicts from diagrams like:



  - The $W^{\pm}$ mass (in GeV/c^2) predicted to be:

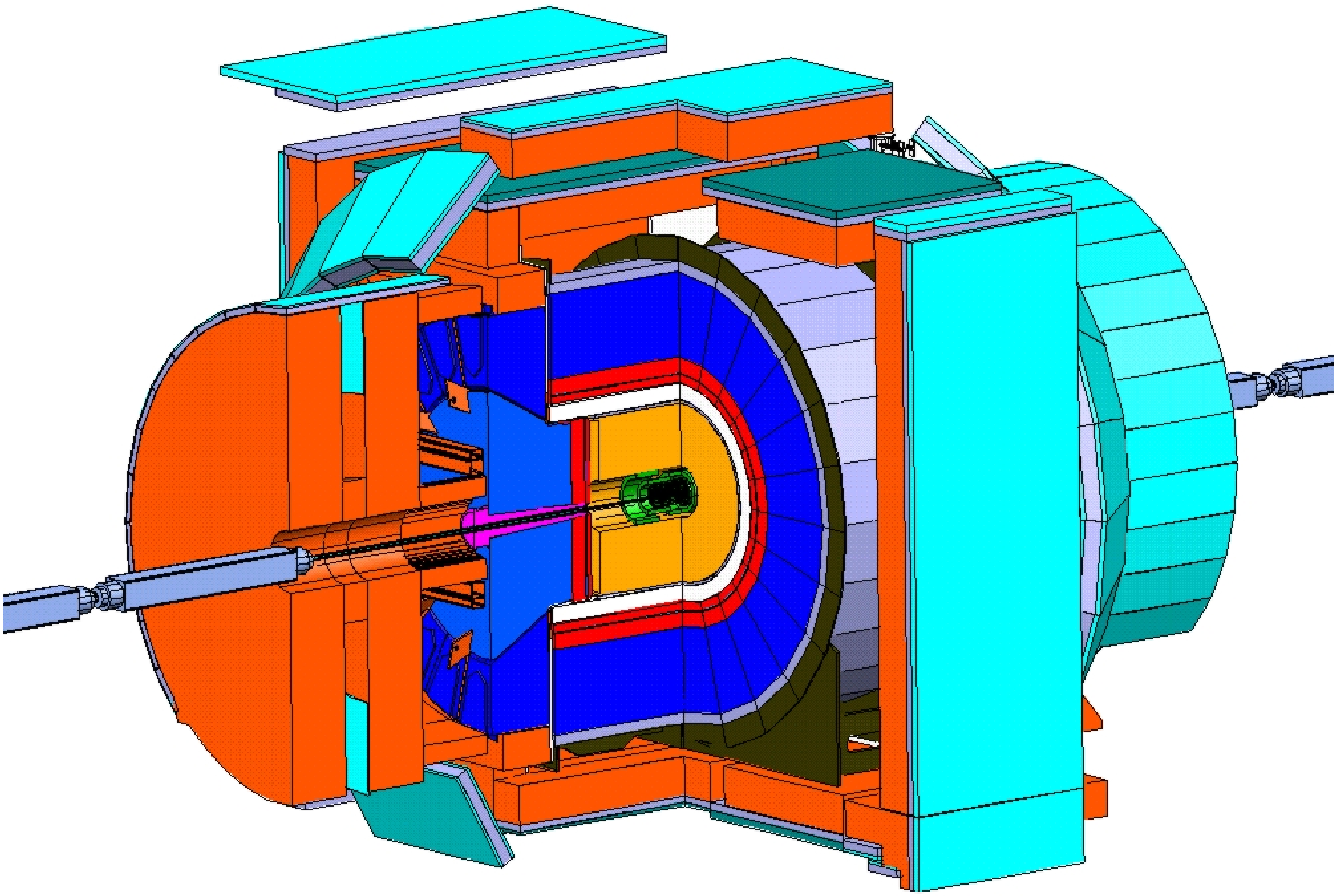
$$M_W = 80.38 - 0.06 \ln\left(\frac{M_H}{100\text{GeV}}\right) + 0.54\left[\left(\frac{M_t}{175\text{GeV}}\right)^2 - 1\right]$$

- Measurements with a precision of
  - $\delta M_W \approx 0.02\ \text{GeV}/\text{c}^2$
  - $\delta M_t \approx 3\ \text{GeV}/\text{c}^2$
    - Give comparable constraints on Higgs mass
    - $20 - 40\text{GeV}/\text{c}^2$

The Fermilab Accelerators

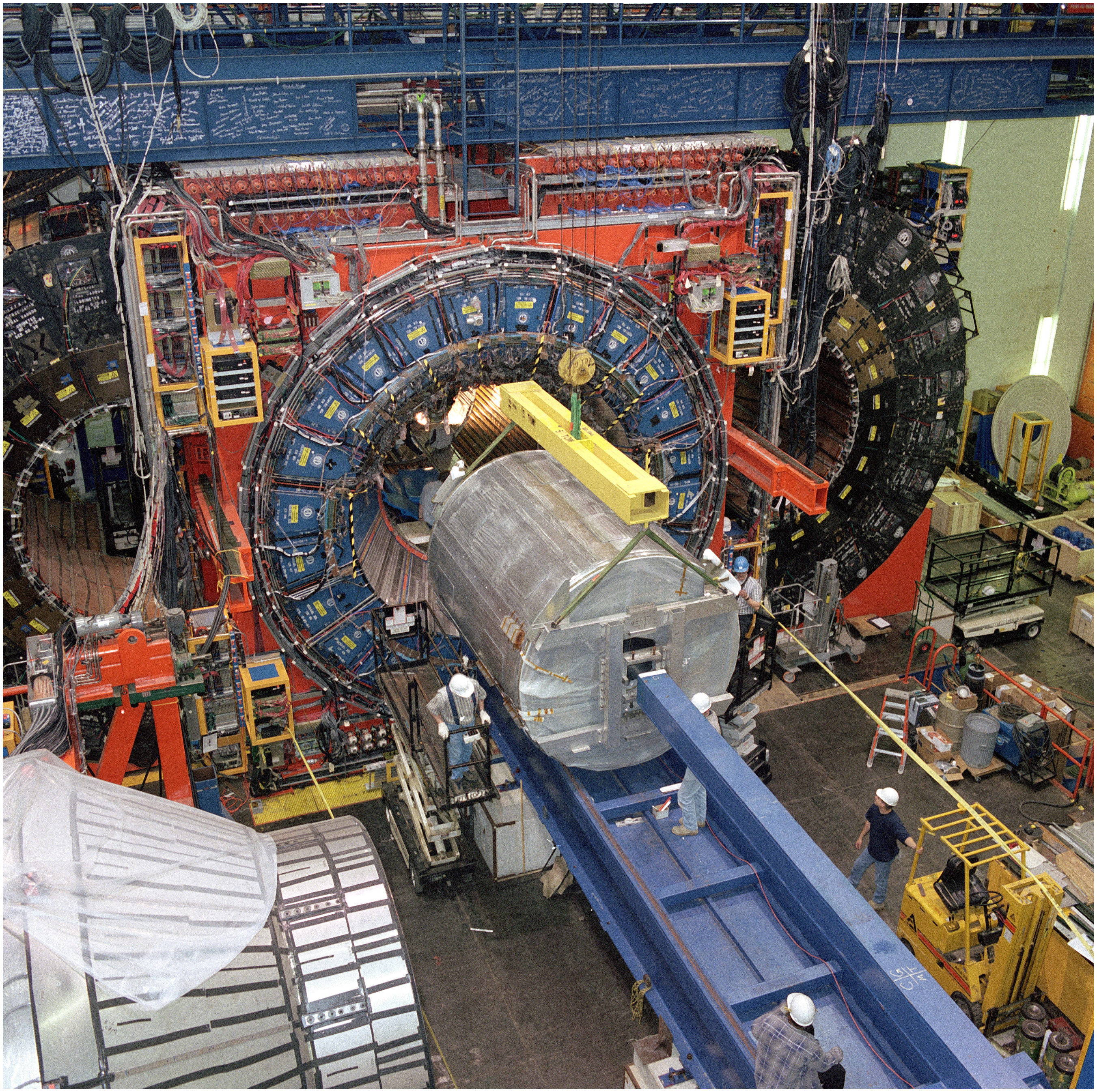
- Collide 2 TeV protons and 2 TeV anti-protons
  - Produce six W bosons per minute
  - Produce one $t\bar{t}$ pair per hour

The CDF-II Experiment



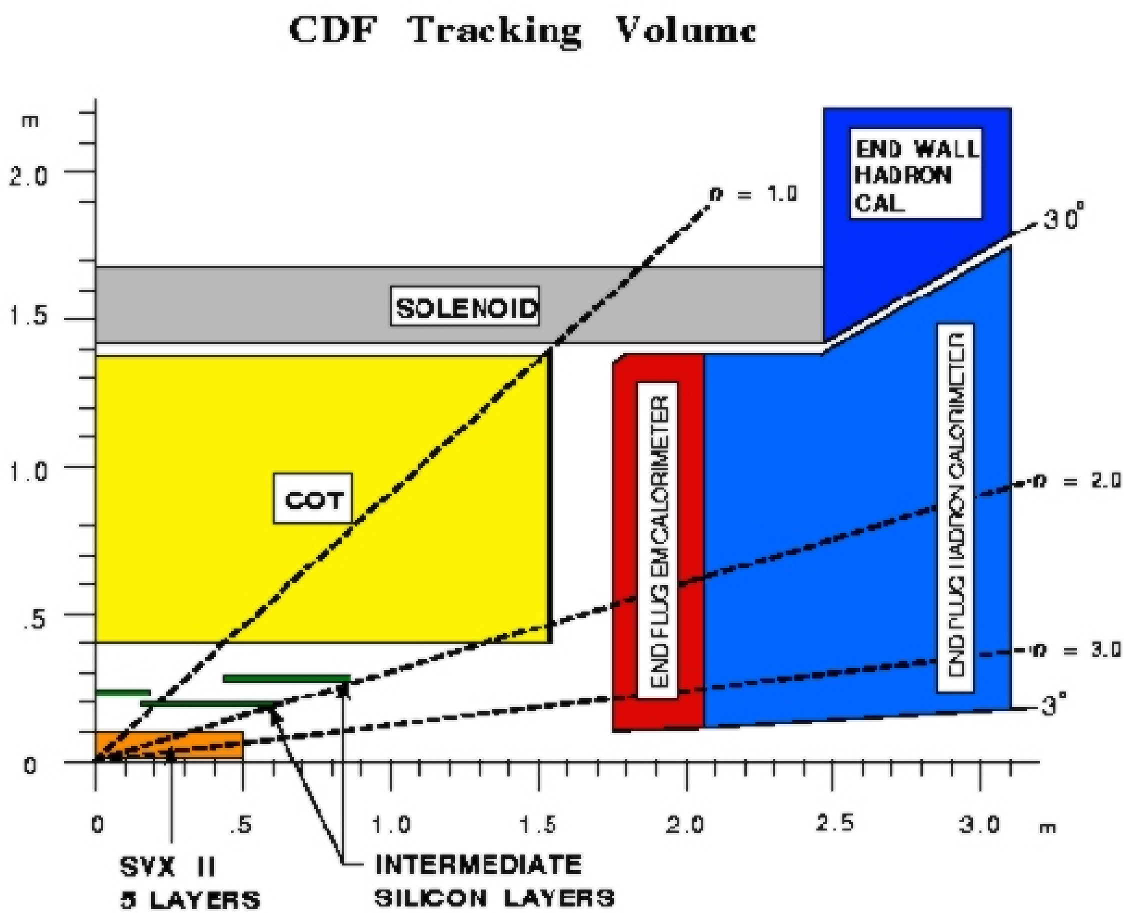
- Three story high experimental apparatus
  - Weighs about 5000 tonnes
  - Over one million individual detector elements

CDF-II Being Assembled



- Took two years to assemble and commission

CDF-II Quarter Section



- Measure charged particle trajectories with
  - 0.01 mm precision in silicon sensors
  - 4 % momentum precision in gaseous tracker
- Measure electromagnetic particle energies with
  - 2 % energy resolution in calorimeters

The CDFII Collaboration

- To build and operate CDF takes alot of people

CDF/PHYS/BOTTOM/CDFR/6207
March 3, 2003 - Version 4.2 - Draft

Measurement of the Mass Difference $m(D_s^+) - m(D^+)$ at CDF II

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We present a measurement of the mass difference $m(D_s^+) - m(D^+)$, where both the D_s^+ and D^+ are reconstructed in the $\phi\pi^+$ decay channel. This measurement uses 11.6 pb^{-1} of data collected by CDF II using the new displaced-track trigger. The mass difference is found to be $m(D_s^+) - m(D^+) = 99.41 \pm 0.38(stat) \pm 0.21(syst)$ MeV/c^2.

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I. INTRODUCTION

Meson masses are predicted by different models of quark interactions and the inter-quark potential. Analytically, the spectrum of heavy-light mesons can be described in the QCD framework using the principles of Heavy Quark Symmetry and Heavy Quark Effective Theory [1, 2]. These theories state that in the limit of infinitely heavy quark mass, the properties of the meson are independent of the heavy quark flavor and that the heavy quark does not contribute to the orbital degrees of freedom. The theory predicts that up to corrections of order $1/m_{b,c}$, $m(B_s^0) - m(B_d^0) = m(D_s^-) - m(D^-)$ [3]. Recently, lattice QCD calculations have also given their predictions for the meson mass spectrum [4–6]. By measuring the masses of mesons precisely, we narrow the range of parameters and approximations that theoretical models use to make predictions. For charm meson masses, a simultaneous fit [7] of all measurements including the mass difference between the D_s^- and D^- is used to compare experimental measurements with theoretical predictions. In this report a measurement of the mass difference $m(D_s^-) - m(D^-)$ in the decay channels $D_s^- \to \phi\pi^-$ and $D^- \to \phi\pi^-$ where $\phi \to K^+K^-$ is presented [8]. The advantage of measuring the mass difference in a common final decay state is that many of the systematic uncertainties cancel. Gathering the large sample of charmed mesons used in this analysis is done using a novel displaced-track trigger, the Silicon Vertex Tracker (SVT) [9], which enables recognition of the decay of long-lived particles early in the trigger system.

- 750 collaborators at 56 institutions

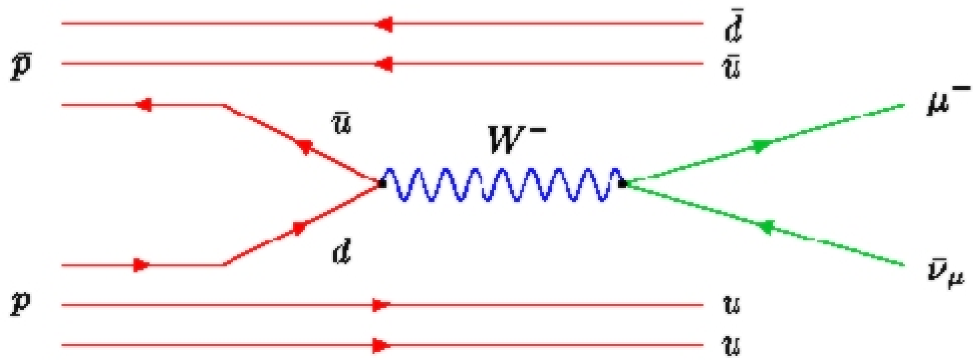
The CDF-Canada Collaboration

- In fact the physics performed in small groups

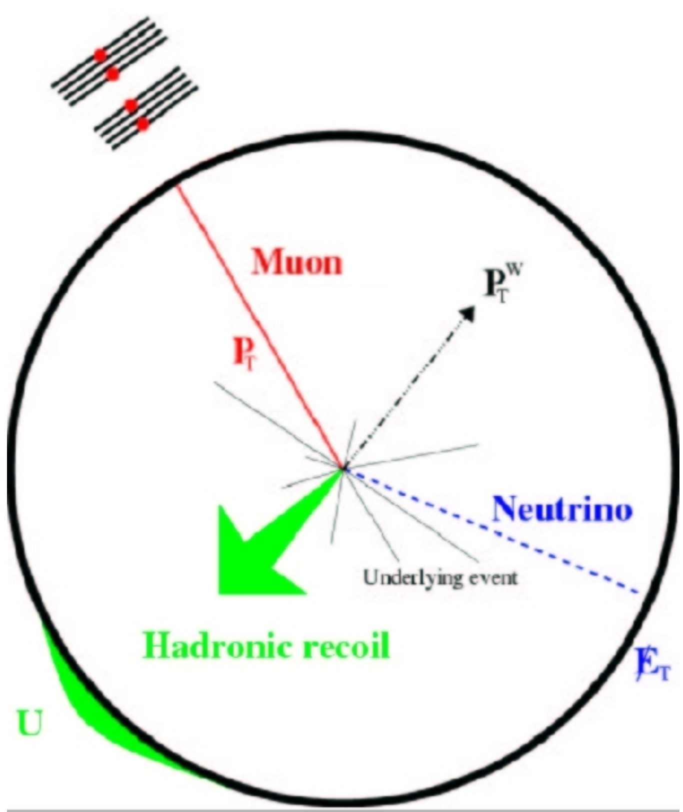
- The CDF-Canada collaboration consists of
  - Six faculty members
  - Four research associates
  - Nine graduate students

$W^{\pm}$ Bosons in Hadron Collisions

- Quarks fuse to make $W^{\pm}$ bosons
  - 1/9$^{\text{th}}$ decay into muon and muon-neutrino

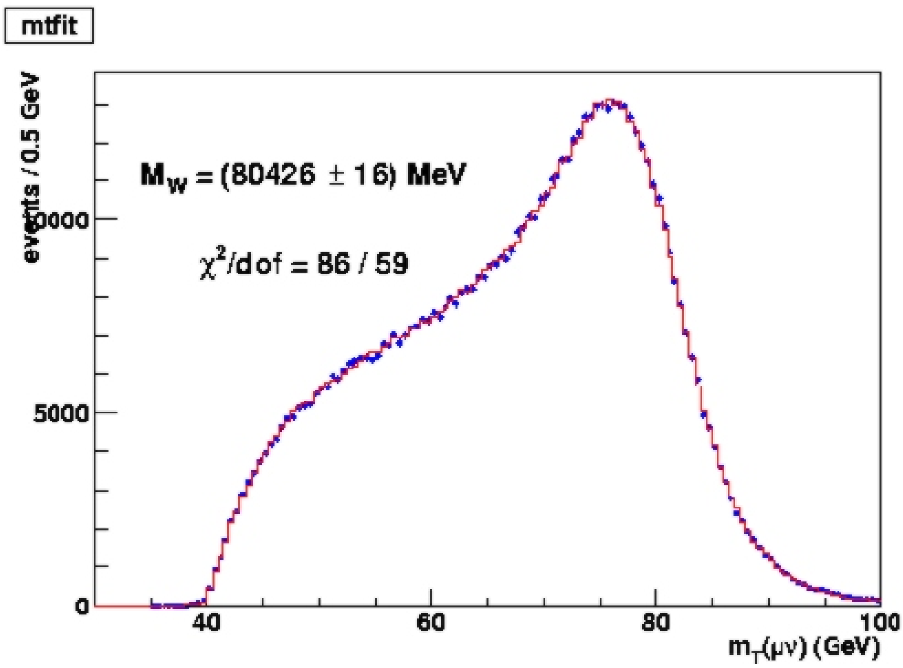


- Proton remnants disappear down beamline
- Measure muon momentum, infer neutrino



Measuring the $W^{\pm}$ Boson Mass

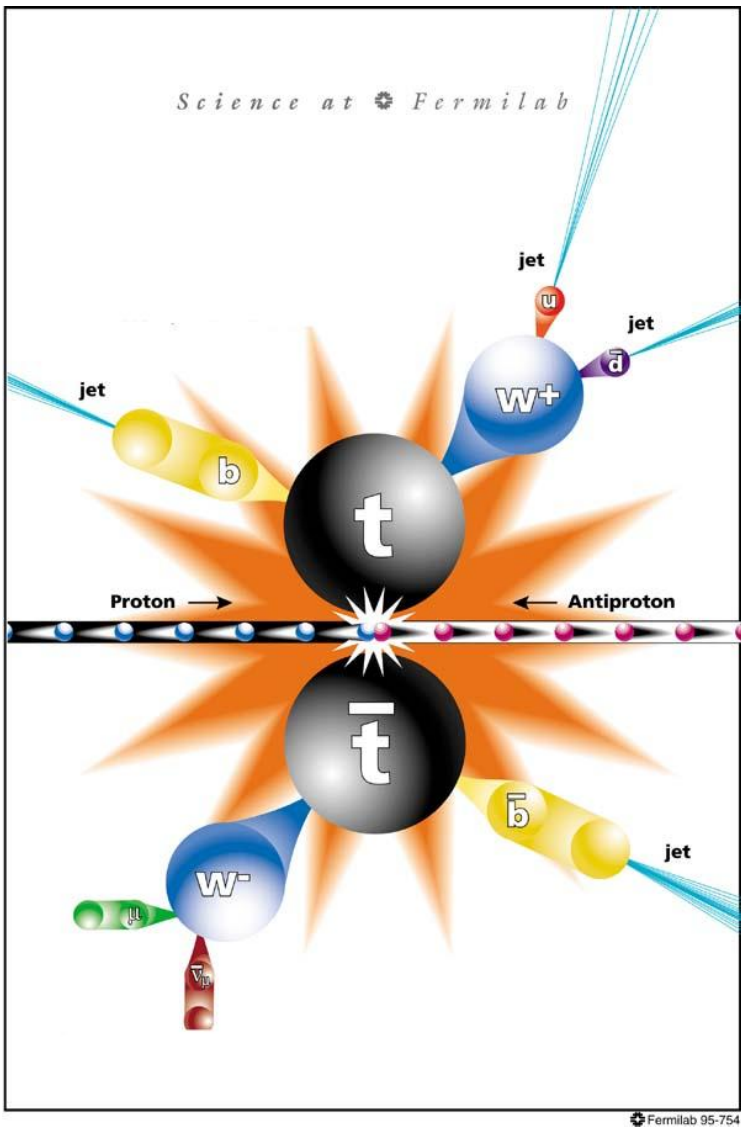
- Only measure transverse neutrino momentum
  - Measure the Transverse Mass



- Will have plenty of $W^{\pm}$ statistics
- Key to improving the measurement will be
  - Understanding calibration to one part in 10,000
    - Magnetic field
    - Tracker alignment
    - Passive material

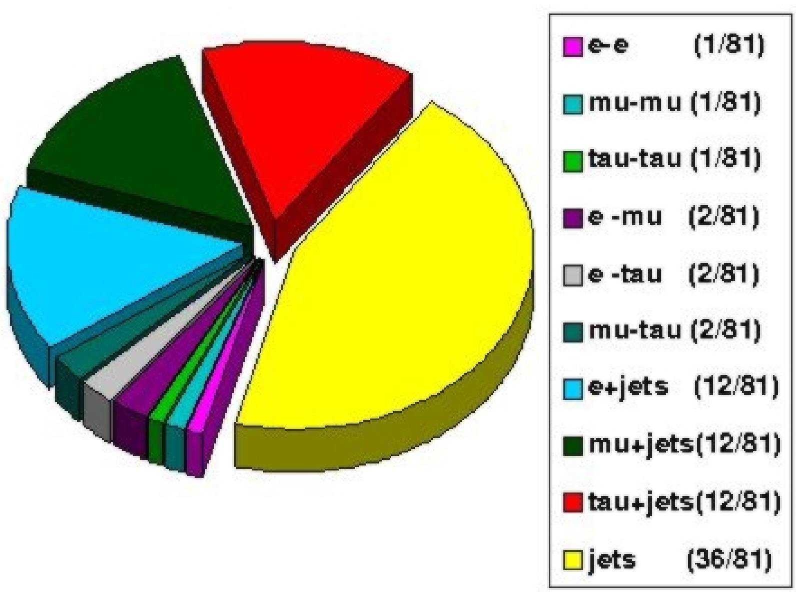
Top Quark Production in Hadron Collisions

- Exploit distinctive features of t quark decay



Top Quark Branching Fractions

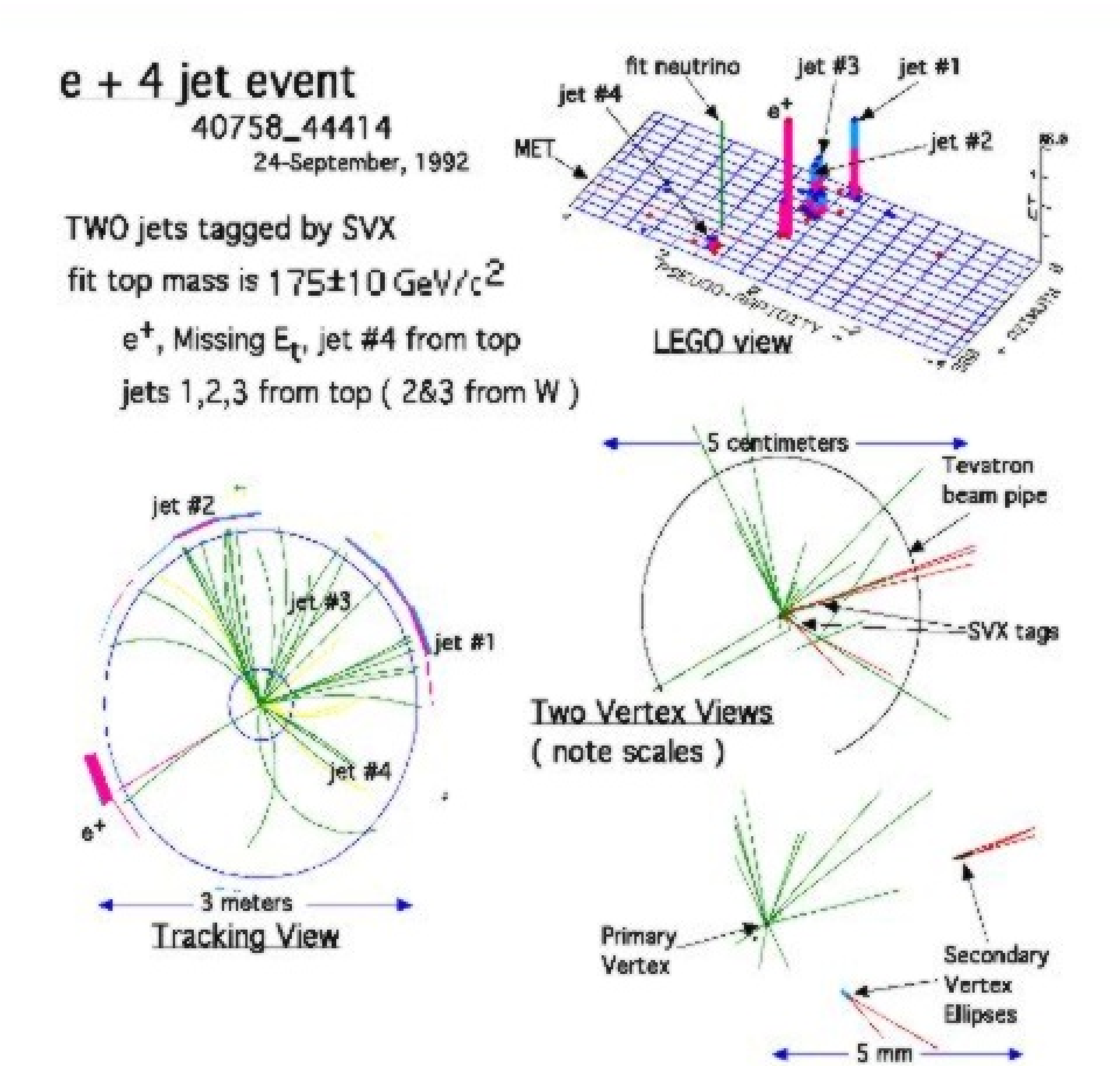
- 100% of t quarks decay to
  - W boson and a b quark
  - To be recorded one W must decay
    - To a high momentum electron
    - Or a high momentum muon
  - This gives the following $t\bar{t}$ combinations



- At the end of the day we can only find/reconstruct
  - A few % of the $t\bar{t}$ events produced

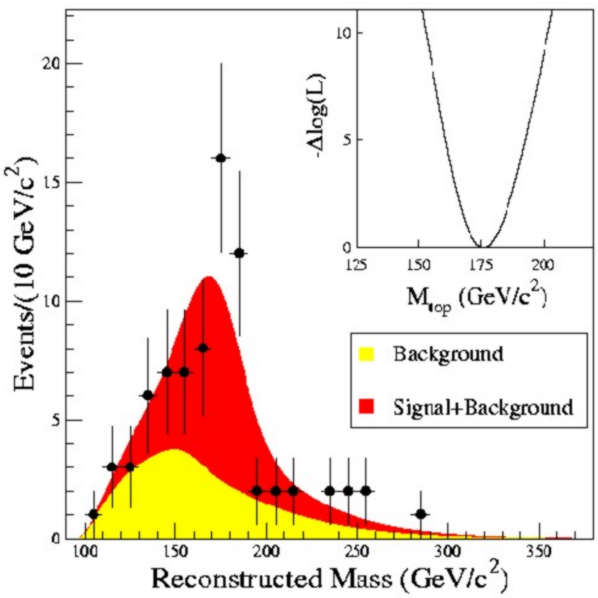
Distinctive $t\bar{t}$ Final States

- To sift $t\bar{t}$ candidates out of background
  - Look for electrons and muons (W decays)
  - Jets with displaced vertices (b quark decays)
  - Large missing energy (escaping ν)



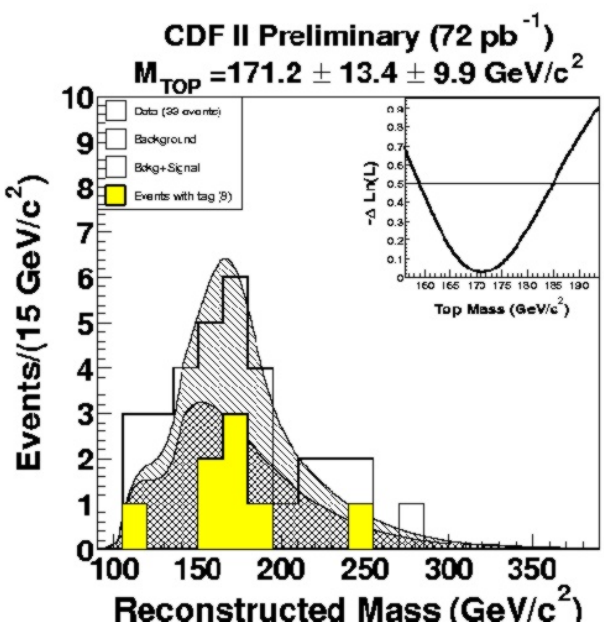
Measuring the t Quark Mass

- Combine most promising decay channels
  - Data taken by CDFI in middle 1990s gives:



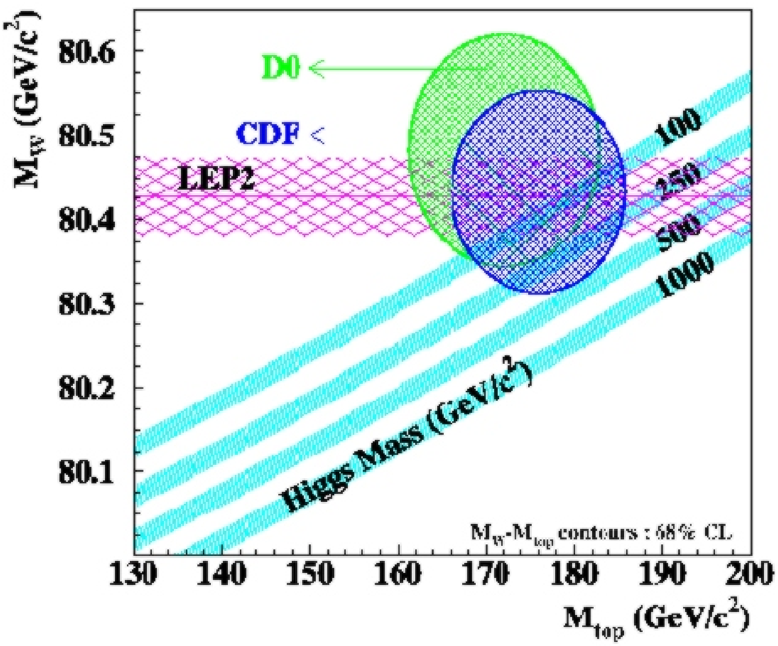
$$M_t = 176 \pm 7\text{GeV}/\text{c}^2$$

  - First look at CDFII data shows:

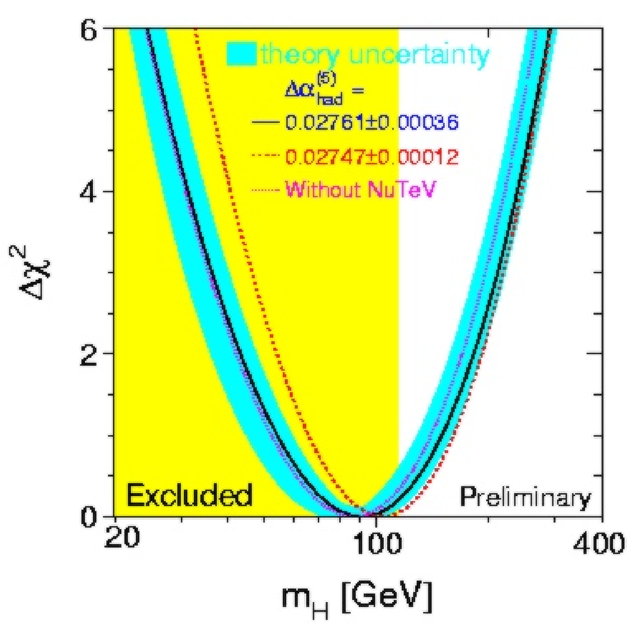


Constraints on the Higgs Mass

- Combine measurements of M_t and M_W

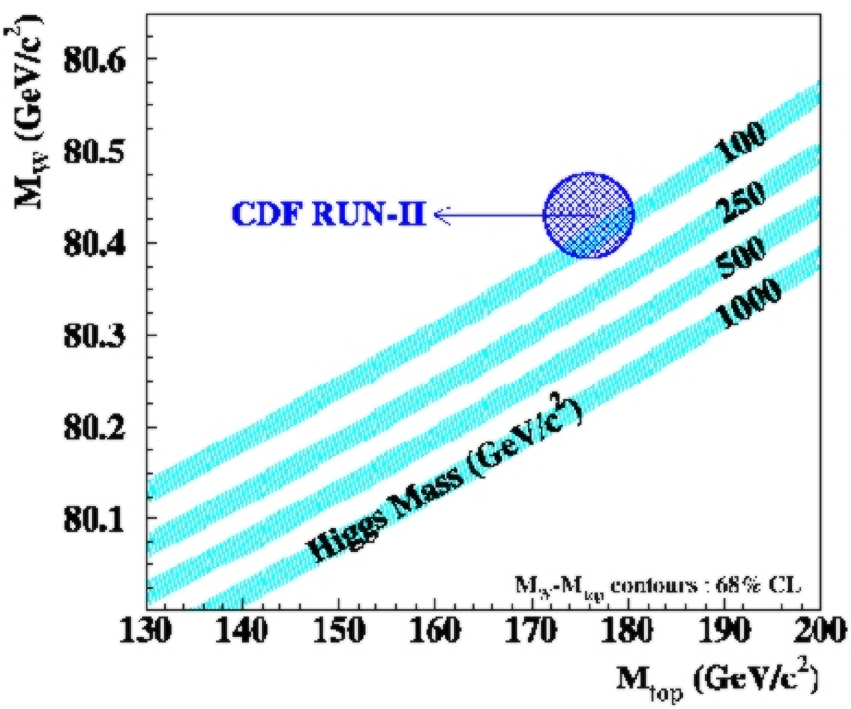


- Others have searched for Higgs directly
  - They haven't found it below $m_H < 115\mathrm{GeV/c^2}$



Prospects for Improvement

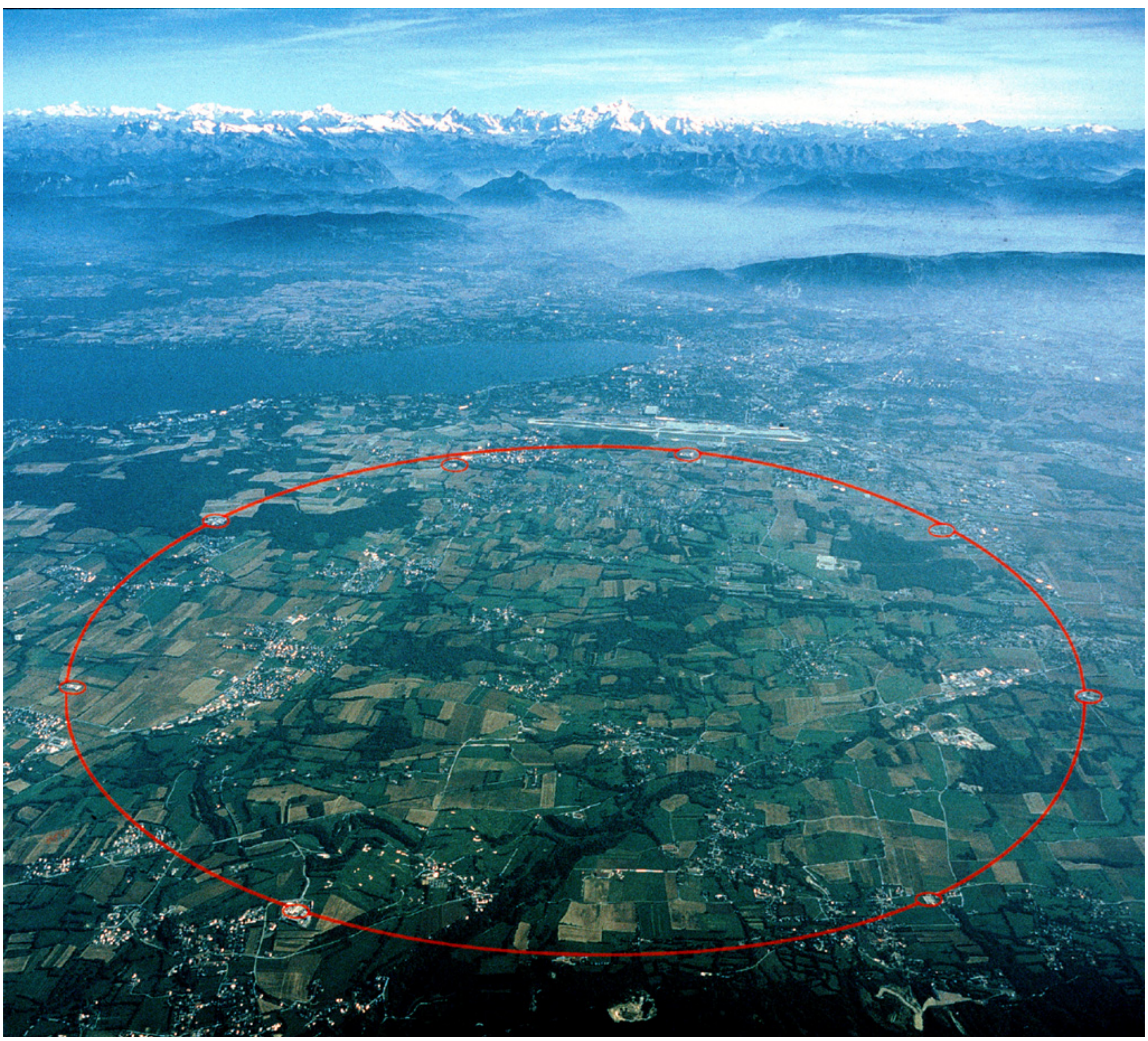
- Now have more data than previous runs



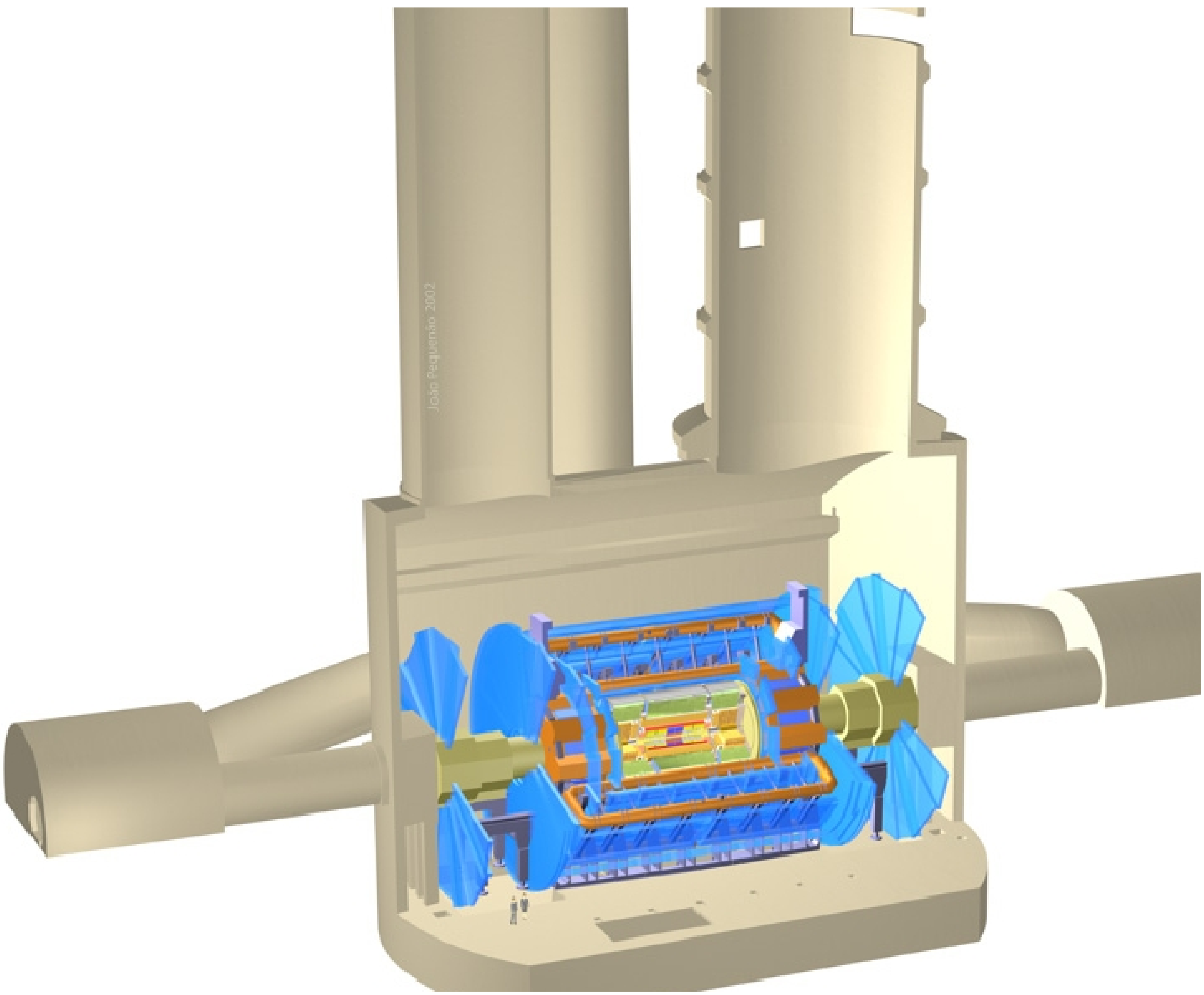
- If Higgs as light as $120\mathrm{GeV}/c^2$
  - Tevatron produces a few per day
  - May see Higgs at CDF/Fermilab
- CDF/Tevatron will be be surpassed by
  - CERNs Large Hadron Collider by end of decade

The Future of High Energy Physics

- The European Centre for Nuclear Research (CERN)
  - Located just outside Geneva, Switzerland
  - Building the world's highest energy machine
  - Proton-proton collisions at 14 TeV
    - Seven times the energy at Fermilab



The ATLAS experiment (Cartoon)



The ATLAS Experiment (Reality)

- Approved in 1995, 10+ years to build machine/experiments
- Civil engineering now nearing completion

2001

- Pieces being assembled on the surface

2003

The ATLAS Experiment (Today)

- It takes even more people than CDF/Fermilab

2002

- But we have started to “move in” to our new home

2004

Further Information

- If you are interested in learning more:

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http://www.fnal.gov/
http://www-cdf.fnal.gov/
http://hep.physics.utoronto.ca/cdf/
http://www.cern.ch/
http://atlasexperiment.org/
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- These slides can be found at:

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http://hep.physics.utoronto.ca/
              WilliamTrischuk/york_ugrad.pdf
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- Feel free to contact me directly at:

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