Physics in the Third Generation

Testing the Standard Model at the Energy Frontier

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Outline

- Introduction
- Fundamental Questions
- The Standard Model of Particle Physics
  - The third generation of leptons and quarks
- The Energy Frontier
  - Fermilab Tevatron
  - Dzero Experiment
- Results
  - B Quark and Top Quark Measurements
- Outlook
- Conclusions

Introduction

- The Standard Model of Particle Physics has been very successful in explaining our observations over the past 20 years
  Only recently have there been some real puzzles:
  - Neutrino Oscillations
  - Large top quark mass
  - Dark Matter, Dark Energy
- Run II at the Tevatron is well on its way
  - Physics at the energy frontier
- We are exploring uncharted territory
  - Top Physics as precision measurements
    - Top mass measurements have large impact on Higgs expectation

Fundamental Questions

What do we want to know?

Daß ich erkenne, was die Welt
Im Innersten zusammenhält

So that I may perceive whatever holds
The world together in its inmost folds

Faust, Johann Wolfgang von Goethe

Relax.

What is Mind?

No matter.

What is Matter?

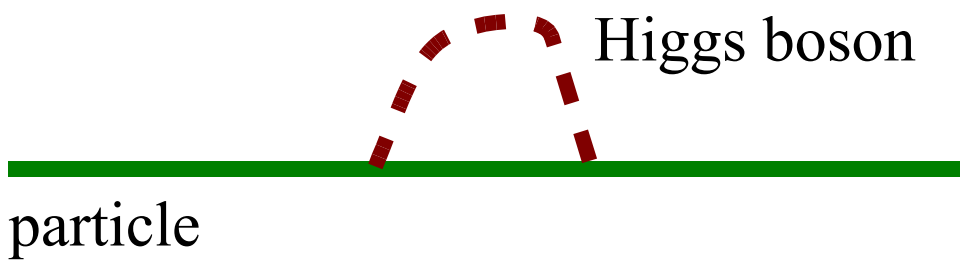
Never mind!

Homer J Simpson

Particle Physics Questions and Challenges

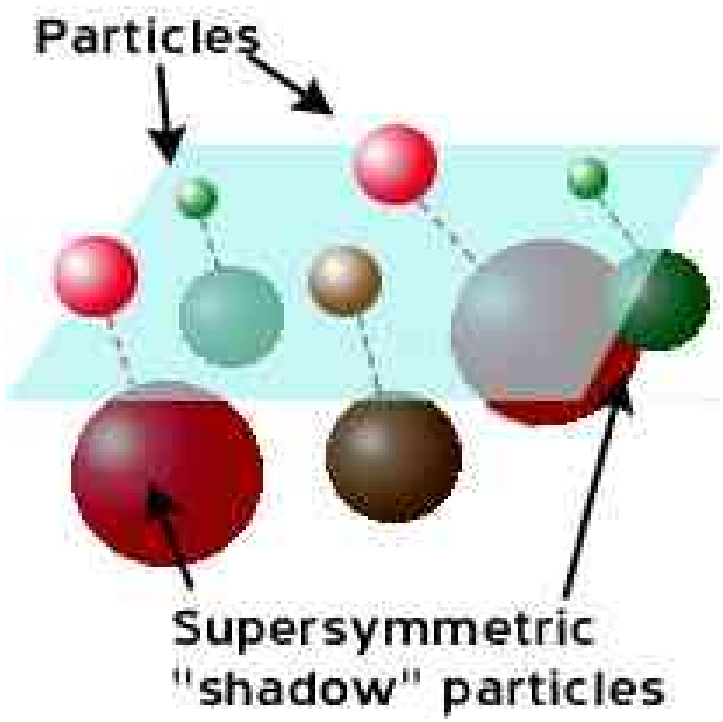
- What is the origin of mass?
  - What is the origin of electroweak symmetry breaking?
  - Is it really the Higgs Mechanism?
    - Particles acquire mass through interactions with the Higgs boson
  - Does the Higgs boson exist?

Feynman diagram for
Higgs Boson Interactions



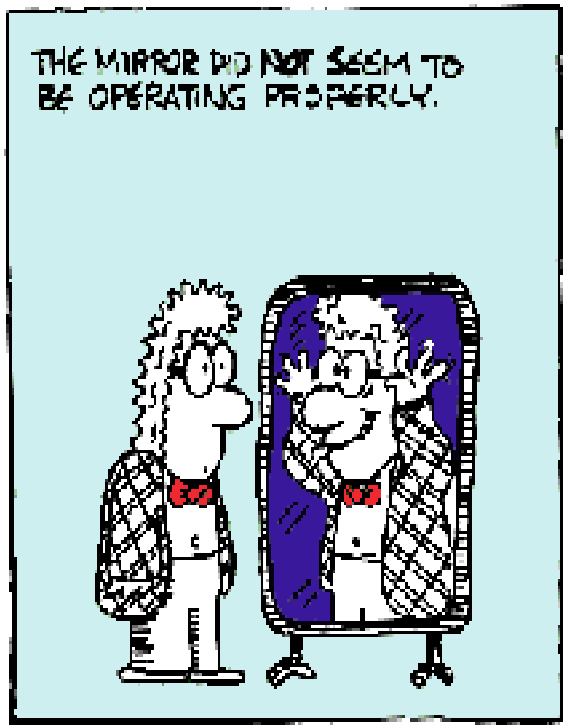
Particle Physics Questions and Challenges

- What is the origin of mass?
  - What is the origin of electroweak symmetry breaking?
- Is there an underlying symmetry?
  - Supersymmetry? – String Theory?
  - Extra spatial dimensions?
  - Technicolor?



Particle Physics Questions and Challenges

- What is the origin of mass?
  What is the origin of electroweak symmetry breaking?
  - Is it the Higgs Mechanism? Does the Higgs boson exist?
- Is there an underlying symmetry?
  - Supersymmetry? – String Theory?
  - Extra spatial dimensions?
  - Technicolor?
- The Cosmological Connection:
  - Why is there more matter in the universe than anti-matter?
    - Why does anti-matter not behave like matter?
  - What is dark matter?
  - What is dark energy?



Experimental Particle Physics

Not asking general questions and receiving limited answers, but asking limited questions and finding general answers!

Io stimo più il trovar un vero, benchè di cosa leggiera, ch'l disputar lungamente delle massime questioni senza conseguir verità nissuna.

Galileo

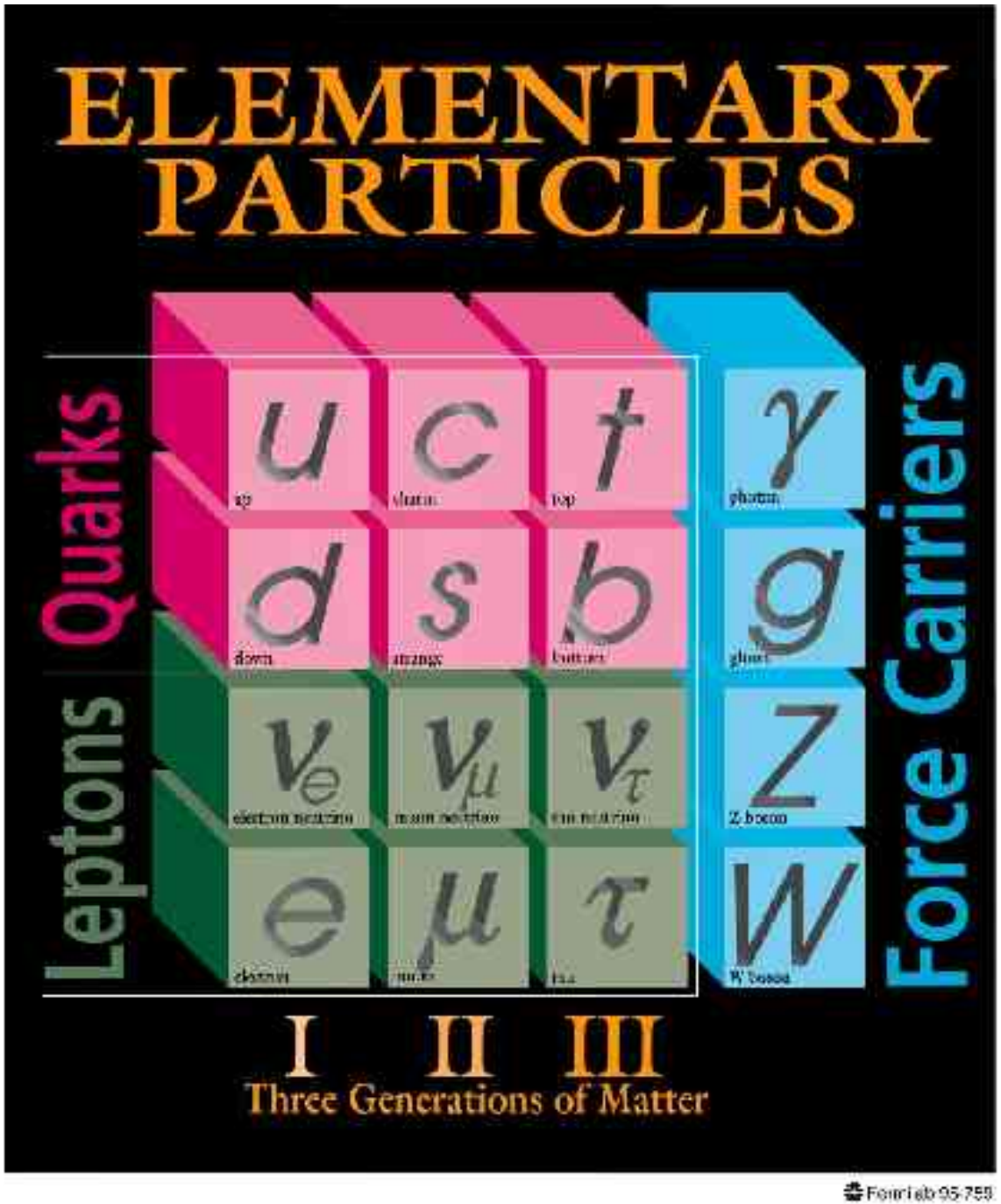
This talk will be about those limited questions and how we go about answering them

The minute particular

State of the Art

What do we know already?

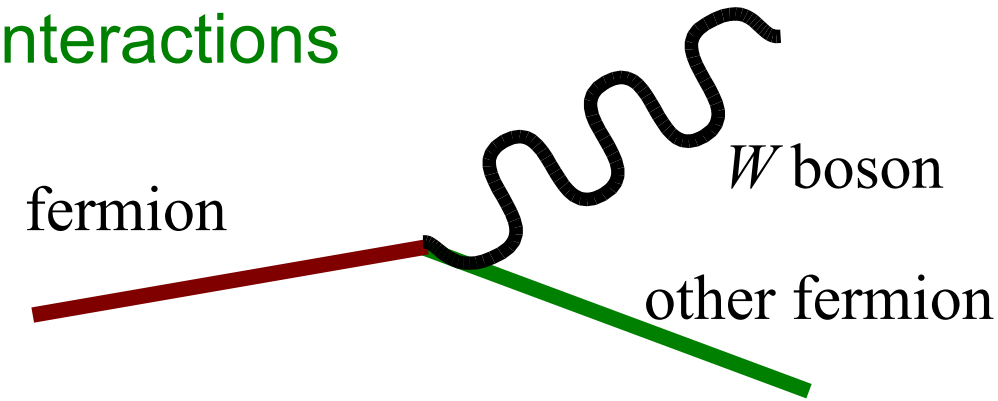
The Standard Model of Particle Physics



- Three generations of spin-½ fermions
- They interact through the exchange of spin-1 bosons force carriers
- $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge structure
- Plus Antimatter: An anti-particle for each particle
- Plus the Higgs boson giving mass to particles

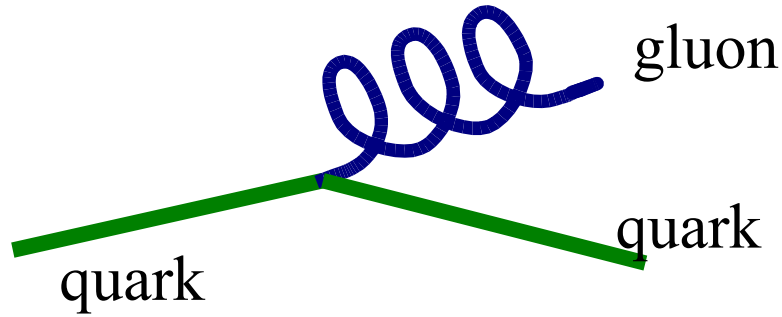
Interactions in the Standard Model

Charged Current Electroweak Interactions



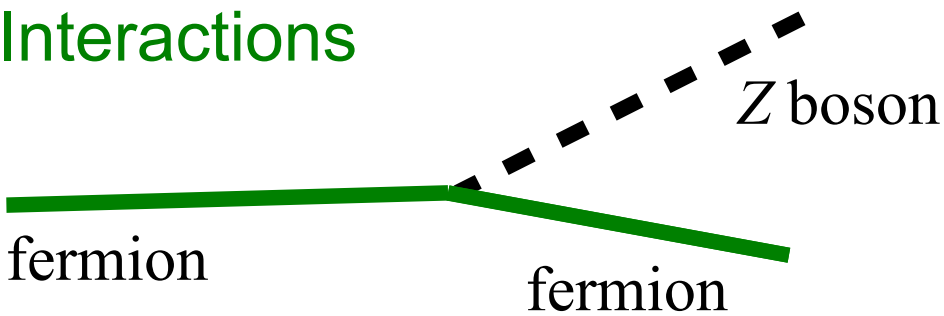
- Responsible for nuclear beta decay

Strong Interactions



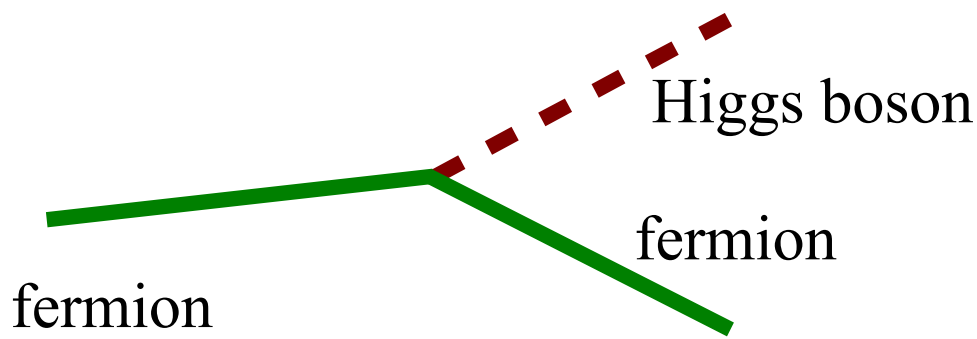
- Holds atomic nuclei together

Neutral Current Electroweak Interactions



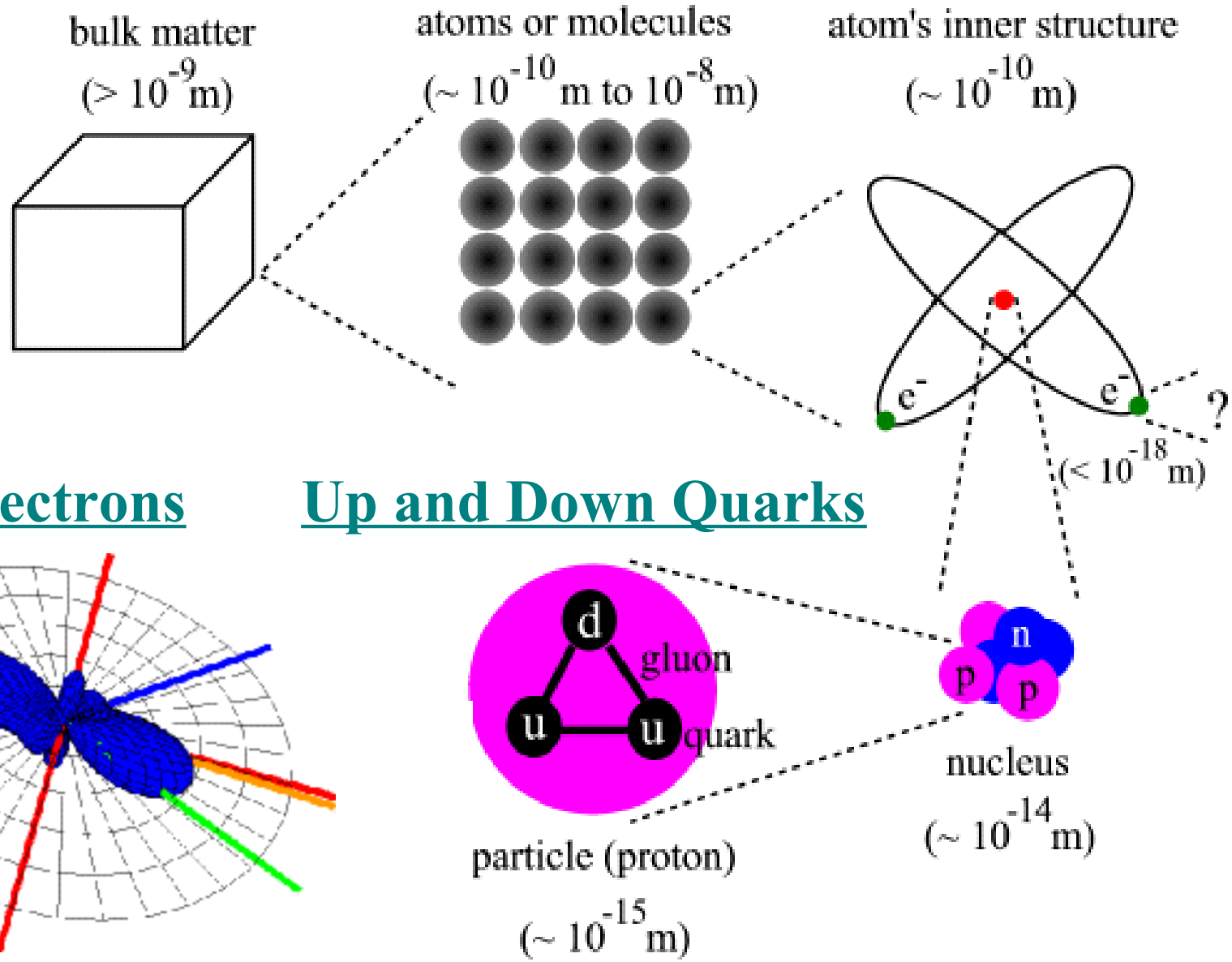
- and electro-magnetism

Yukawa Coupling



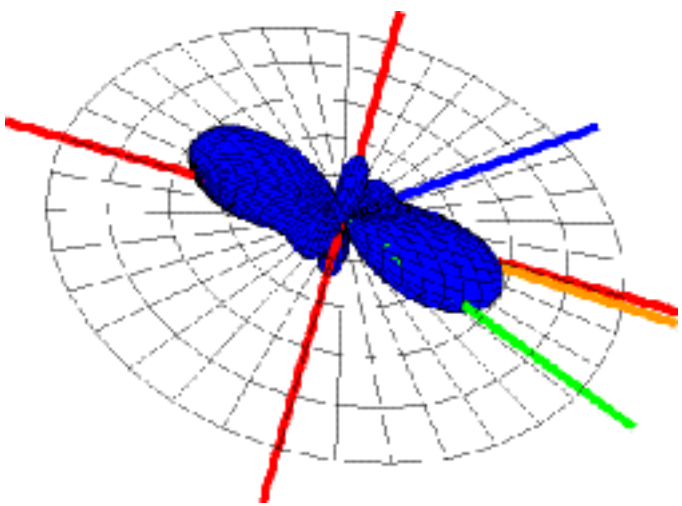
- Gives masses to particles

What matter is made of: The 1st Generation



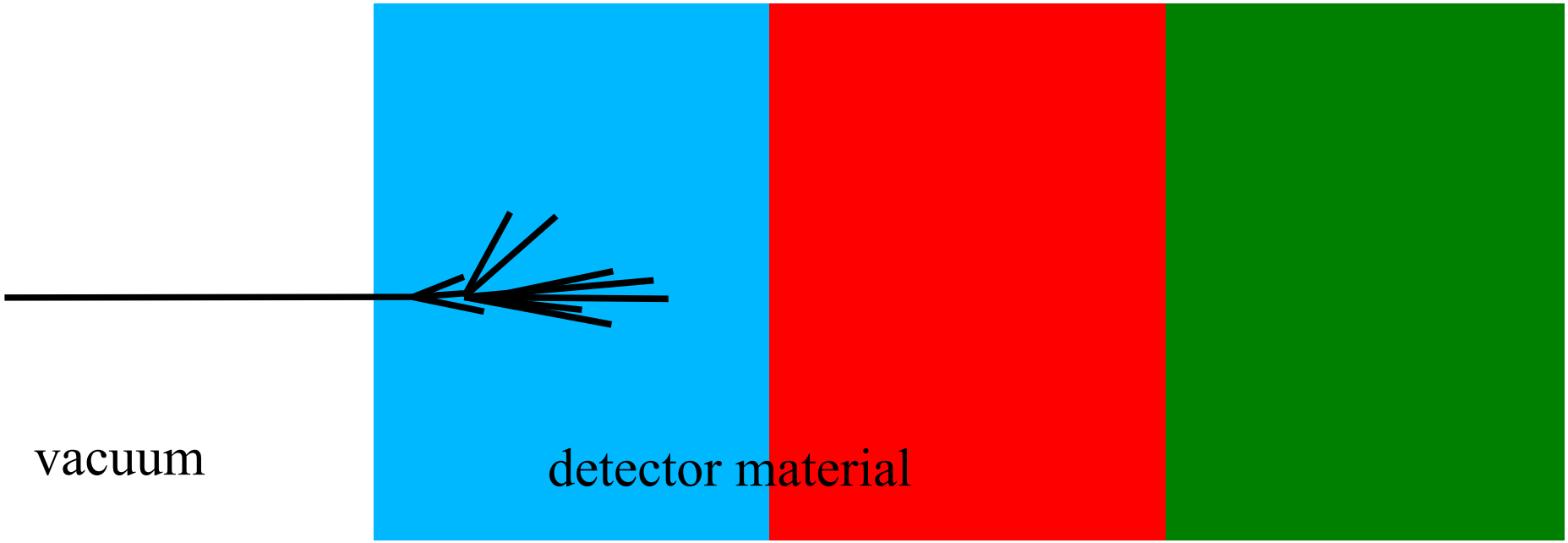
Electrons

Up and Down Quarks



How a High-Energy Experimentalist sees the 1st Generation Fermions

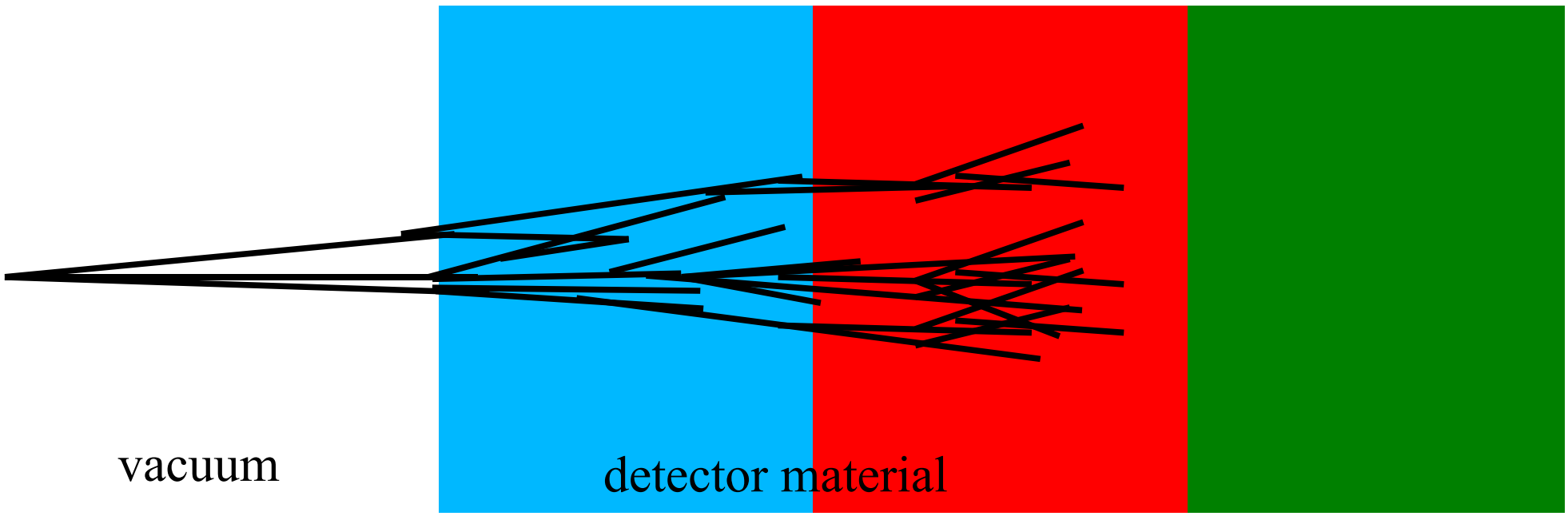
- Electrons:



  - Stable, charged (→ deflected in a magnetic field)
  - Produces electromagnetic shower in matter
    - Synchroton radiation of photons which convert to electron-positron pairs which emit synchroton radiation which.....

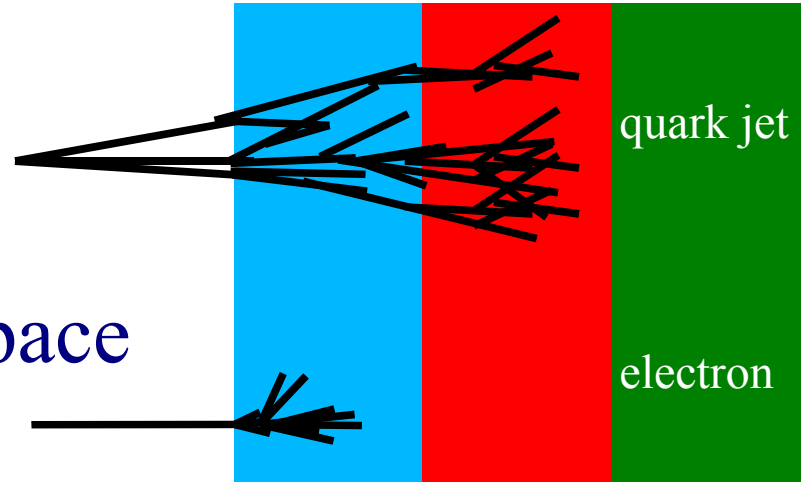
How a High-Energy Experimentalist sees the 1st Generation Fermions

- Up or Down Quarks:



  - Free quarks don't exist (quark confinement)
    - Quarks produced in interactions hadronize to mesons or hadrons
    - These typically travel in the same direction→ hadronic jet
  - Jet produces a hadronic shower through interactions with nuclei

How a High-Energy Experimentalist sees the 1st Generation Fermions

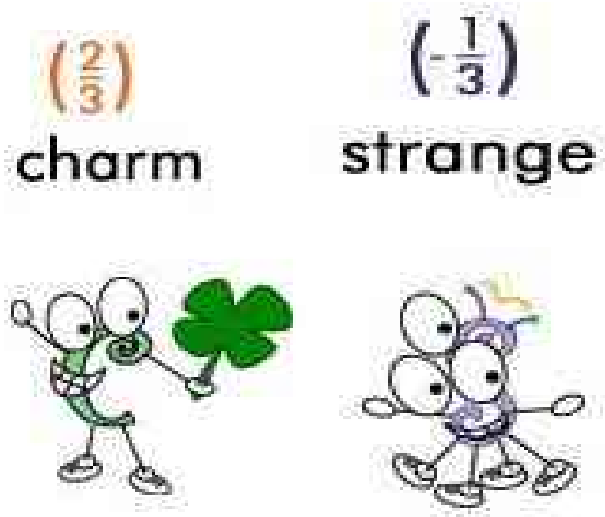


- Particles at high energy
- Particles propagating in free space
- Particles interacting with matter
  - In a detector

Use high-energy electrons and quarks as experimental tools

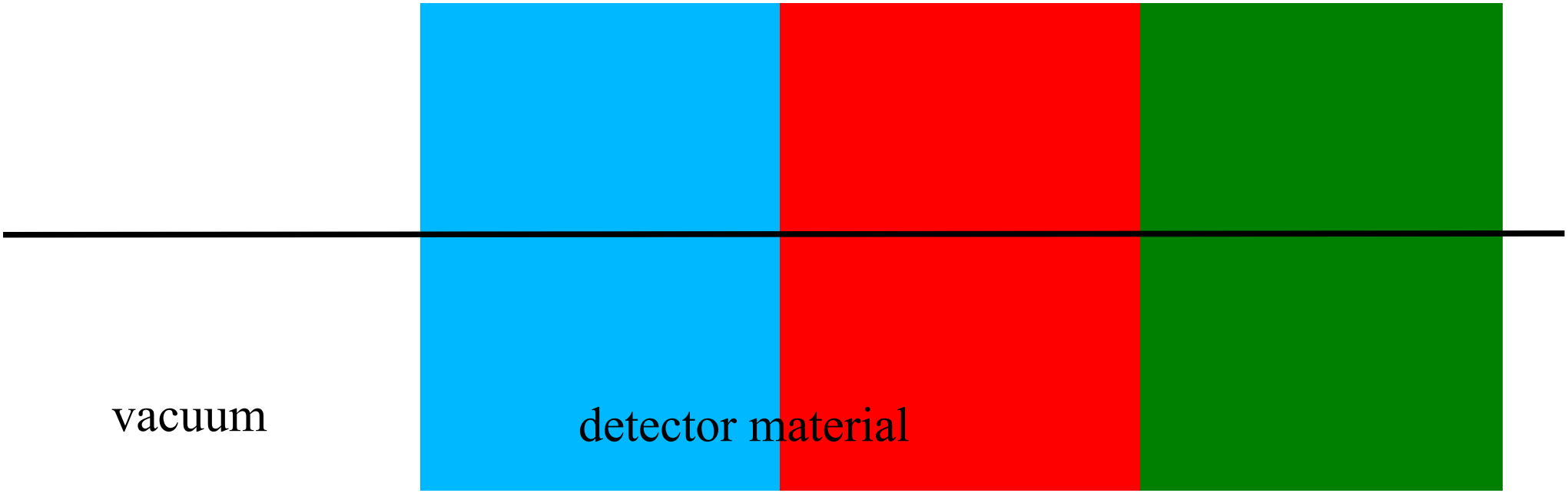
The 2nd Generation

- Another set of leptons and quarks
  - Muon and muon neutrino
  - Strange and charm quarks
- Duplication of 1st generation, but at higher mass
- Subject of detailed measurements
    - Very High Statistics Precision experiments to probe details of the Standard Model
  - Muon magnetic moment (g-2)
  - CP-violation in the Kaon sector



How most High-Energy Experimentalists see the 2nd Generation Fermions

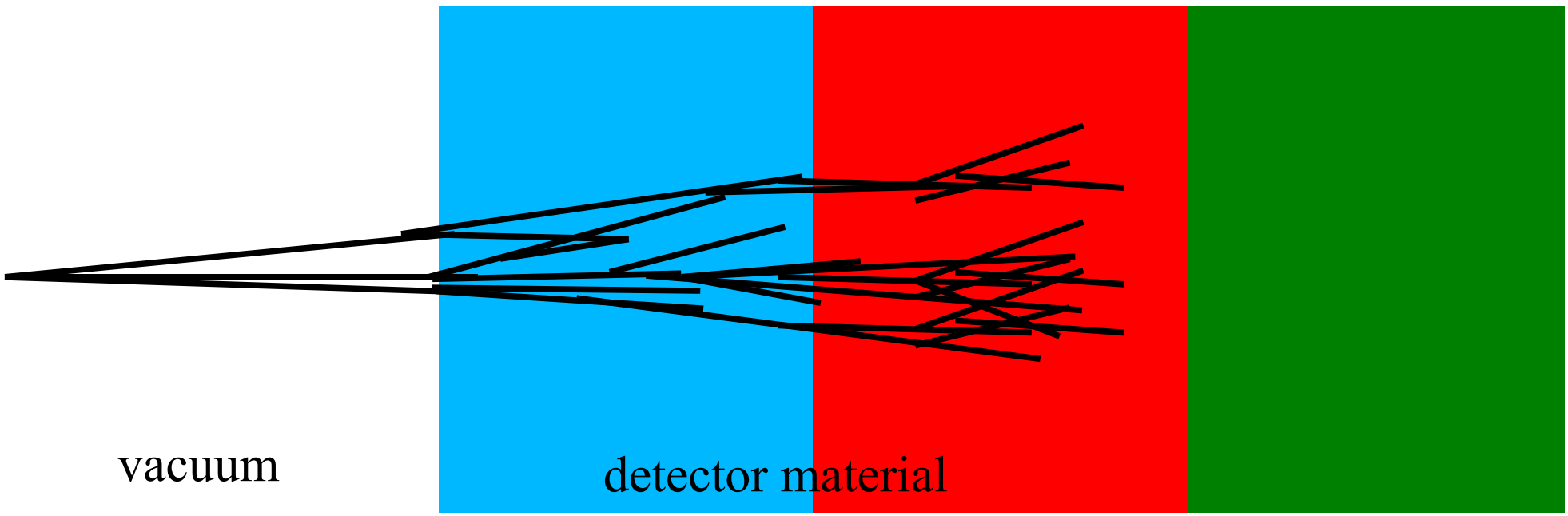
- Muon:



  - Muons do not shower as they pass through matter
    - They are charged, thus they loose energy through ionizing atoms as they pass through: Trail of ionization

How most High-Energy Experimentalists see the 2nd Generation Fermions

- Strange or Charm Quarks:



  - Hadronic jet that produces a hadronic shower
  - Strange and charm quarks look just like up or down quarks

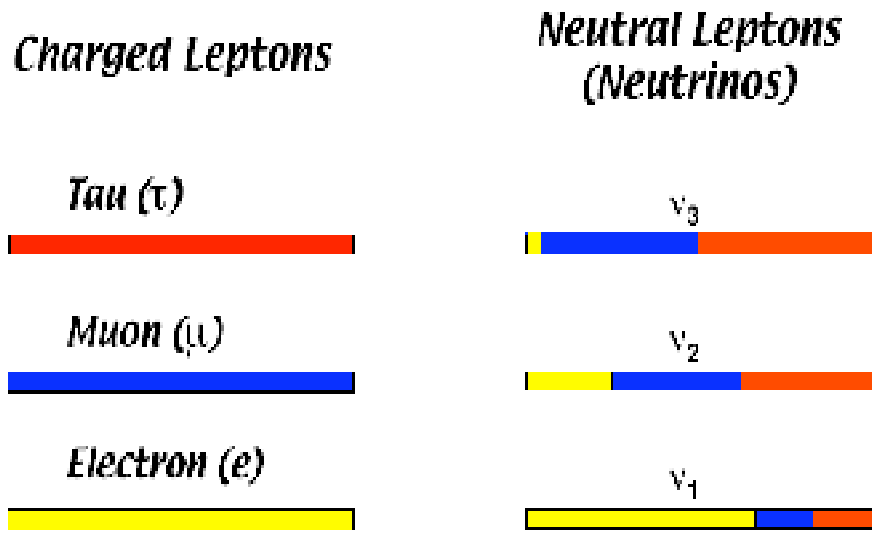
The 3rd Generation

- Another set of leptons and quarks
  - Tau and tau neutrino
  - Bottom and top quarks
- Duplication of 1st generation, but at much higher mass
- Detailed investigations are just beginning

Focus of this talk

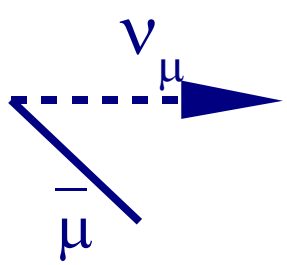
The Third Generation of Leptons: Neutrino Oscillations

- Neutrino mass Eigenstates are not weak interaction Eigenstates

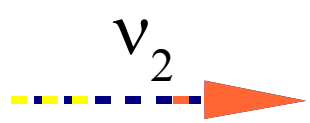


- Consequence: neutrino oscillations

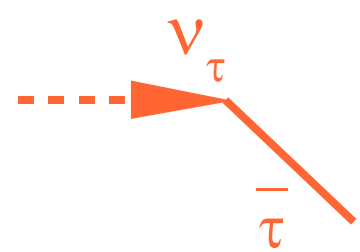
Production



Propagation

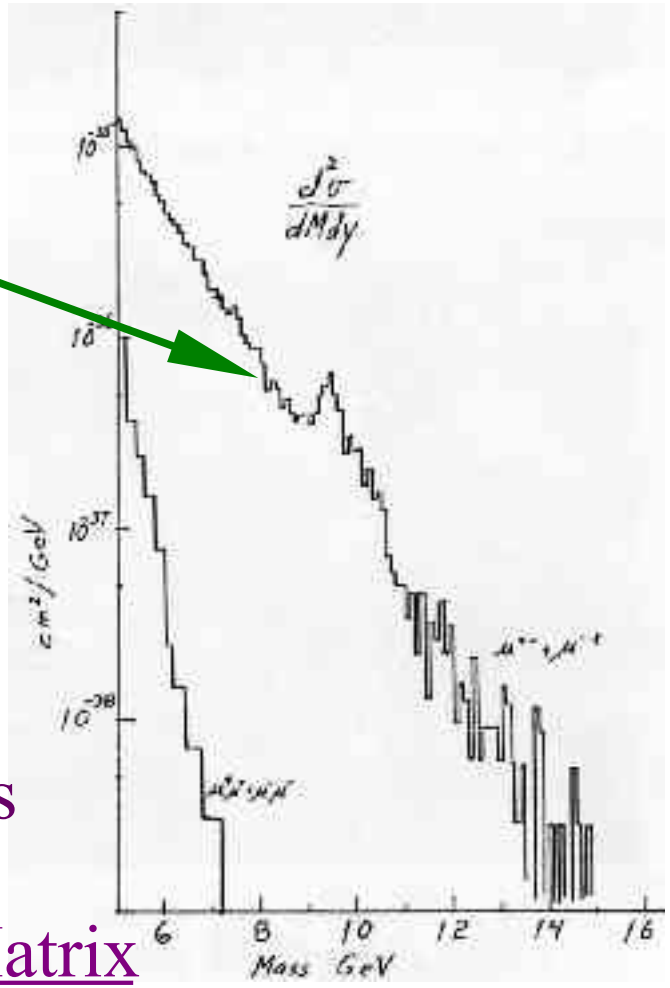


Interaction

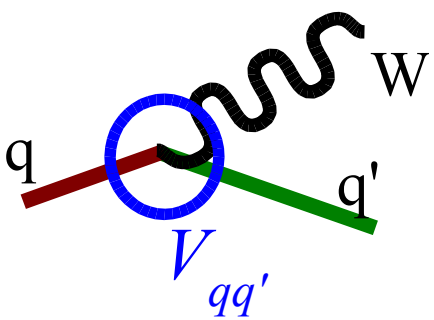


The Third Generation of Quarks: Bottom Quark

- Discovered 1977 at Fermilab
- Currently being studied extensively at e+e- colliders
  - B-Factories
    study decay of B^0 mesons
  - Detailed measurement of quark electroweak charged current Interactions
    - Complex phase of CKM Matrix



CKM Matrix

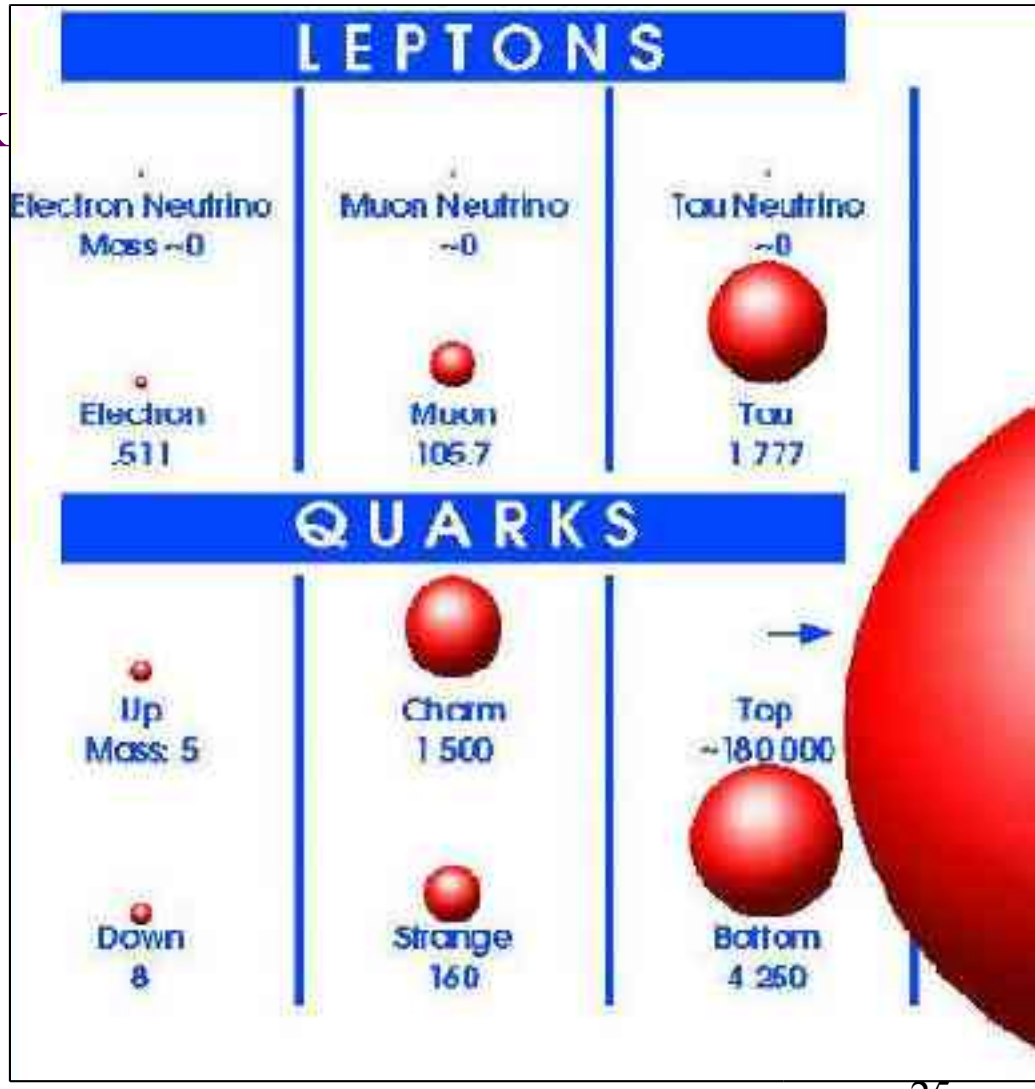


$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

The Top Quark

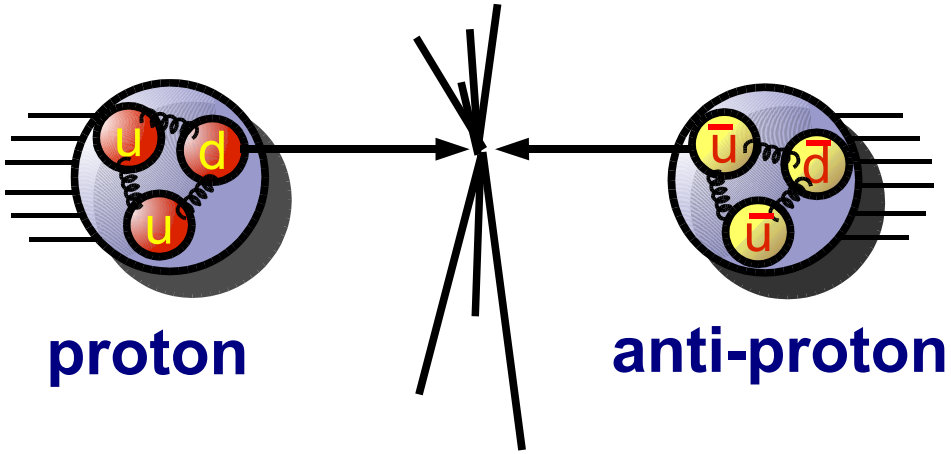
King of Fermions

- Discovered in 1995 at Fermilab by CDF and DØ
- Heaviest of all fermions
  - 40 times heavier than b quark
- Couples strongly to Higgs boson
  - Study electroweak symmetry breaking
- Only quark that decays before it hadronized
  - Clean laboratory to study quark properties



Experimental Setup: The Energy Frontier

Probe Physics at small distance scales by colliding particles at high energy



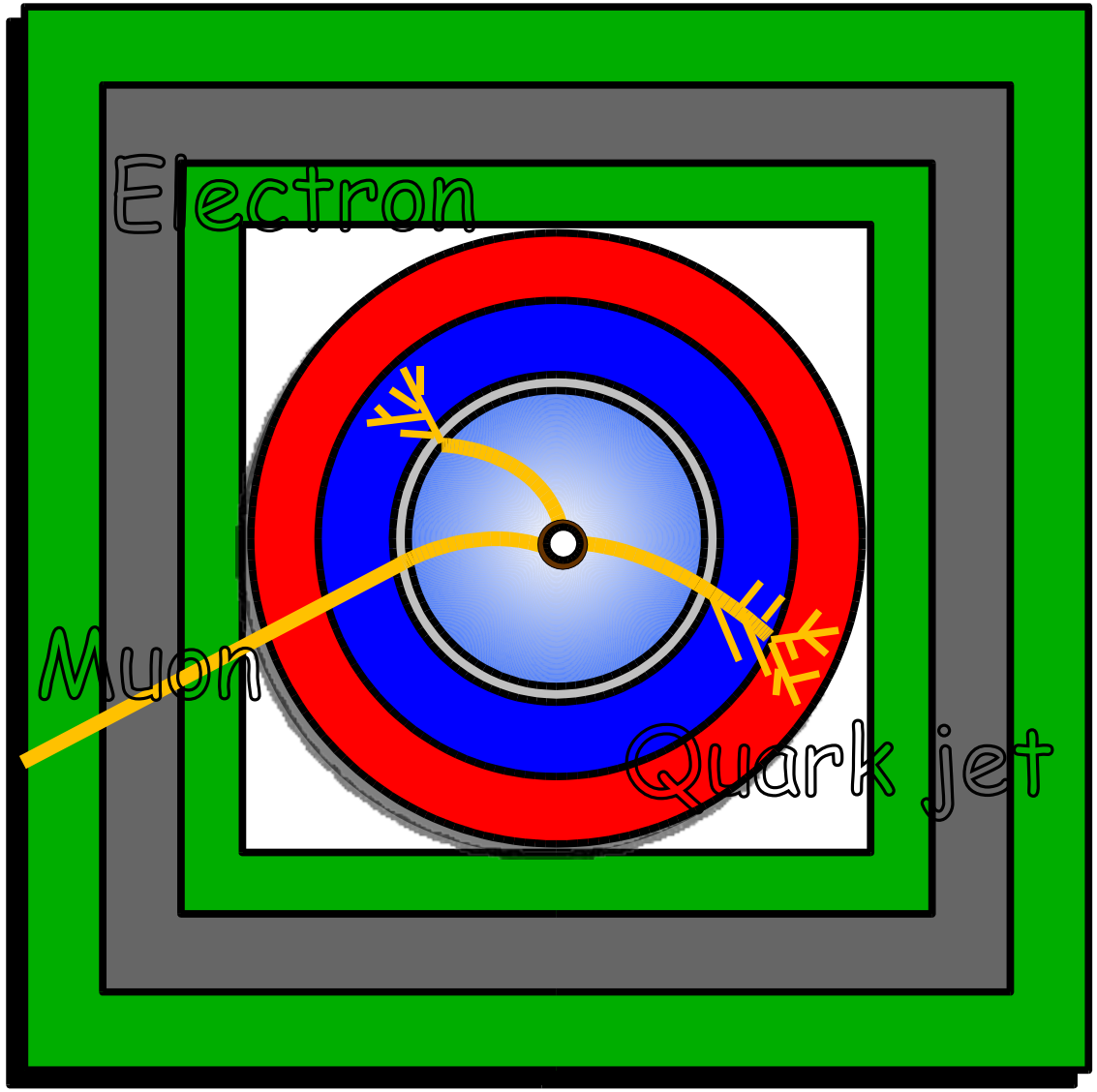
Experimental Setup: Fermilab Tevatron in Run II

Experimental Setup: Fermilab Tevatron in Run II

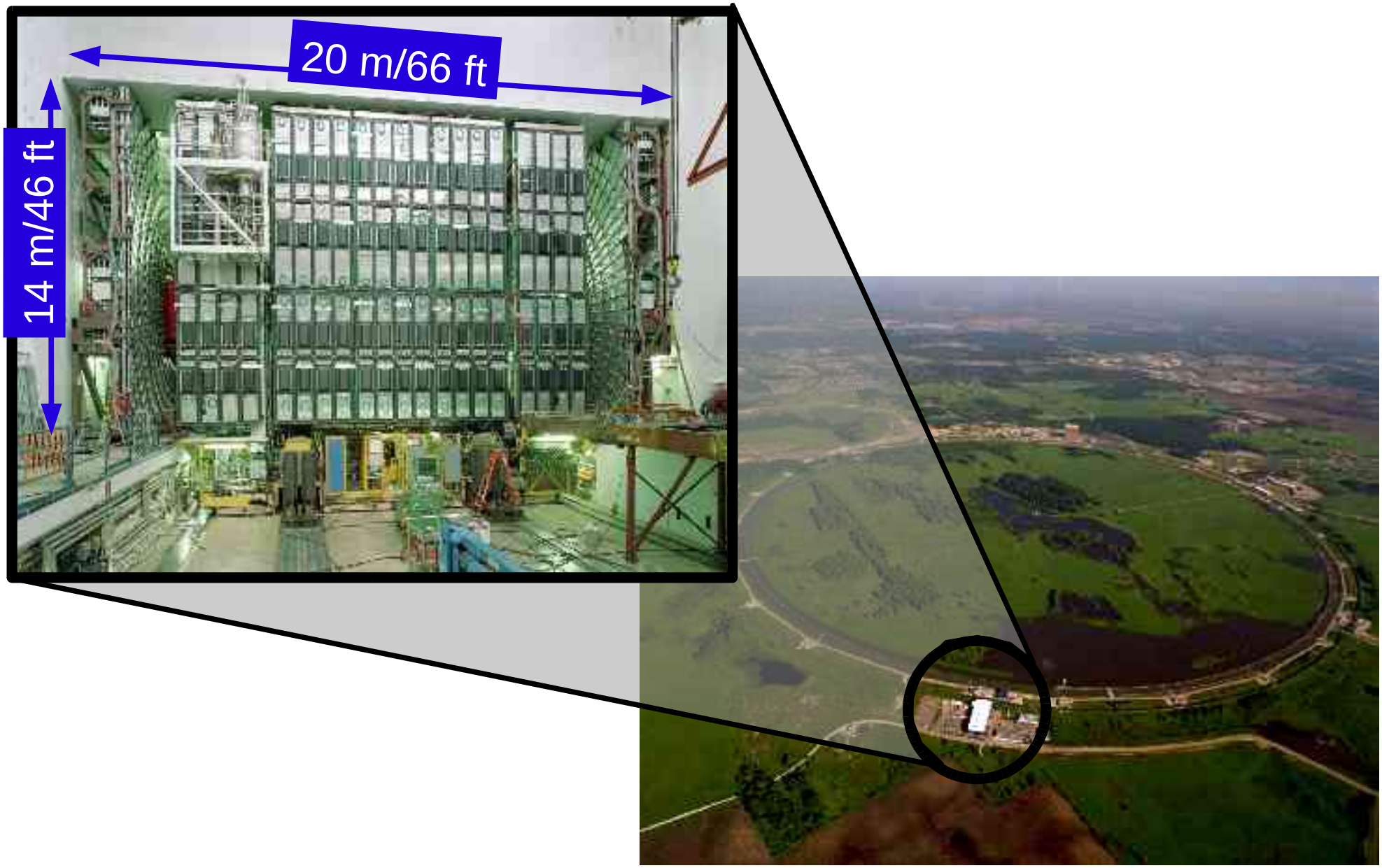
- **Proton-Antiproton Collider**
- **CM Energy 1.96TeV**
  → ***Energy Frontier***
- **One interaction every 396ns**
  → ***Interaction Rate Frontier***

Experimental Setup: Detector Configuration

- Beam pipe
- Tracking detector
- Magnet
- EM calorimeter
- Hadronic calorimeter
- Muon detectors
- Magnet



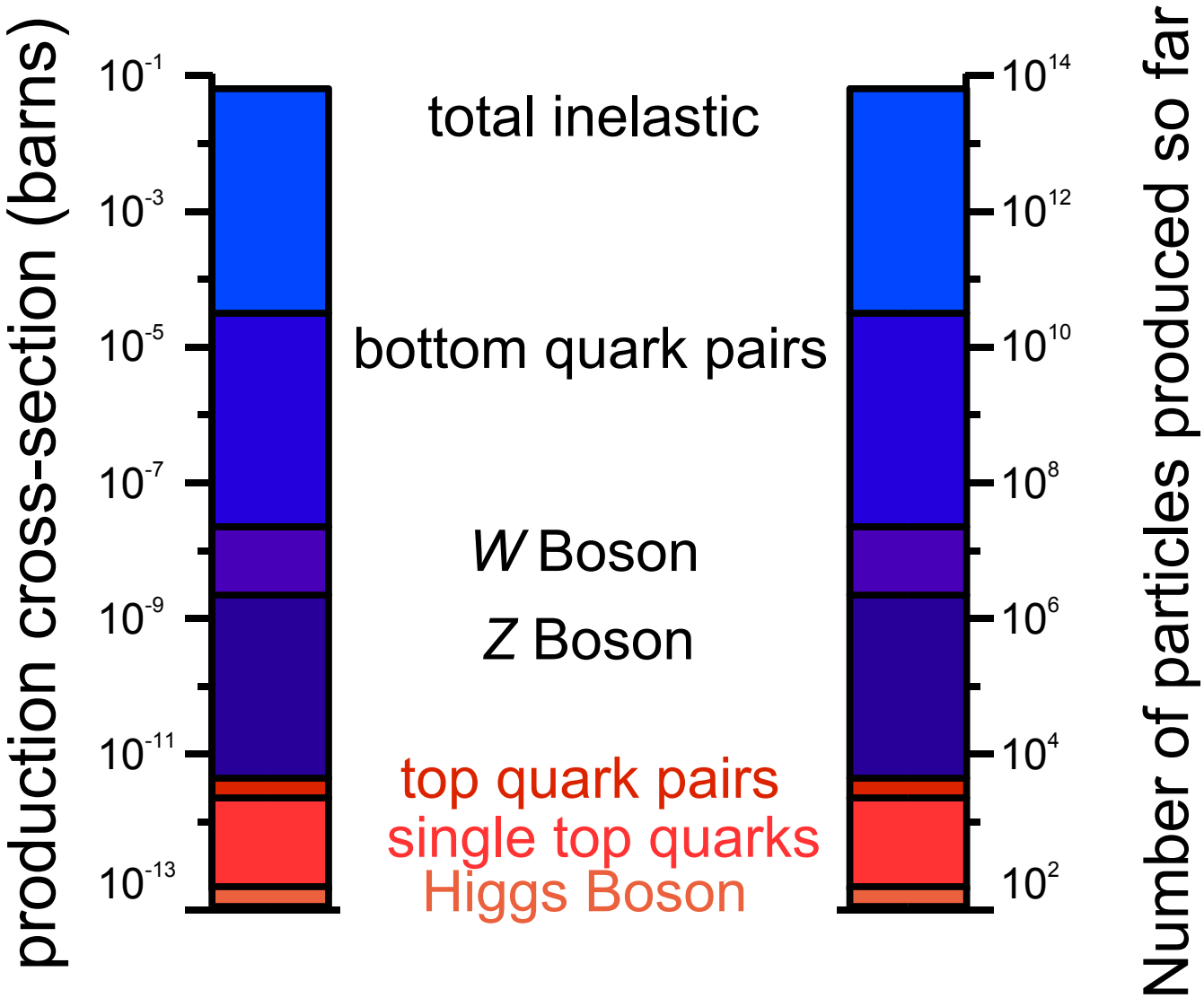
Experimental Apparatus: DØ Detector



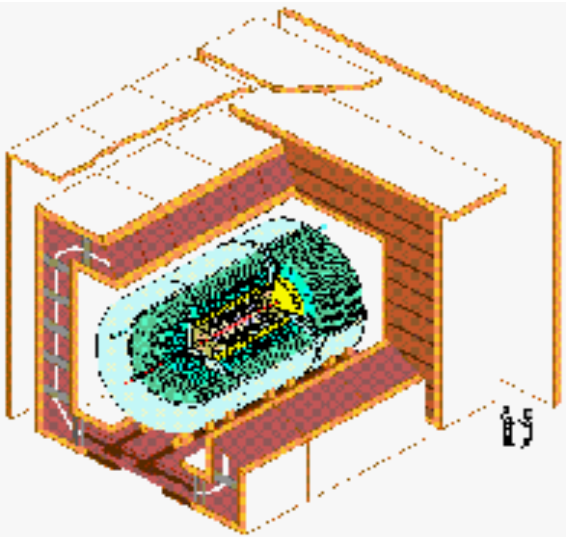
Experimenters: The DØ Collaboration

- **19 countries**
- **80 institutions**
- **670 physicists**

Particle Production at the Tevatron



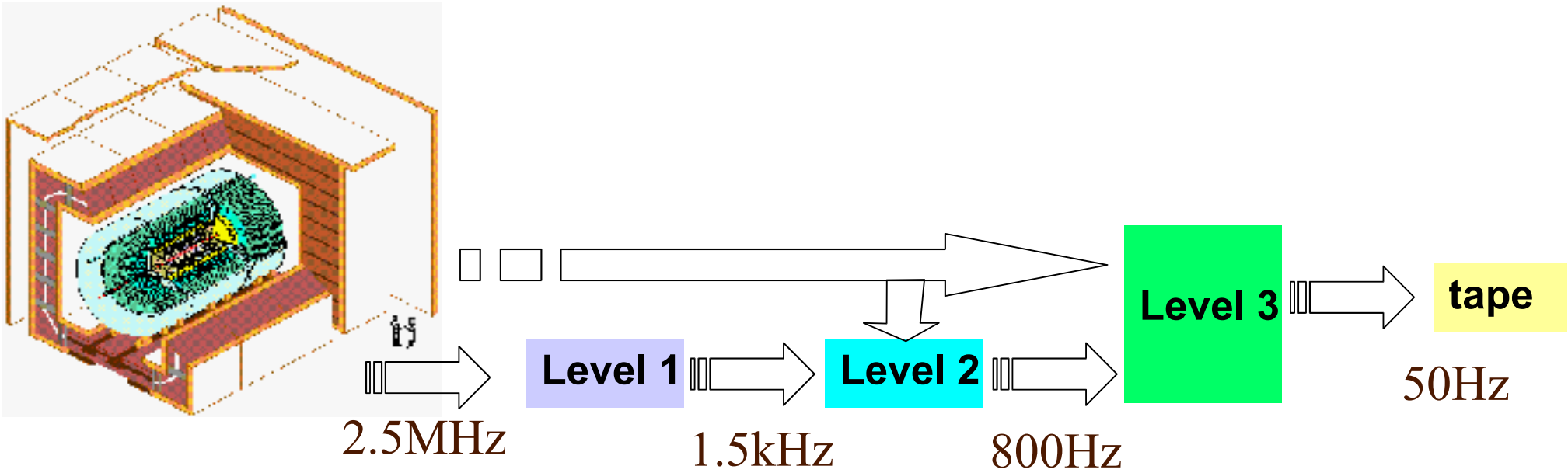
Collecting Interesting Events: Trigger System



2.5MHz → **Select interesting events** → 50Hz → **Storage tape**

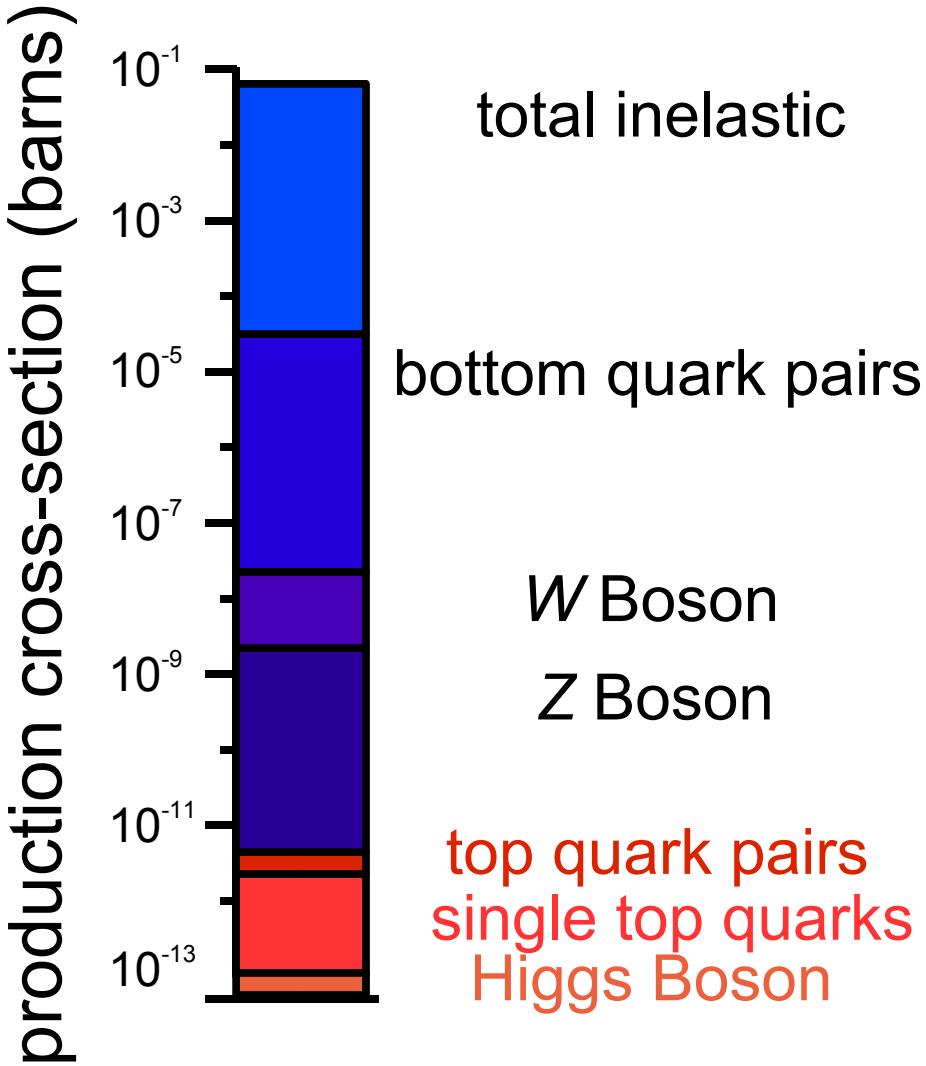
- Reduce rate of interactions (inelastic collision rate) to manageable level that can be written to storage tapes
- Record "interesting" events
  - Select events containing high-energy final state objects
    - Electrons, muons, quark jets

Collecting Interesting Events: Trigger System



- DØ experiment: three-level trigger system
  - Reconstruct objects at every level
    - Decreasing event accept rate
    - Increasing time per decision
    - Increasing level of sophistication

Tevatron Physics Program



Precision QCD Physics

B Physics

Precision Electroweak Physics

Top quark measurements

Searches for new Physics

Higgs Searches

Tevatron Physics Program

- Precision QCD Physics
  - Detailed studies of strong interactions
  - Jet production cross section and angular correlations
- Precision Electroweak Measurements
  - Detailed studies of electroweak interactions
  - W and Z boson (+ jets) production cross section
  - W Boson mass measurement
  - Angular correlations
- Direct Higgs Searches
  - Search for the Standard Model Higgs Boson
  - Detailed studies of background processes
- Direct Searches for New Physics
  - Search for Supersymmetry, extra spatial dimensions, ...

Tevatron Physics Program

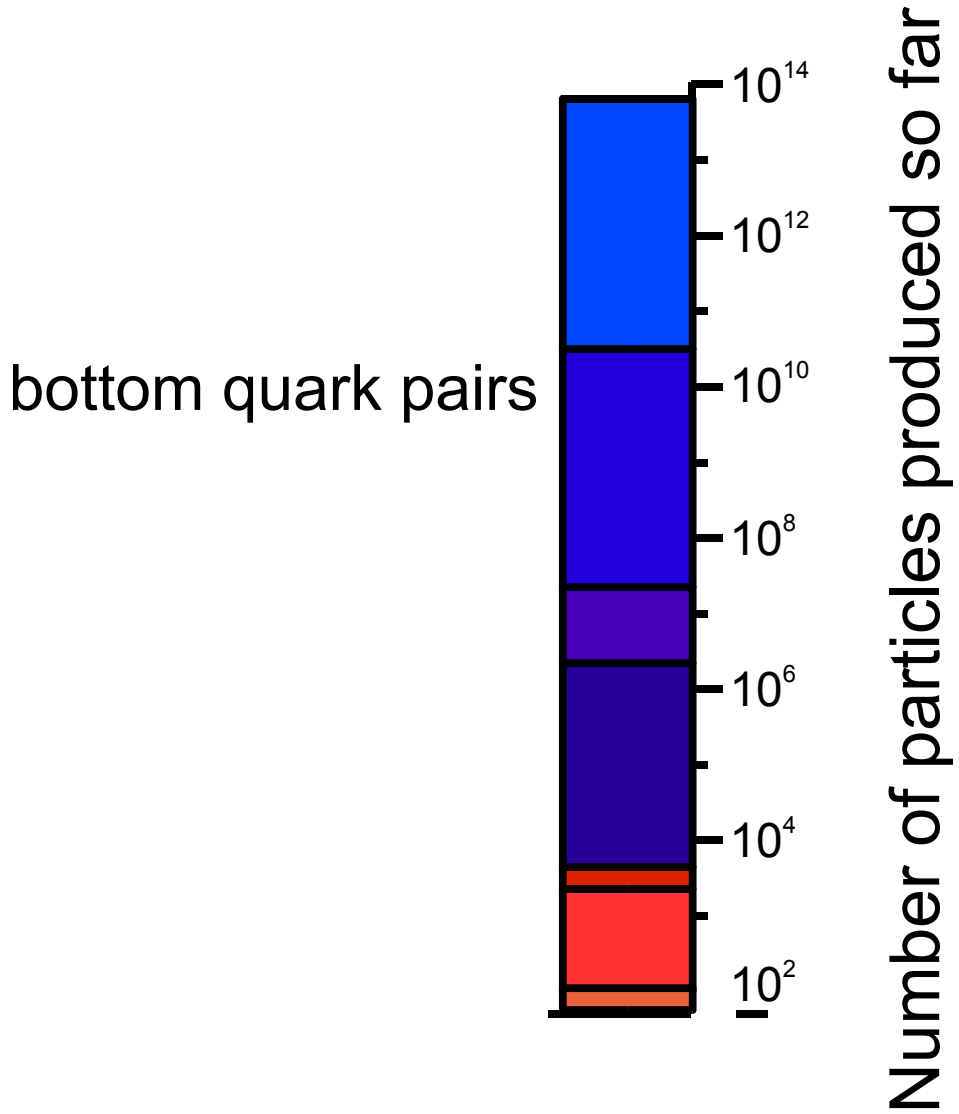
- Precision QCD Physics
- Precision Electroweak Measurements
- Direct Higgs Searches
- Direct Searches for New Physics
- B Quark Physics
  Why is there more matter than antimatter in the Universe?

B Physics

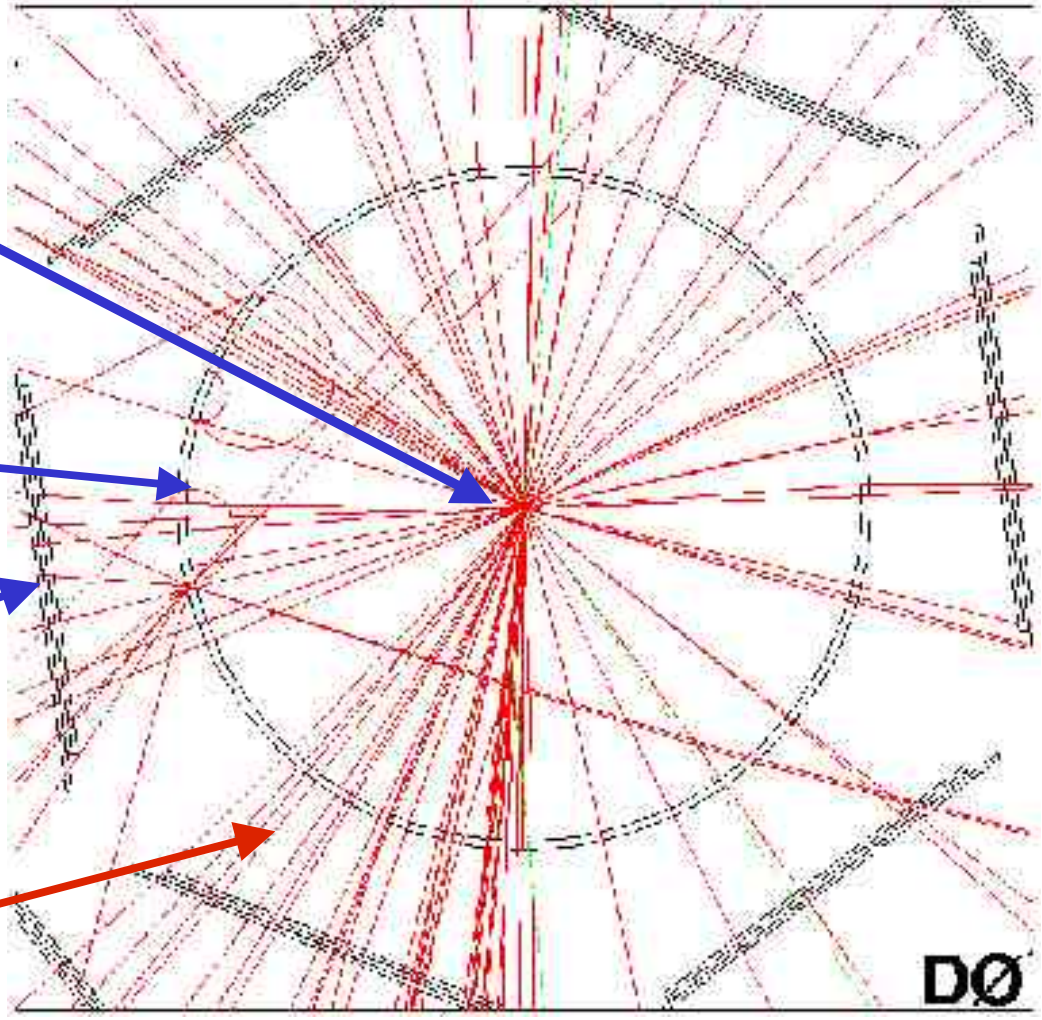
- Precision measurements of B meson lifetime and decay properties
  - Does matter behave differently than anti-matter?

Studying the Third Generation of Quarks at the Tevatron

B Physics



B-Physics: Charged Particle Track Reconstruction



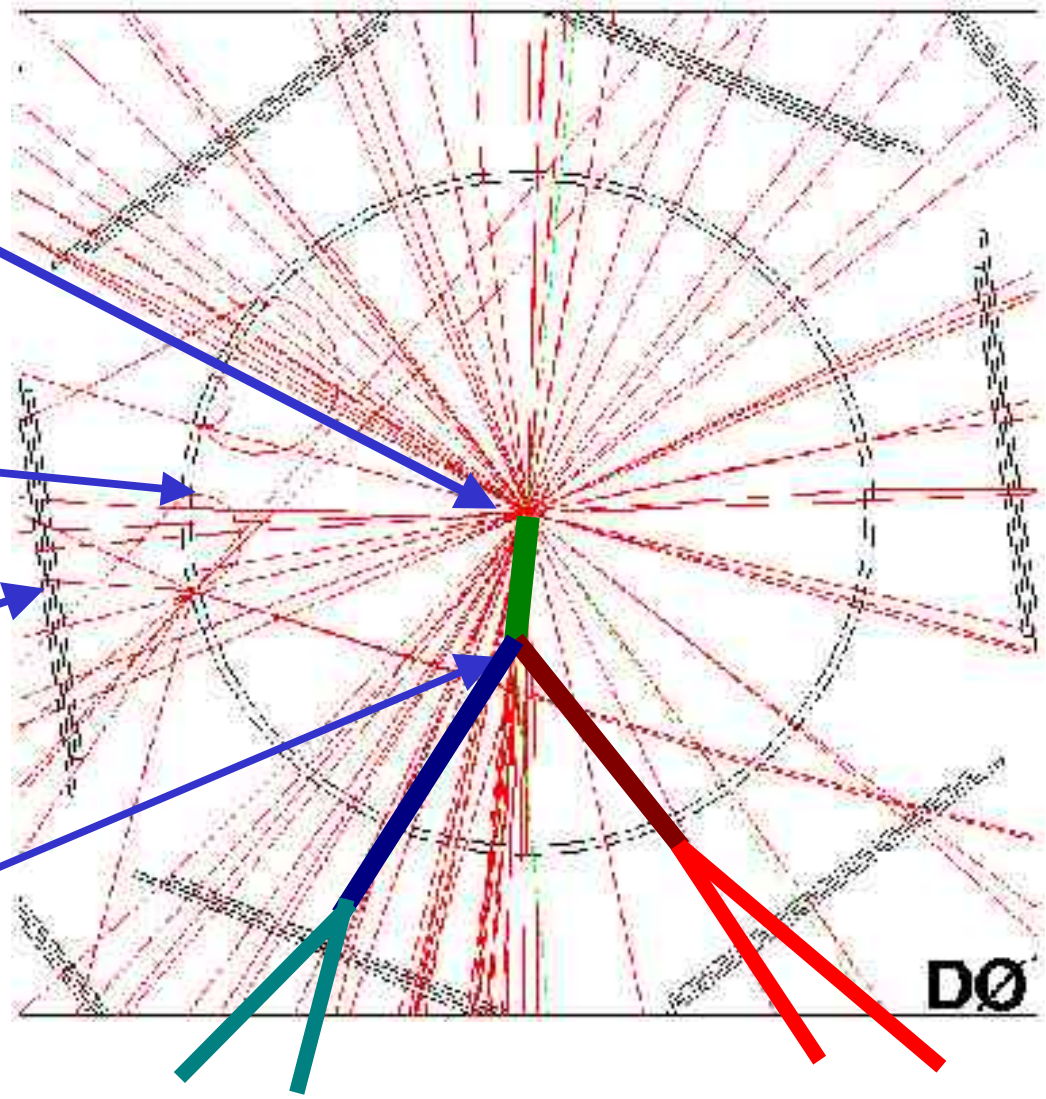
Interaction point ("primary vertex")

Beampipe

Silicon detector

Charged particle tracks

B-Physics: Precision Track Reconstruction



Interaction point ("primary vertex")

Beampipe

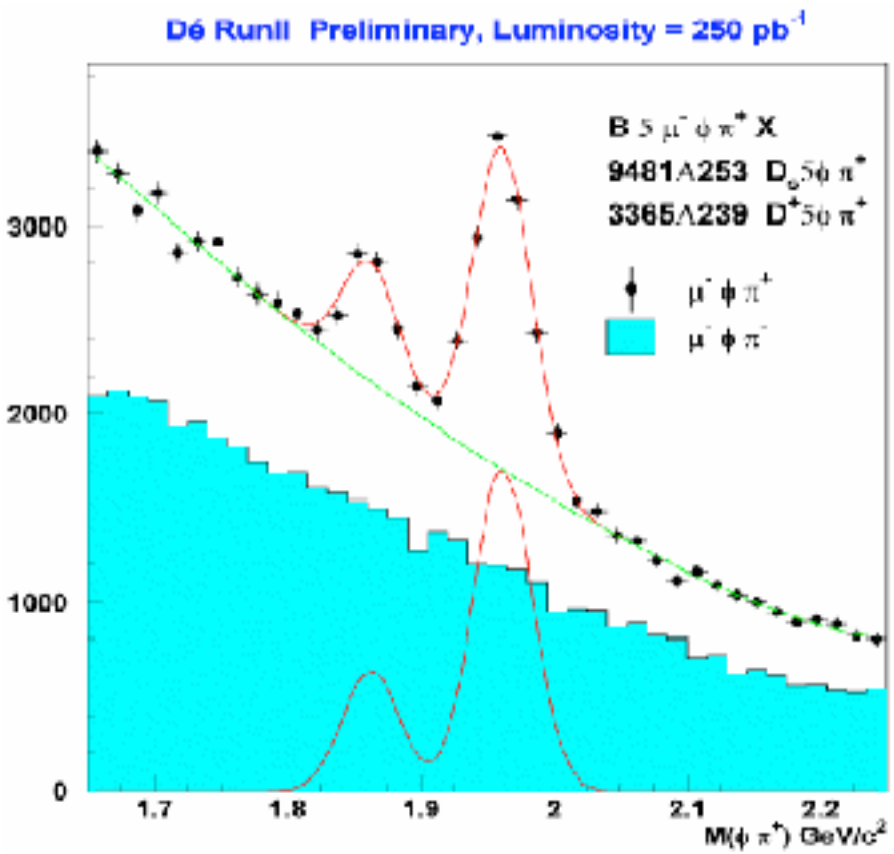
Silicon detector

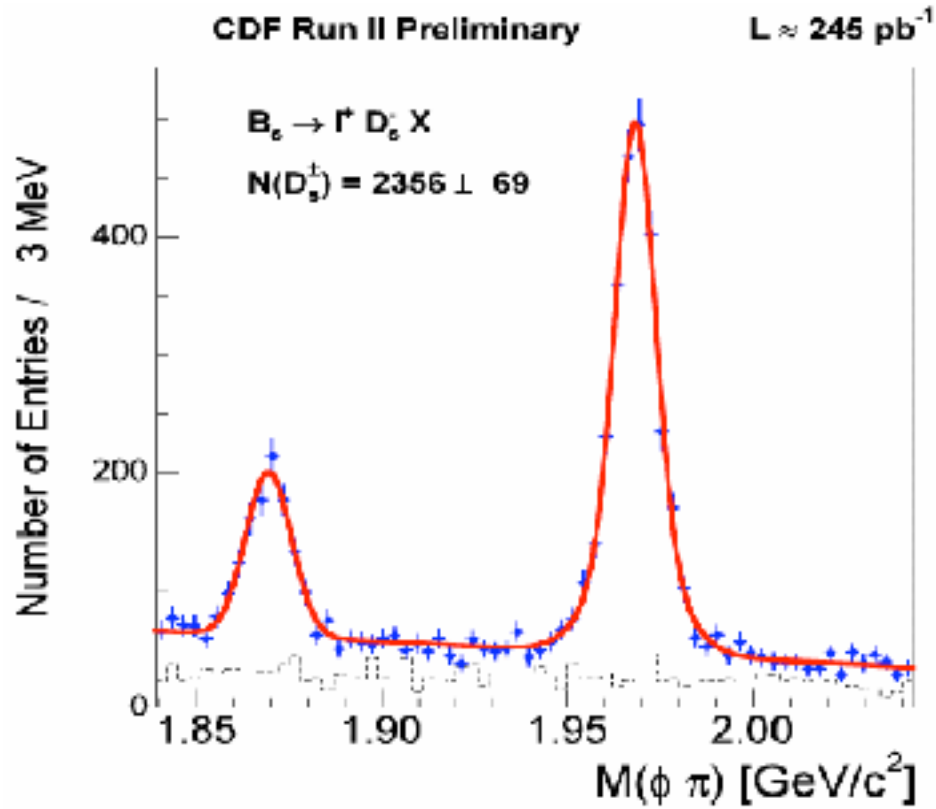
B decay ("secondary vertex")

Example: $B^0 \rightarrow J/\psi\ K^0_s$, $J/\psi \rightarrow \mu\mu$, $K^0_s \rightarrow \pi^+\pi^-$

B-Physics at the Tevatron

- B meson lifetimes, B_s lifetime differences
- Branching ratios, asymmetries
- B_s Mixing



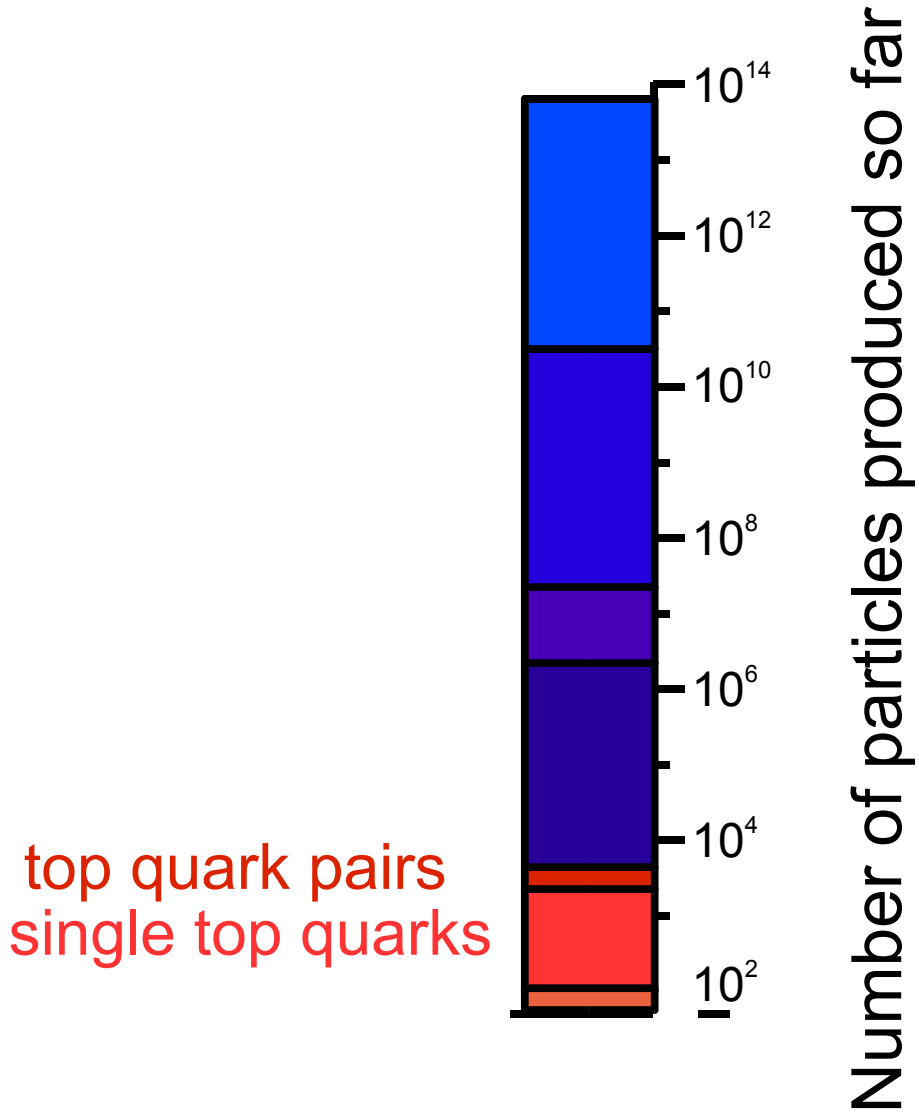


Tevatron Physics Program

- Precision QCD Physics
- Precision Electroweak Measurements
- Direct Higgs Searches
- Searches for New Physics
- B Quark Physics
- Top Quark Physics

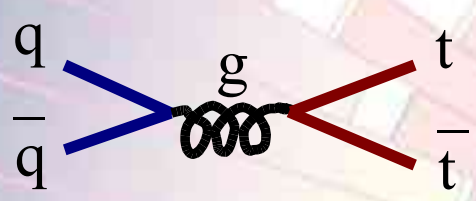
Studying the Third Generation of Quarks at the Tevatron

Top Physics



Tevatron Top Pair Physics

- Top Pair Production at a Proton-Antiproton collider



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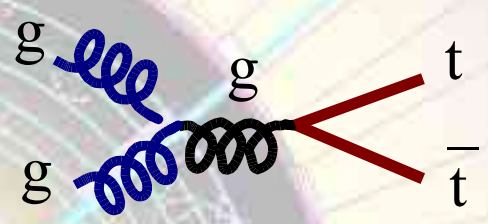

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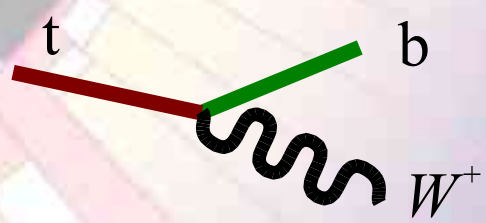
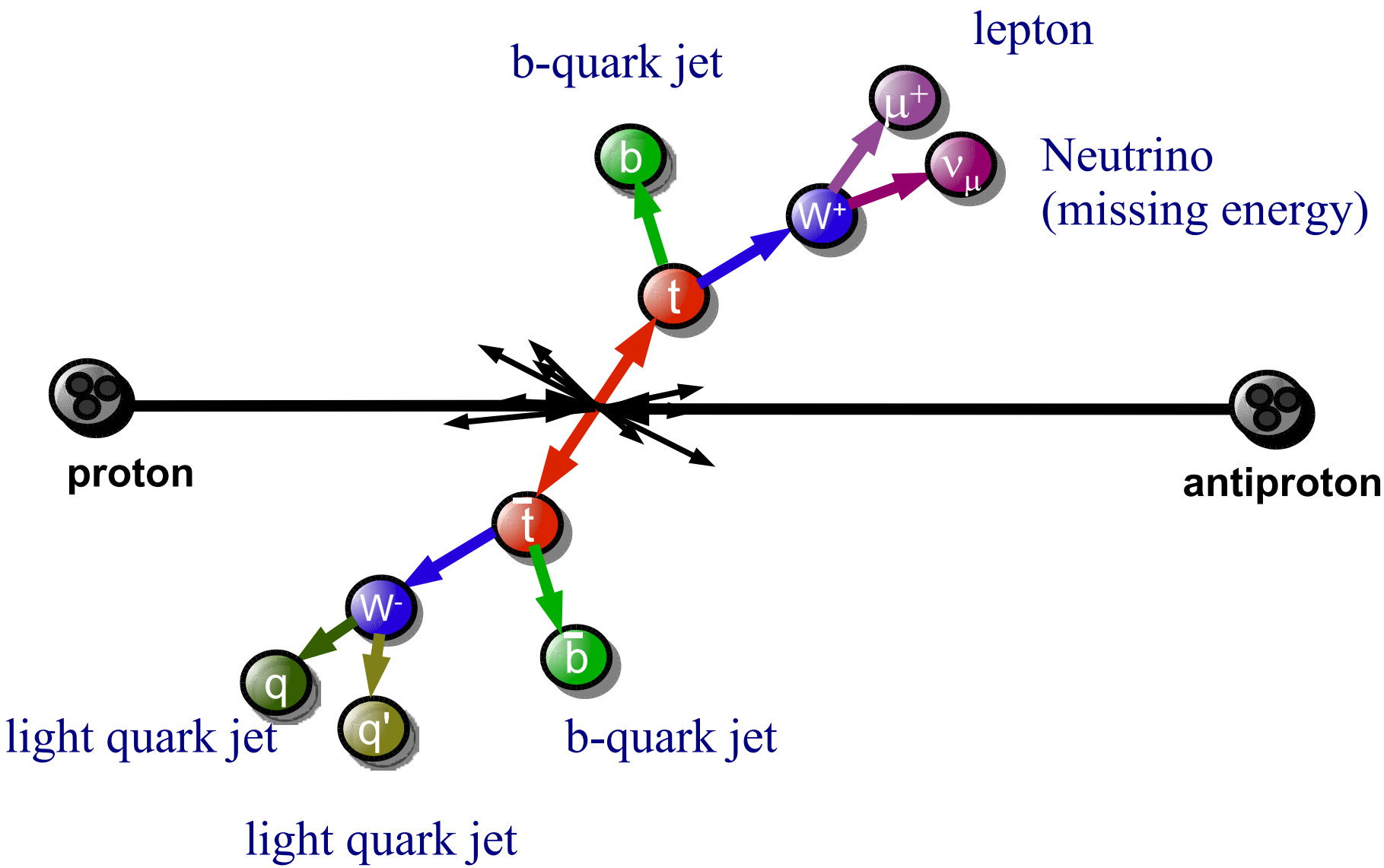
- Top Pair Studies at the Tevatron
  - Production cross section
    - Many different final states
    - Test of QCD
  - Top mass measurements
    - Implications for Standard Model Higgs
  - Probe Top Quark electroweak interactions
    - Top spin and W helicity measurement

Top quark decay



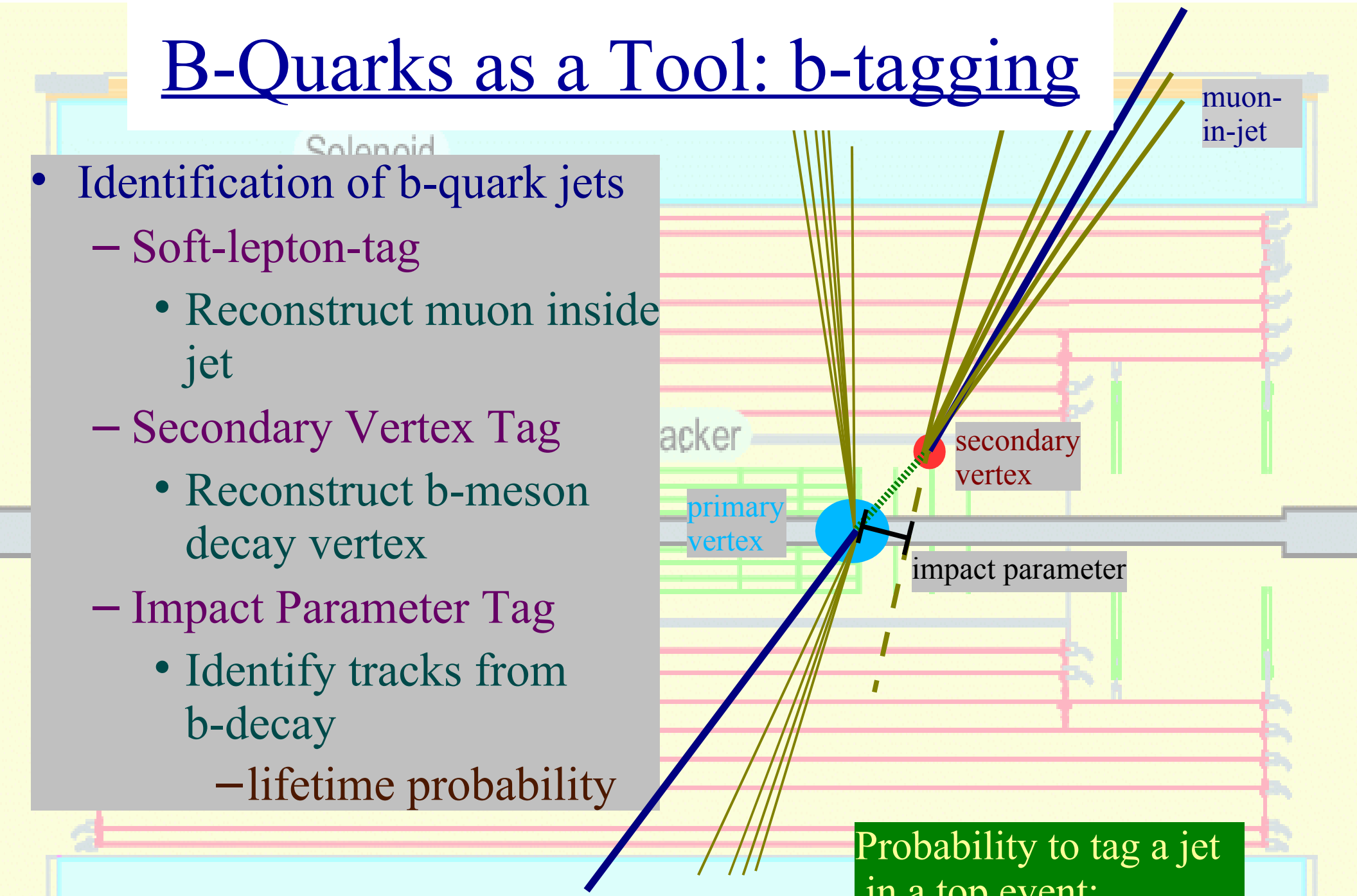
Top Pair Physics

- Unique final state:



B-Quarks as a Tool: b-tagging

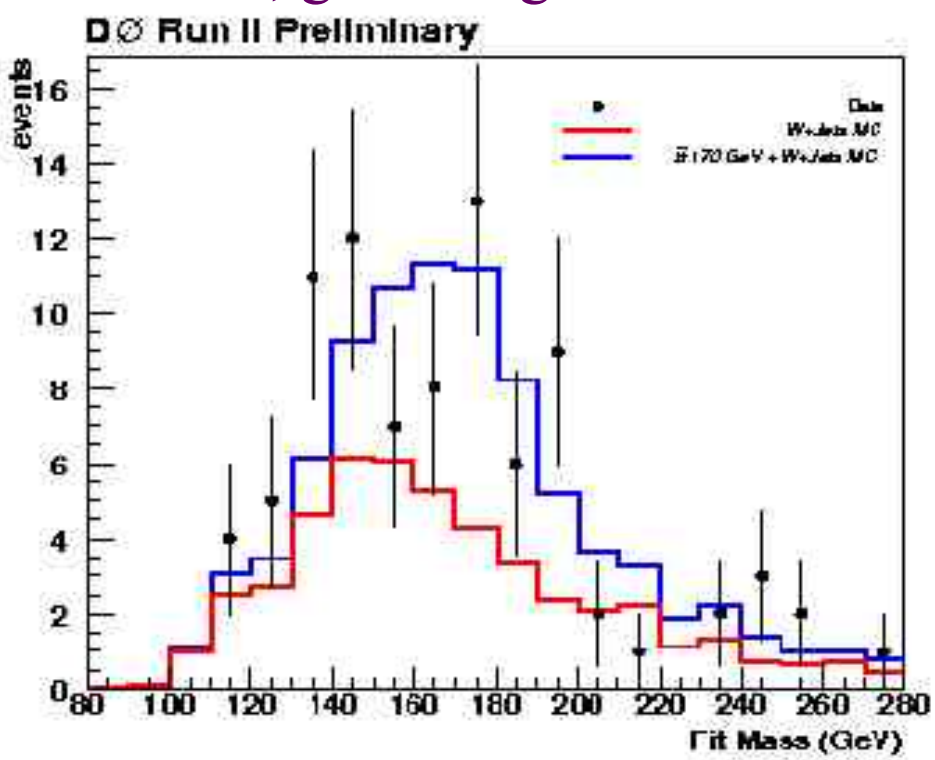
- Identification of b-quark jets
  - Soft-lepton-tag
    - Reconstruct muon inside jet
  - Secondary Vertex Tag
    - Reconstruct b-meson decay vertex
  - Impact Parameter Tag
    - Identify tracks from b-decay
      - lifetime probability

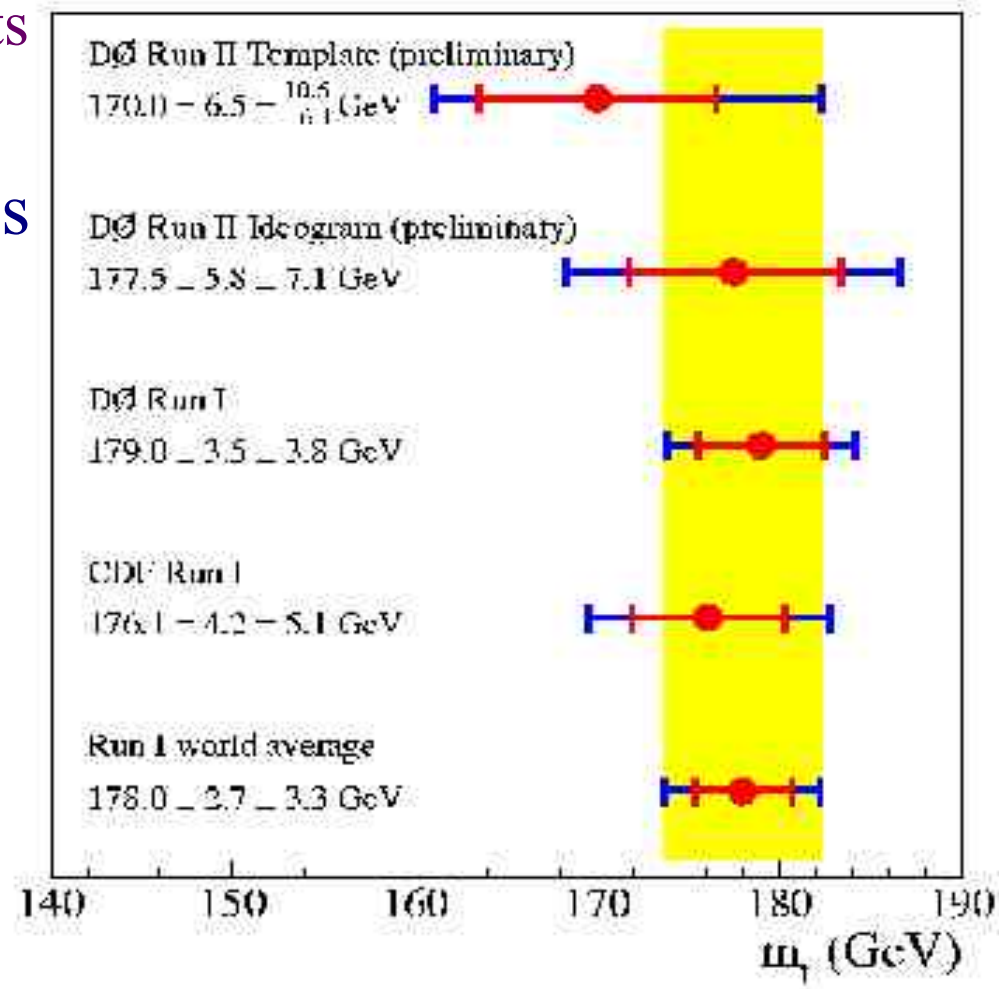


Probability to tag a jet in a top event:
- b-quark jet: ~55%
- light-quark jet: ~0.5%

Top Quark Mass

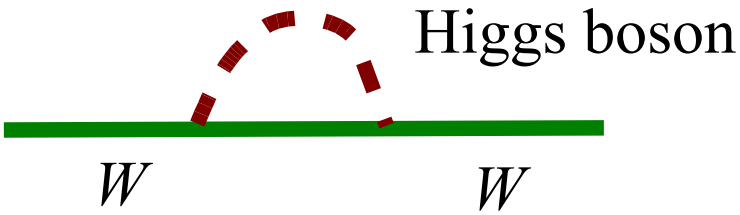
- Reconstruct both top quarks from decay products
- Main measurement in lepton+jets mode
  - Top 1: *l*+ν+jet Top 2: jet+jet+jets
  - Many possible jet permutations
- Several measurement techniques
  - Identify proper permutation
  - Use all, give weight to each

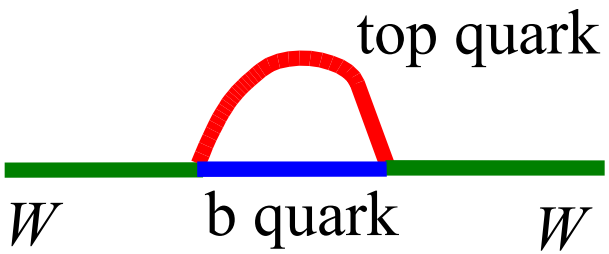




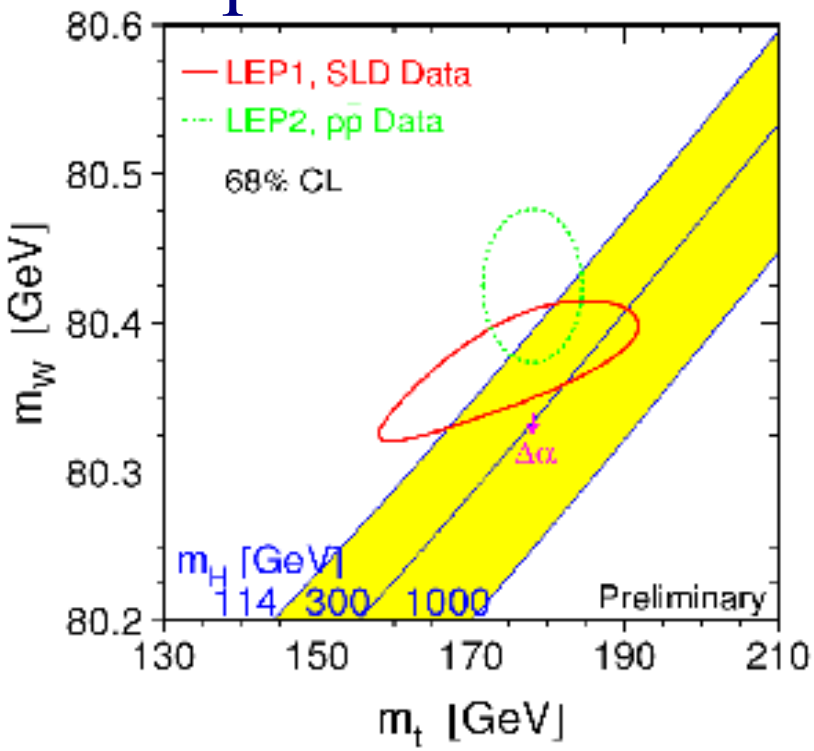
Implications for Higgs Boson Mass

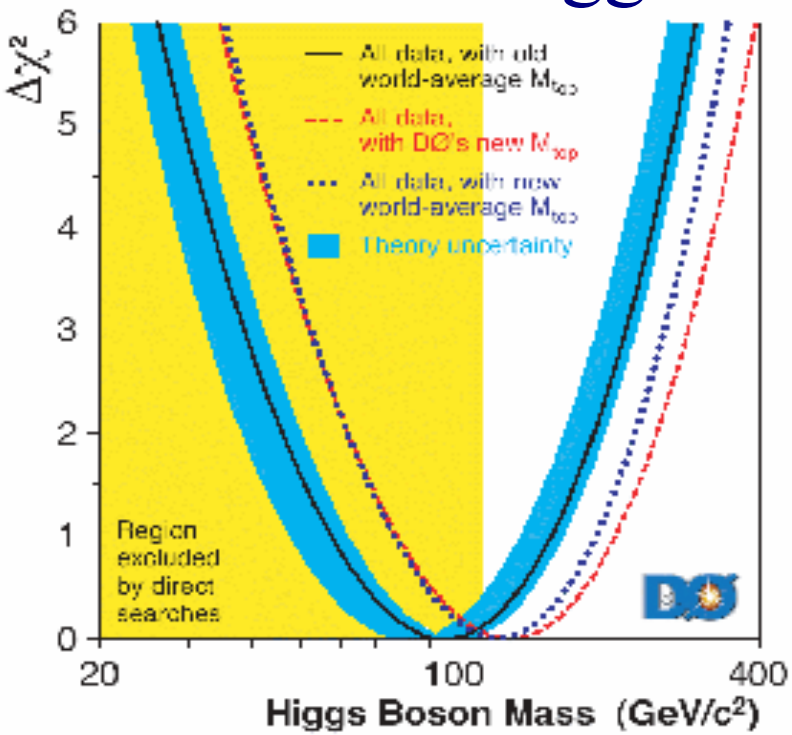
- *W* boson mass has virtual corrections due to top quark mass and Higgs boson mass





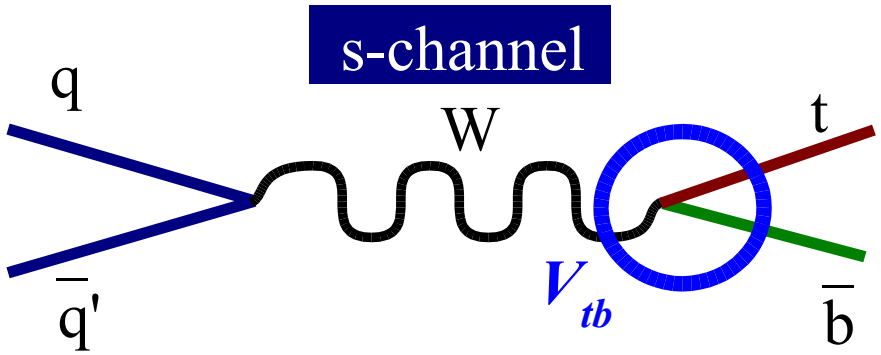
- *W* and top mass measurements constrain Higgs:

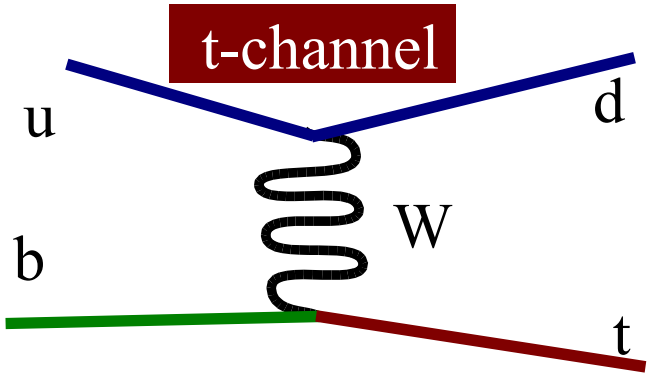




Single Top Physics at the Tevatron

- Electroweak Production of Single Top Quarks



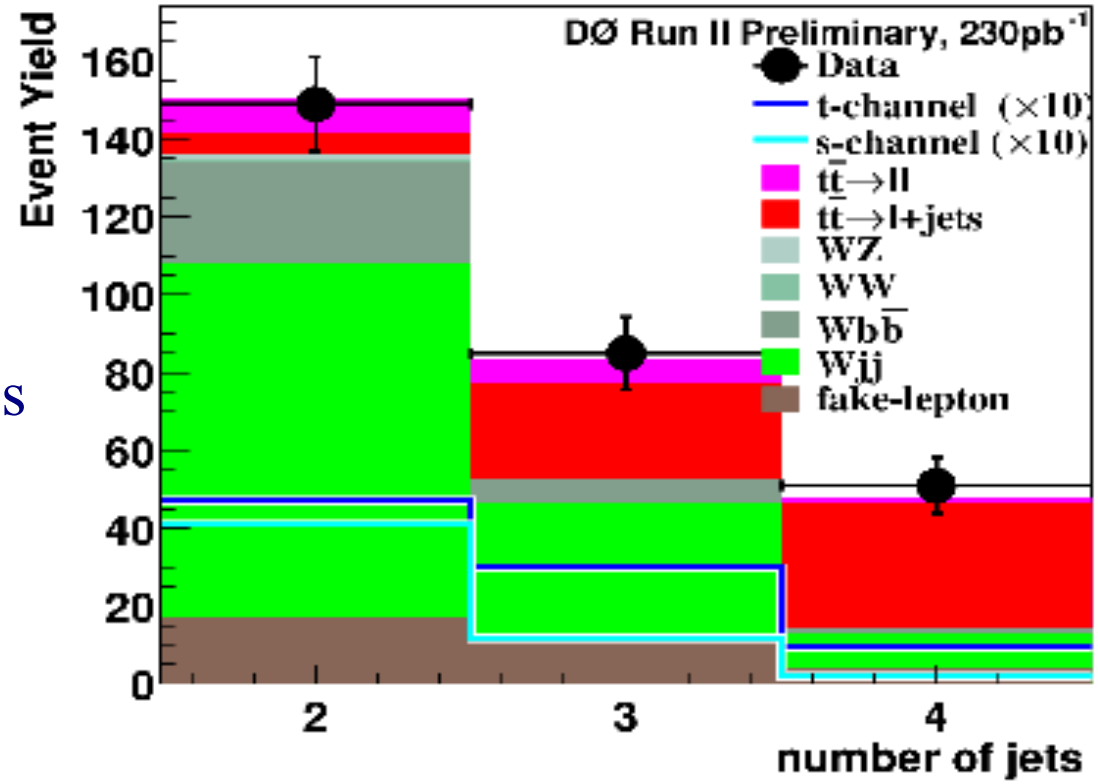


Tevatron Single Top in Run II:

- Observe Single Top Production
- Measure Production cross section
  - Confirm Standard Model Prediction
    - CKM matrix element V_{tb}
- Look for Physics beyond the Standard Model
- Measure top quark spin

Path towards Single Top Observation

- Cross Section is small in the Standard Model
- Backgrounds are large
- Need to use advanced signal-background separation techniques
  - Require b-jet tag
  - Multivariate analysis

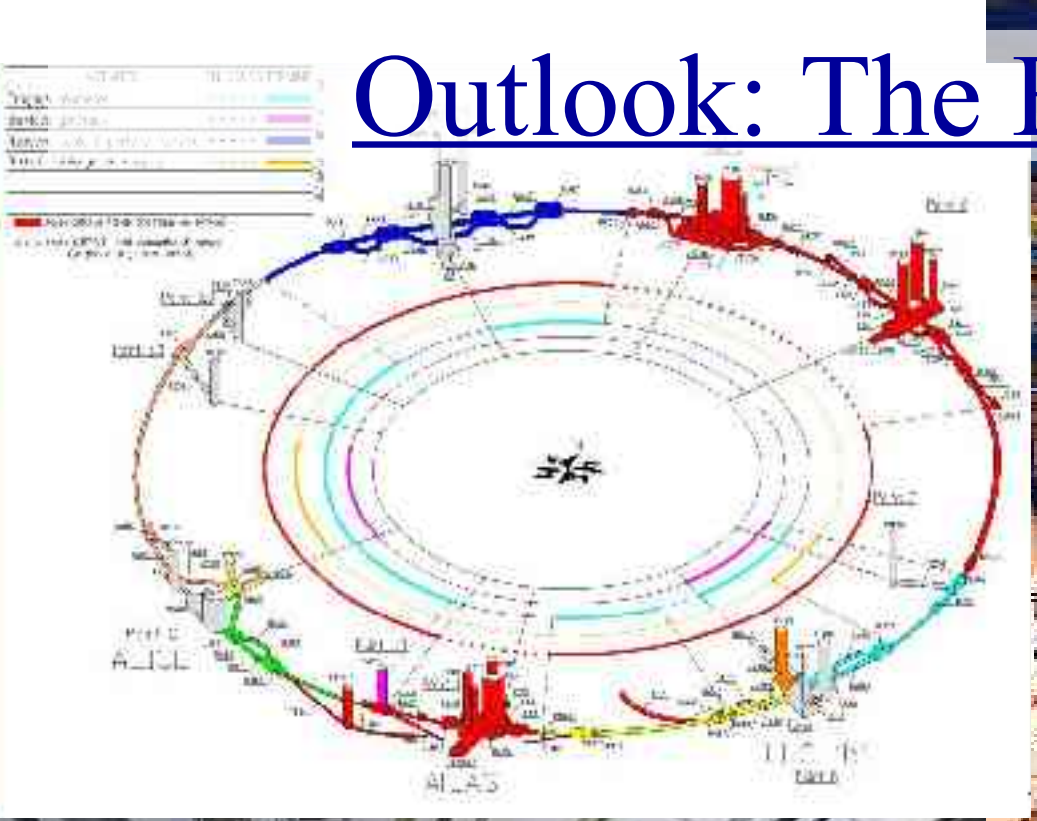


95% C.L. Limits	Theory	CDF	DØ (160pb^{-1})	DØ (new)
σ (s-channel)	0.88pb	<13.6pb	<19pb	<6pb
σ (t-channel)	1.98pb	<10.1pb	<25pb	<5pb
σ (s+t channels)		<17.8pb	<23pb	

Outlook: Tevatron Future

- Luminosity expected to increase by a factor of ~10
  - Collect 4-8fb^{-1} by 2009
  - Keep running until the LHC produces Physics results
- B Quark Physics:
  - Many precision measurements
  - Observe B_s mixing
- Top Quark Physics:
  - Measure top quark mass → further constrain Higgs mass
  - Discover single top quark production
    - Measure CKM matrix element V_{tb}
    - Measure top quark spin

Outlook: The Energy Frontier



Outlook: The Energy Frontier

- The LHC at CERN is scheduled to start up in 2007
  - Proton-Proton collisions at 14TeV
  - Bunch crossing every 25ns (40 MHz)
- Main Goals:
  - Study origin of electroweak symmetry breaking
  - Find the Higgs boson (if it exists)
  - Discover supersymmetric particles (if they exist)
- Collect large samples of B quarks
  - Precision B measurements
- Collect large samples of Top Quarks
  - Precision Top Mass Measurement
  - Precision Single Top measurements
  - Top Quarks as tools

Conclusions/Outlook

- This is an exciting time in Particle Physics
  - On the threshold of a whole new regime of understanding
- The third generation fermions is at the heart
  - Origin of mass, matter vs anti-matter, neutrino oscillations
- The Tevatron and detectors are performing well
  - We are collecting a large dataset at the energy frontier
- The LHC will turn on in a few years
  - Extend energy frontier by a factor of 10

A decade of discovery ahead!

Resources

- Quantum Universe
  http://interactions.org/quantumuniverse/
- Quarks Unbound
  http://www.aps.org/units/dpf/quarks_unbound/index.html
- Particle Adventure
  http://particleadventure.org/particleadventure/index.html
- Fermilab
  http://www.fnal.gov
- Cern
  http://www.cern.ch