Kolloquium des Instituts für Physik
Humboldt-Universität zu Berlin
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A Heavyweight among the Quarks: Top Physics at CDF

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Yale University

Outline

Fundamental Building Blocks of Matter

Experimenting with Elementary Particles

How to Find Top Quarks at a Collider

CDF's Top Physics Program

What's Next?

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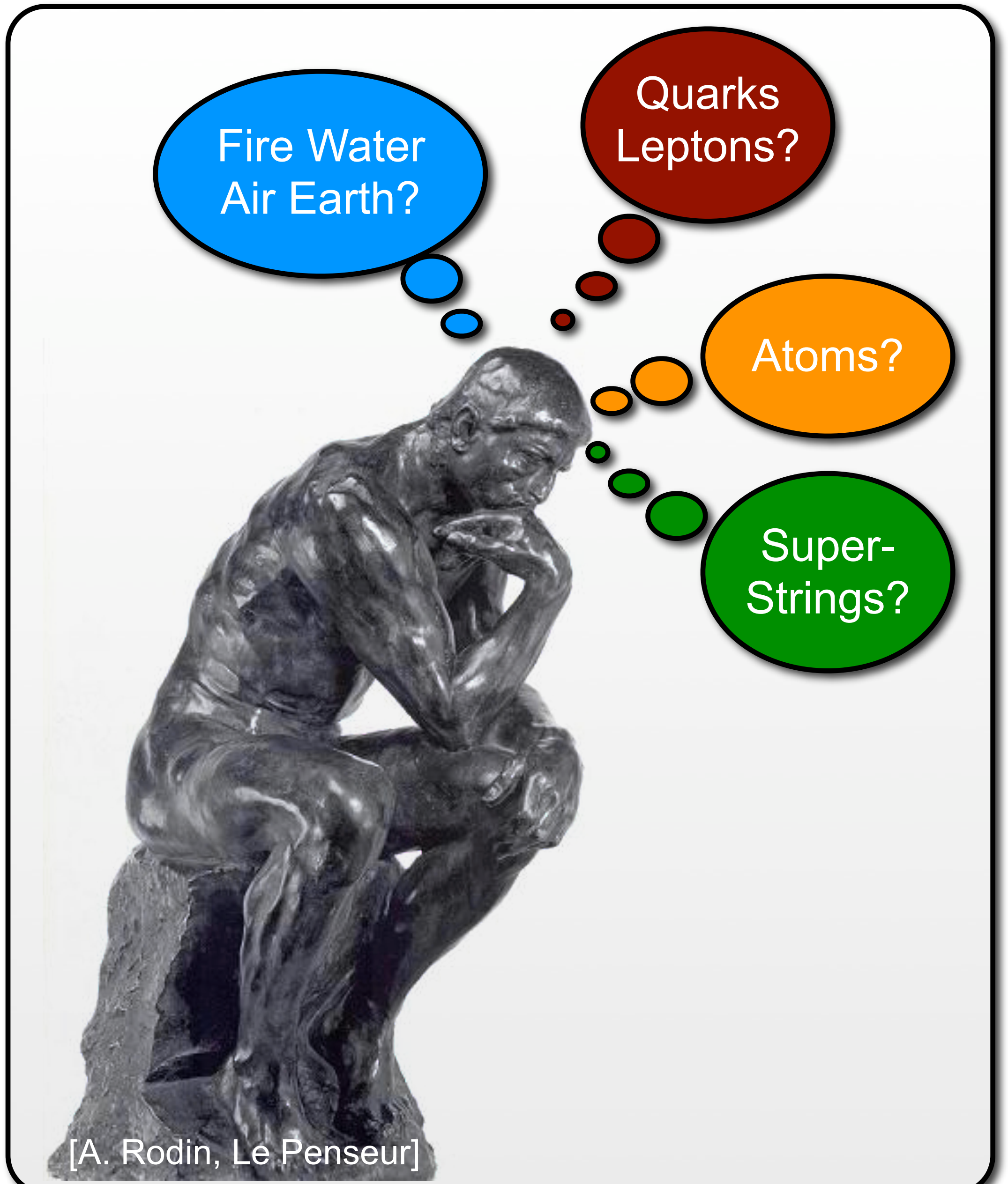
Fundamental Building Blocks of Nature

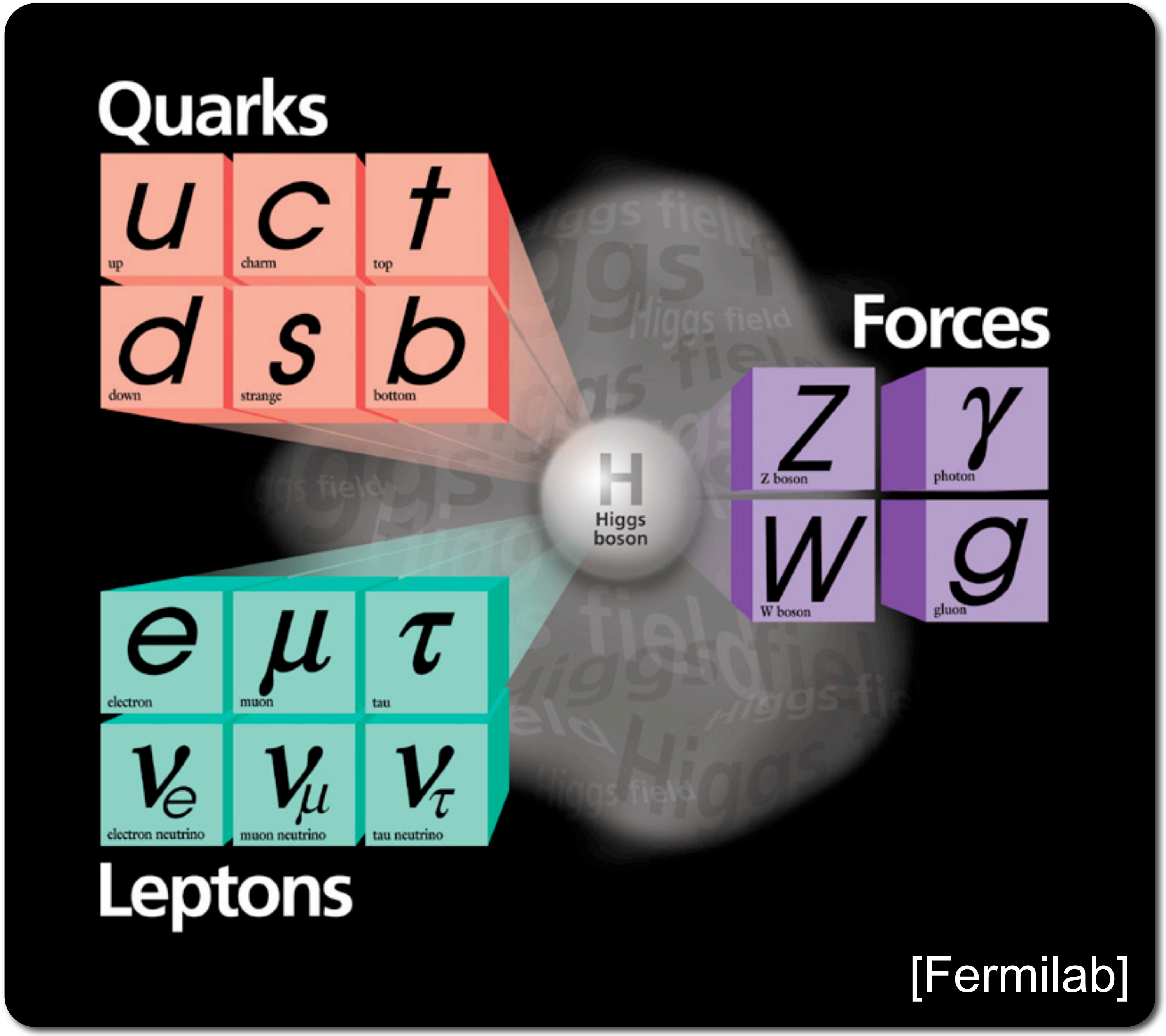
- A question as old as mankind: What is the world made of at the fundamental level?
- Idea of fundamental building blocks of matter found in many ancient cultures
- 20th century physics:
  - Atoms and subatomic particles
  - Quantum mechanics
  - Relativity
  - Standard model of particle physics
- 21st century physics:
  - Precision cosmology
  - We may be on the eve of the next great discovery



[A. Rodin, Le Penseur]

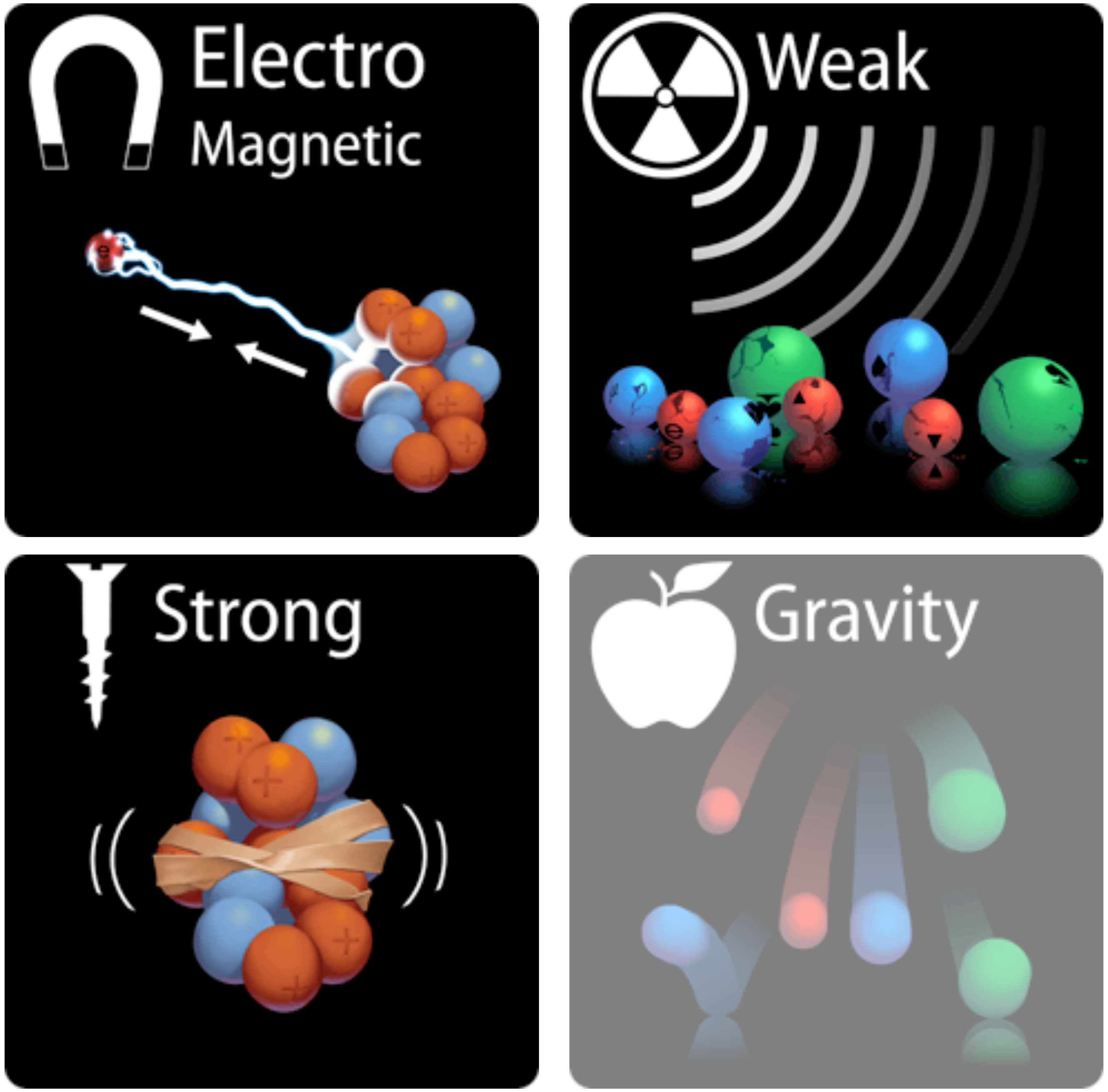
The Standard Model of Particle Physics

- Theory formulated in 1960ies, still valid after 30+ years of precision experiments
- 12 building blocks of matter, organized in 3 generations
  - 6 quarks (6 antiquarks)
  - 6 leptons (6 antileptons)
- 3 fundamental forces:
  - Electromagnetic force
  - Weak force
  - Strong force
- All standard model particles observed by experiment, except the Higgs boson



Forces in the Standard Model

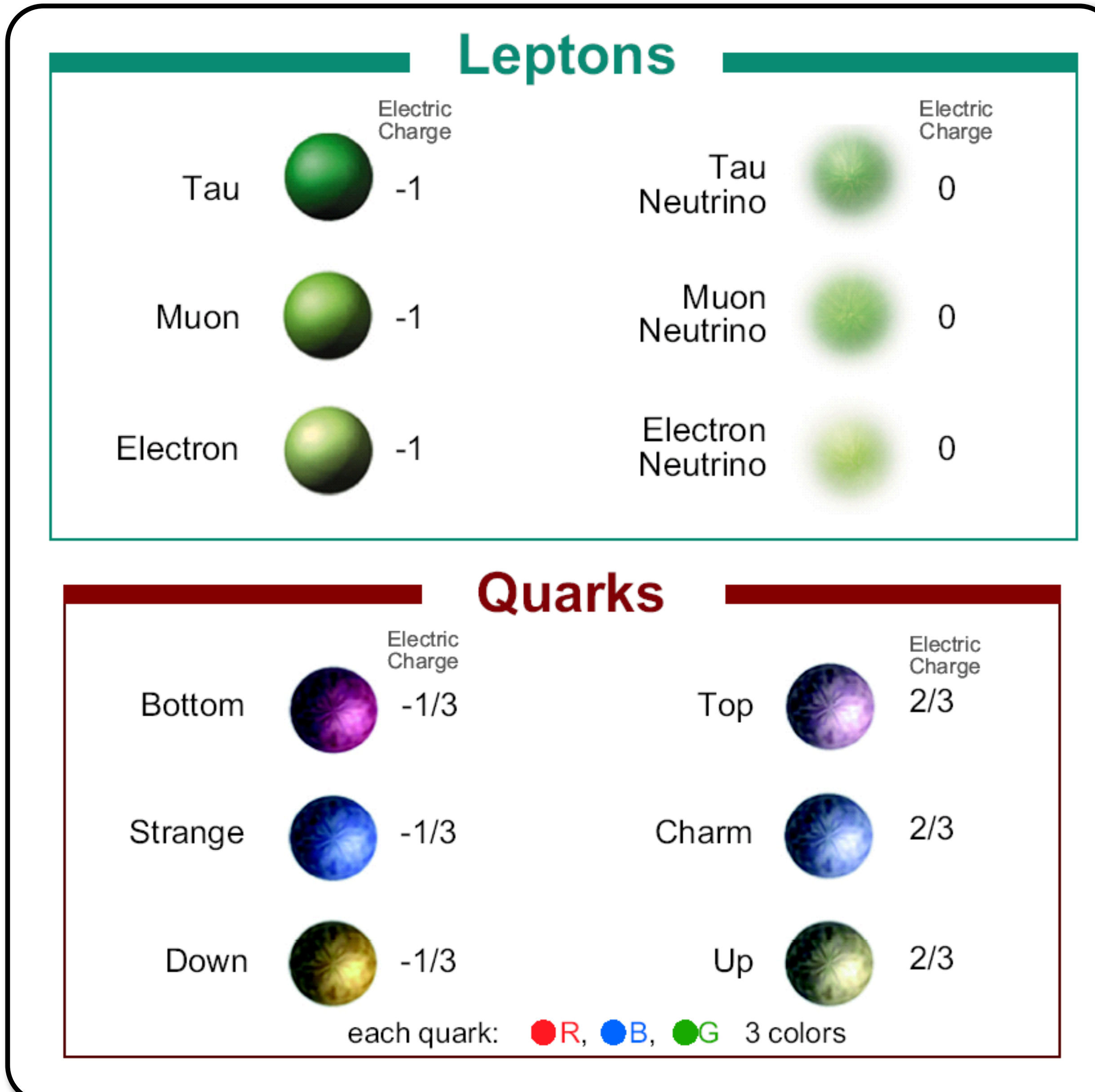
- Quantum field theory picture: forces mediated by exchange of force carriers ("gauge bosons")
  - Electromagnetic force: photon
    → atoms, chemistry, electronics
  - Weak force: $W^{\pm}$, Z bosons
    → burning of the sun, radioactivity, neutrinos
  - Strong force: 8 gluons
    → mesons & baryons
- What about gravity?
  - Gravitational forces negligible on length scale of elementary particles
  - No consistent quantum theory of gravity yet

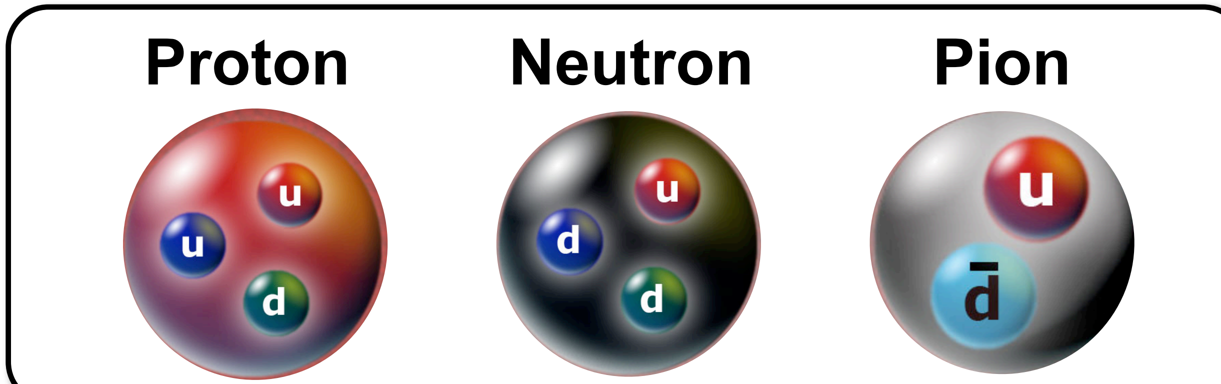


[http://www.particlephysics.ac.uk/]

What's the Matter?

- Leptons: integer charge (0, ±e)
- Quarks: fractional charge (±1/3 e, ±2/3 e)
- Strong force confines quarks, two classes of hadrons
  - Baryons: quark + quark + quark (examples: proton, neutron)
  - Mesons: quark-antiquark pair (example: pion)
- Matter on earth built from first generation (up, down, electron)
- Second and third generation still very important:
  - Second generation: cosmic rays
  - Uncertainty principle: $\Delta E\, \Delta t \geq \hbar/2$ → second/third generation particles in quantum corrections





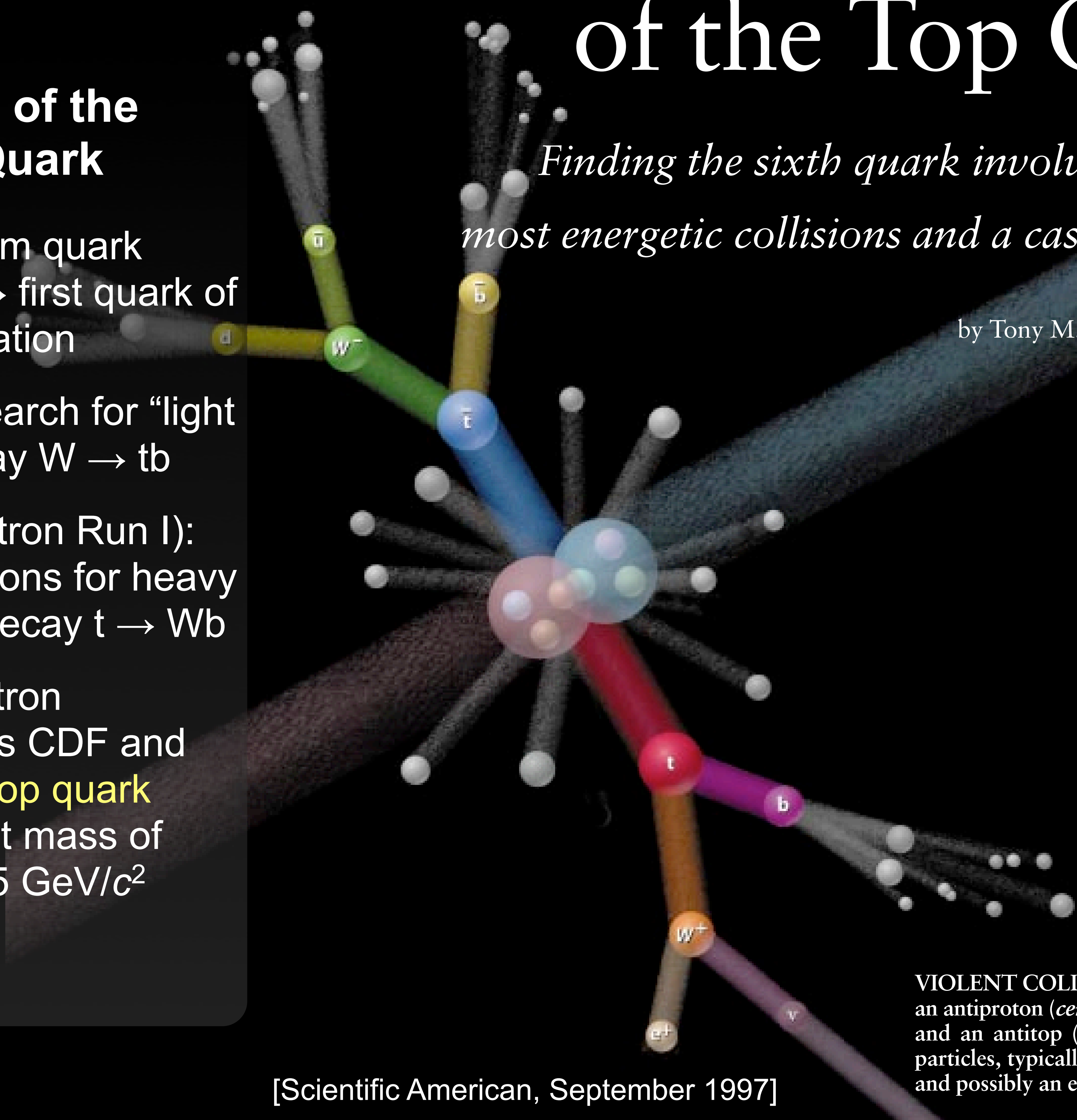
The Discovery of the Top Quark

Finding the sixth quark involved the world's most energetic collisions and a cast of thousands

by Tony M. Liss and Paul L. Tipton

History of the Top Quark

- 1977: bottom quark discovery→ first quark of third generation
- 1980ies: search for "light top" in decay W → tb
- 1992 (Tevatron Run I): first indications for heavy top quark decay t → Wb
- 1995: Tevatron experiments CDF and DØ report top quark discovery at mass of approx. 175 GeV/c^2

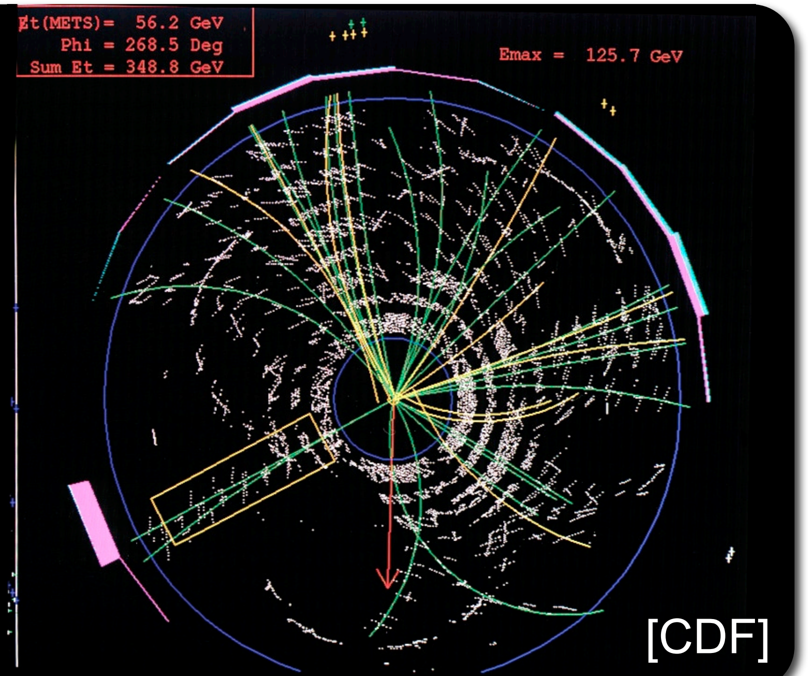


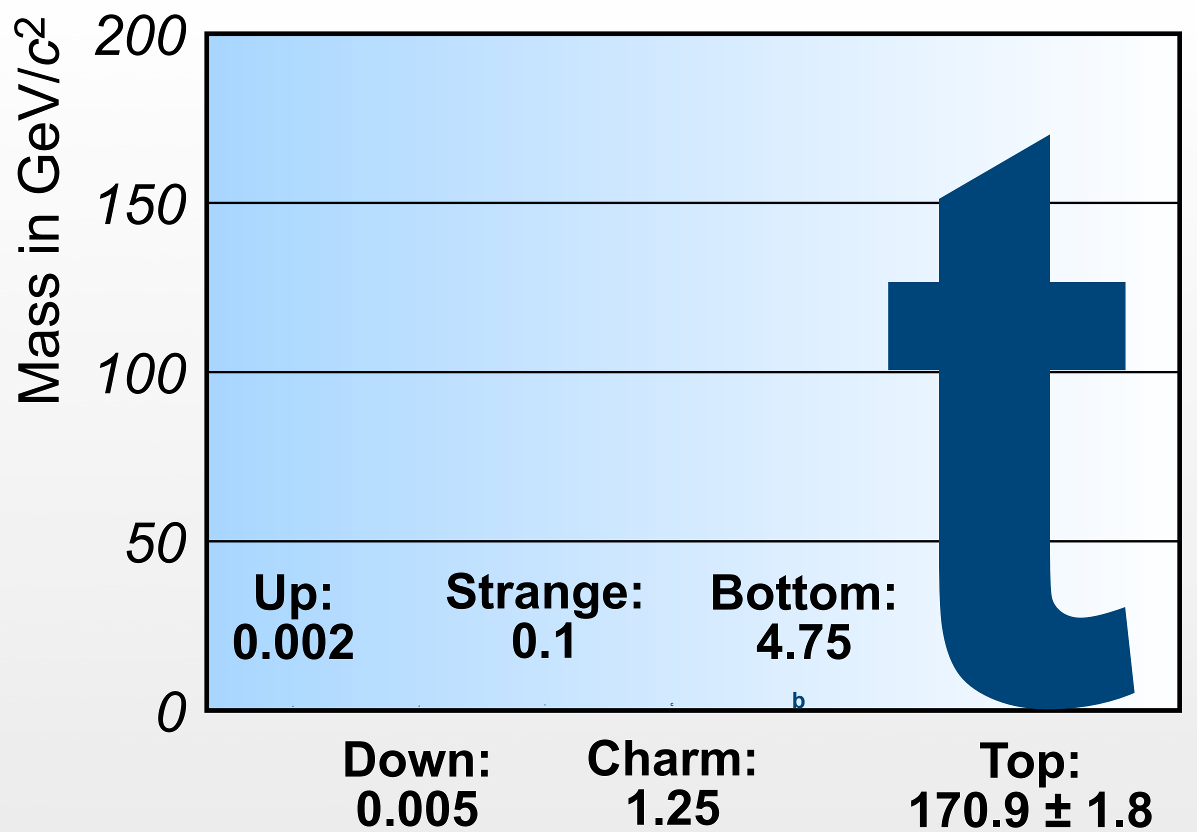
VIOLENT COLLISION between a proton and an antiproton (*center*) creates a top quark (*red*) and an antitop (*blue*). These decay to other particles, typically producing a number of jets and possibly an electron or positron.

[Scientific American, September 1997]

The Top Quark is Special

Event display: top quark decay candidate at CDF (09/24/92)





- Top reveals astonishing properties:
  - Pointlike, but very large mass (approximate mass of gold atom, 40 times bottom quark mass)
  - Extremely short lifetime ($<10^{-24}$ s): decays before creation of bound states → the only "free" quark
- After top discovery: detailed studies of top quark properties
- Central question: Is the top quark really the 6th quark of the standard model?
- This talk: Overview of CDF's comprehensive top program

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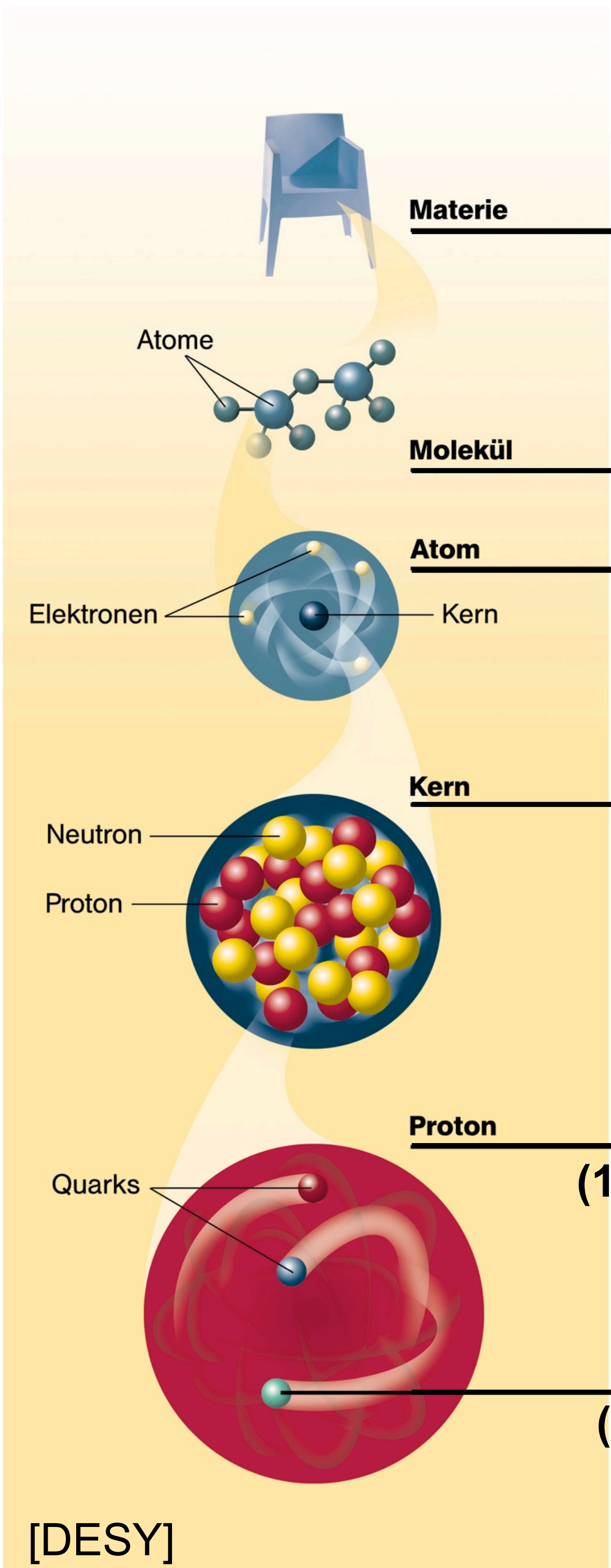
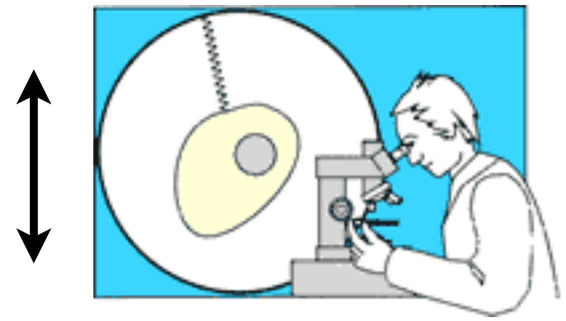
Exploring the Atto-World

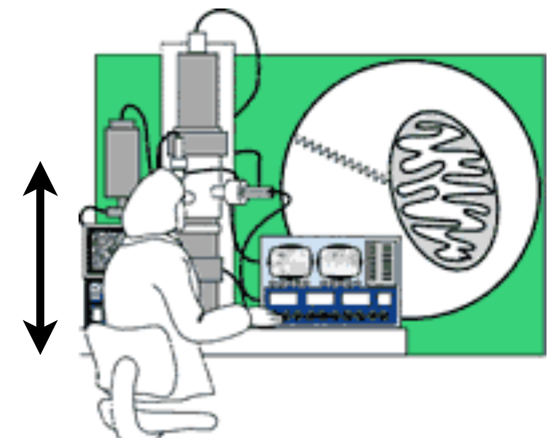


	Length	Energy
Materie	1 m	200 neV
Molekül	10^{-9} m	200 eV
Atom	10^{-10} m	2 keV
Kern	10^{-14} m	20 MeV
Proton	10^{-15} m (1 femtometer)	200 MeV
	$<10^{-18}$ m (1 attometer)	>200 GeV

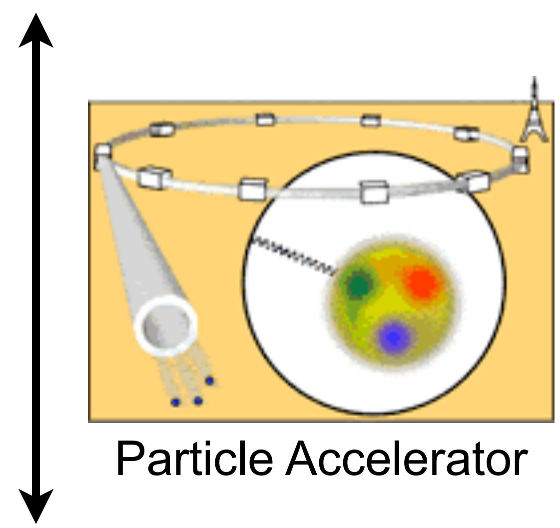
Detection Devices



Light-optical Microscope



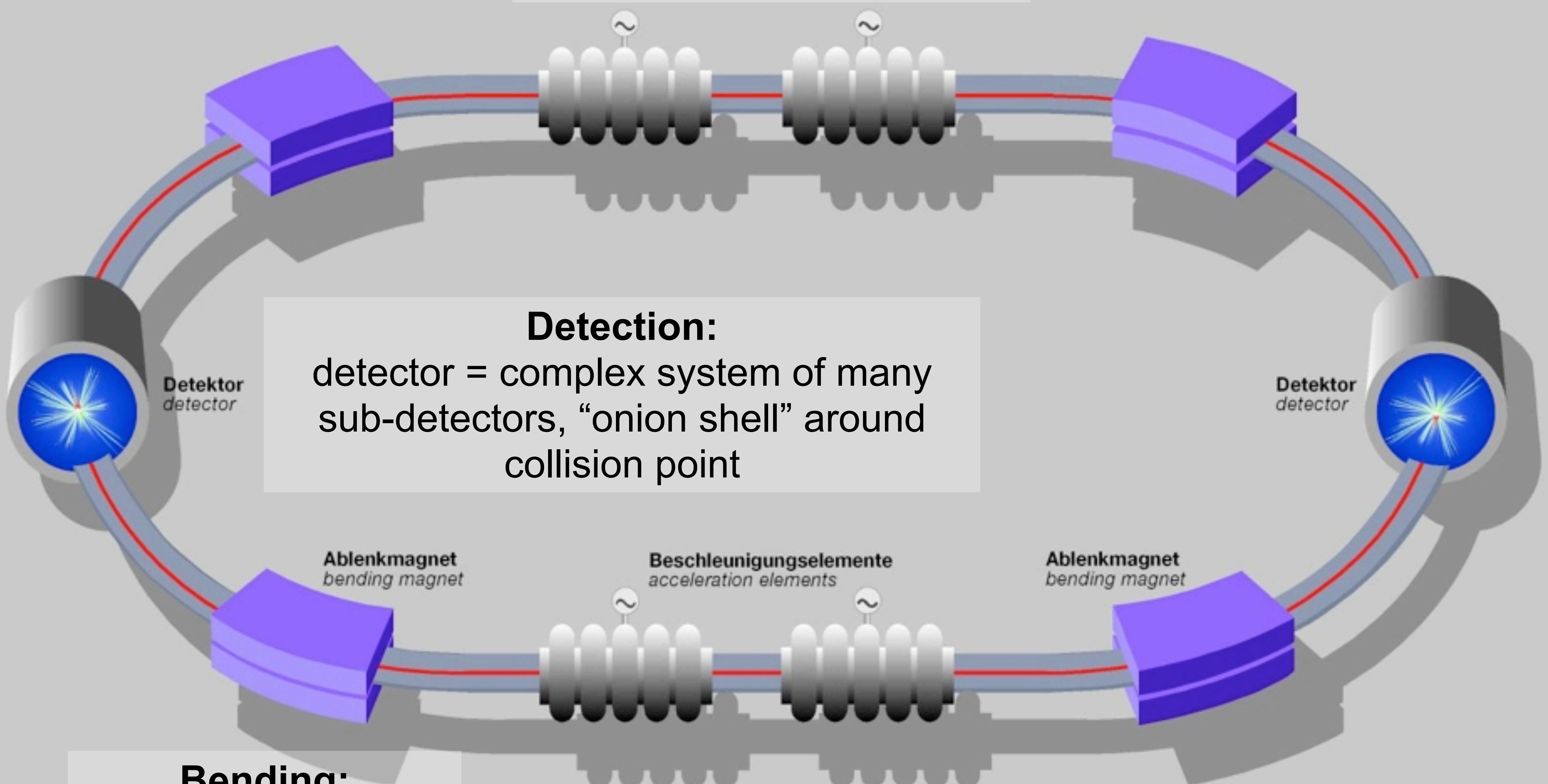
Electron Microscope



Particle Accelerator

Principle of a Particle Collider

Acceleration:
radio-frequency cavities
with alternating electric fields

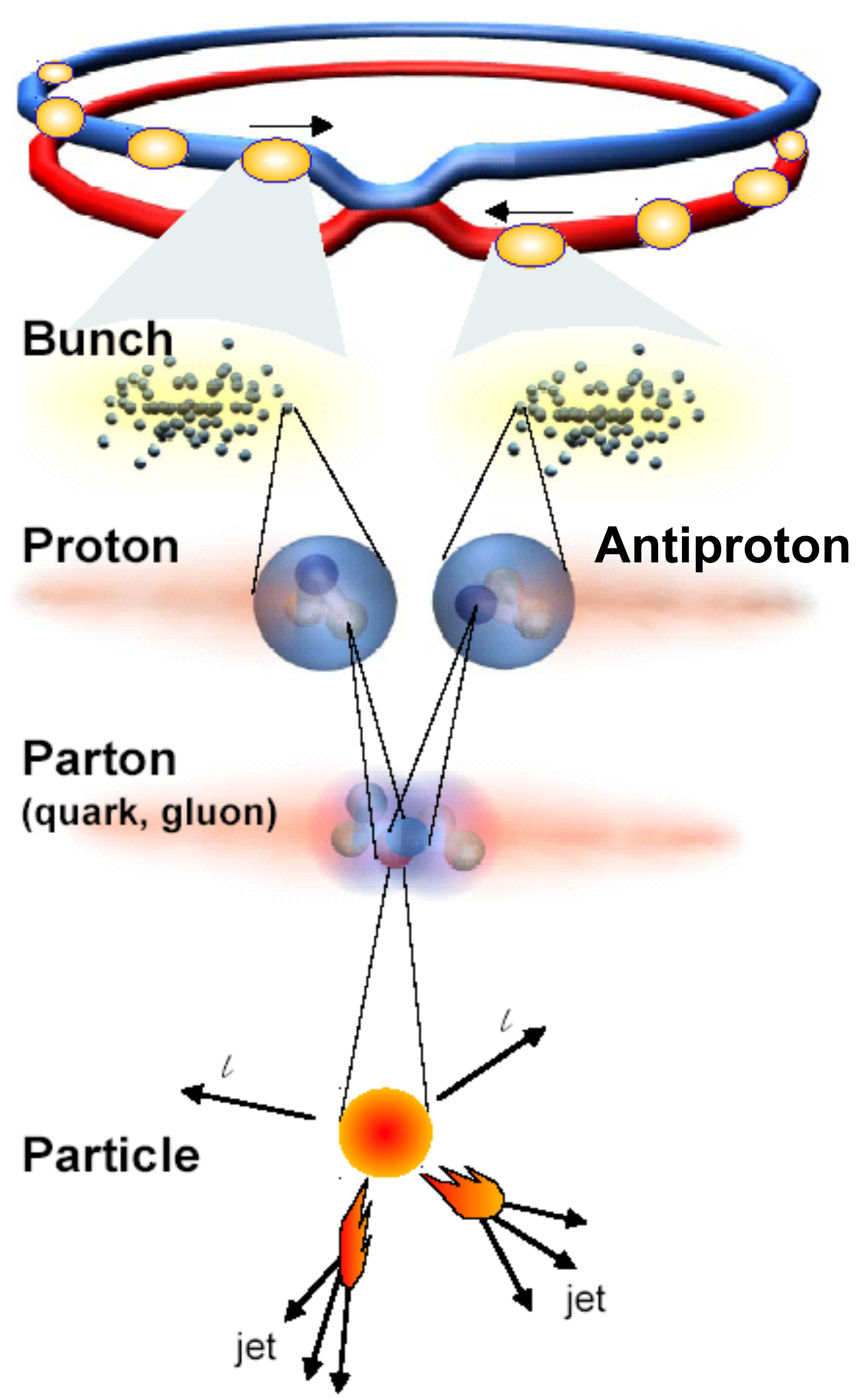


Detection:
detector = complex system of many sub-detectors, “onion shell” around collision point

Bending:
magnetic dipole fields

[DESY]

Colliding Beams and Luminosity



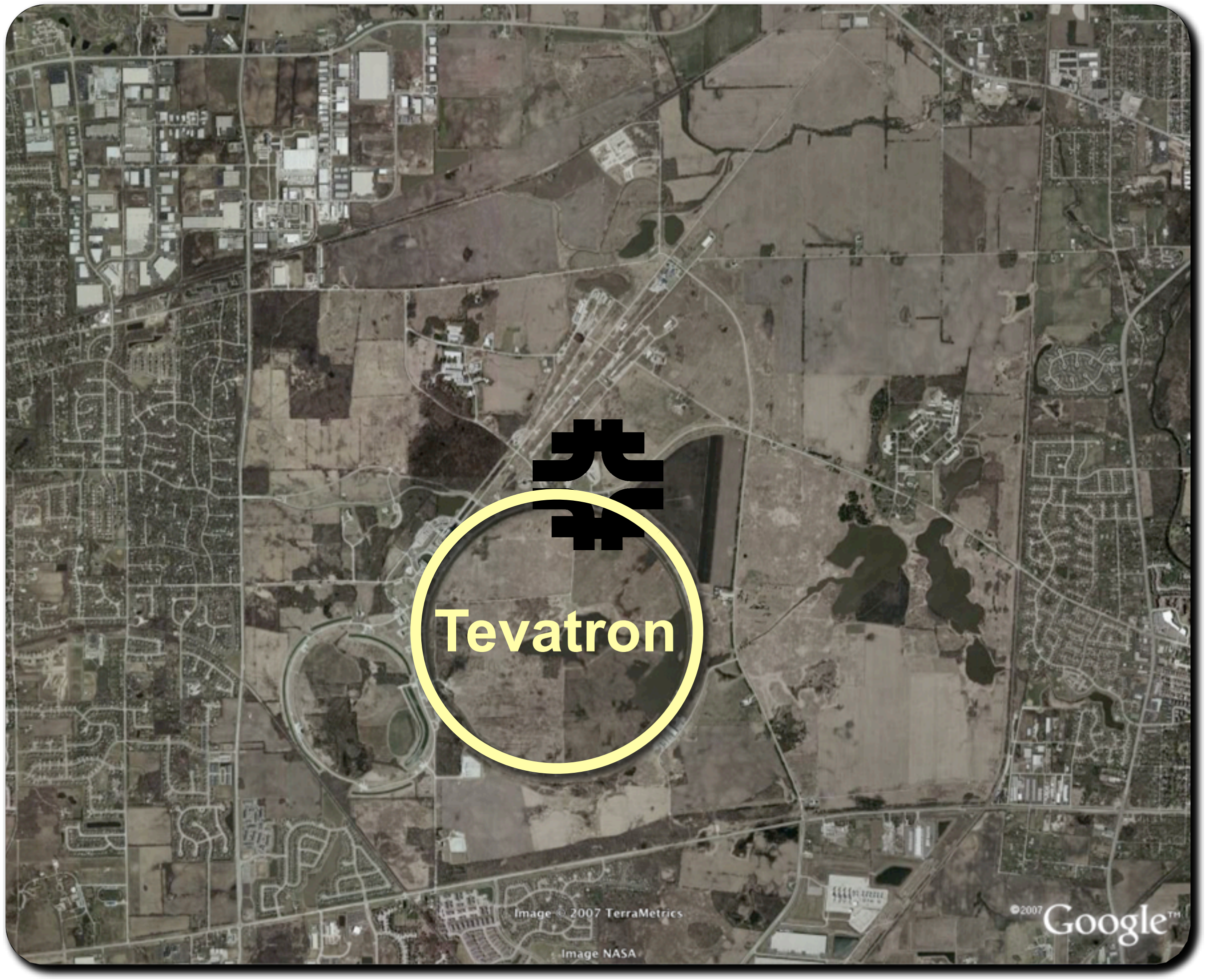
- Goal: observation of rare physics processes (one in a billion or less)
  - Large bunches of approx. 100 billion protons/antiprotons (just 0.2 femtograms)
  - Beams need to be focused before collision
- Luminosity: measure of collider performance

$$\mathscr{L} = \underbrace{f \cdot N}_{\text{revolution frequency and number of bunches}} \cdot \frac{\overbrace{n_1 n_2}^{\text{number of particles}}}{\underbrace{4\pi\,\sigma_x \sigma_y}_{\text{beam area}}}$$

- Integrated luminosity $\int L\, dt$: measure of amount of data
  $\rightarrow$ Tevatron today: more than 3 fb^{-1}

Fermilab and the Tevatron

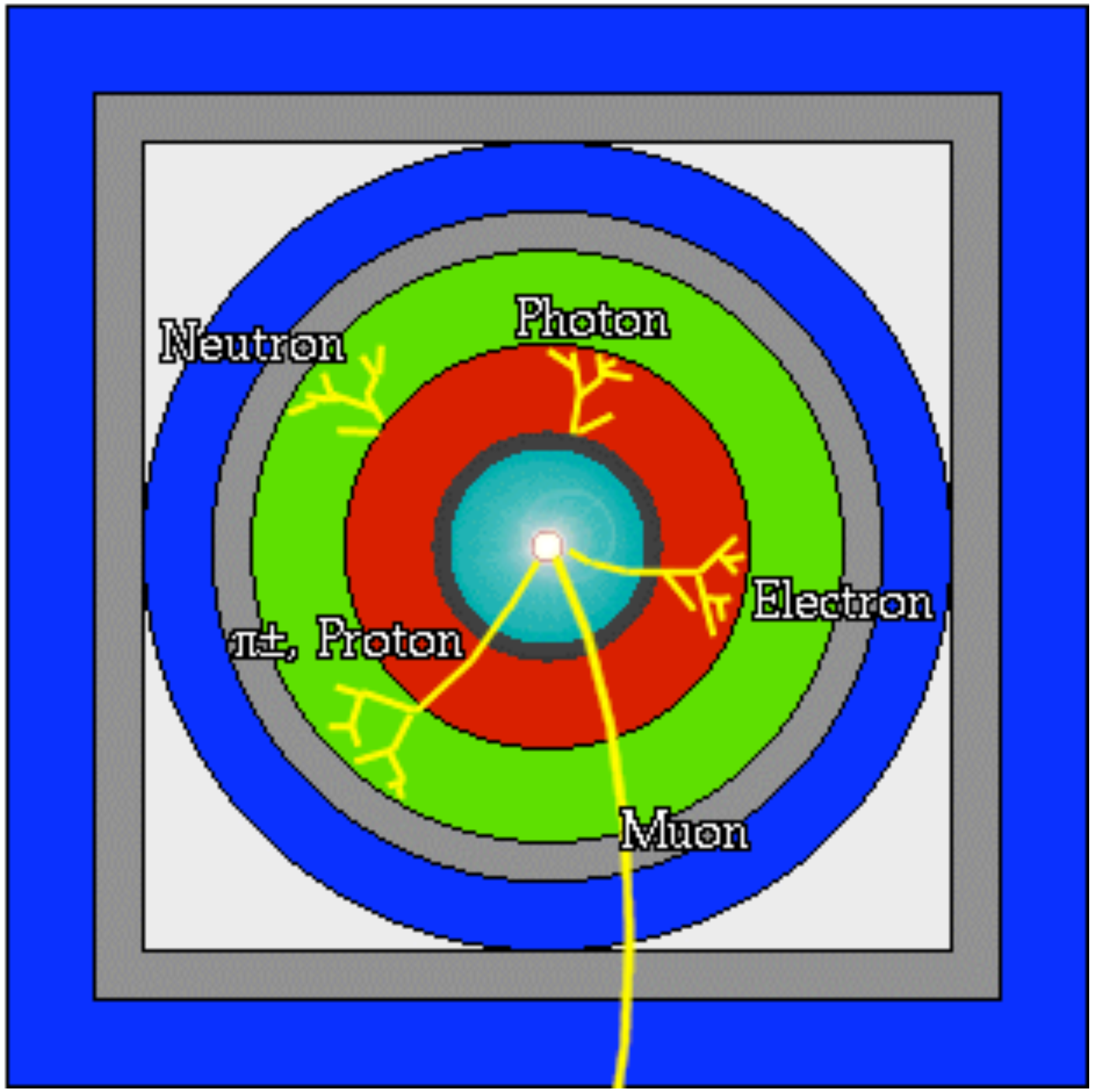
- Fermi National Accelerator Laboratory (FNAL)
  - US national particle physics lab near Chicago (founded 1967)
  - Major discoveries: bottom quark (1977), top quark (1995)
- Tevatron (since 1983)
  - Proton-antiproton collider (2 km diameter)
  - Two large multipurpose experiments: CDF (Collider Detector at Fermilab) and DØ
  - Run I (1992–1996): 800 GeV beams
  - Run II (2001–2009): 980 GeV beams
  - Running better than ever: extended running until 2010?



Principle of Collider Detectors

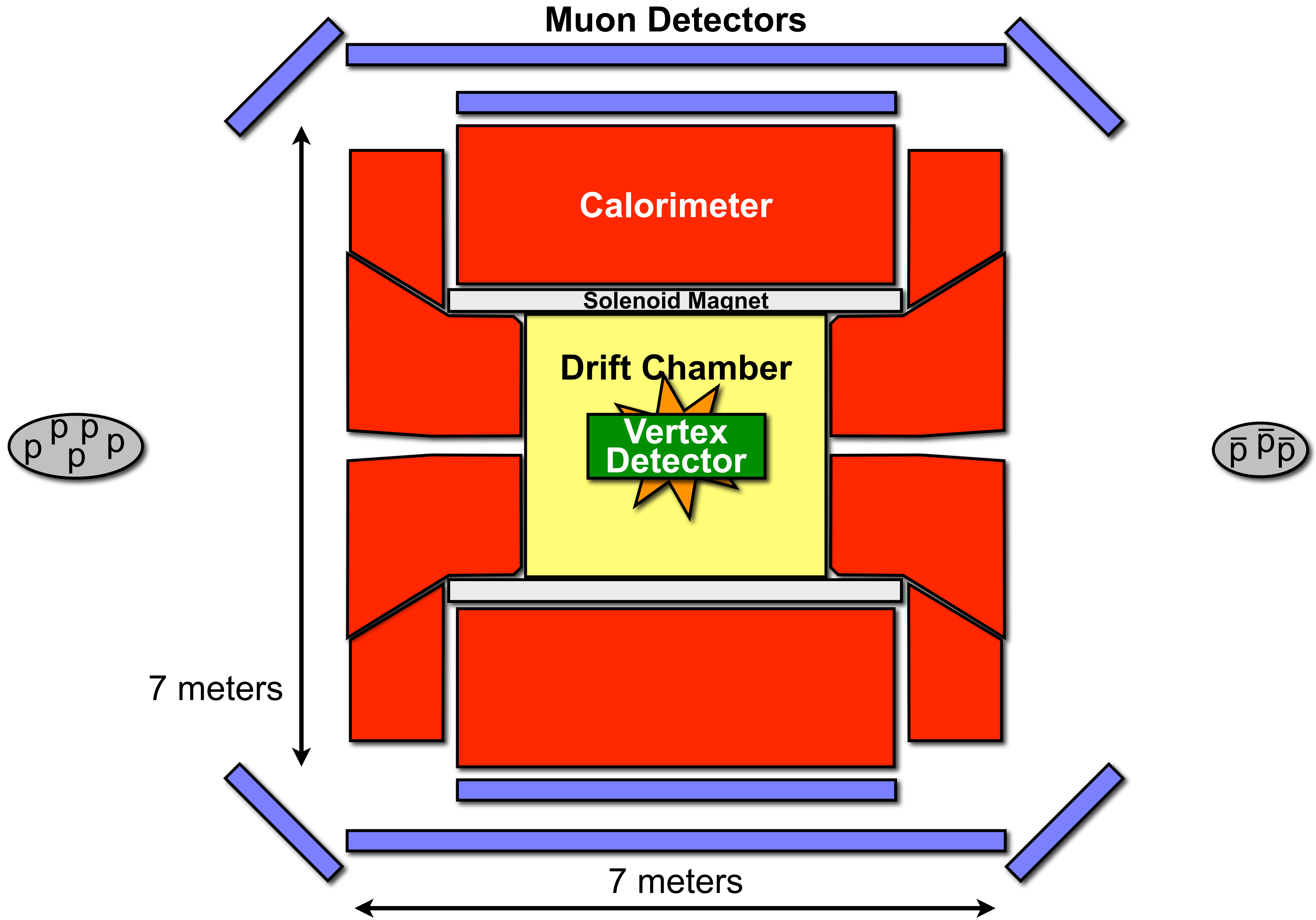
Goal: completely surround collision with detectors → onion shell design

- **Vertex Detector & Tracking Chamber:** Origin ("production vertex") and momentum of charged particles
- **Magnet Coil:** Deflection of charged particles for momentum measurement
- **Electromagnetic Calorimeter:** Energy of electrons and photons from electromagnetic shower
- **Hadronic Calorimeter:** Energy of hadrons (pions, kaons, protons, …) from hadronic shower
- **Muon Detector:** Muons are the only particle type to penetrate calorimeters



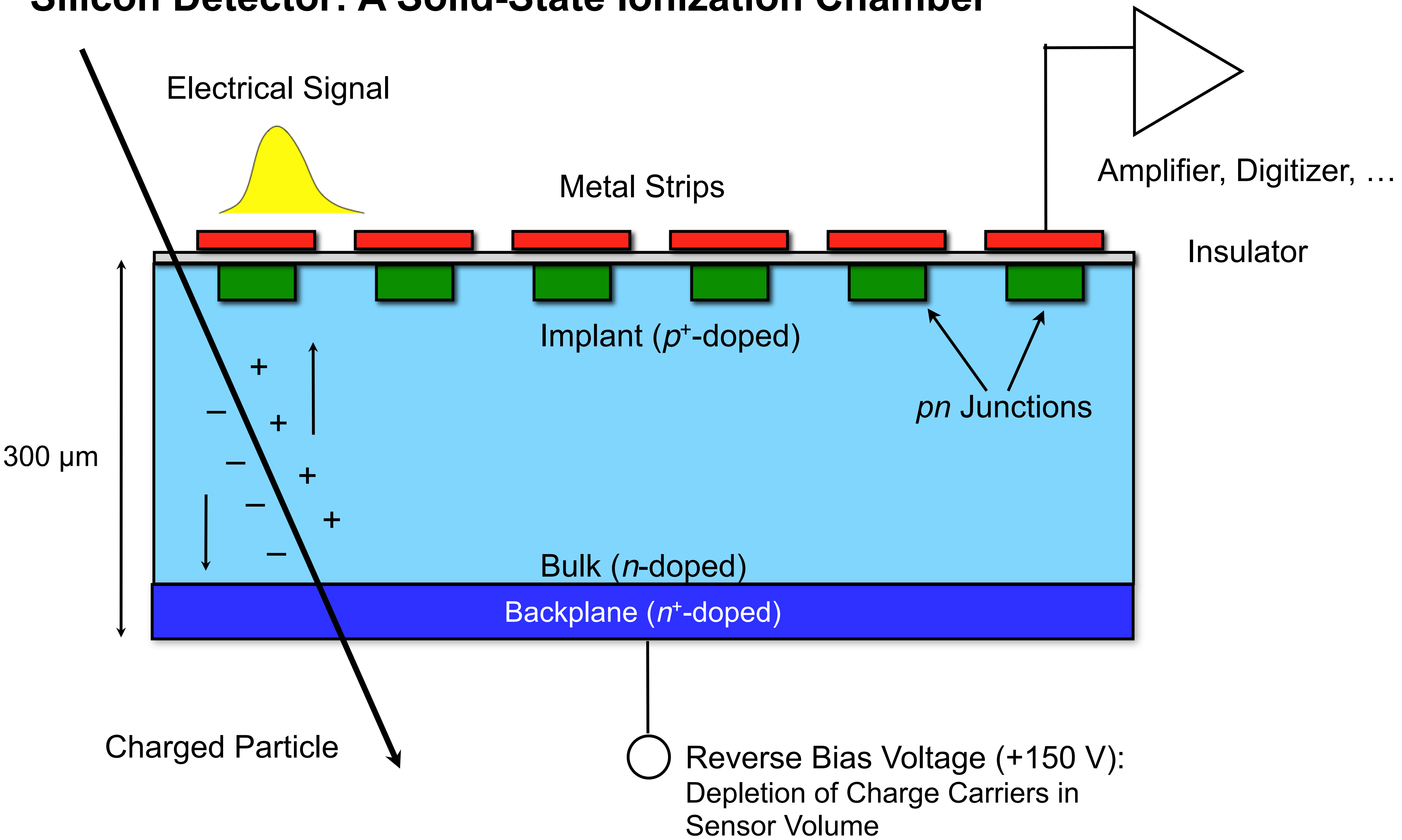
[http://www.particleadventure.org]

Collisions in the CDF Detector



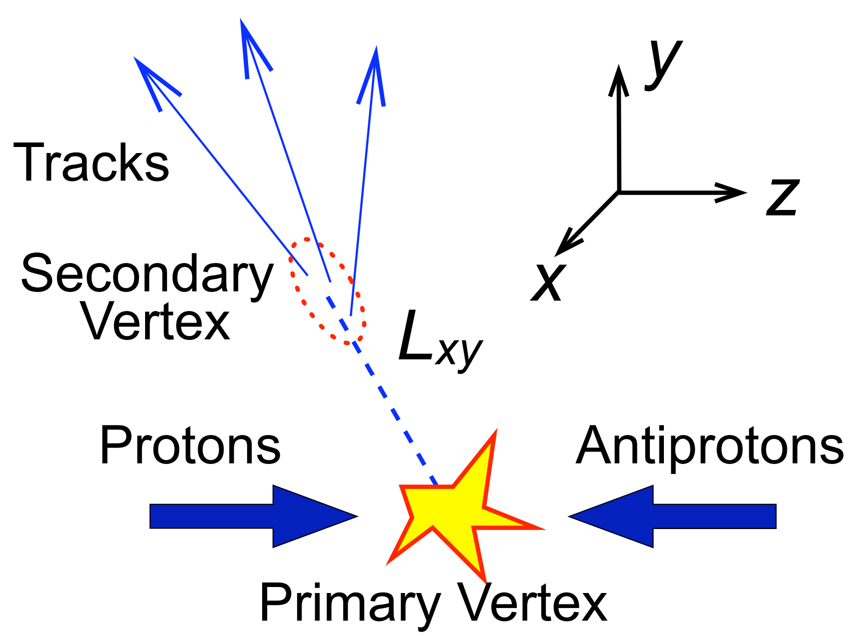
How a Silicon Tracking Detector Works

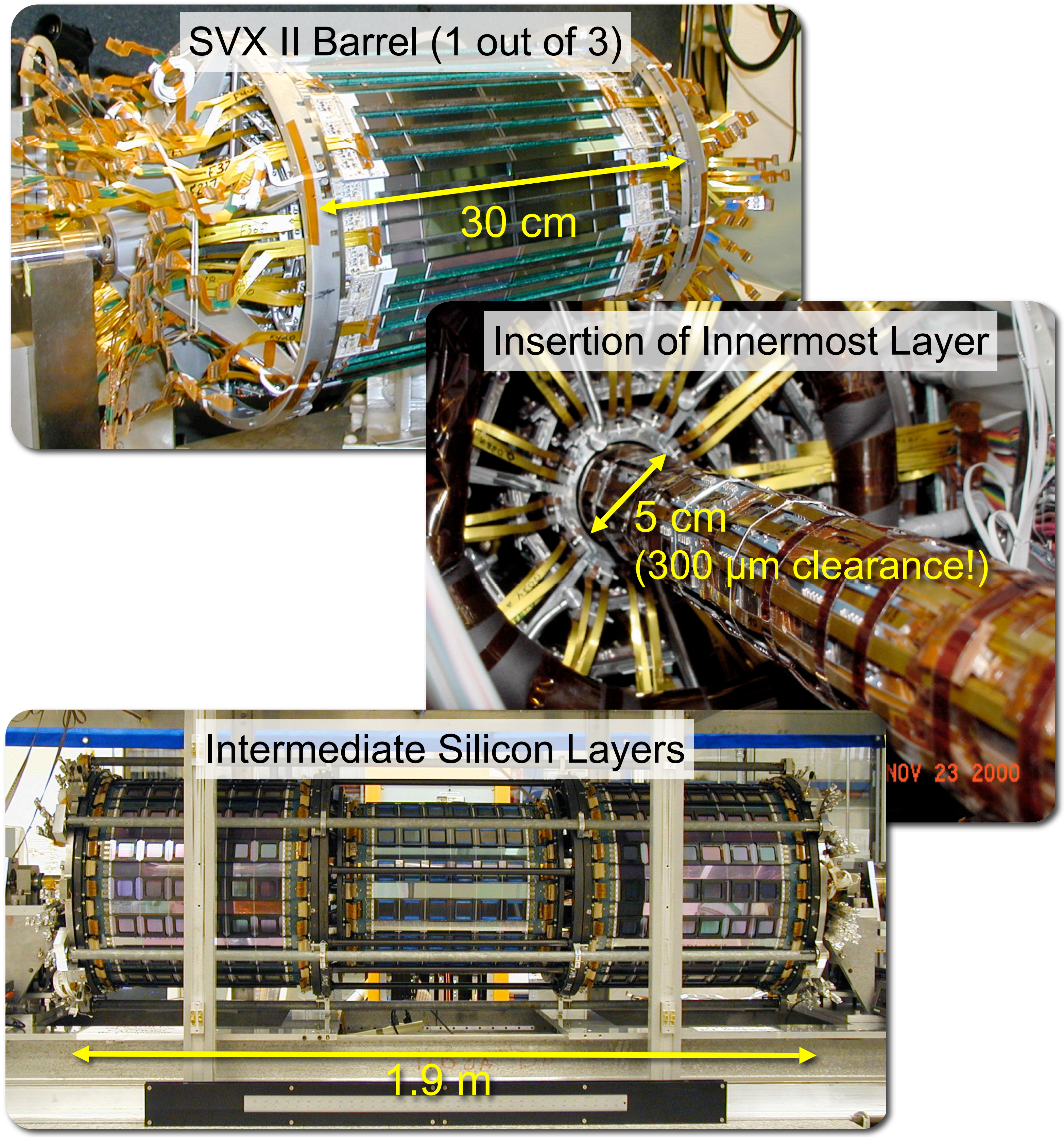
Silicon Detector: A Solid-State Ionization Chamber



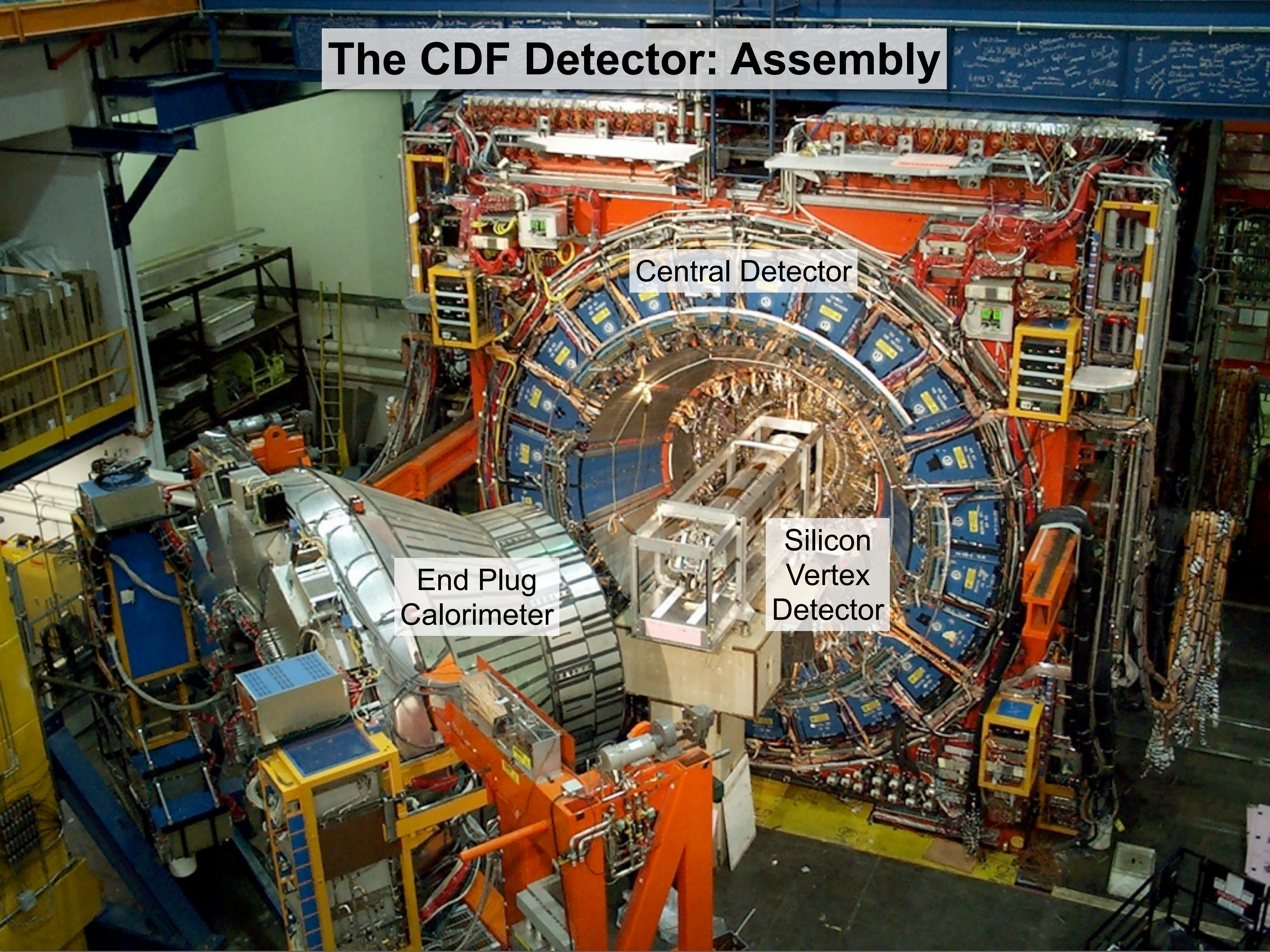
The CDF Silicon Detectors

- Largest operational silicon detector in particle physics: 8 layers, 7 m^2 surface area, 700,000 readout channels
- Crucial for identification of long-lived particles
  - B mesons from top quark decays: lifetime 1.5 ps ⟶ decay length 10 mm
  - Reconstruct secondary vertices ⟶ “B-tagging”

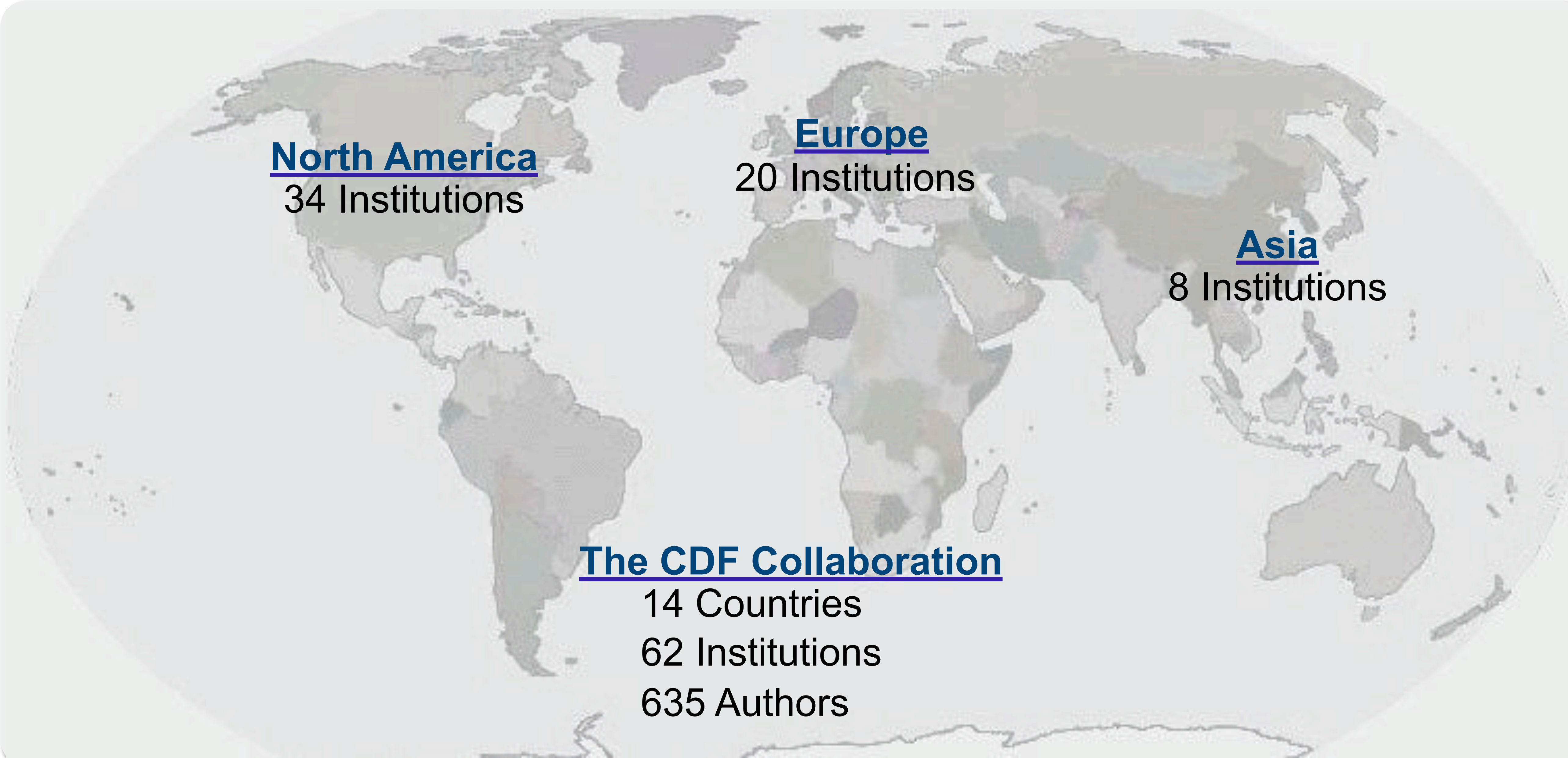




The CDF Detector: Assembly



CDF: An International Collaboration

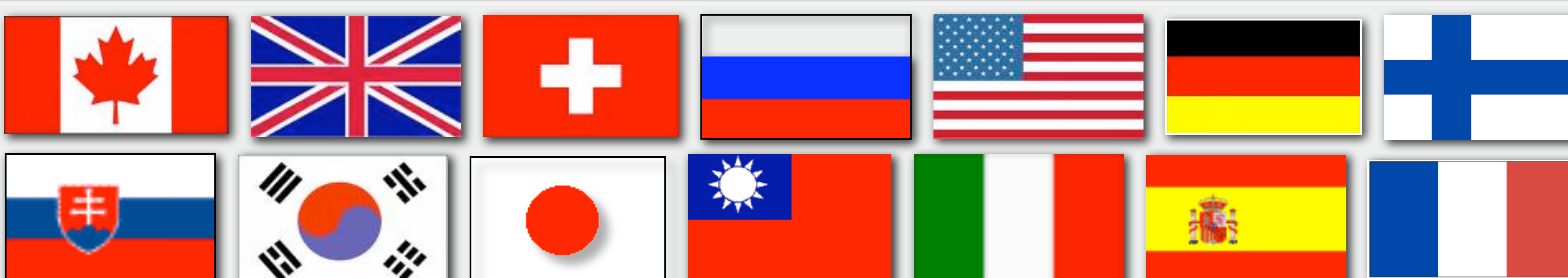


North America
34 Institutions

Europe
20 Institutions

Asia
8 Institutions

The CDF Collaboration
14 Countries
62 Institutions
635 Authors



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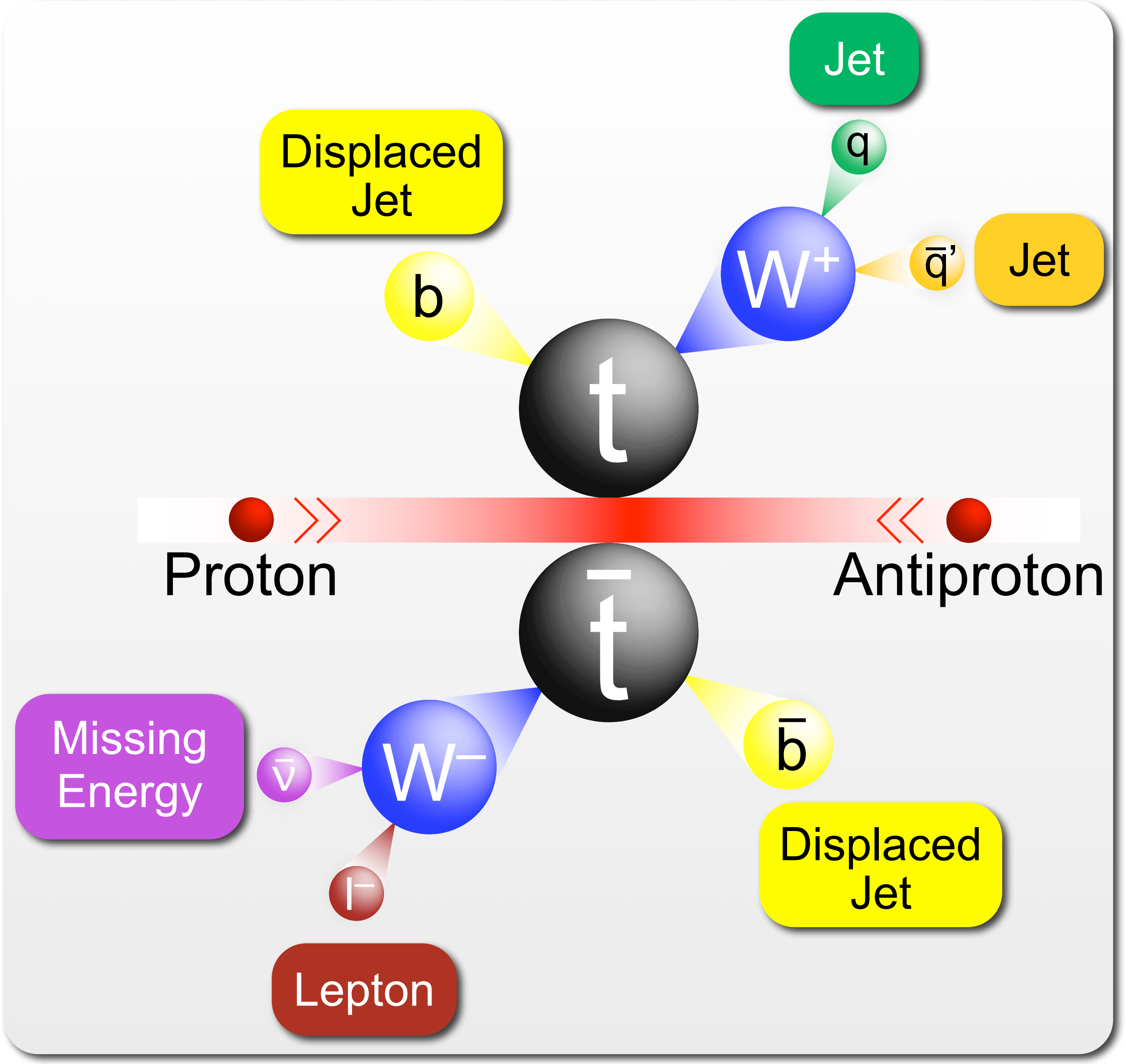
Top Pair Decay Signatures

- Standard model prediction: top quarks decay via $t \rightarrow Wb$ approx. 100% of the time
- Each W boson can decay into:
  - Quark and antiquark (2/3 of the time), or
  - Charged lepton and neutrino (1/3 of the time)
- Strong force confines quarks
  - Creation of additional quark-antiquark pairs out of the vacuum
  - "Jets": bundles of particles
- Two jets come from from b quarks: B-tagging possibility



How do you know that energy is missing?

Answer: energy/momentum conservation for all visible objects (i.e. jets and leptons)

Hadron collider: component in beam direction unknown → missing transverse energy

Finding a Top Needle in a Haystack

Step 1:
Collisions in the Detector

Cross section for top pair production: approx. 10^{10} times smaller than cross section for inelastic proton-antiproton scattering

Cross section: effective area of particle collision (unit: 1 barn = 10^{-28} m^2), measure of probability for a physical process

Top Pairs : Everything Else

8,000 : 100,000,000,000,000

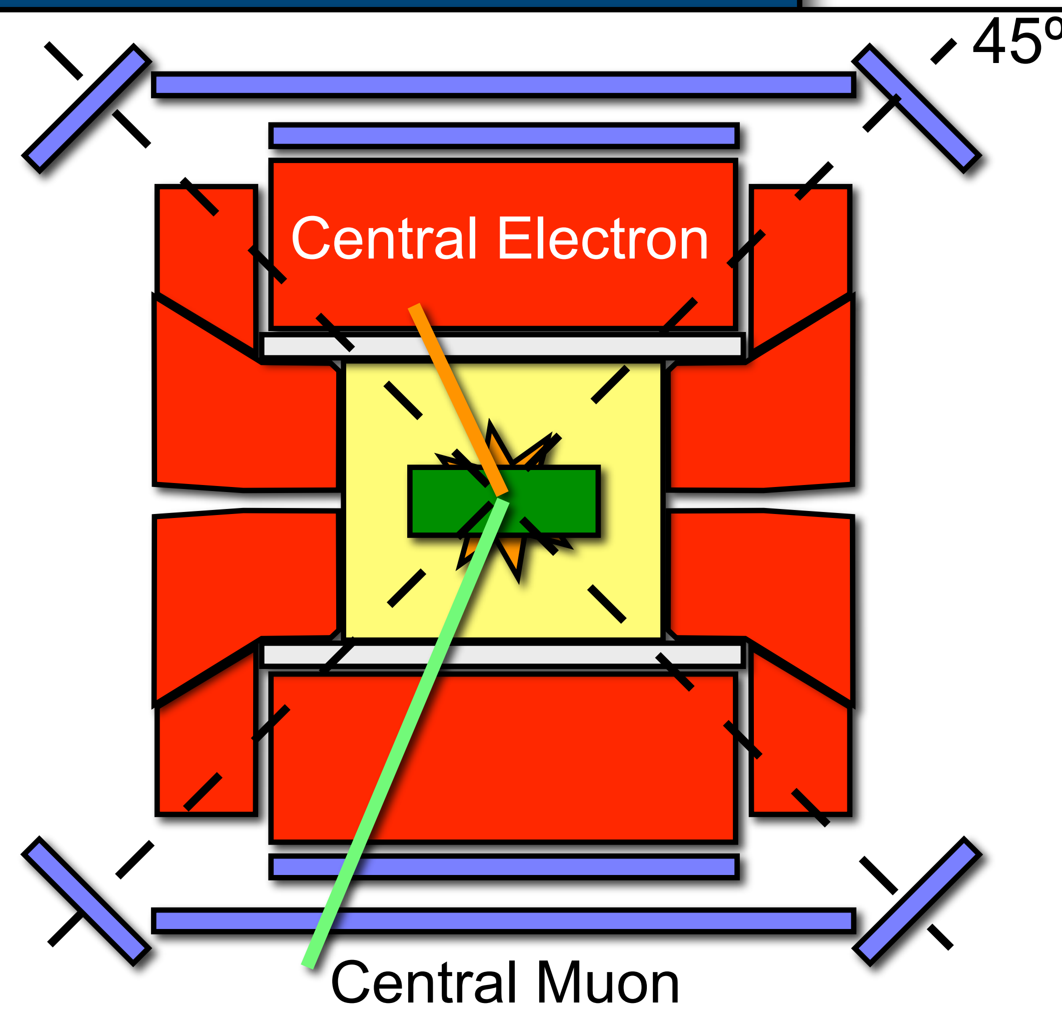
in 1 fb^{-1} of data

Finding a Top Needle in a Haystack

Step 2:
Online Event Selection

"Central Electrons":
Find high momentum charged particle track and energy deposition in central calorimeter

"Central Muons":
Find high momentum track and "stub" in central muon detector



Top Pairs : Everything Else

700 : 10,000,000,000

in 1 fb^{-1} of data

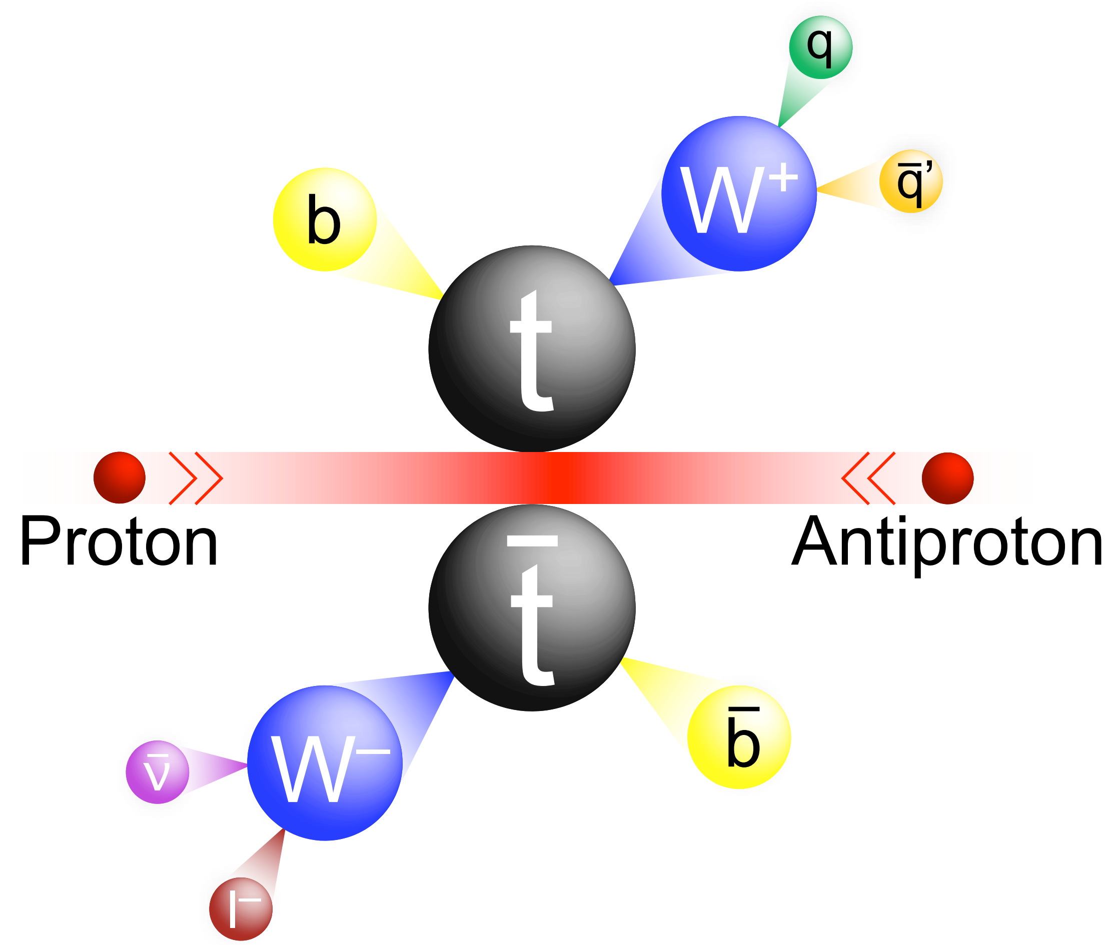
Finding a Top Needle in a Haystack

Step 3:
Offline Event Selection

Top signature: lepton, neutrino, 4 jets

Select only events with:

- 3 or more jets
- Large missing energy
- Large total energy sum



Top Pairs : Everything Else

600 : 1,800

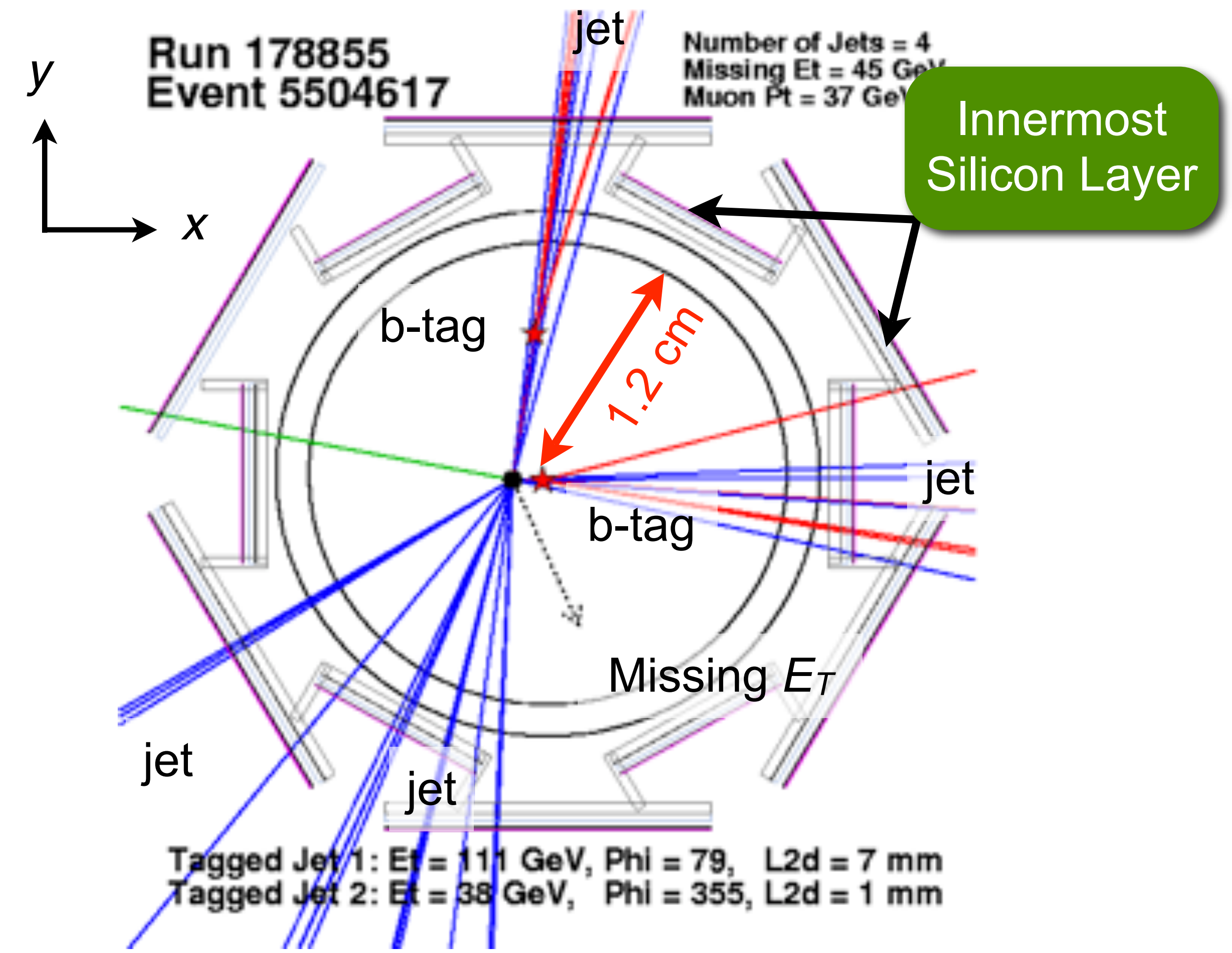
in 1 fb^{-1} of data

Finding a Top Needle in a Haystack

Step 4:
Tagging of b Quark Jets

Top signature: two jets from b quarks

Search for events with at least one displaced vertex from B meson decay



Top Pairs : Everything Else

350 : 75

in 1 fb^{-1} of data

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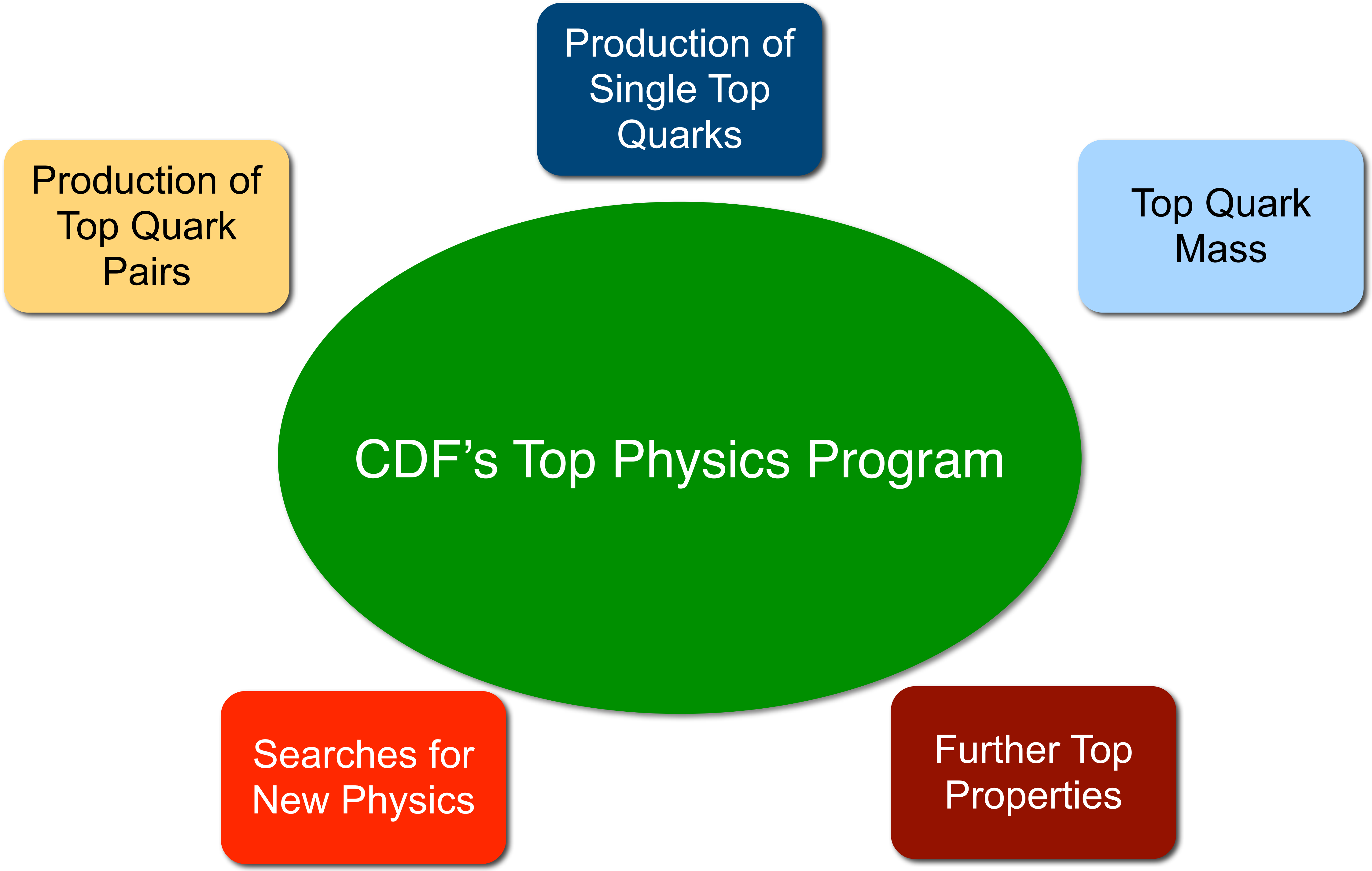
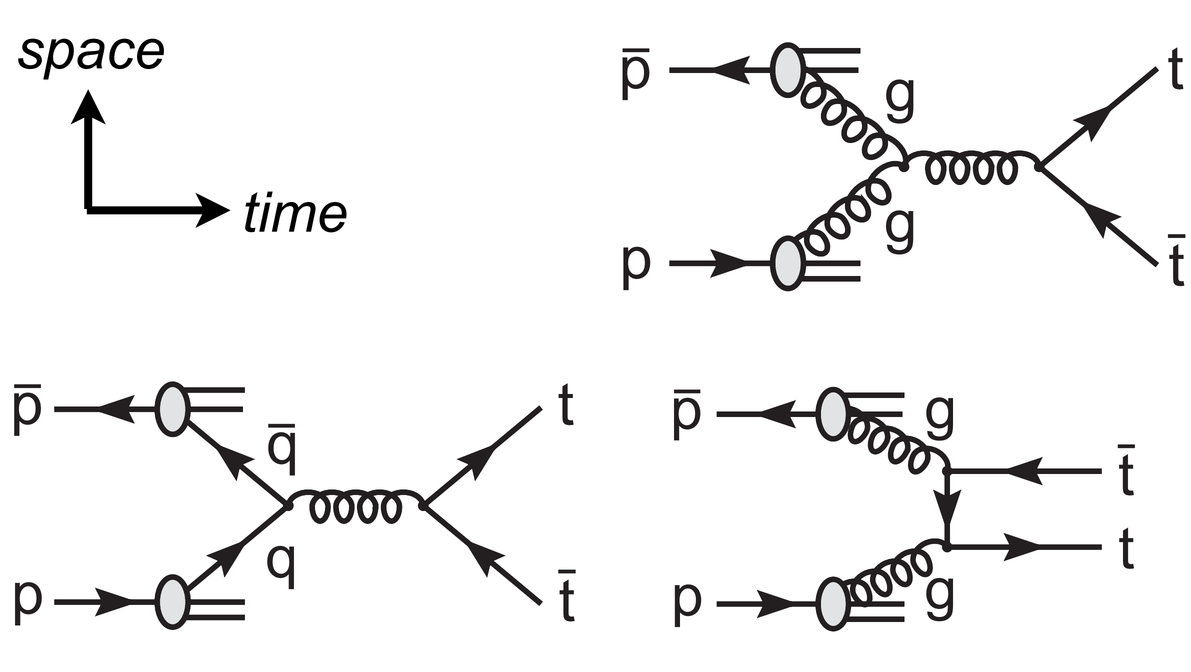
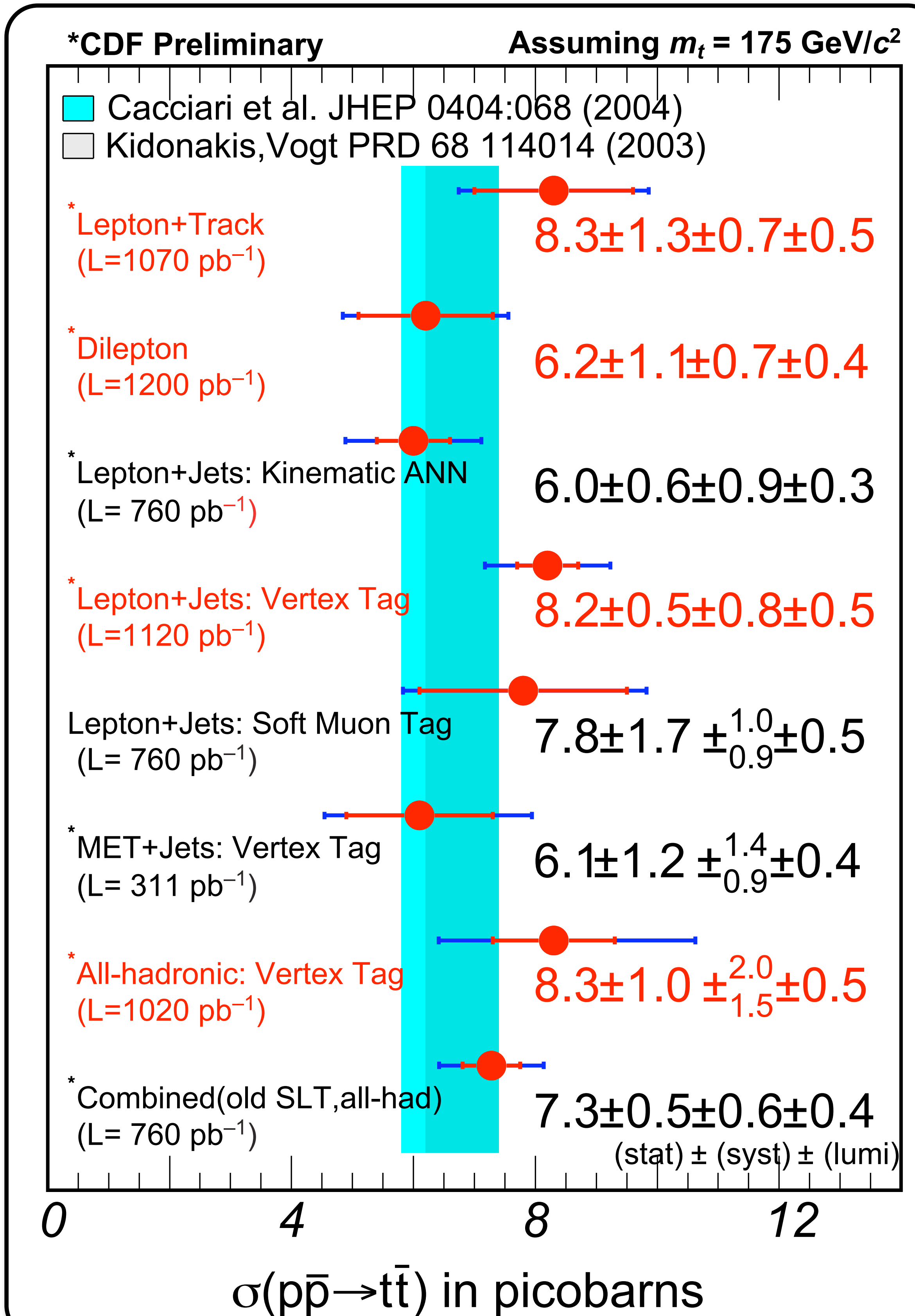


Top Pair Production Cross Section

- $t\bar{t}$ pairs produced via strong force
- Cross section measurement answers important questions:
  - Is nature described correctly by the strong force, even on the level of quantum corrections? ✔
  - Are results consistent in all top quark decay channels, or is there a hint for new physics? ✔

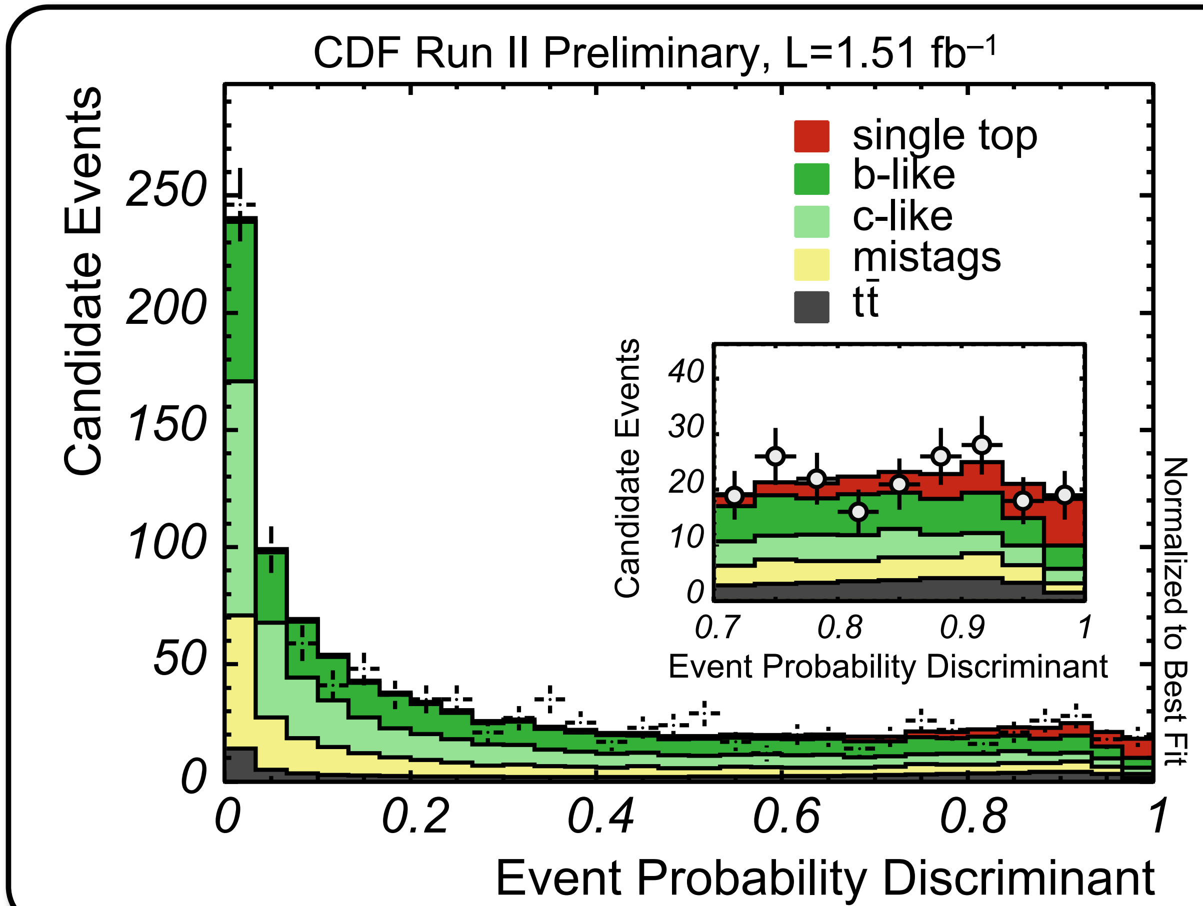
Top Pair Production: Feynman Diagrams





Single Top Production

- Single top production: weak force
- Much more difficult to find than $t\bar{t}$:
  - Production cross section half of $t\bar{t}$ cross section
  - Very hard to separate from large W+jets background: need multivariate analysis techniques
- First evidence by DØ (late 2006), confirmation of evidence by CDF (Summer 2007)
- Heading for single top observation with twice the data
- Analyses will lead the way to Higgs boson searches: analysis techniques, background estimates, …



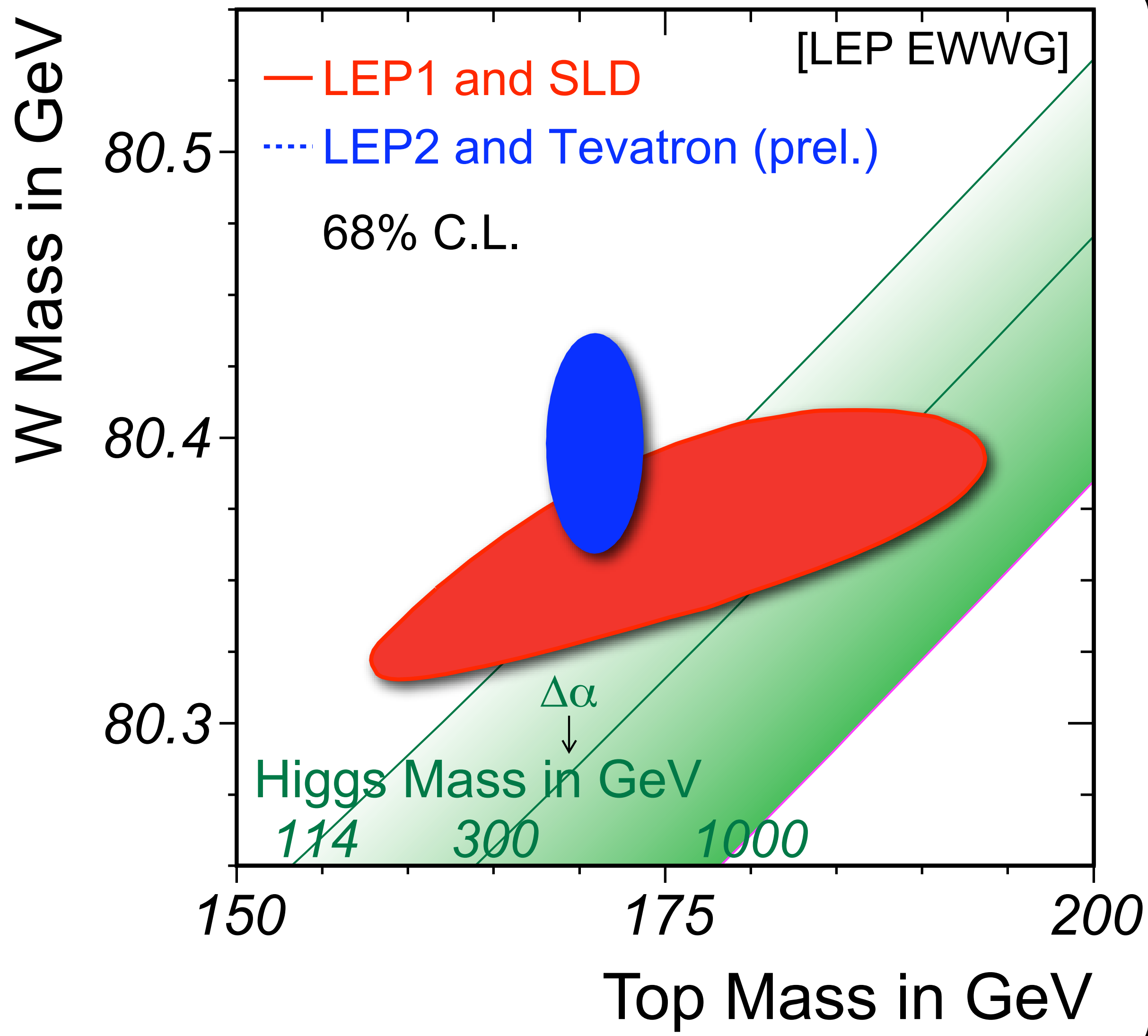
Evidence? Observation?

Well defined statistical meaning in high-energy physics:

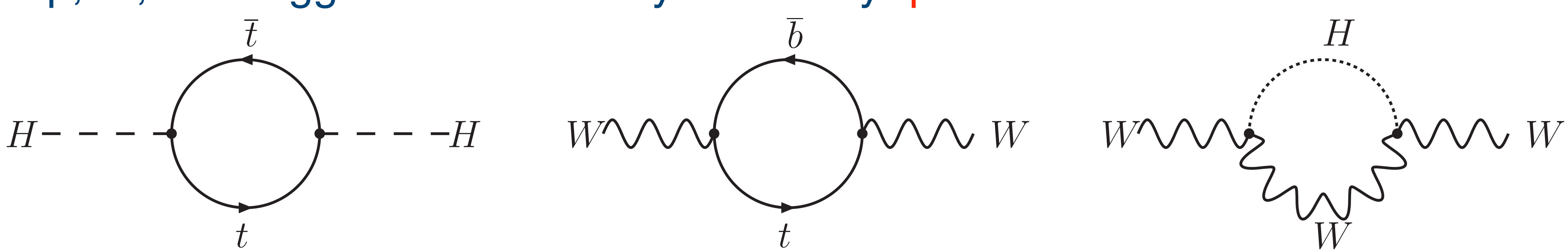
- *Evidence: probability for random fluctuation less than 0.3% (3σ of Gaussian distribution)*
- *Observation: probability for random fluctuation less than 0.00006% (5σ of Gaussian distribution)*

The Top, the W, and the Higgs

- Higgs boson:
  - Cornerstone of standard model: explains why all particles have mass
  - Not yet observed in experiments
- Very precise measurements of top and W masses (LEP e^+e^- collider and Tevatron):
  - Only small range of allowed Higgs masses left
  - Statistically most likely: "Light" Higgs (mass < 144 GeV/c^2)

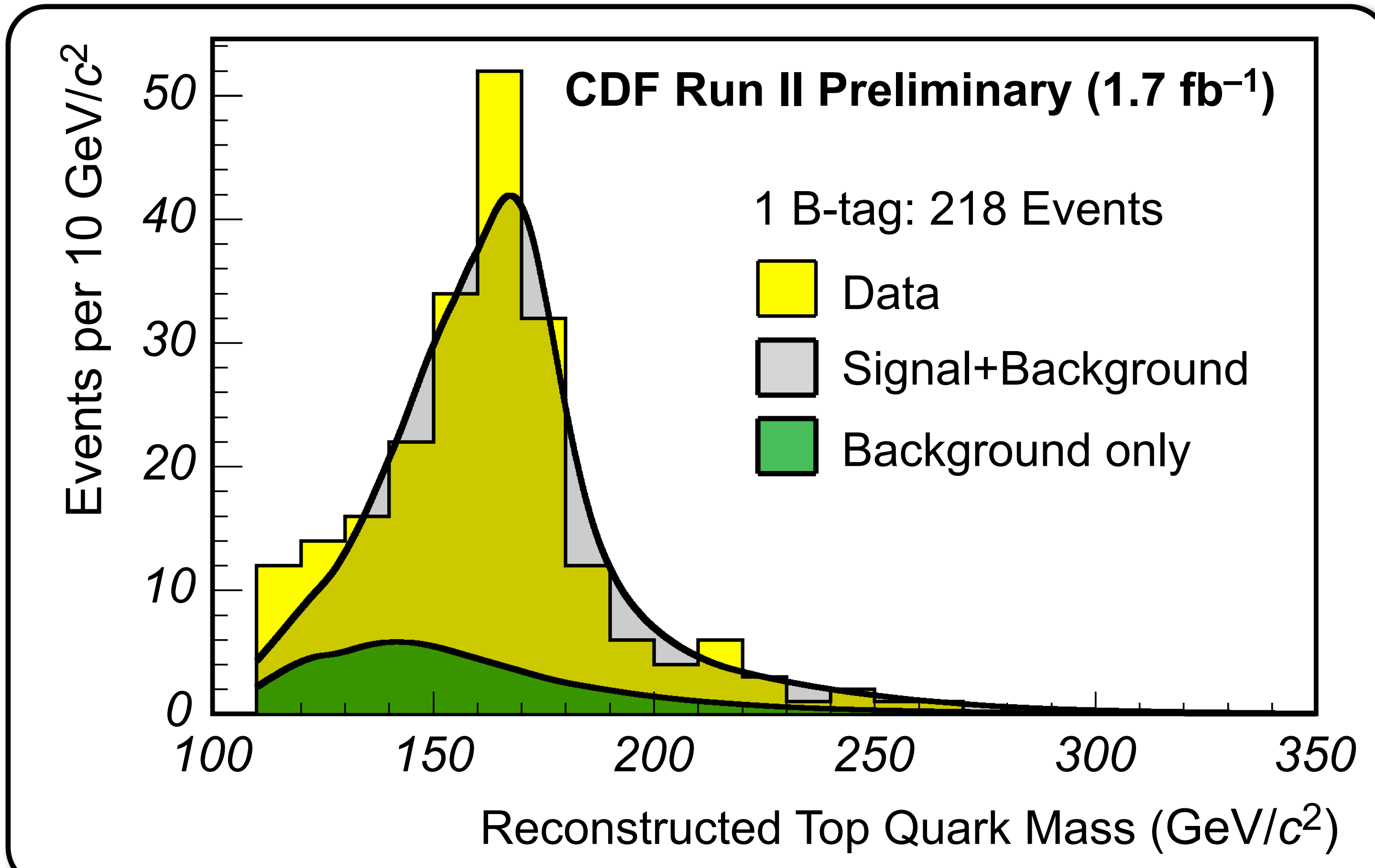


Top, W, and Higgs masses closely related by quantum corrections

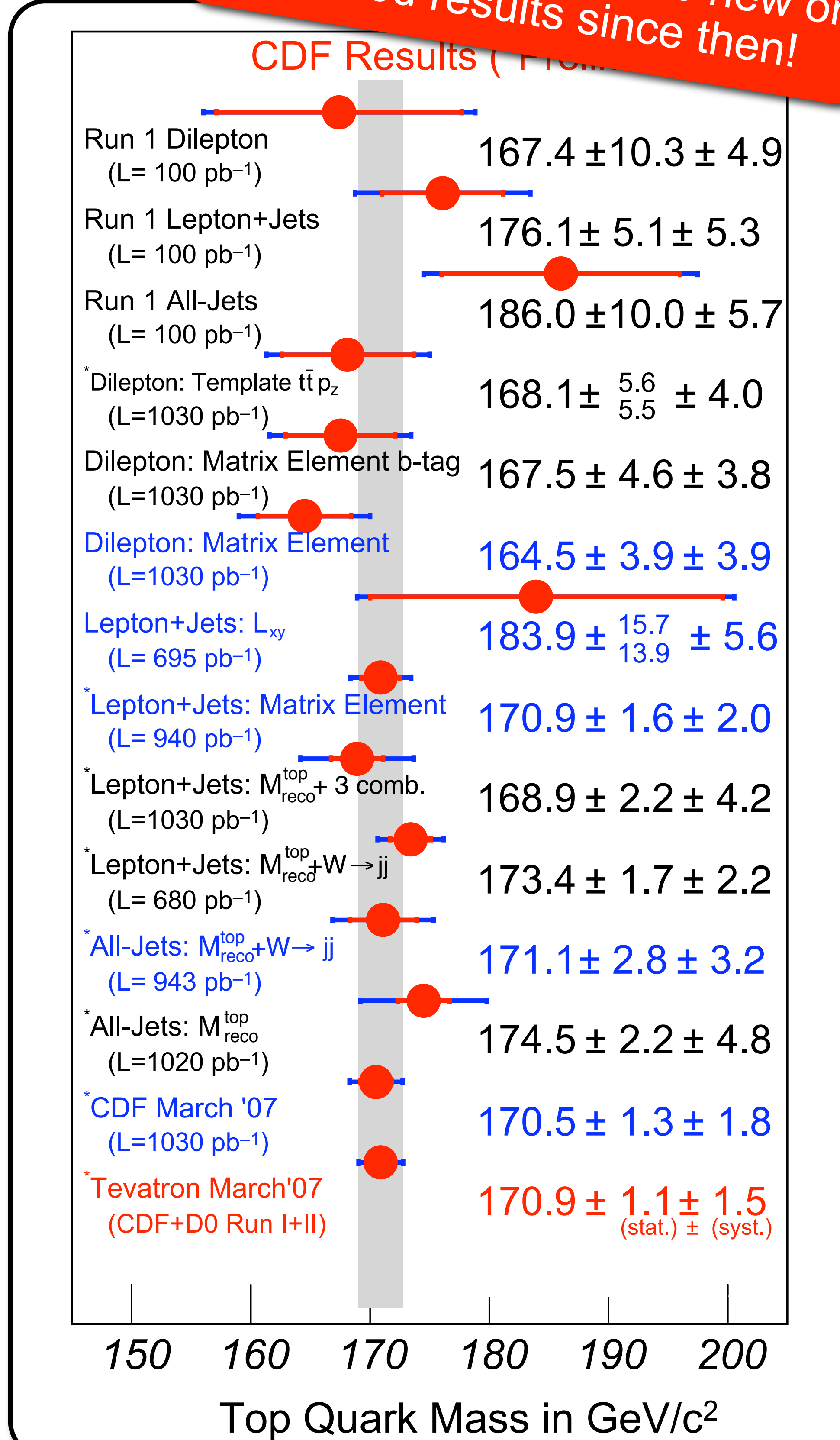


Top Mass

- Challenge: infer top mass from jet energy → calibrate against known W mass
- Precision measurements in many decay channels with different techniques:
  - Consistent results ✔
  - Combination of all results: reduced uncertainty ✔

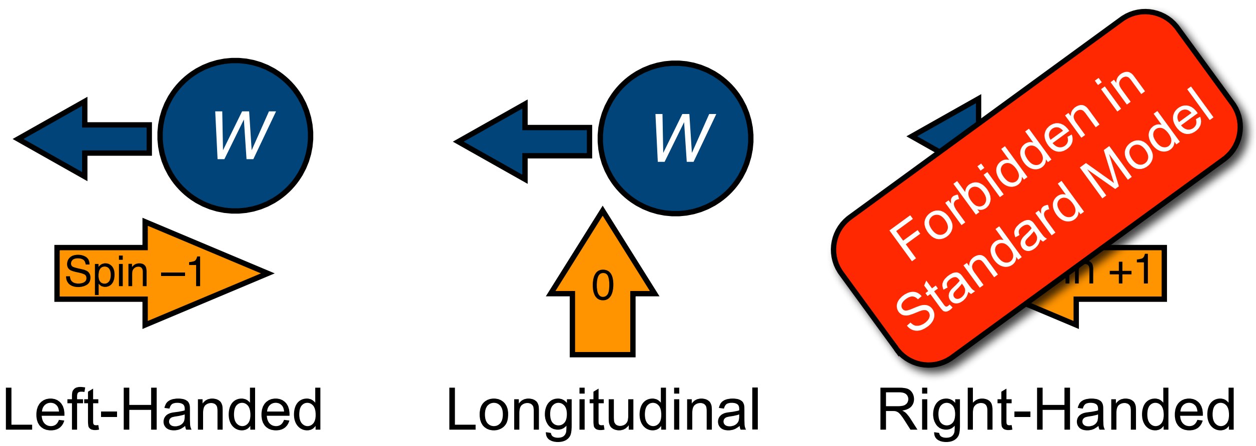


As of March 2007. Nine new or updated results since then!

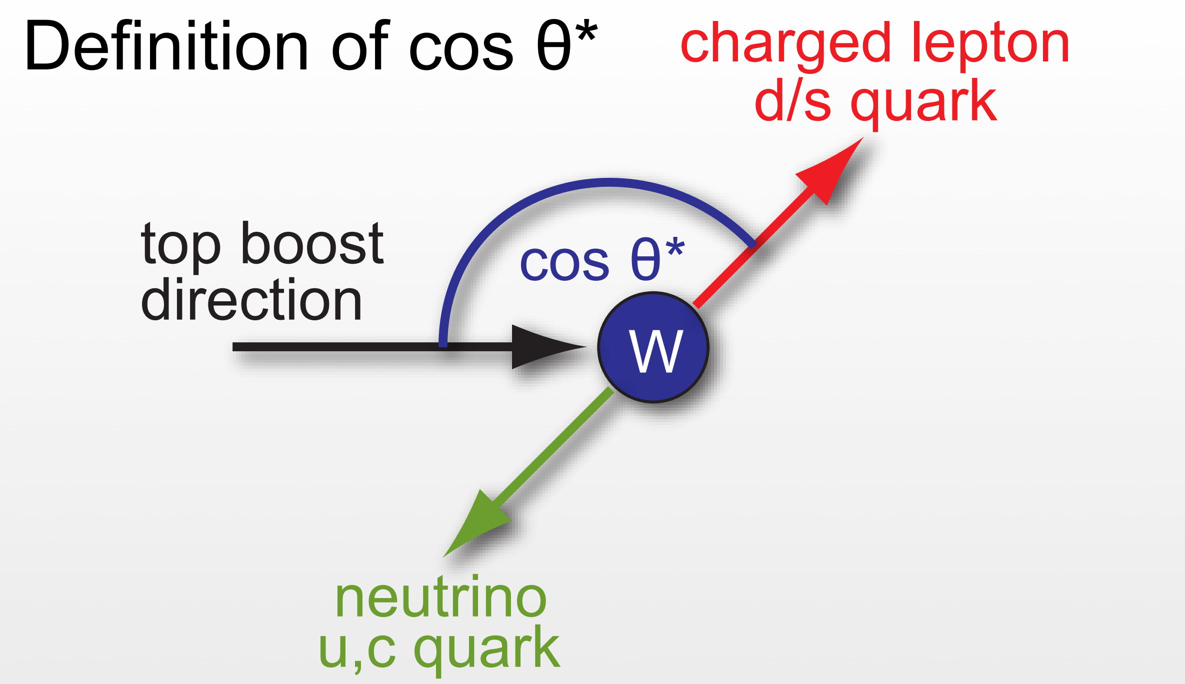


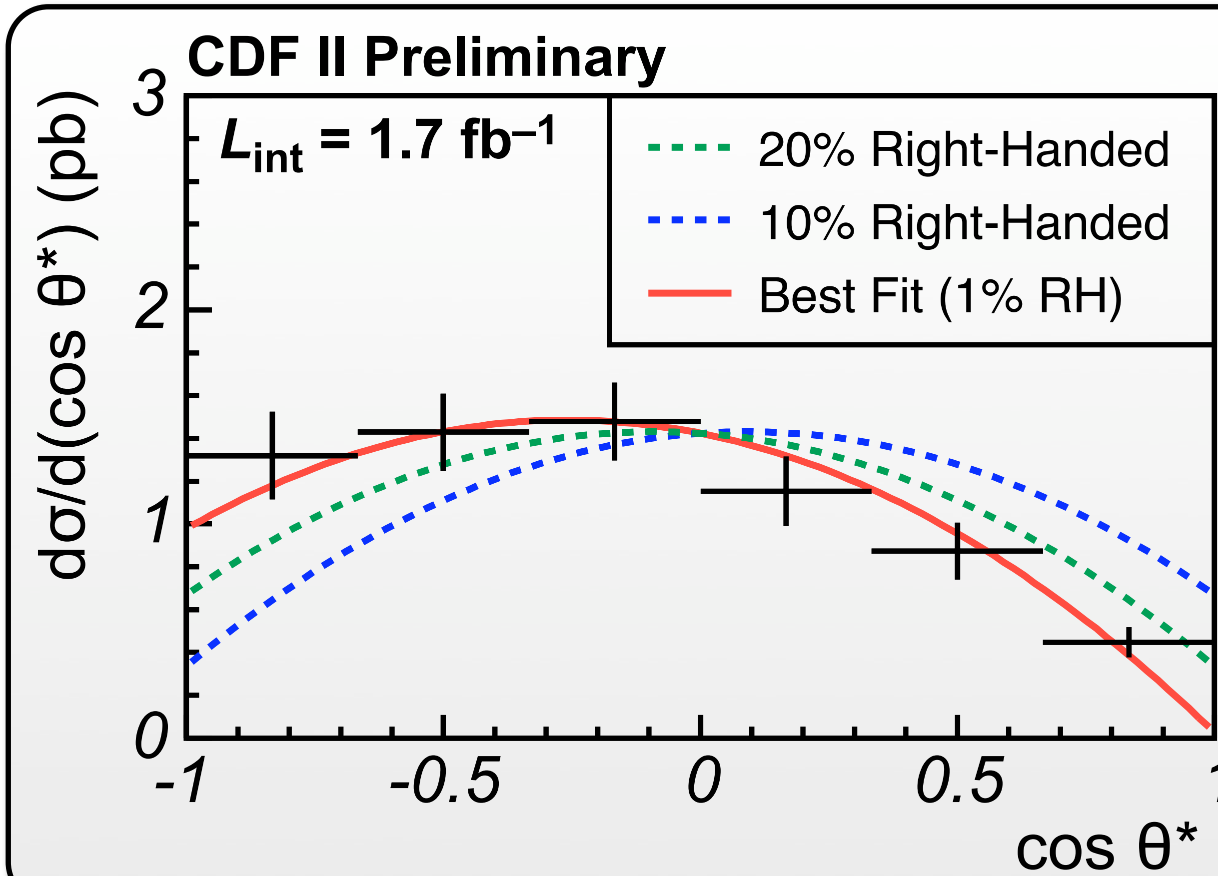
Further Top Properties

- Central question: Is the top really the standard model top?
- Example: Is the decay t → Wb governed by weak force (“V–A decay”)?
  - Standard model: no “right-handed” W bosons from top decays

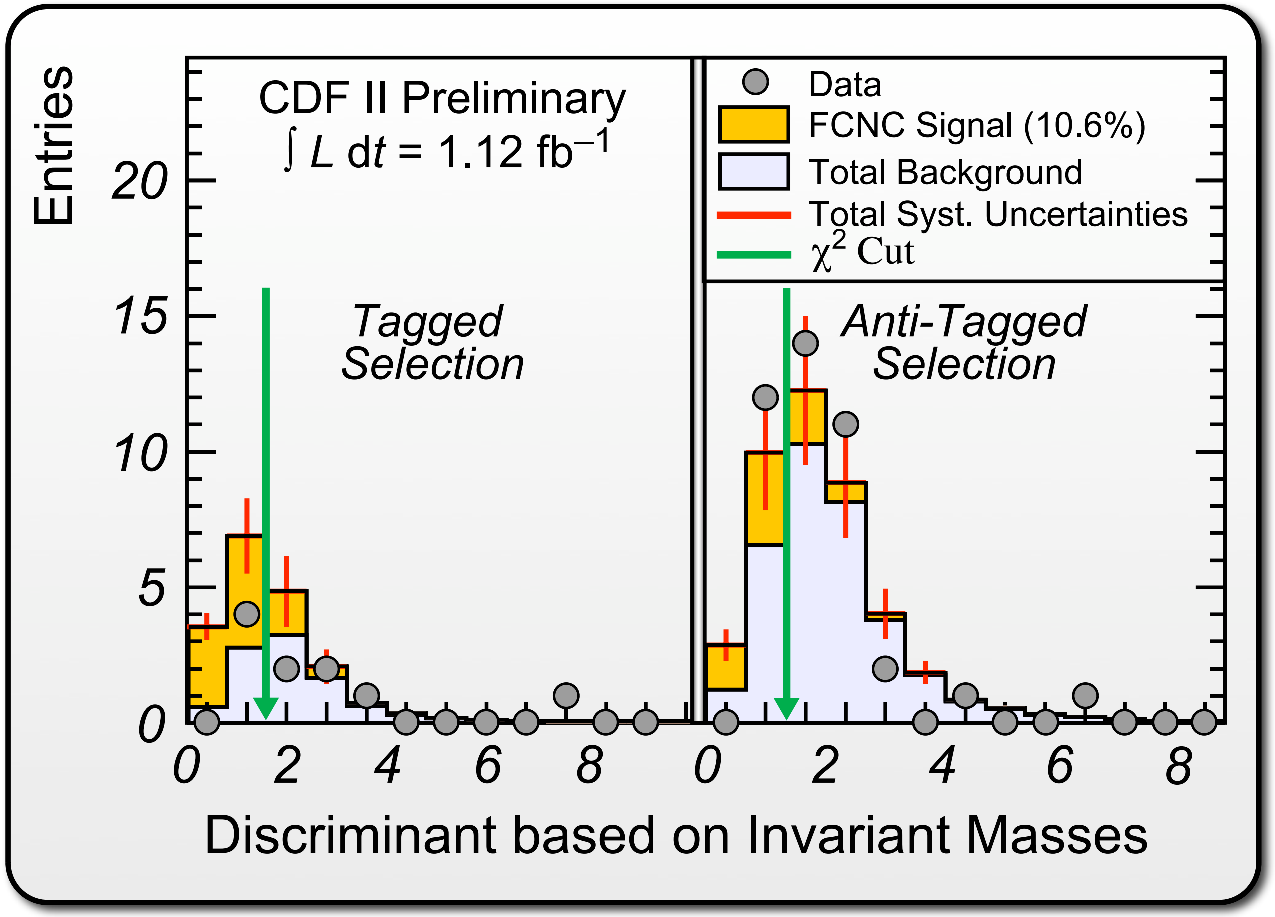


  - Measure angular distribution of leptons from W decay: excellent agreement with standard model prediction
- Many more studies: top charge, lifetime, …





- My analysis at CDF: search for "flavor changing neutral current" (FCNC) top decays $t \to Zq$
  - Standard model: one top quark in 100 million billion (10^{14}) decays into Zq (q = u,c)
  - Any signal at the Tevatron: new physics
  - No signal observed: world's best limit – fewer than 11% of all top quarks decay via $t \to Zq$



Further new physics searches with top quarks at CDF:

- Are top quarks produced via a heavy $t\bar{t}$ resonance?
- Does top decay into charged Higgs boson?
- Does top have a heavy sibling t'?
- …

So far: no indications for new physics in the top quark sector

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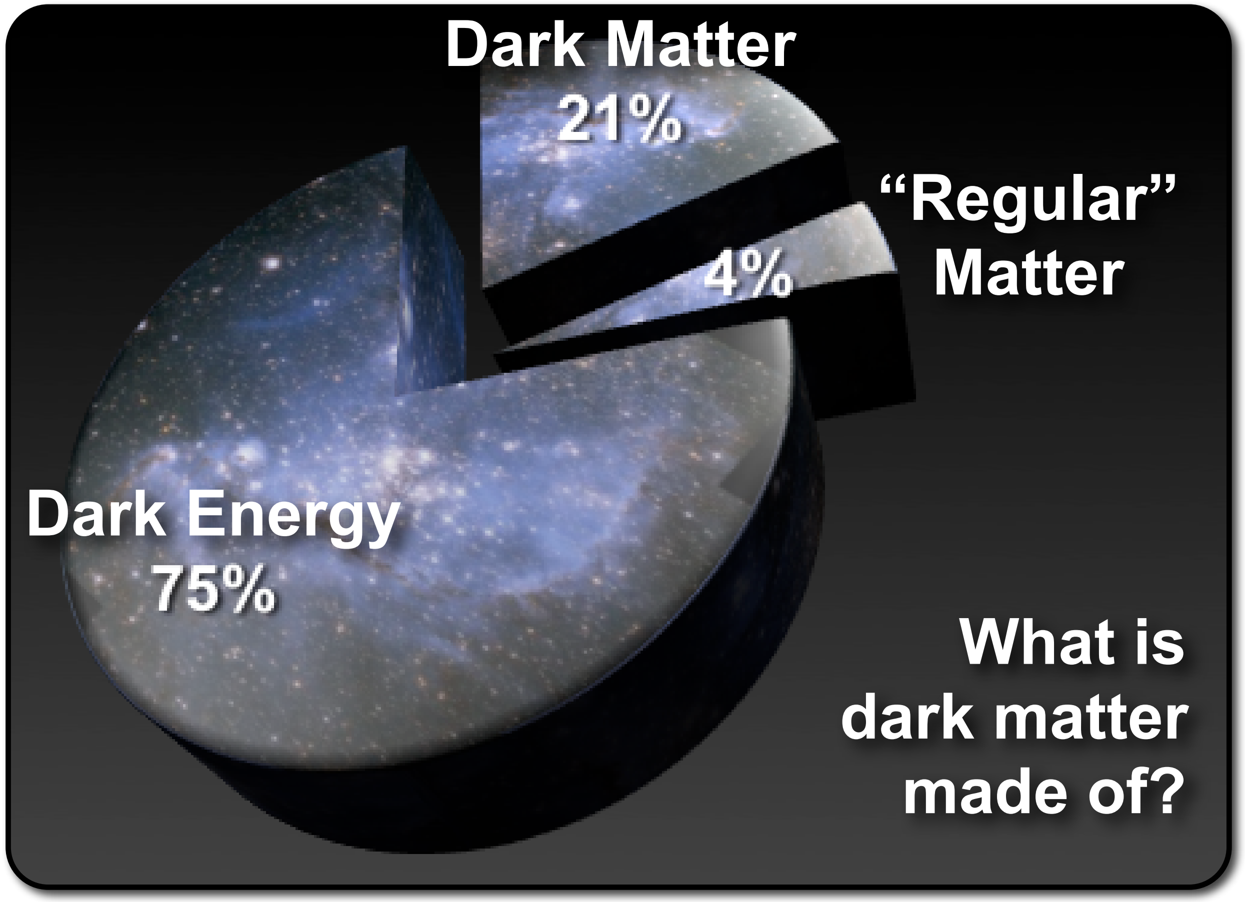
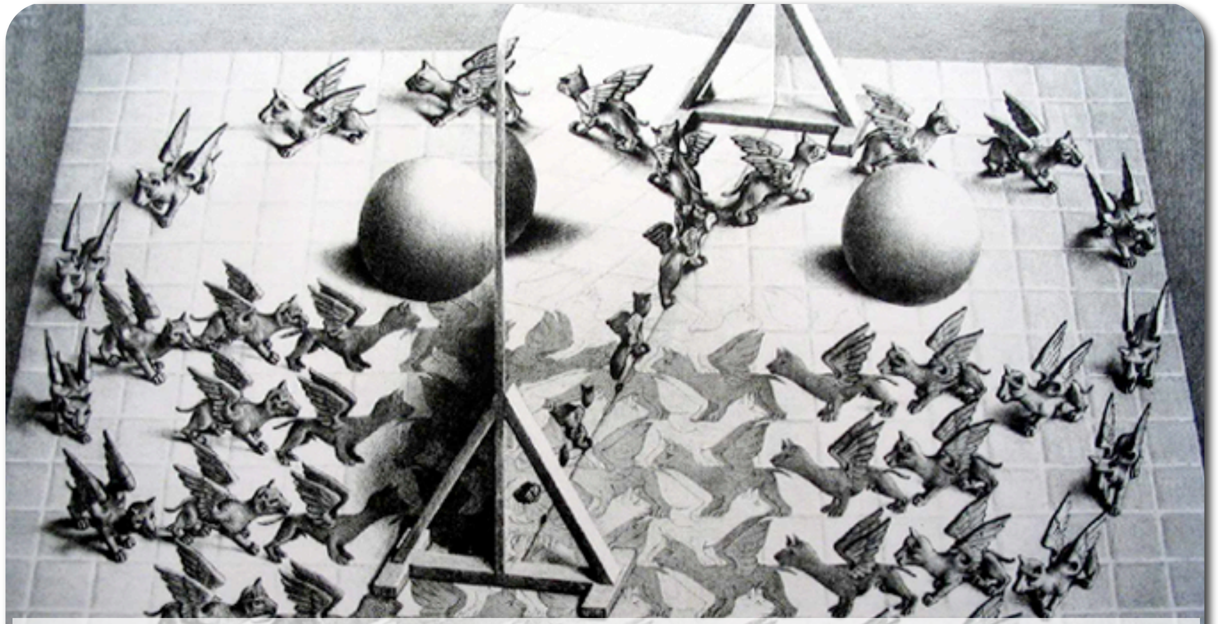
Open Questions 2007

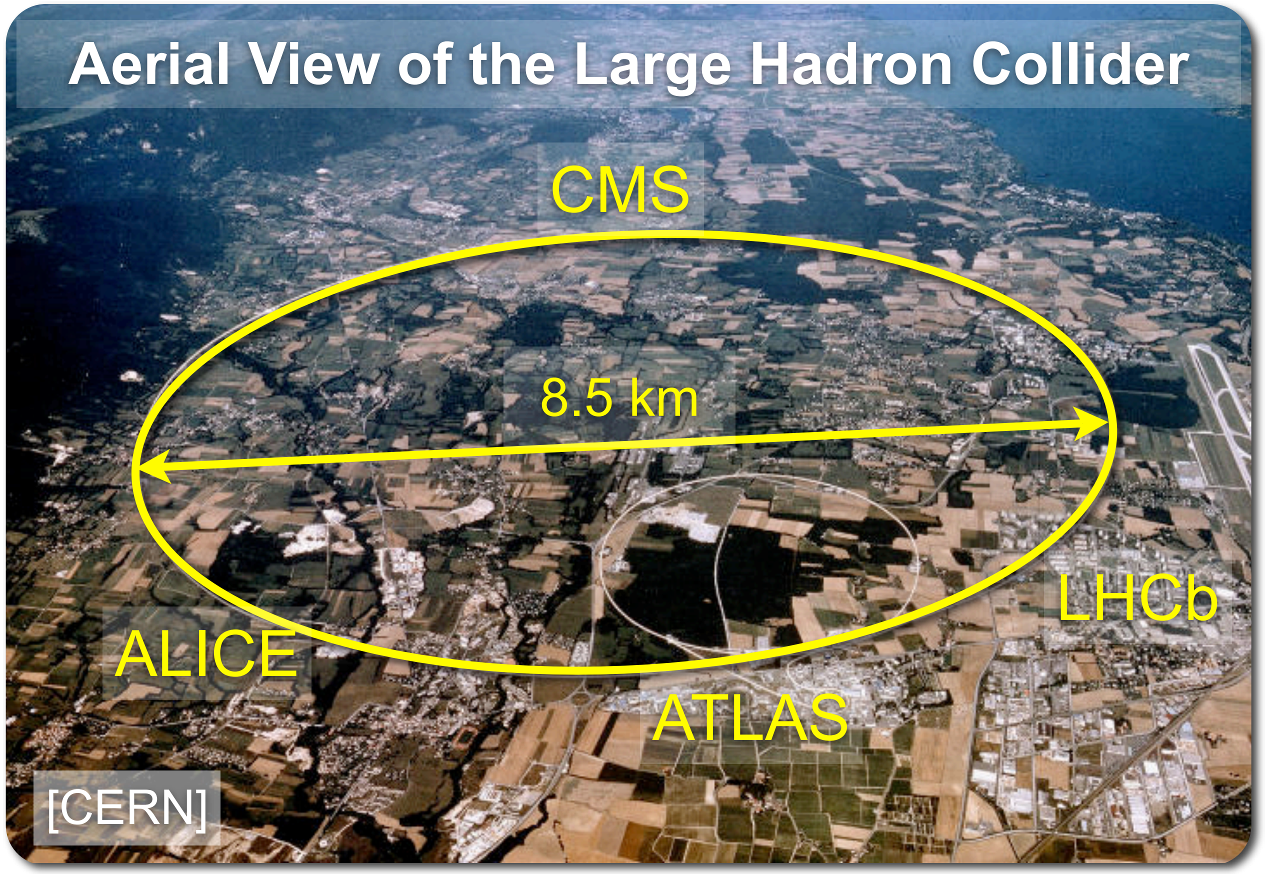
- Ten years ago: standard model of particle physics explains all matter in the universe
- Last missing piece of the standard model: Higgs bosons
- Today: precision cosmology
  - Standard model describes only 4% of the energy in the universe
  - Dark matter and dark energy not explained within standard model
- There must be physics beyond the standard model:
  - Supersymmetry?
  - Strings and extra dimensions?
  - Something unexpected?

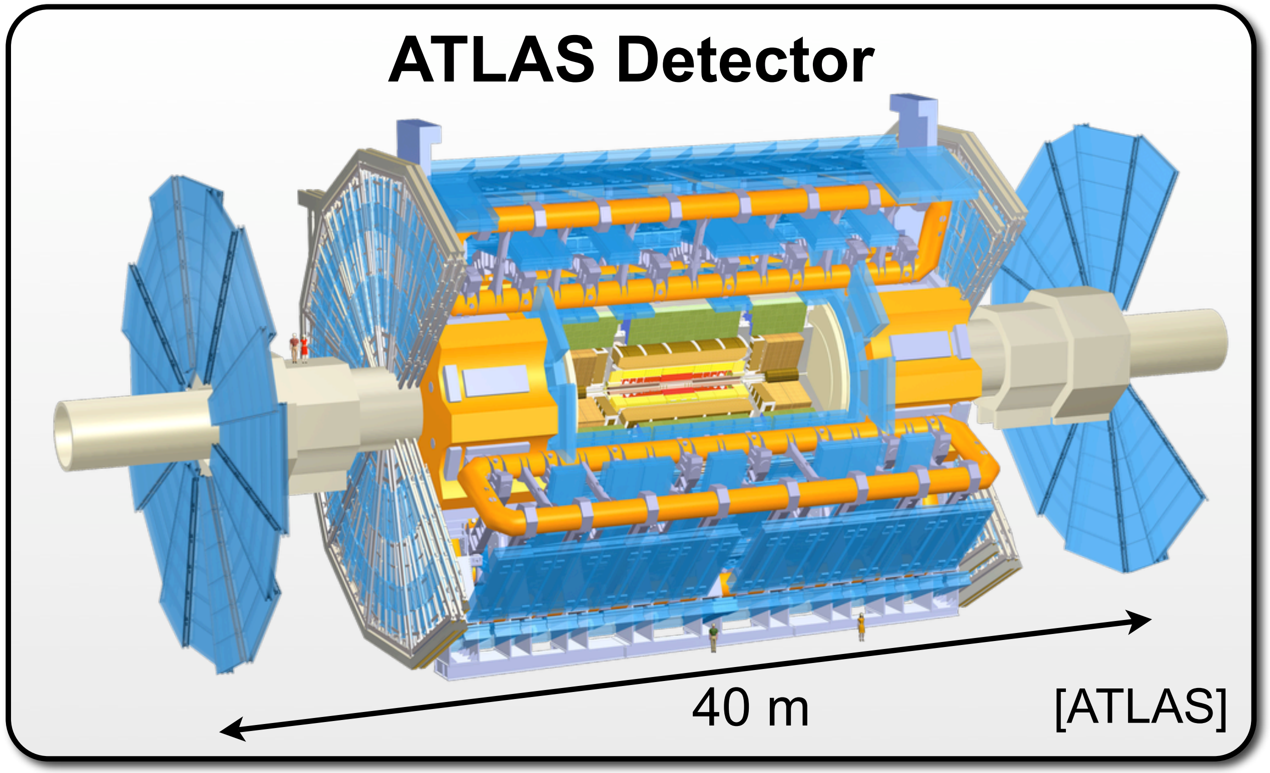



Are there supersymmetric "mirror particles?"

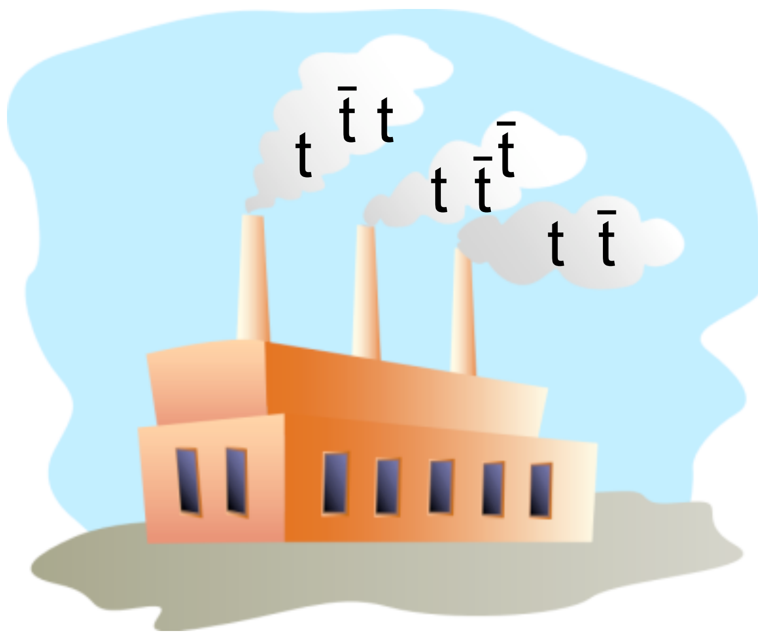
The Next Step: Large Hadron Collider

- Large Hadron Collider (LHC): the new "discovery machine"
  - Startup expected in 2008
  - Proton-proton collisions at unprecedented beam energies: 7 TeV
  - Access to TeV energies ("Terascale") → new era of discoveries
- Four LHC experiments: ATLAS, CMS, ALICE, LHCb
- Challenge: experiments much larger and more complex than Tevatron, e.g.
  - CDF: 1 million channels, 7 m^2 of Si
  - ATLAS: 100 million readout channels
  - CMS: >200 m^2 of silicon

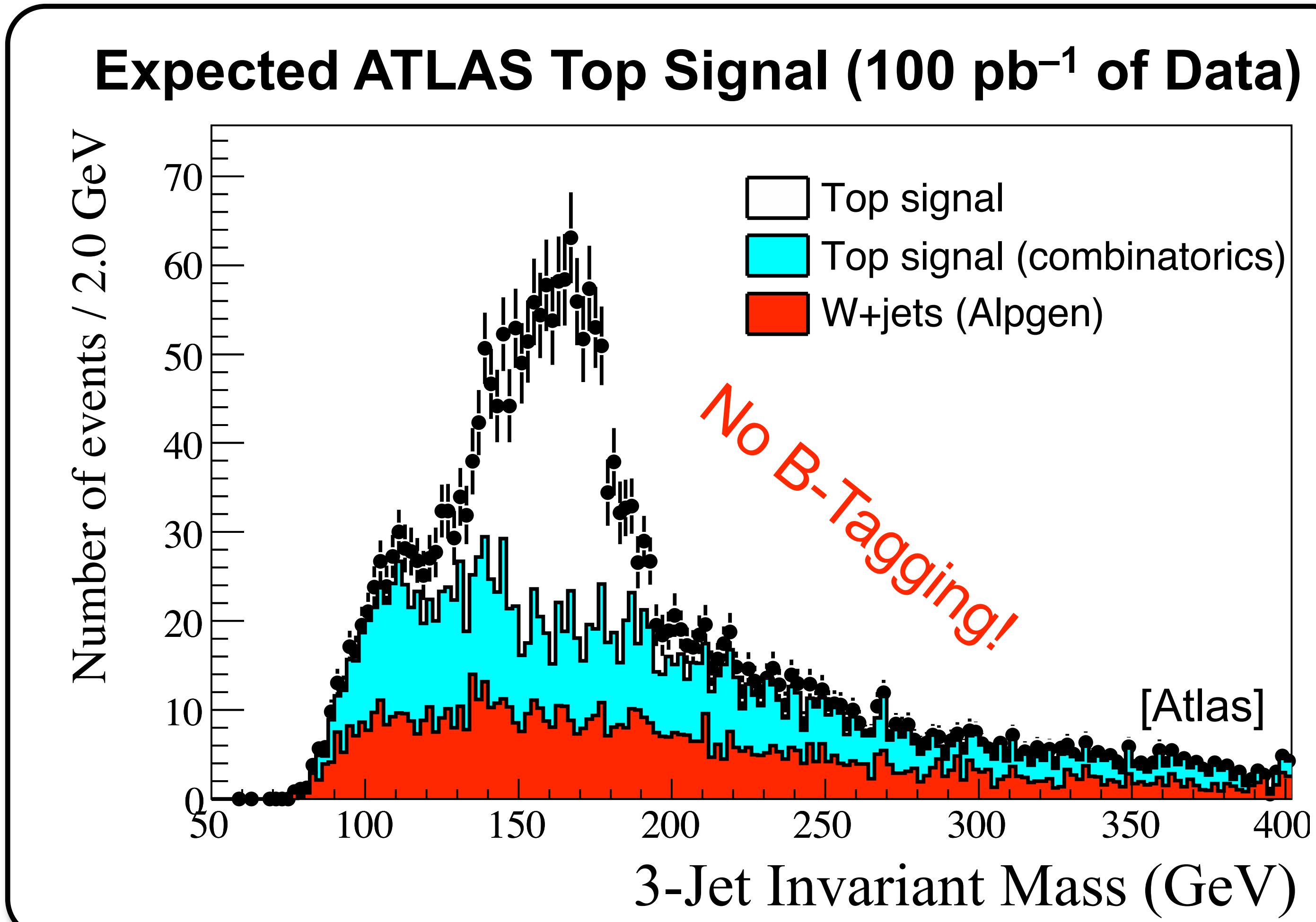




Top as Key to LHC Physics: Startup



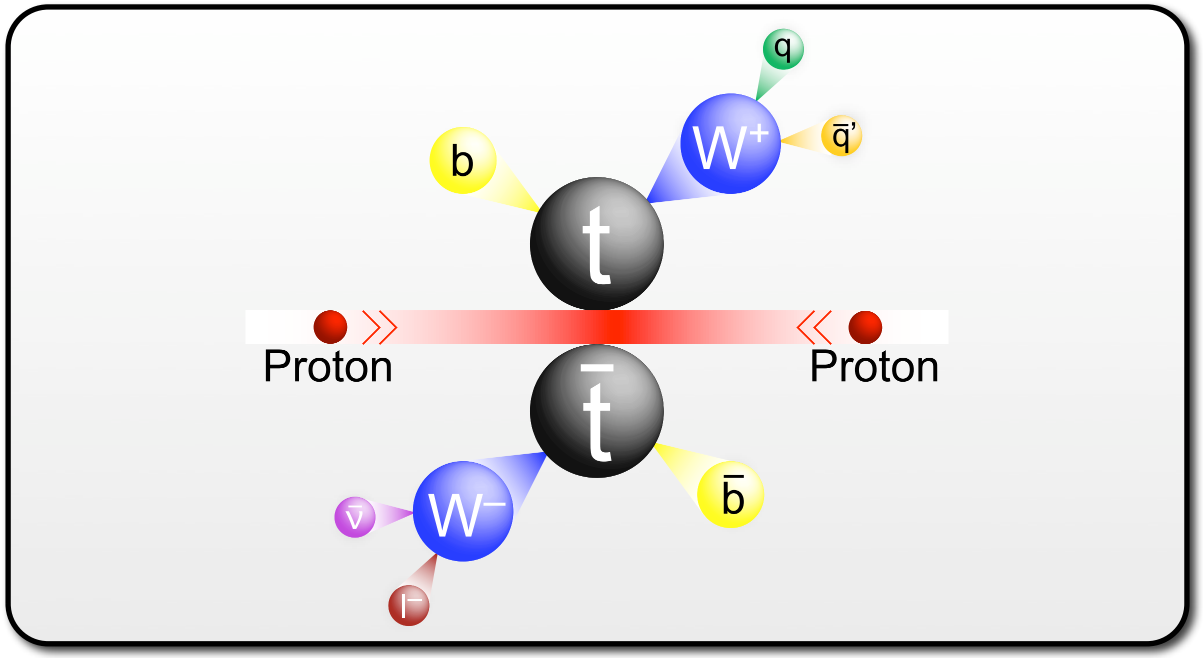
- LHC is a top quark “factory”:
  - Production cross section 100 times higher than at the Tevatron
  - Background processes: only mild increase in cross section

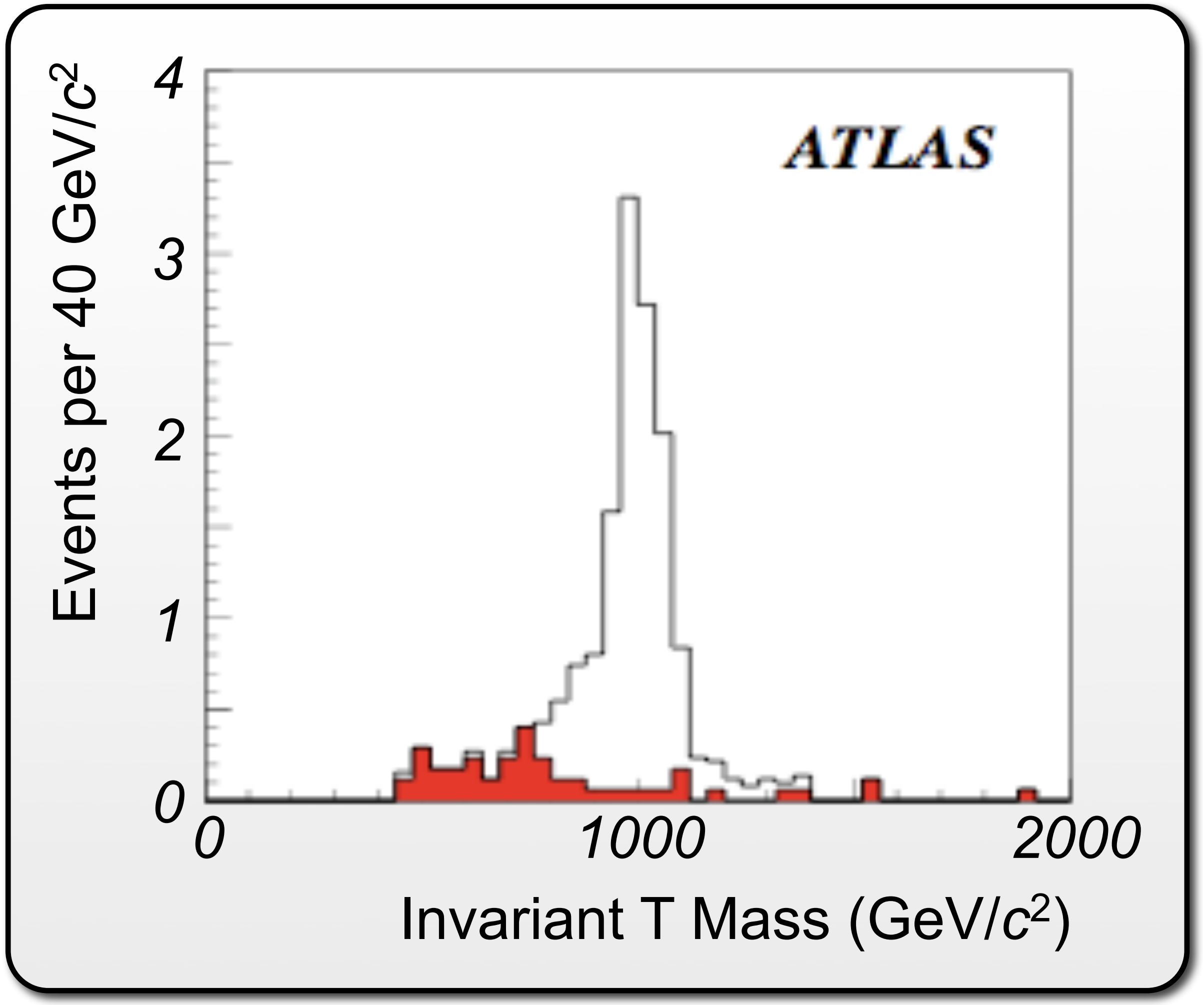


- LHC startup: top physics essential to achieve peak detector performance
  - Top properties well known from Tevatron: mass, decays, …
  - Decay modes probe all detector components: tracking, calorimetery, particle identification

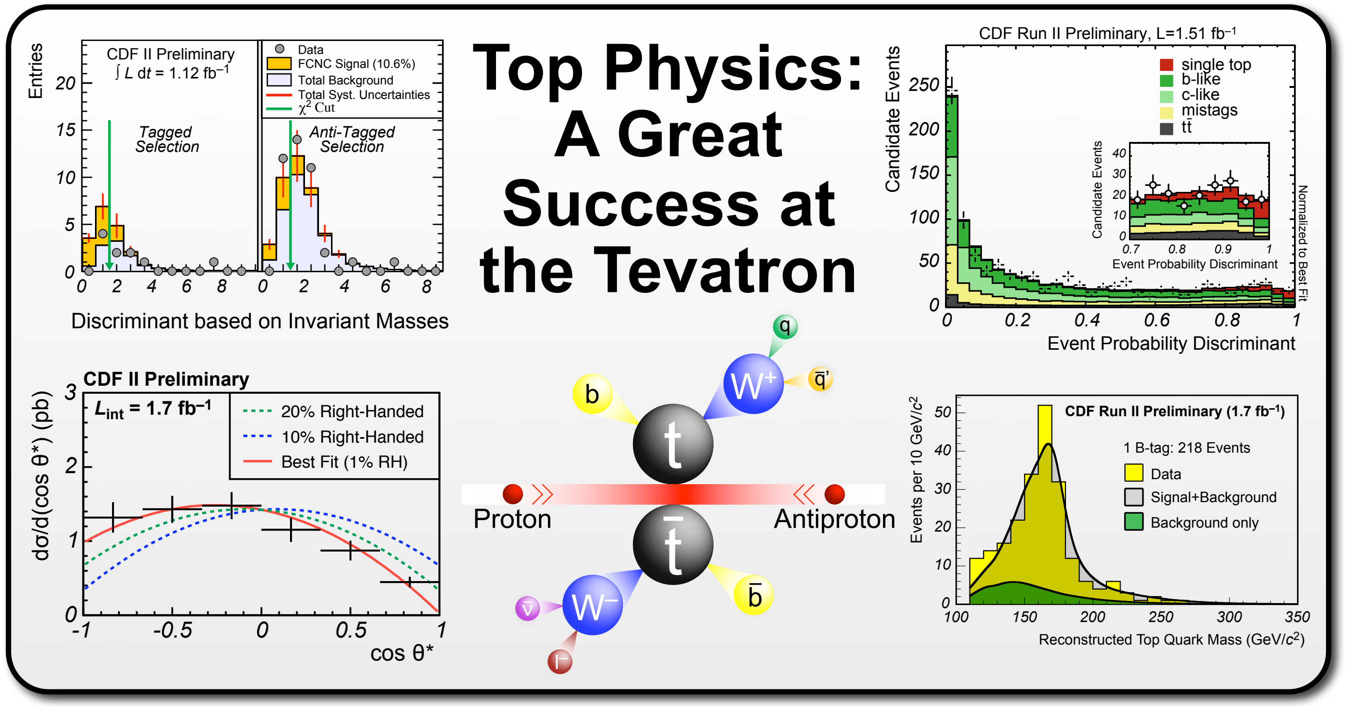
Top as Key to LHC Physics: First Years

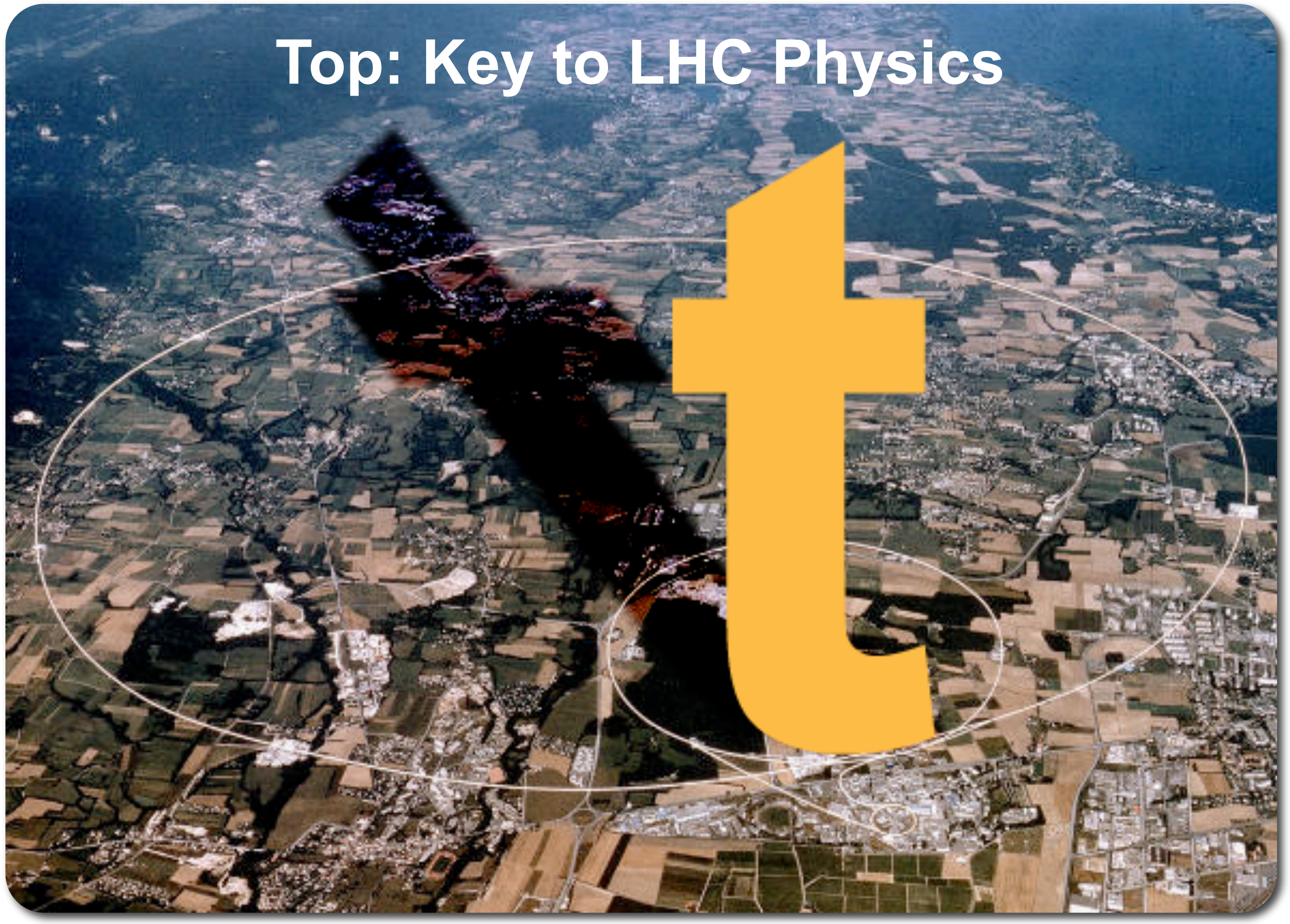
- Rediscovering the top:
  - Precision measurements of mass, cross section, …
  - Try new ideas with large data sets
- Today's signal is tomorrow's background:
  - Top decays: important background for new physics searches
  - If you want to claim discovery, show that you understand top
- Search for new physics with top quarks, e.g.
  - FCNC search: sensitivity expected to improve by 2–3 orders of magnitude
  - Heavy top T quark as predicted e.g. by Little Higgs models
  - Unexpected new physics?





- Top physics at CDF: exciting and very active field of research
  - Tevatron: top discovery in 1995, only place so far to study top
  - Precision measurements, detailed studies of top properties
  - So far: everything consistent with standard model
- Top leads the way to LHC physics
  - Most important calibration signal
  - Precision top physics and searches for new physics





Outlook

[C. Grupen]

Is there anything beyond the Standard Model?