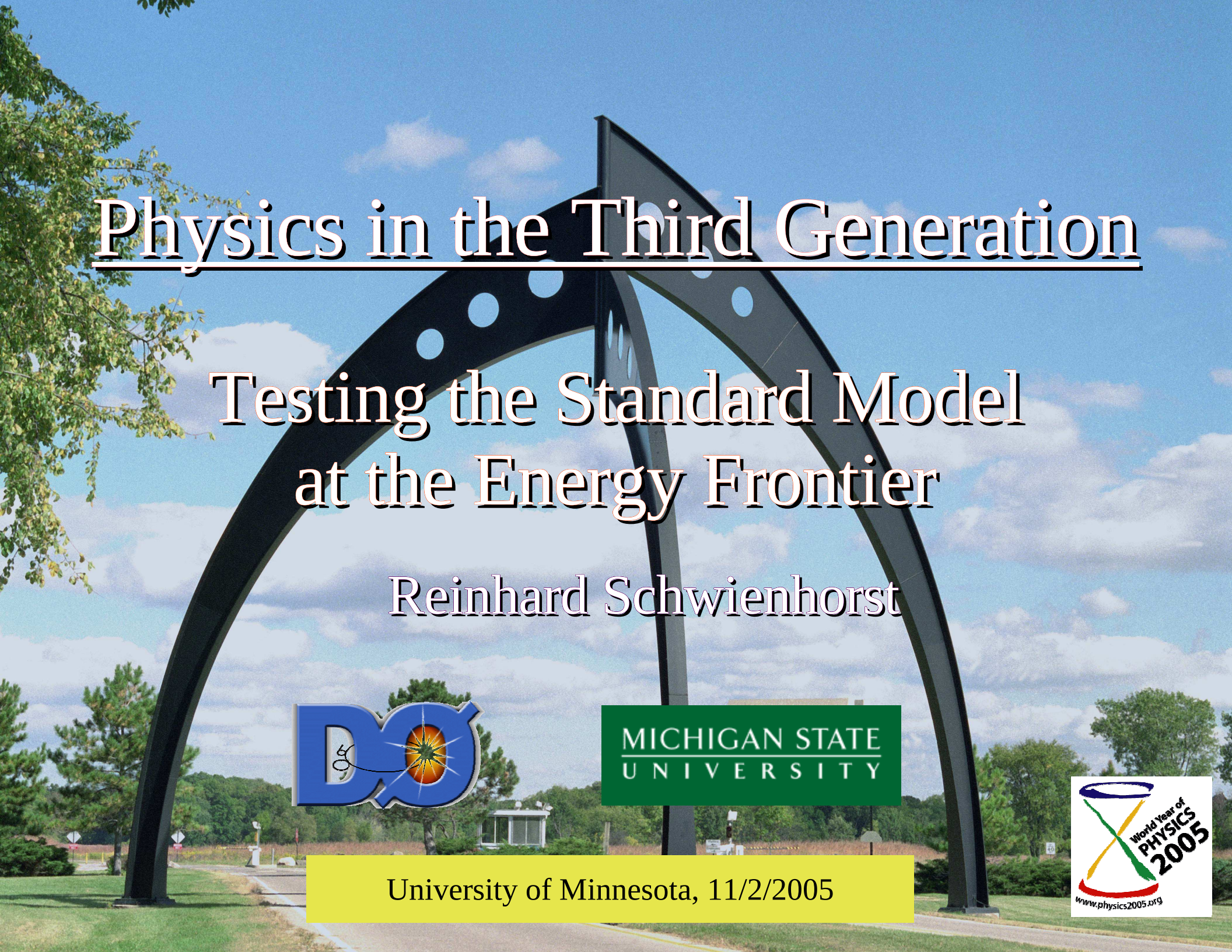


Physics in the Third Generation

Testing the Standard Model at the Energy Frontier

Reinhard Schwienhorst

MICHIGAN STATE UNIVERSITY

University of Minnesota, 11/2/2005

World Year of PHYSICS 2005
www.physics2005.org

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

Outline

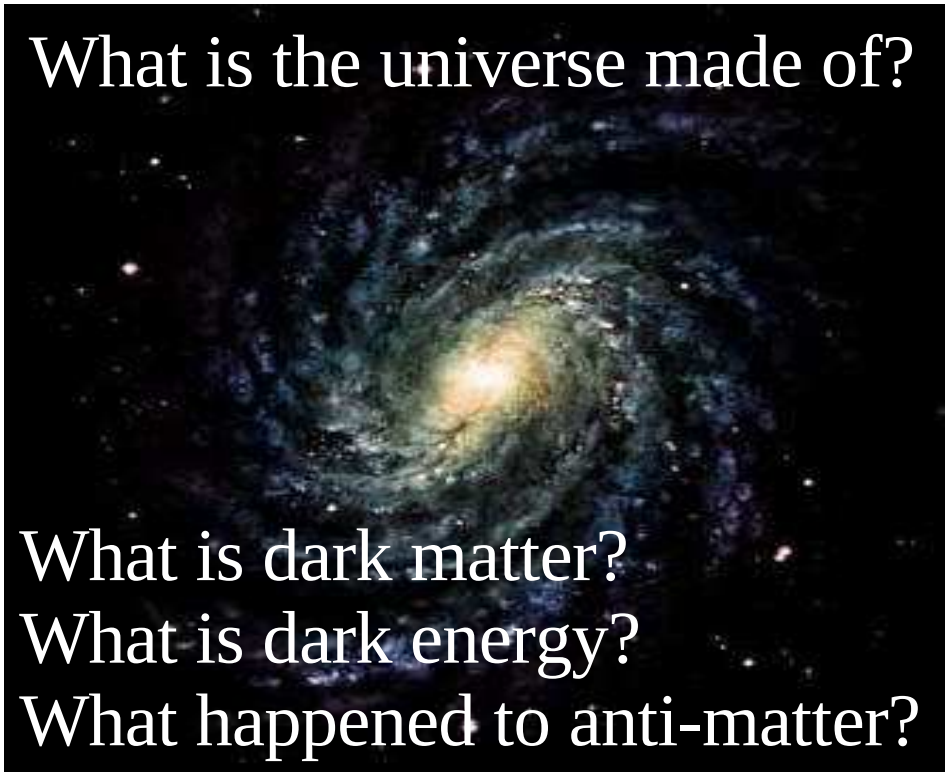
- A fundamental question
- The standard model of particle physics
  - Three generations of elementary particles
  - The top quark
- The Energy Frontier
- Results
- Outlook
- Conclusions

A fundamental question

What is the origin of matter?

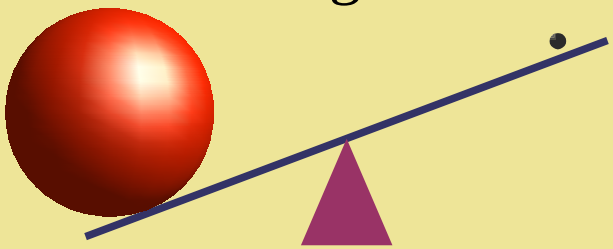
What is the origin of matter?

What is the universe made of?



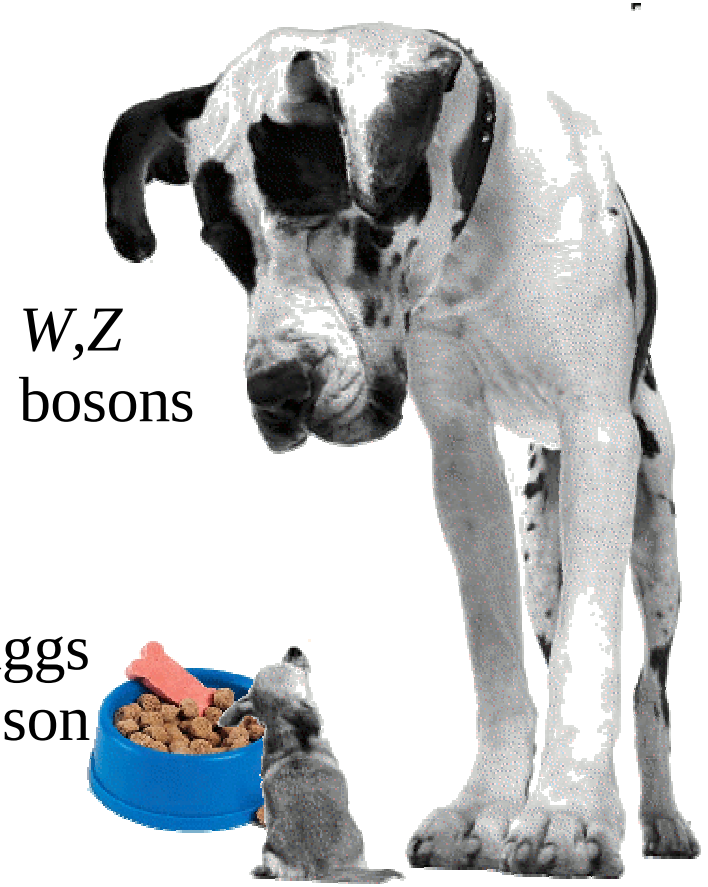
What is dark matter?
What is dark energy?
What happened to anti-matter?

What makes the top quark so heavy and neutrinos so light?



top quark neutrino

Electroweak symmetry breaking?



W,Z bosons

Higgs boson

photon

Supersymmetry? Large extra dimensions? ...

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

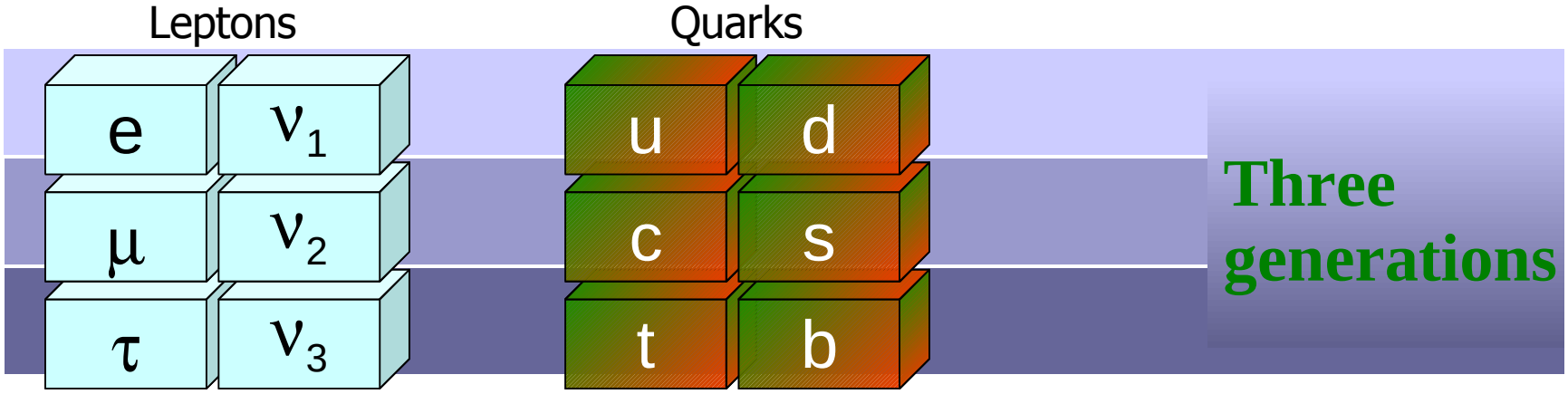
The minute particular

State of the art

What do we know already?

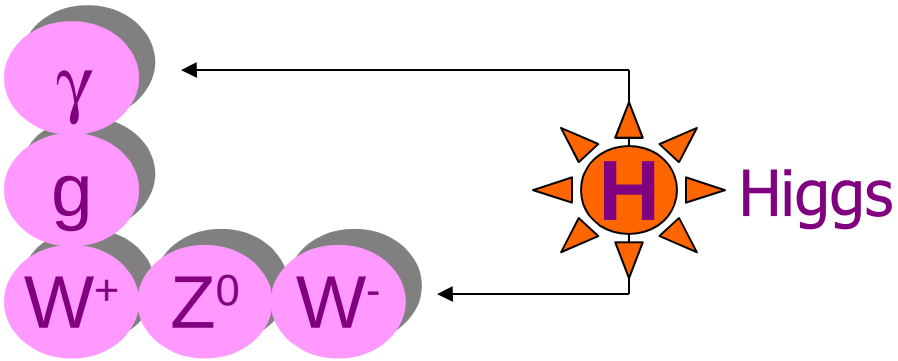
Standard Model of Particles and Forces

- A quantum field theory describing point like, spin-½ constituents



- Which interact by exchanging spin-1 vector bosons

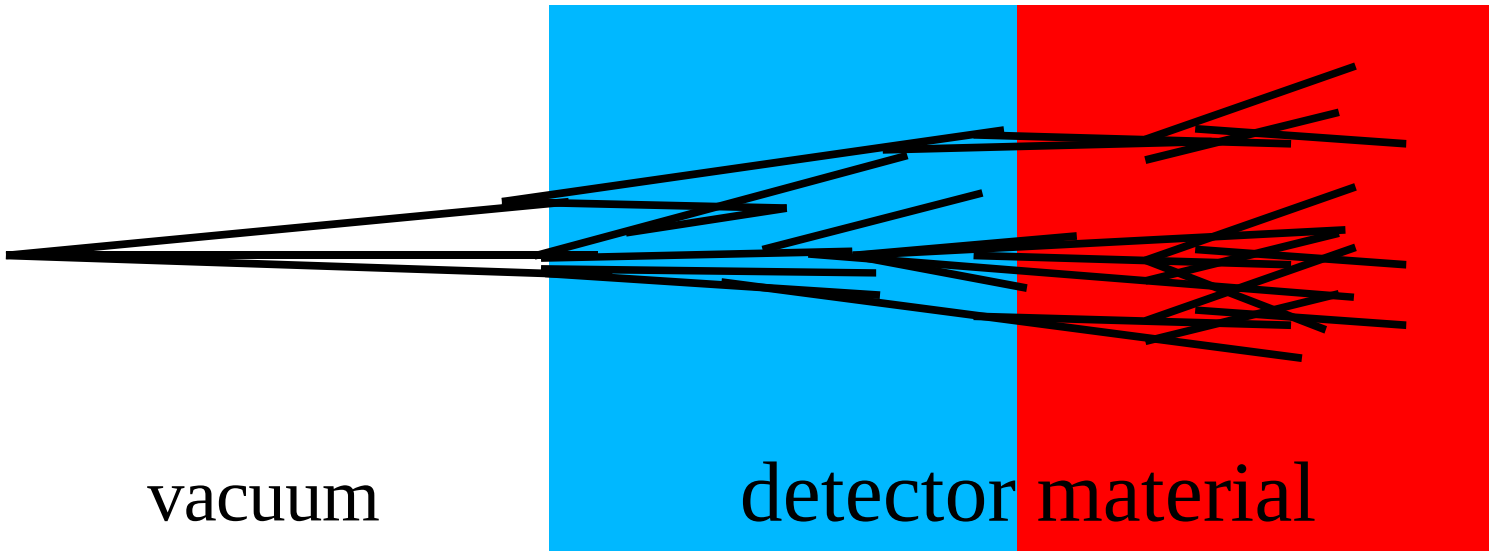
Electromagnetic	10^{-2}
Strong	1
Weak	10^{-6}
Gravity	10^{-40}



Relative strengths

The first two generations of quarks

- up or down or strange or charm 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

Detecting quarks through jets is a standard tool at the energy frontier

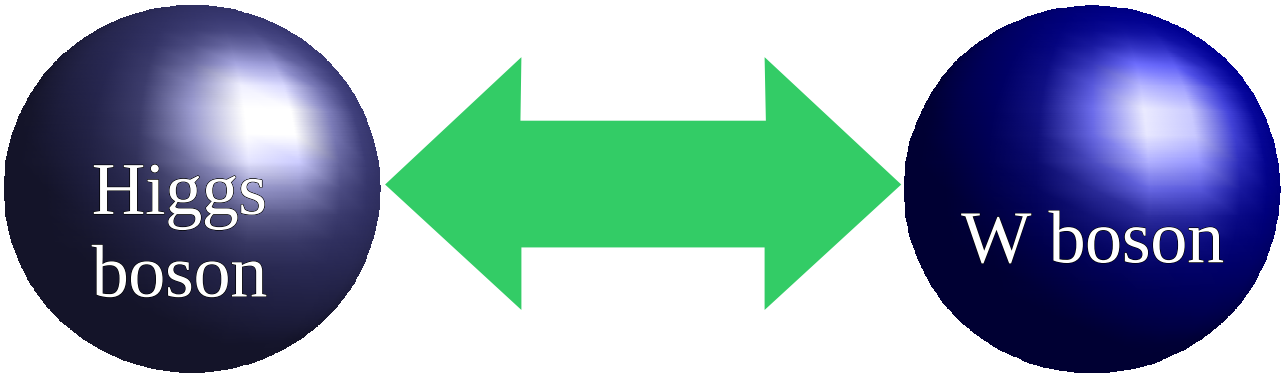
The third generation of quarks

bottom quark

top quark

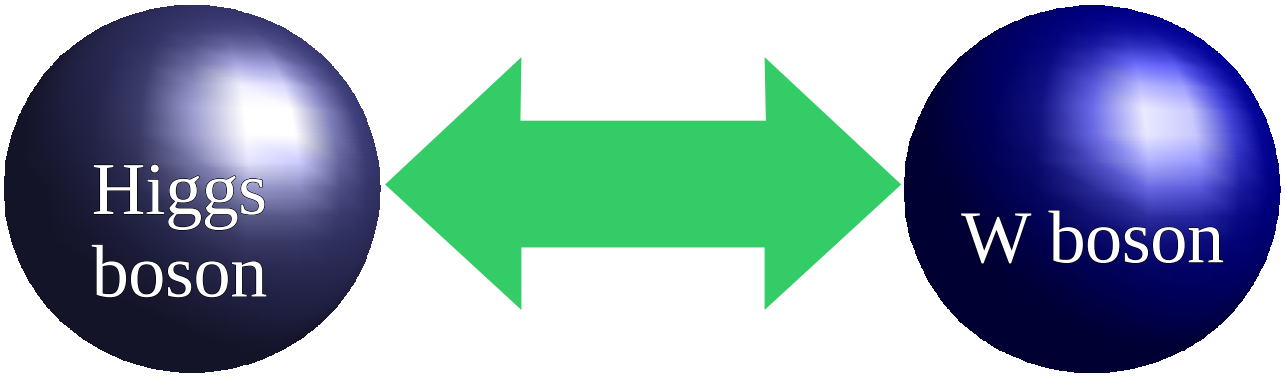
Electroweak Symmetry Breaking

Gauge boson coupling to Higgs field

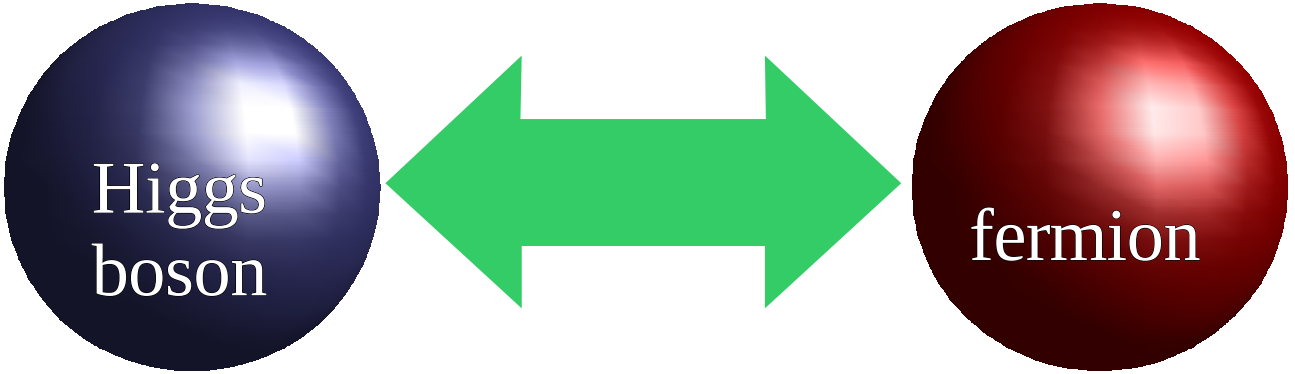


Electroweak Symmetry Breaking

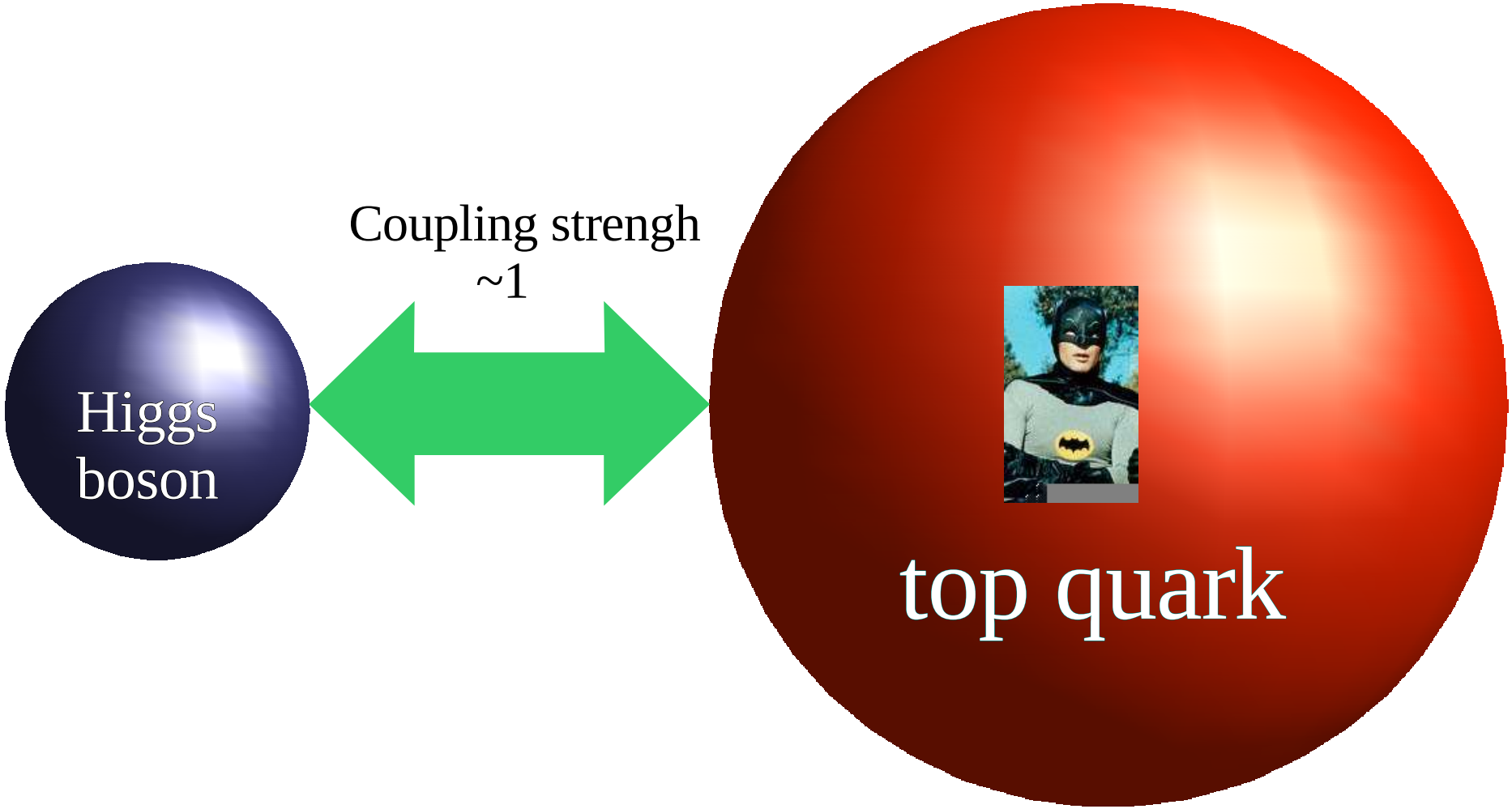
Gauge boson coupling to Higgs field



Fermions acquire mass through Higgs

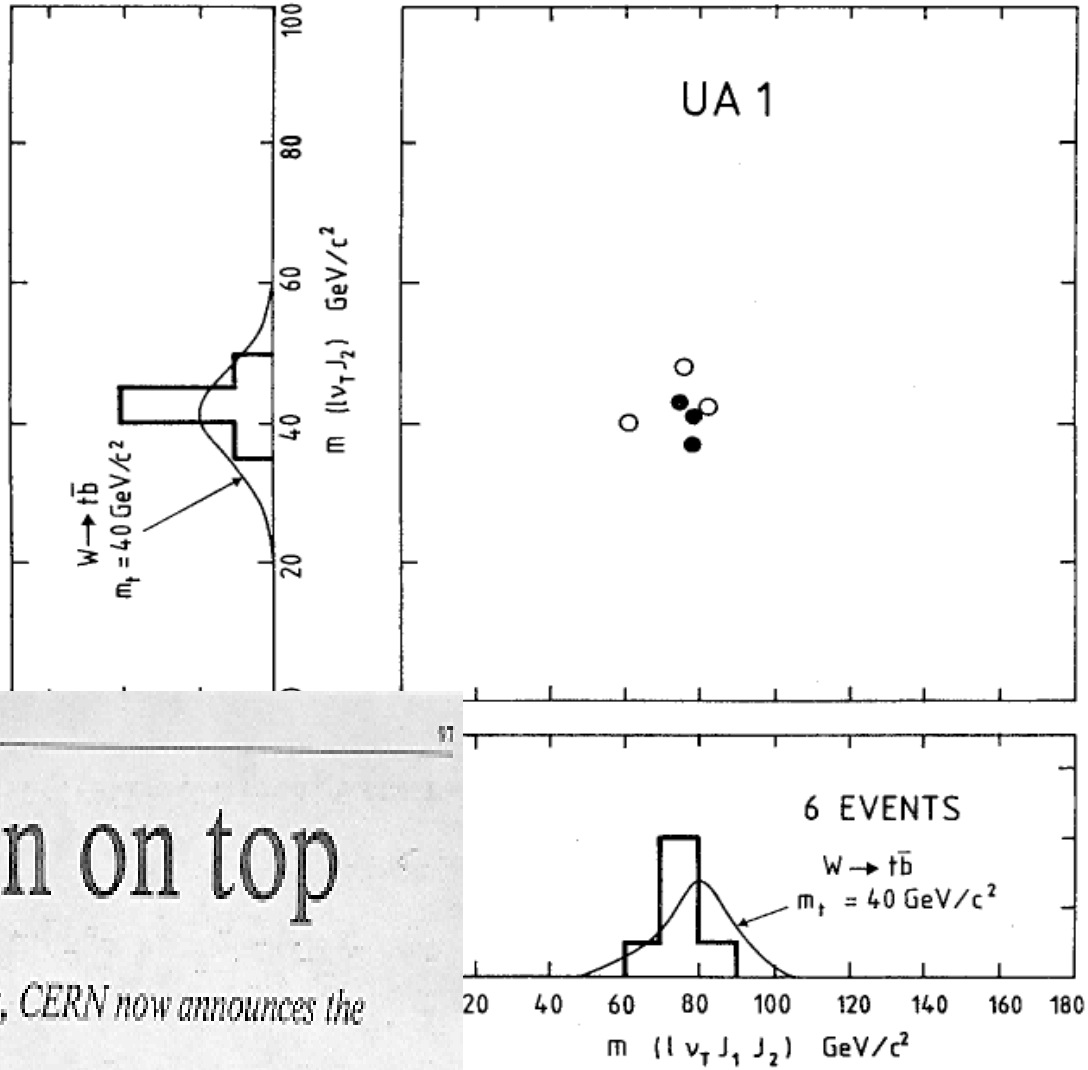


Fermion Mass



Top quark discovery in 1984

- Excess of lepton+MET+2jet events at UA1 in 1984
  - Consistent with production of single top quark
    - $M_{top} \approx 40GeV$



NATURE VOL 310 12 JULY 1984

NEWS AND VIEWS

CERN comes out again on top

With the discovery of the electroweak bosons ($W^{\pm}$ and Z^0) in the bag, CERN now announces the discovery of the quark called top. *What will come next?*

International weekly journal of science

nature

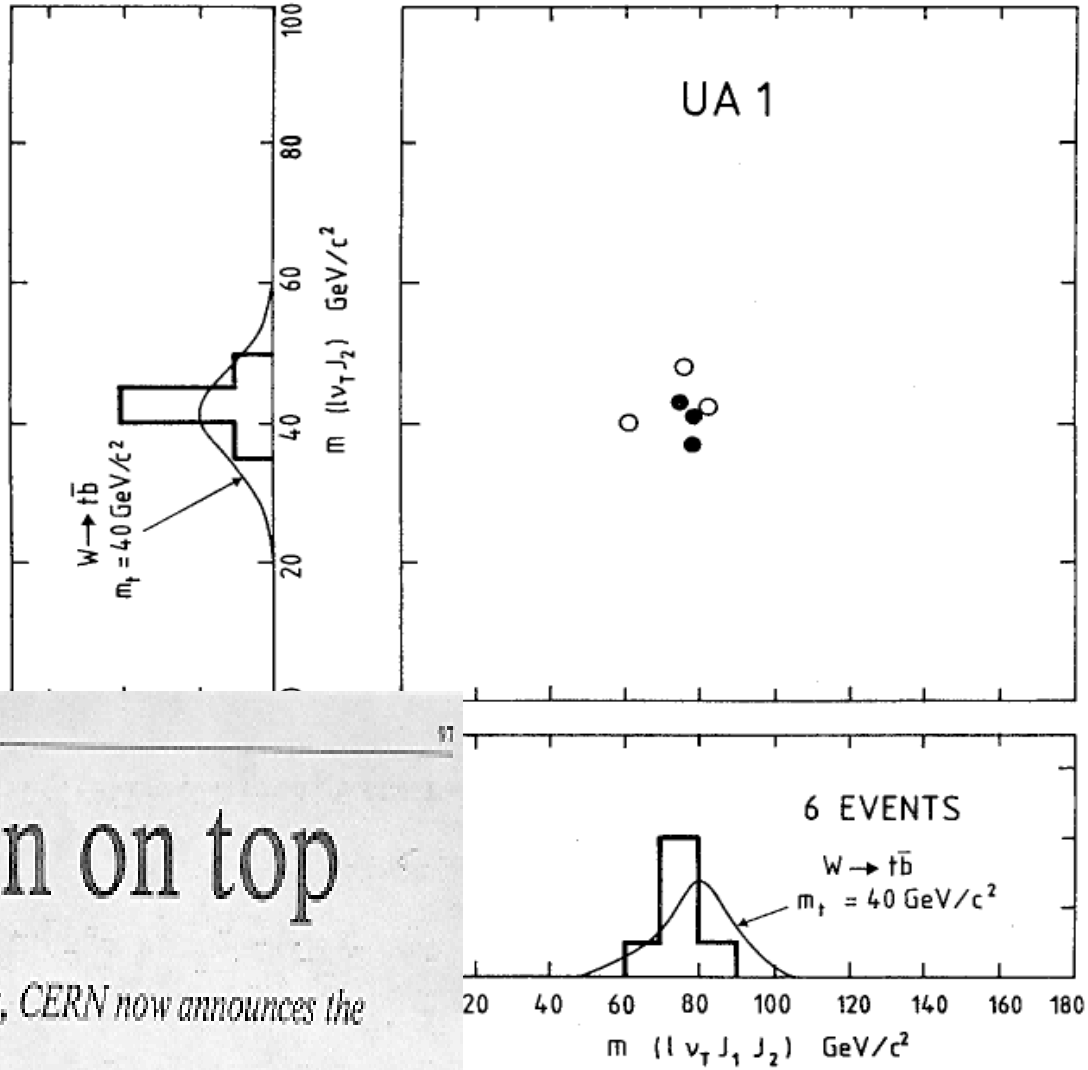
ere signs of have now ed as the

the *strange* particles themselves, are pairs of quarks — the pi-meson is a pair called *up* and *down* for example. But nucleons, such

$10.00 www.nature.com

W+jets ~~Top quark discovery~~ in 1984

- Excess of lepton+MET+2jet events at UA1 in 1984
  - Consistent with production of single t
    - M



PHYSICAL REVIEW LETTERS

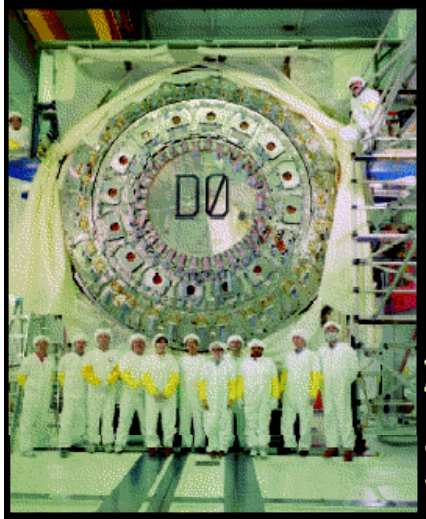
Observation of the Top Quark

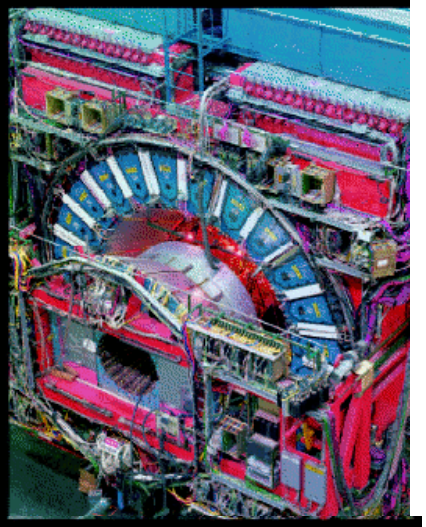
PHYSICAL REVIEW LETTERS

Observation of Top Quark Production in $p\bar{p}$ Collisions with the Collider Detector at Fermilab

TOP TURNS TEN

10th Anniversary of the Top Quark Discovery





news release
fermi national accelerator laboratory

Operated by Universities Research Association, Inc. for the U.S. Department of Energy

Public Information Office, P.O. Box 500, Batavia, IL 60510 • Telephone: 708-840-3351 • Facsimile: 708-840-8780

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Gary Pachford, 708/252-3015 (DØ)
Jeff Sherwood, 708/586-5806 (DØ)

95-1
March 1, 1995

For release after 1:30 p.m. CST, Thursday, March 2

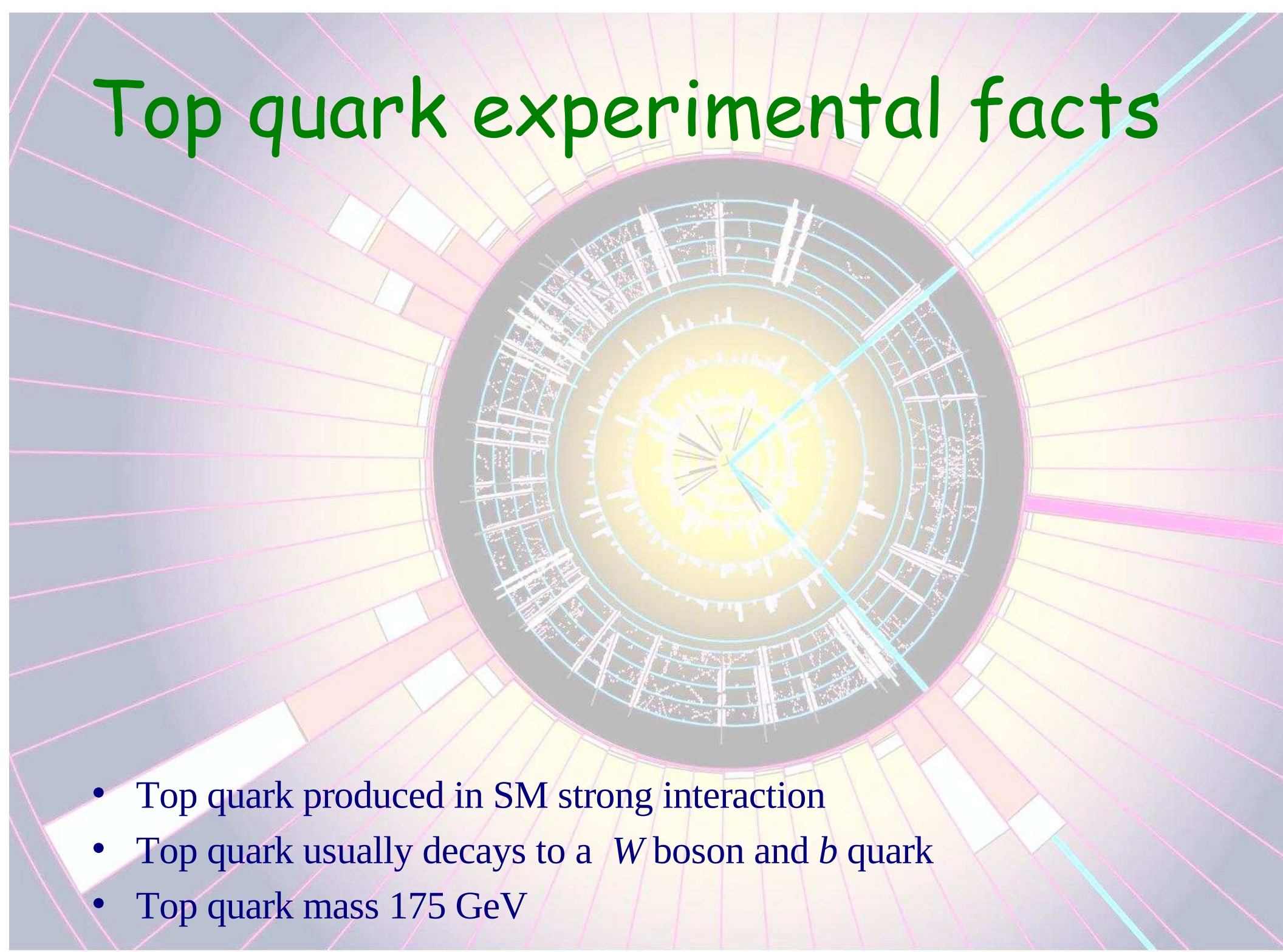
PHYSICISTS DISCOVER TOP QUARK

Batavia, IL—Physicists at the Department of Energy's Fermi National Accelerator Laboratory today (March 2) announced the discovery of the subatomic particle called the top quark, the last unsuccessful quark of the six presented to exist by current scientific theory. Scientists worldwide had sought the top quark since the discovery of the bottom quark at Fermilab in 1977. The discovery provides strong support for the quark theory of the structure of matter.

Two research papers, submitted on Friday, February 24, to Physical Review Letters by the CDF and DZero experiment collaborations respectively, describe the observation of top quarks produced in high-energy collisions between protons and antiprotons, their antimatter counterparts. The two experiments operate simultaneously using particle beams from Fermilab's Tevatron, world's highest energy particle accelerator. The collaborations, each with about 450 members, presented their results at seminars held at Fermilab on March 2.

top quark

Top quark experimental facts



- Top quark produced in SM strong interaction
- Top quark usually decays to a W boson and b quark
- Top quark mass 175 GeV

Fermilab #97-1889

We assume but don't actually know:

- Charge, Spin
- SM electroweak interactions
  - Charged current (*W* boson)
    - Total width
    - CKM matrix
  - Neutral current (*Z* boson, photon)

We really don't know:

- Coupling to Higgs boson?
- Modified coupling to SM particles?
- New physics? New particle?

We assume but don't actually know:

- Charge, Spin
- SM electroweak interactions
  - Charged current (*W* boson)
    - Total width
    - CKM matrix
  - Neutral current (*Z* boson, photon)

Address in RunII at the Tevatron

We really don't know:

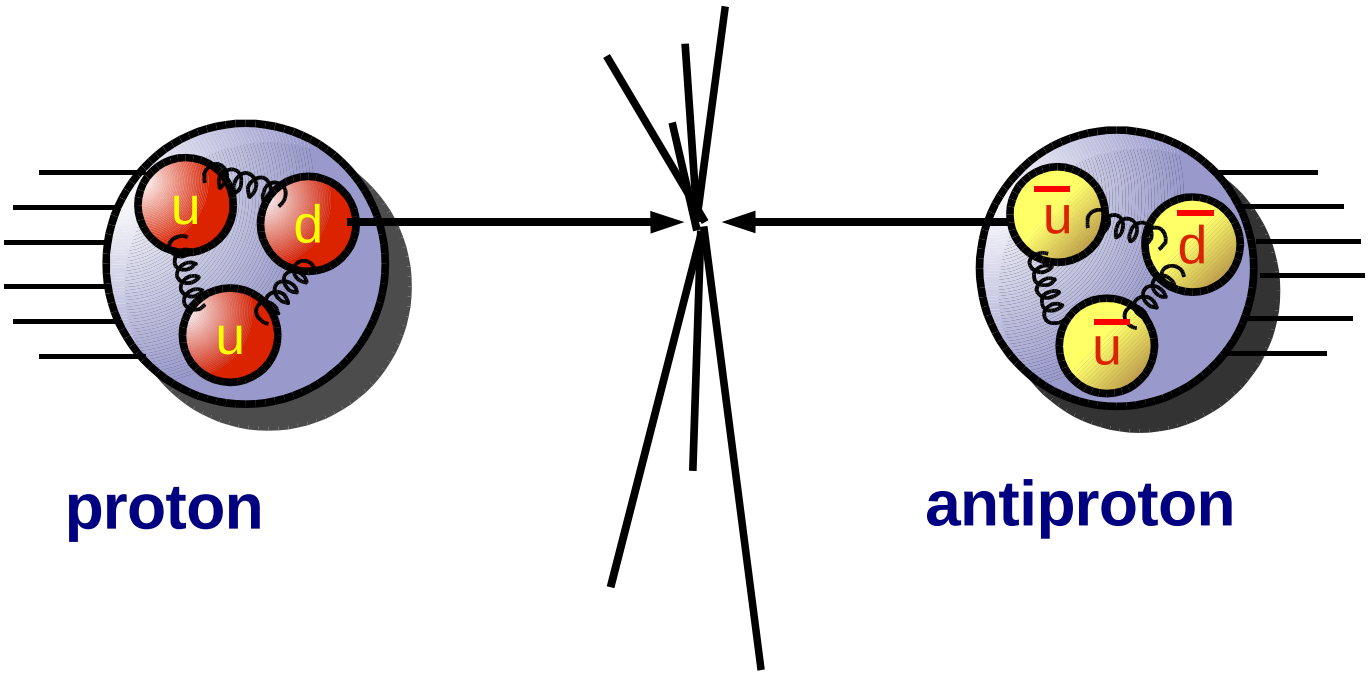
- Coupling to Higgs boson?
- Modified coupling to SM particles?
- New physics? New particle?

Experimental procedure

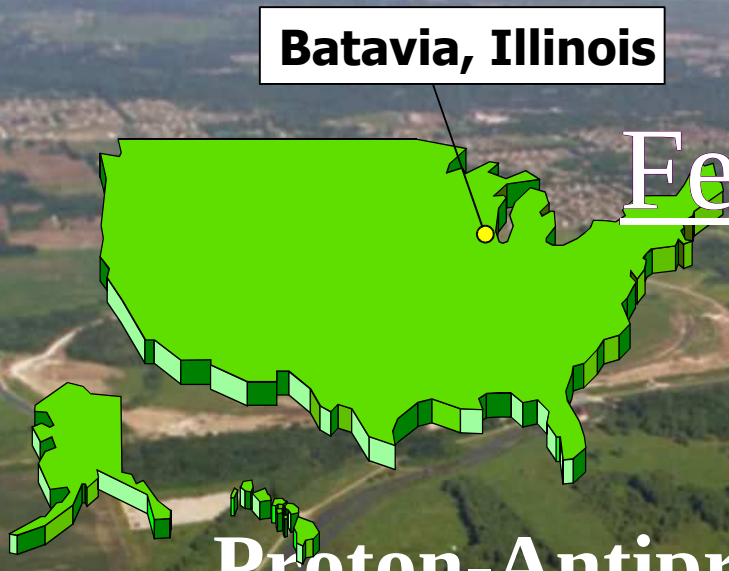
How do we find out?

The energy frontier

Probe physics at small distances
by colliding particles at high energy



Experimental setup: Fermilab Tevatron in Run II



Proton-Antiproton Collider

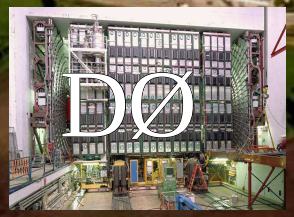
CM Energy 1.96TeV

→ *Energy Frontier*

Instantaneous luminosity 160E30cm^{-2}s^{-1}

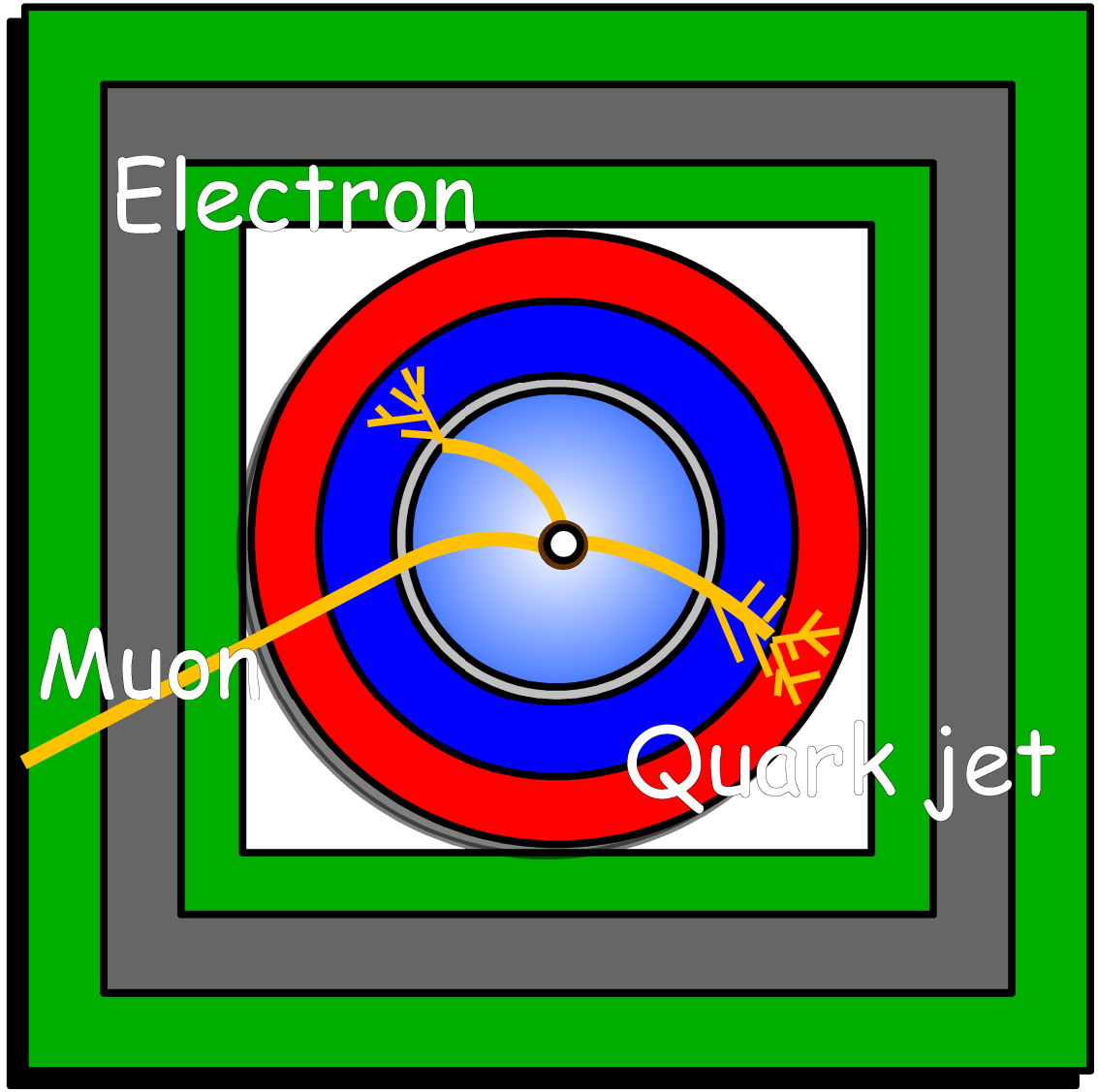
– ~3 interactions per crossing, 1.7M crossing per second

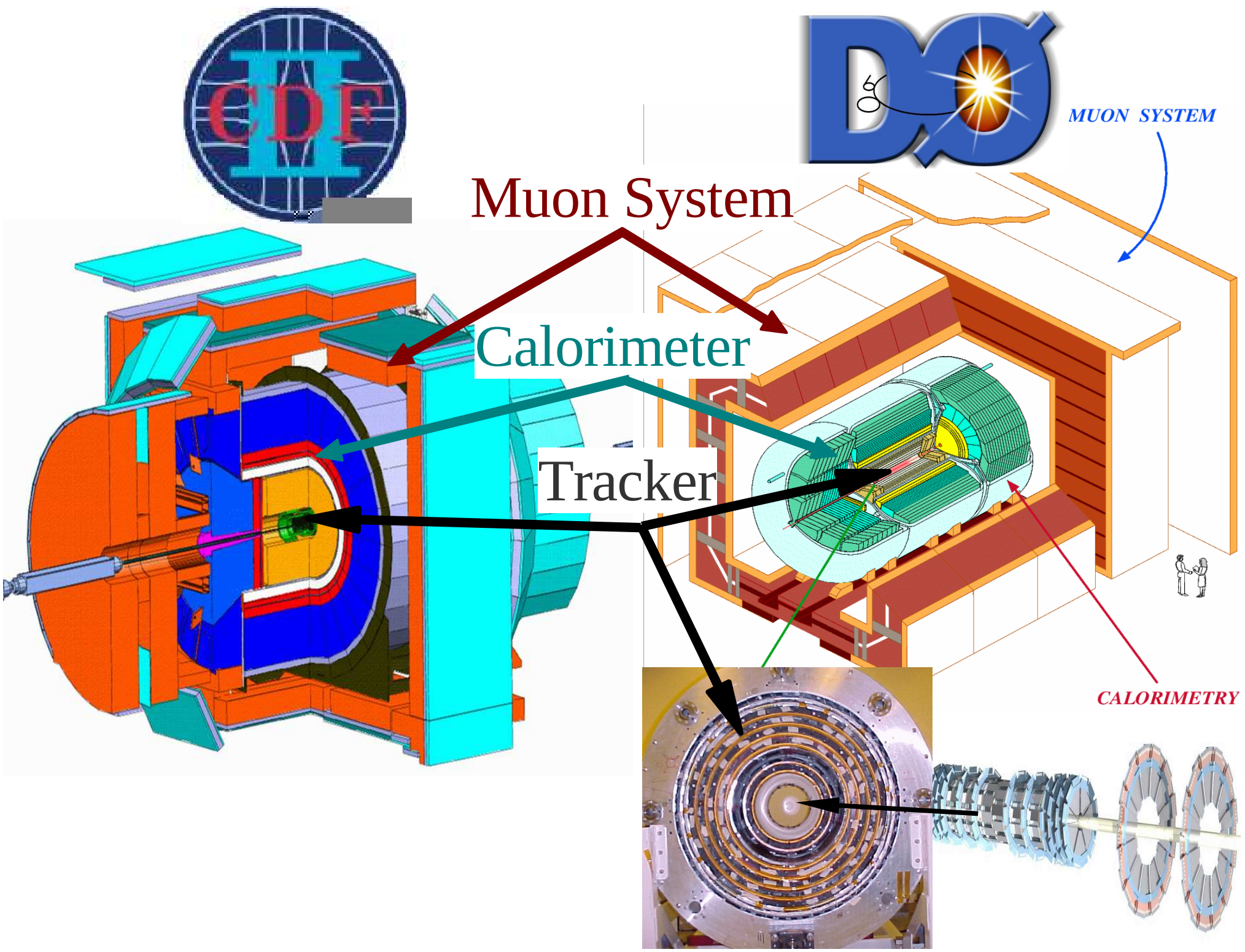
→ *Luminosity Frontier*



Experimental setup: detector configuration

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

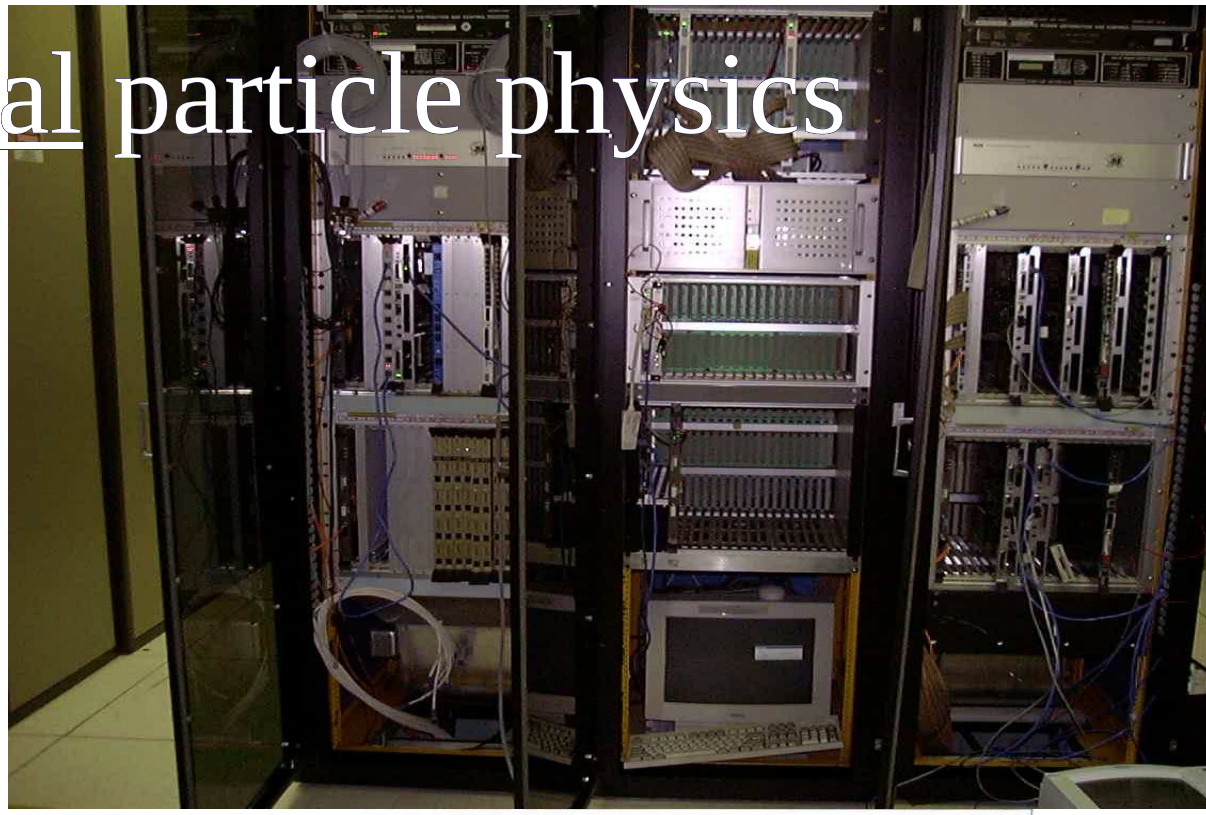


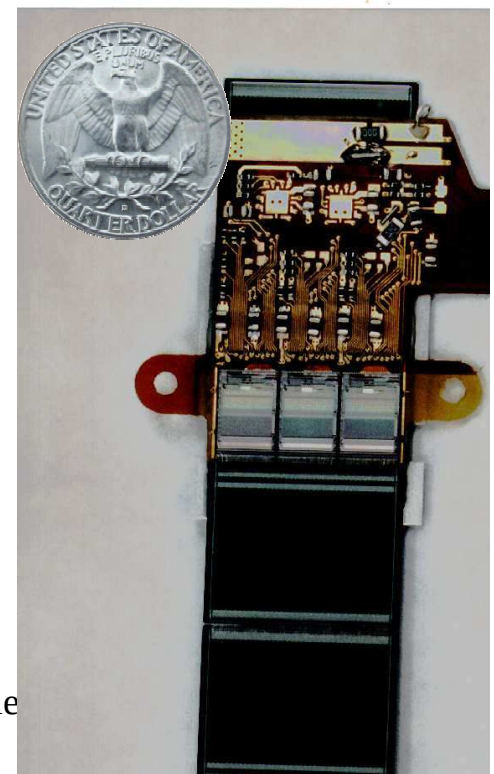

CDF
DØ
MUON SYSTEM
Muon System
Calorimeter
Tracker
CALORIMETRY

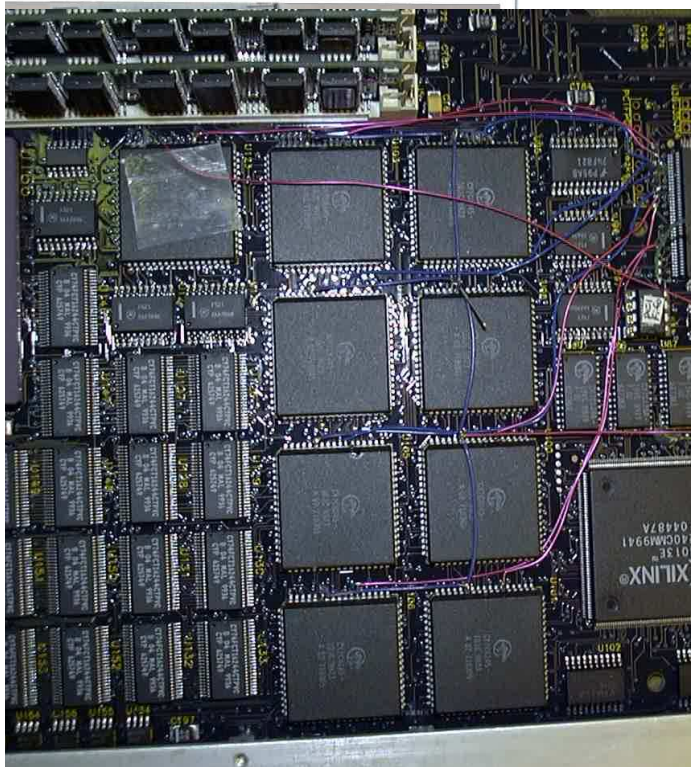
Experimenters

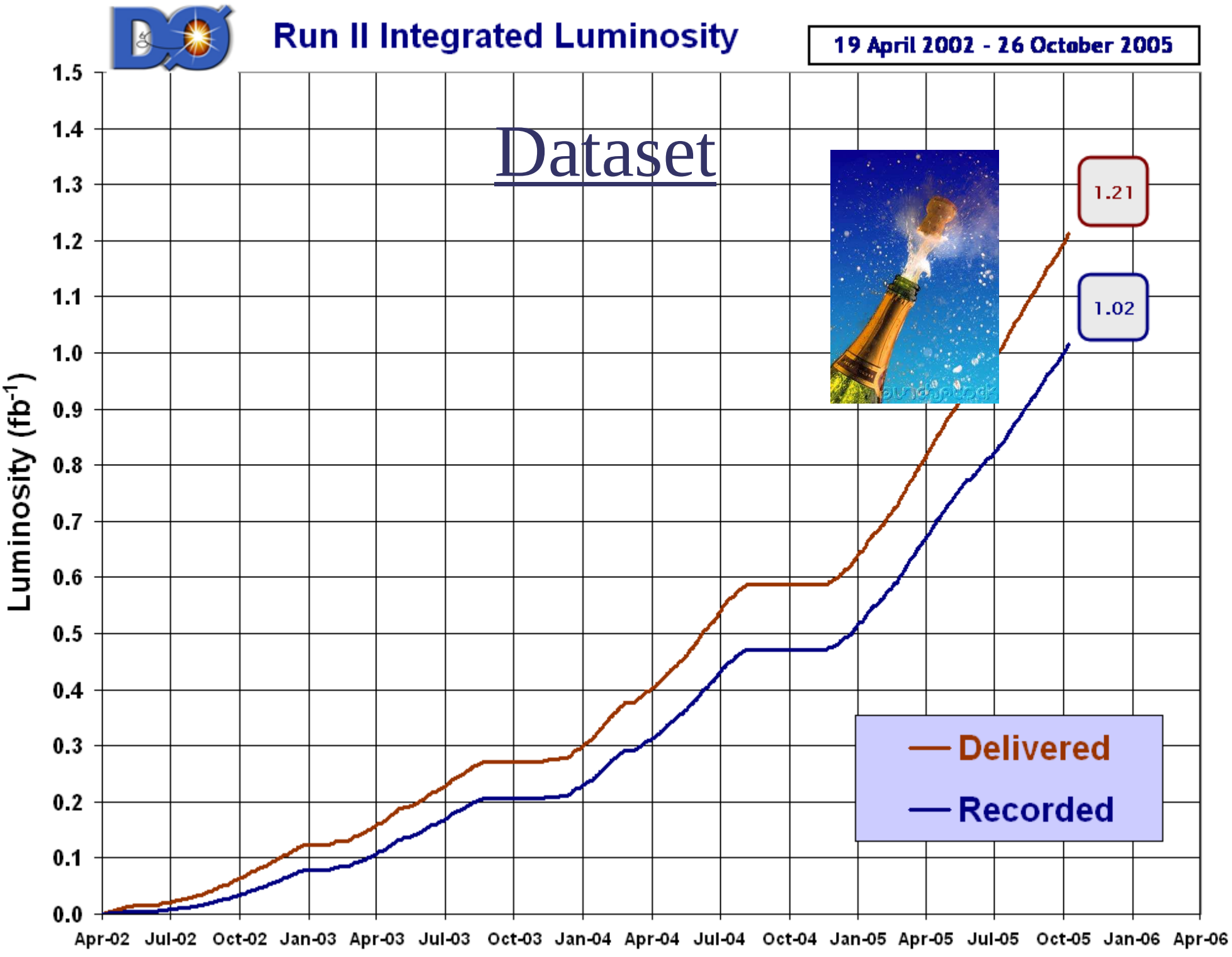
Together
> 1400 physicists
from 21 countries

Experimental particle physics

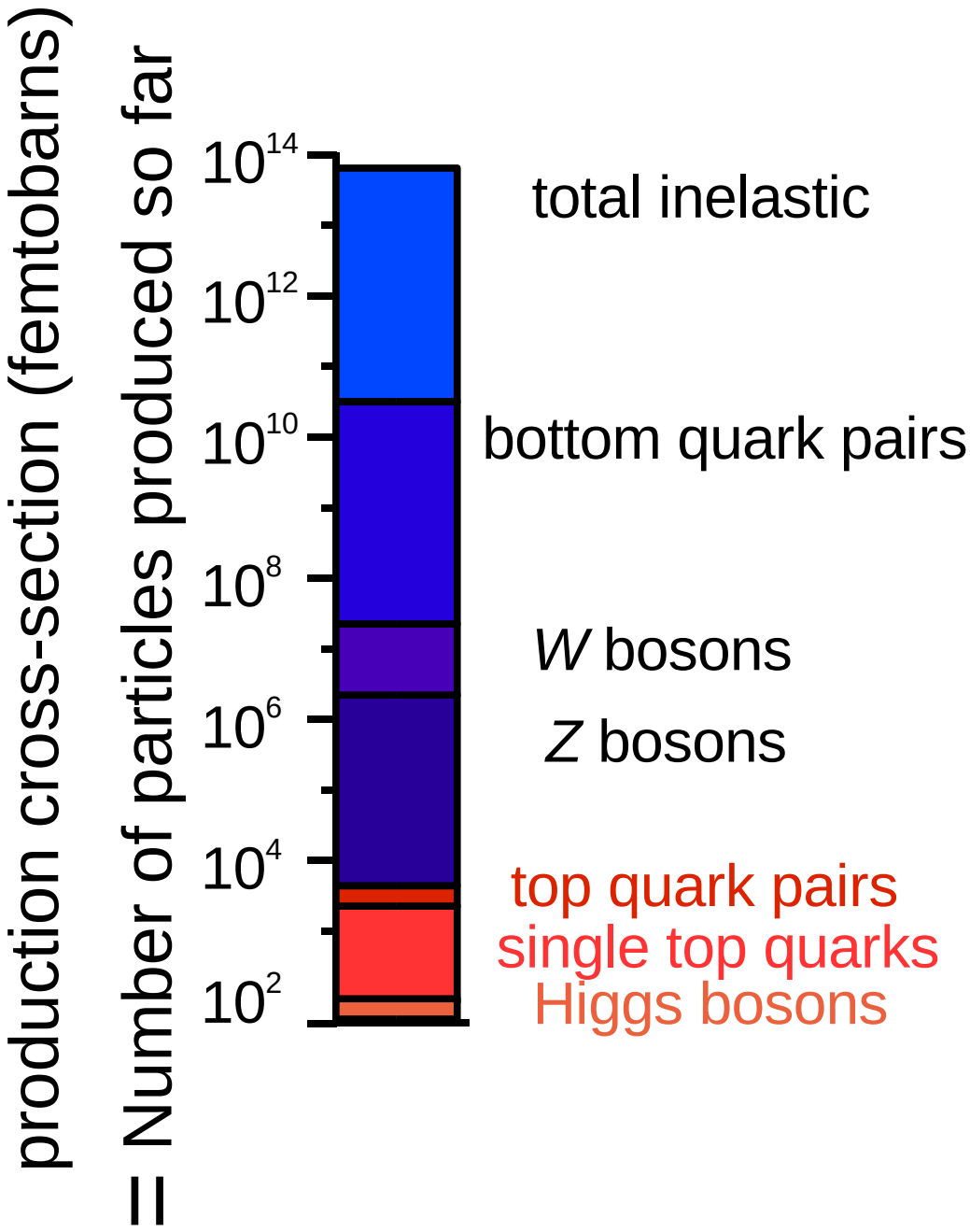




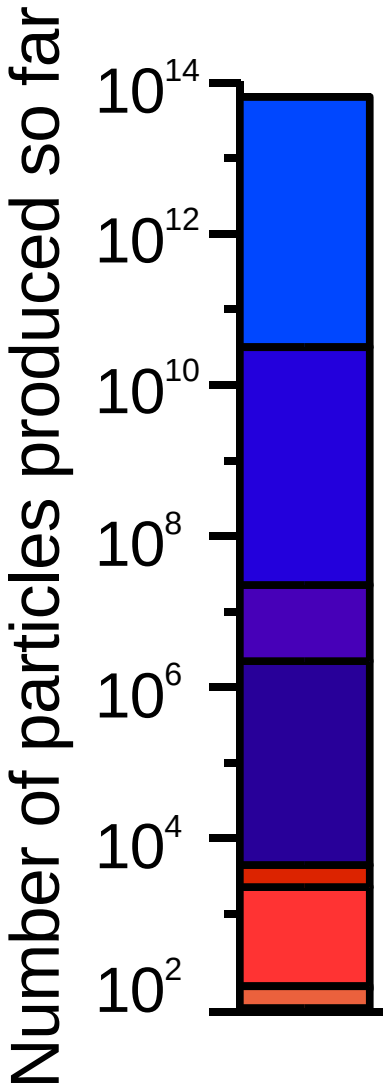



Run II Integrated Luminosity
19 April 2002 - 26 October 2005
Dataset
1.21
1.02
Delivered
Recorded
Luminosity (fb-1)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
Apr-02
Jul-02
Oct-02
Jan-03
Apr-03
Jul-03
Oct-03
Jan-04
Apr-04
Jul-04
Oct-04
Jan-05
Apr-05
Jul-05
Oct-05
Jan-06
Apr-06

Particle production at the Tevatron



Tevatron physics program



total inelastic

bottom quark pairs

W bosons

Z bosons

top quark pairs

single top quarks

Higgs bosons

Precision quark jet physics

Bottom quark physics

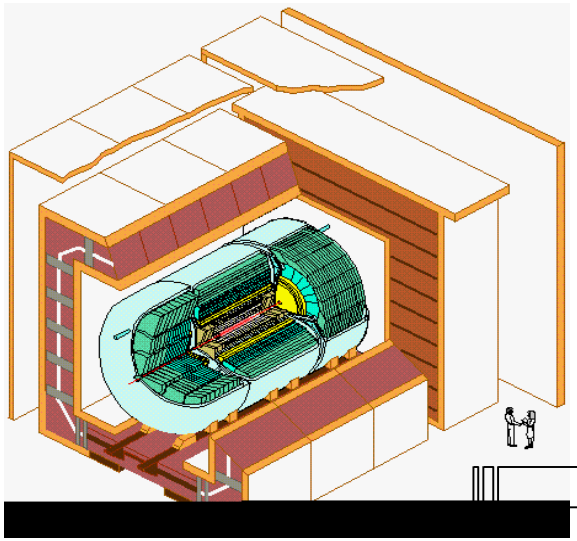
Precision electroweak physics

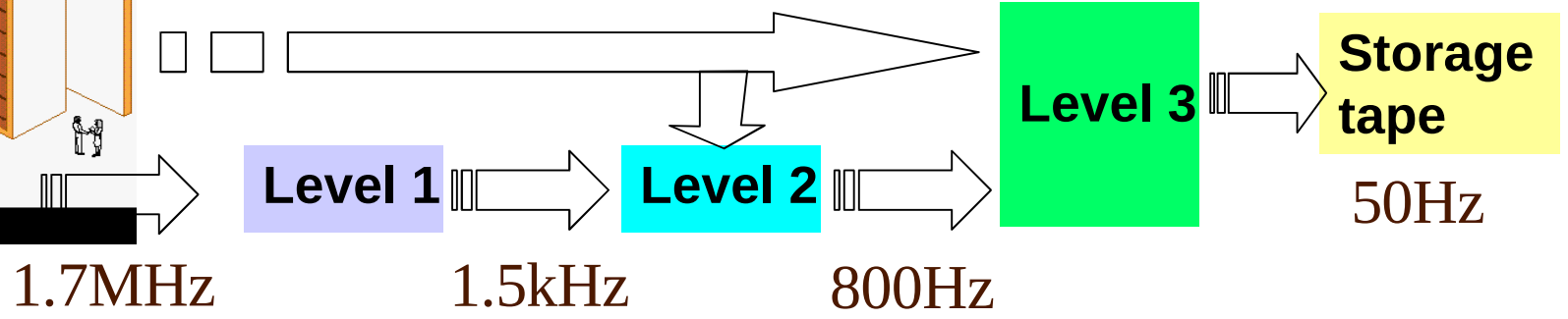
Top quark measurements

Searches for new physics

Higgs boson searches

Collecting interesting events: Trigger System



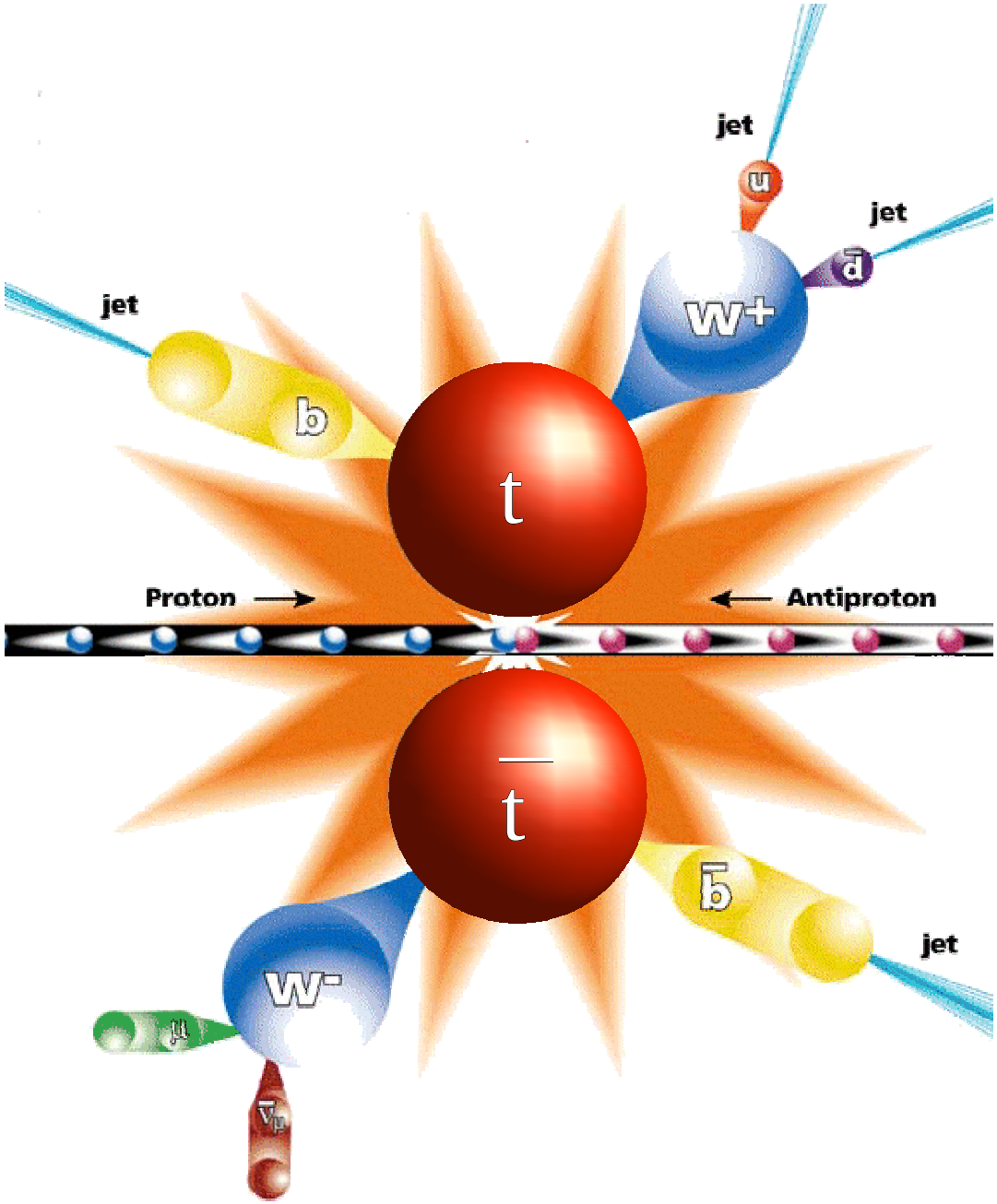


- Reduce rate of interactions (inelastic collision rate) to manageable level that can be stored
- Record "interesting" events → Trigger system
  - Select events containing high-energy final state objects
    - Electrons, muons, quark jets

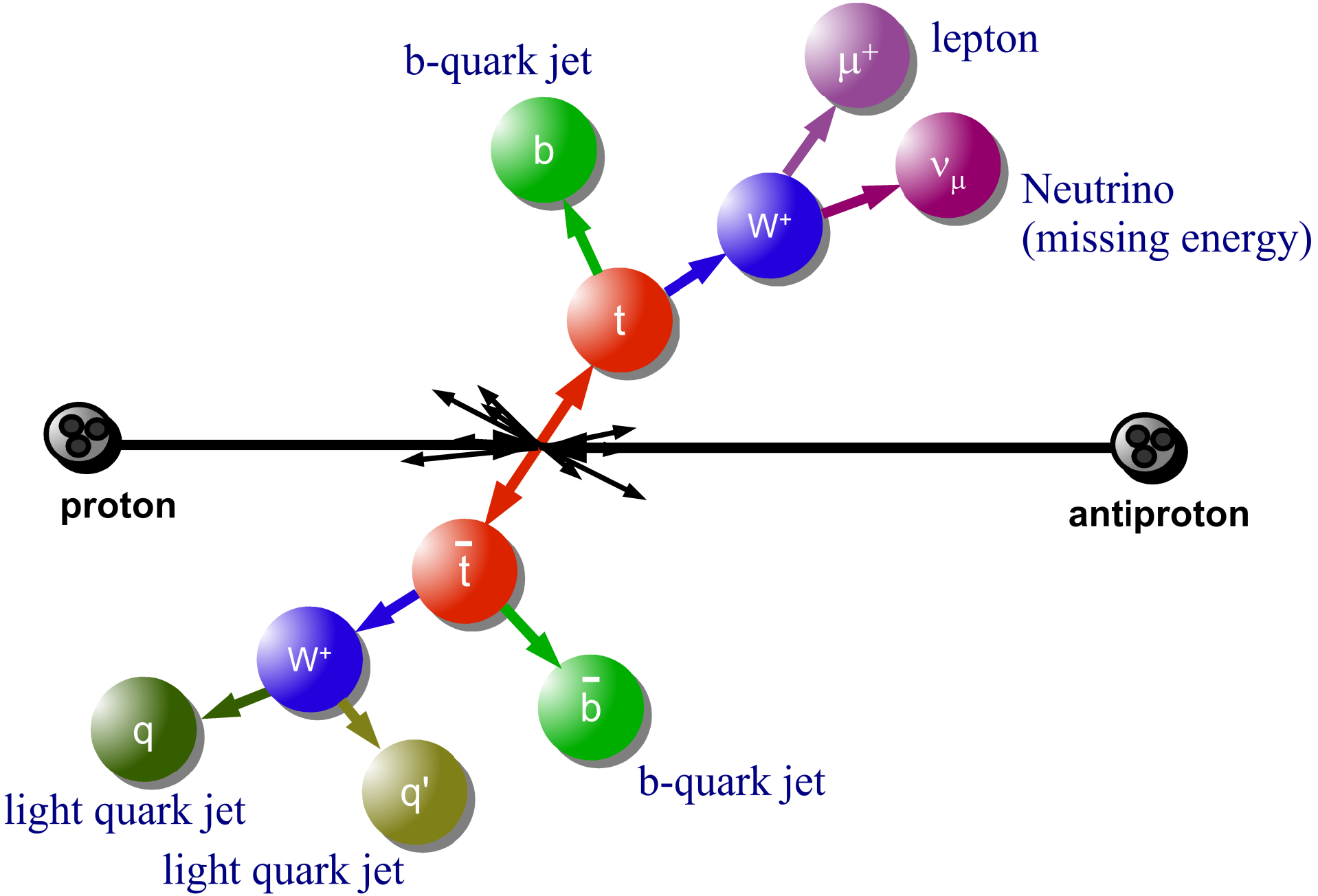
Event Selection

How do we find top quarks?

Top Quark pair production



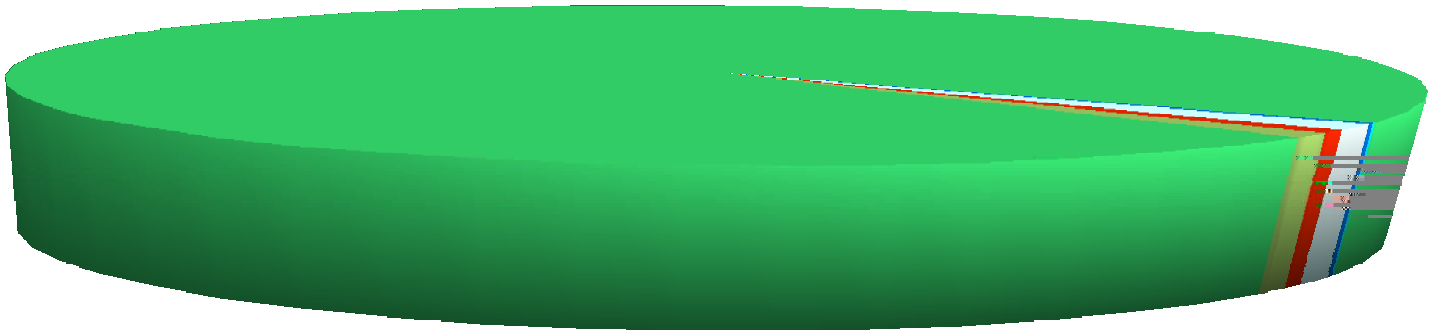
Top quark pair selection: lepton+jets



Event selection result

10,000 events with lepton, neutrino, ≥ 2 jets

expect ~250 top quarks



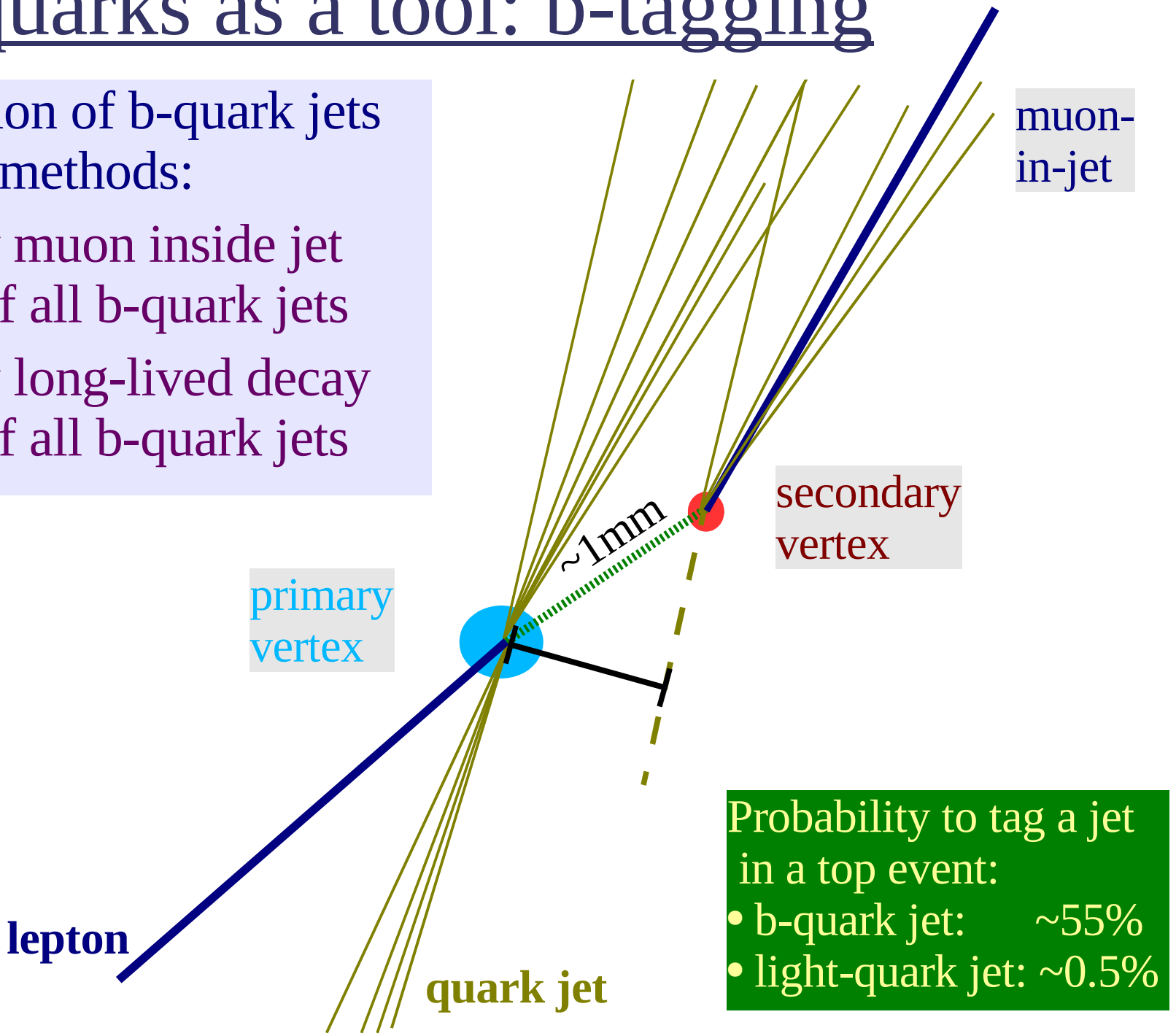
Backgrounds

Top quark pairs

In 360pb^{-1}, lepton+jets

b quarks as a tool: b-tagging

- Identification of b-quark jets
  2 possible methods:
  - Identify muon inside jet
    ~20% of all b-quark jets
  - Identify long-lived decay
    ~35% of all b-quark jets

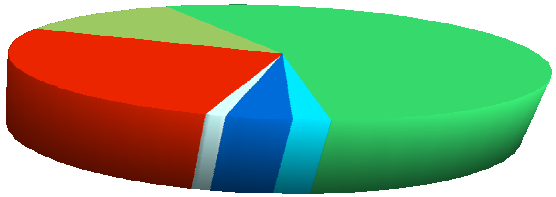


Probability to tag a jet
in a top event:
- b-quark jet: ~55%
- light-quark jet: ~0.5%

Top Quark Events

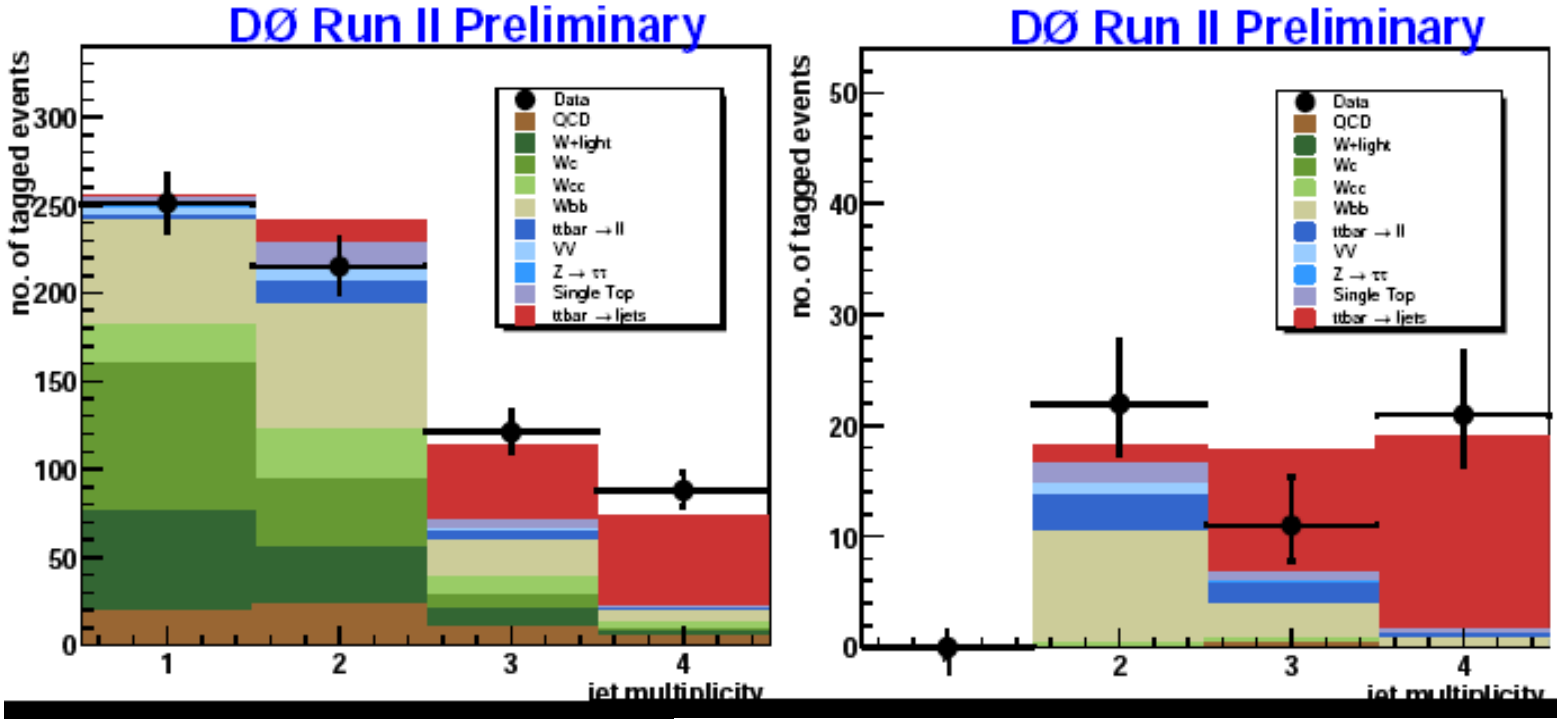
=1 b-tag:
367 events

=2 b-tags:
76 events



Top quark pairs

Backgrounds

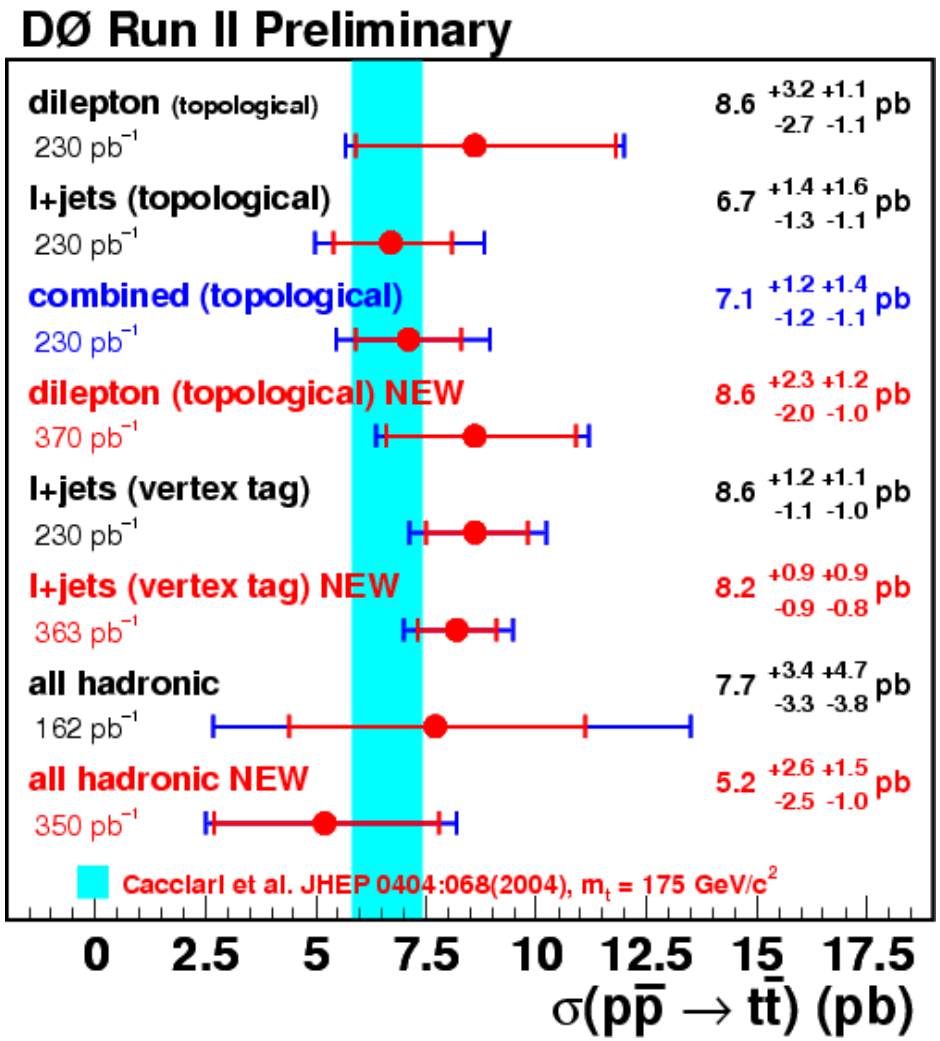


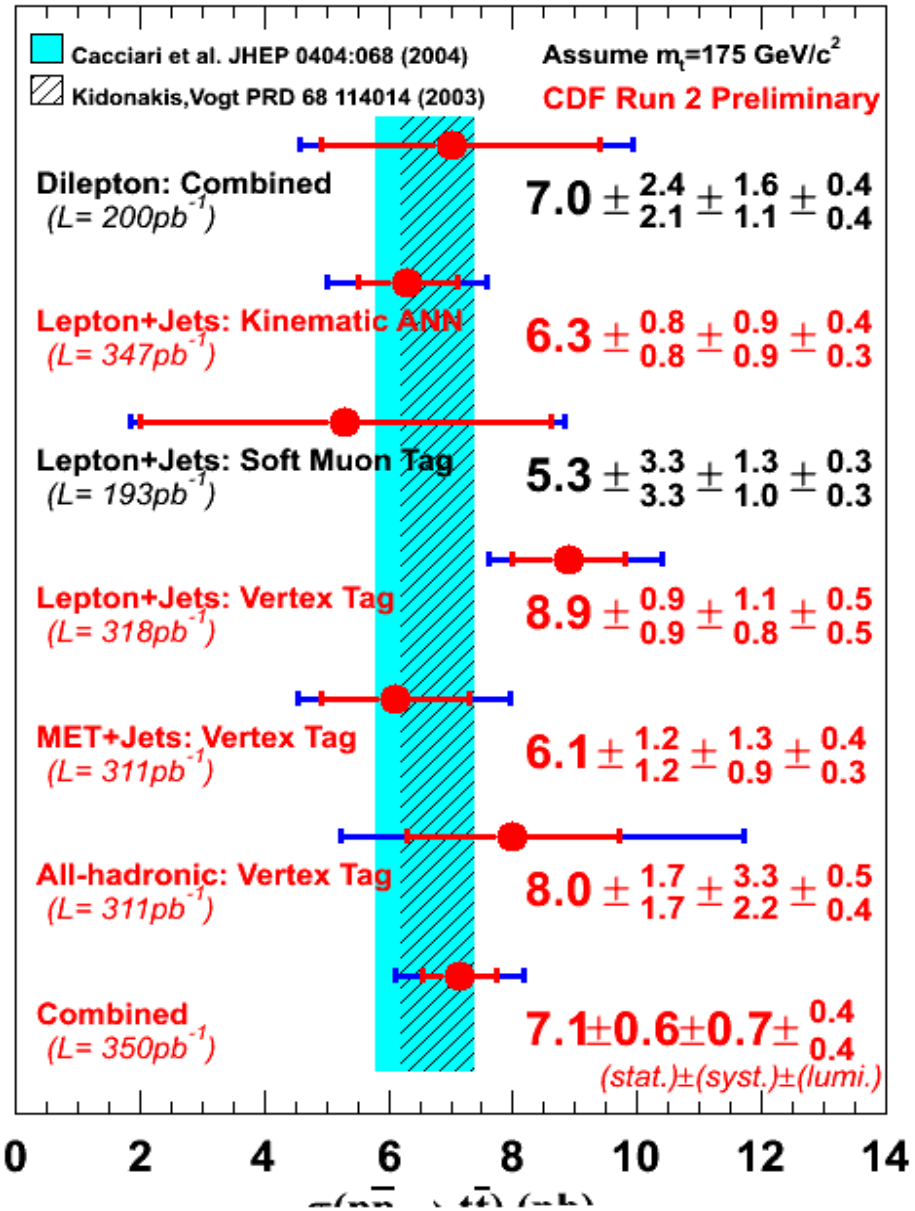
Current Results

What have we learned?

Production cross section

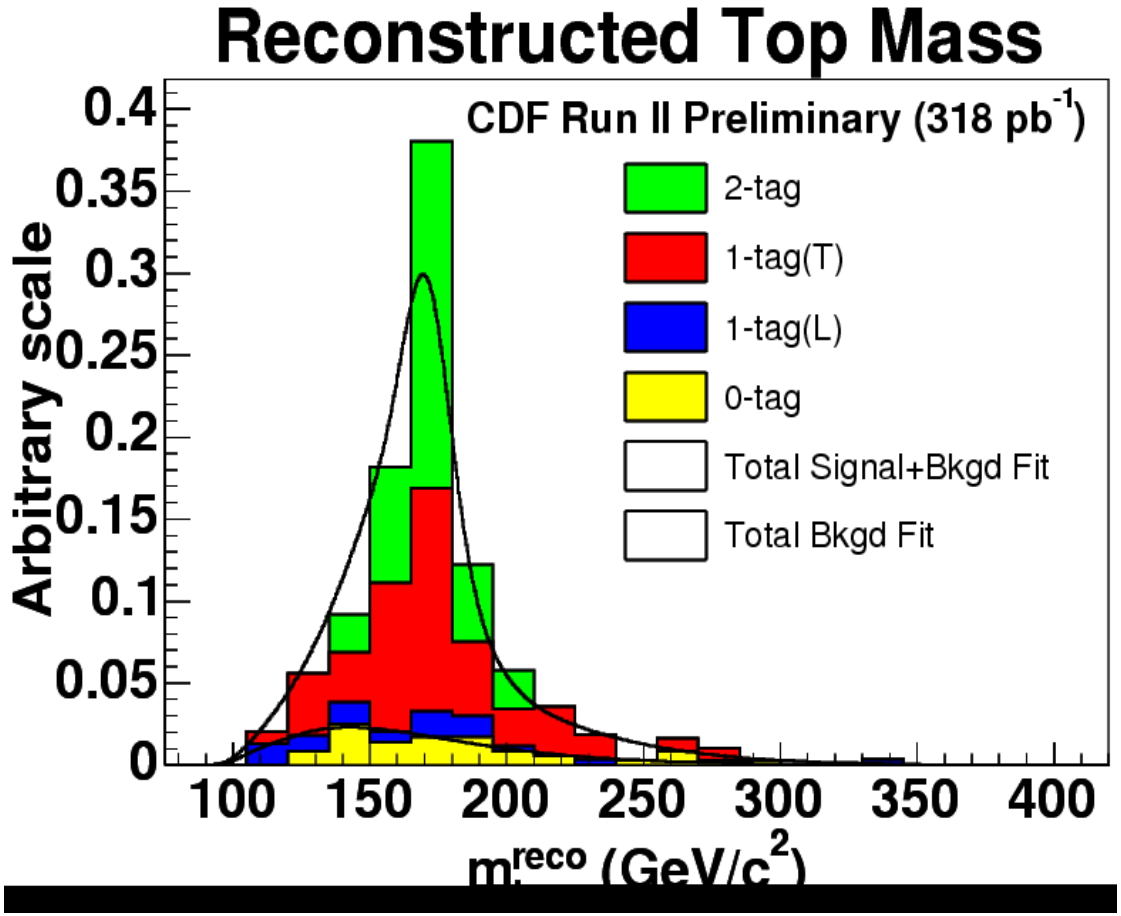
- At what rate are top pairs being produced?
  - Test of strong interaction

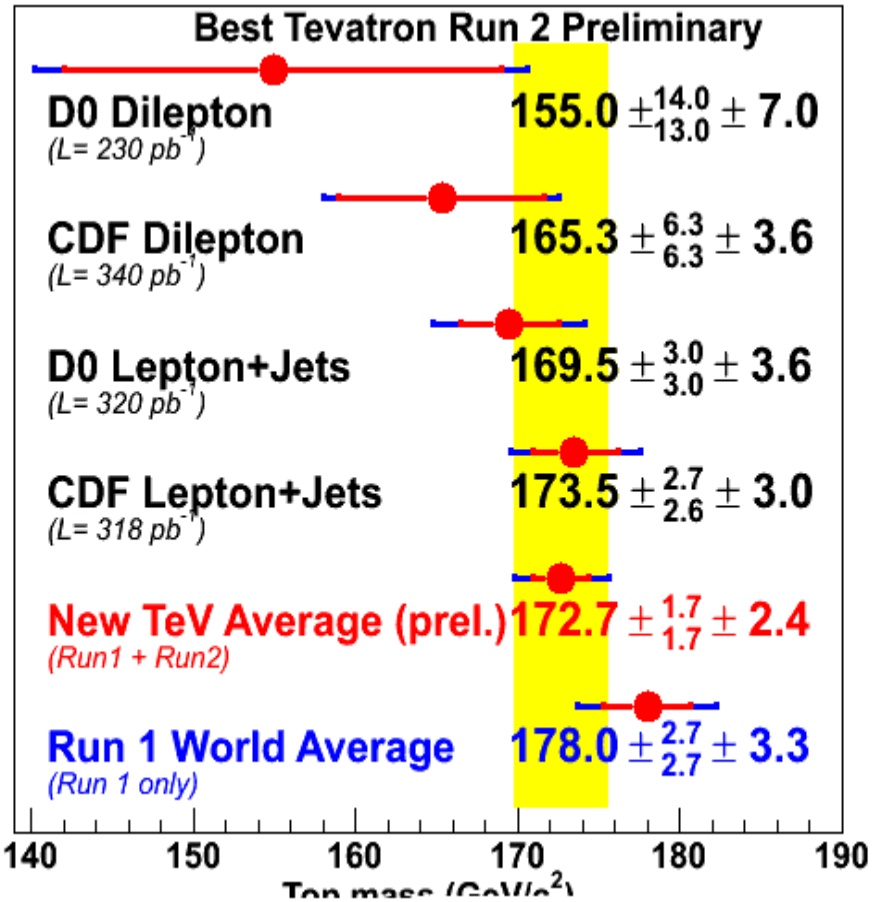


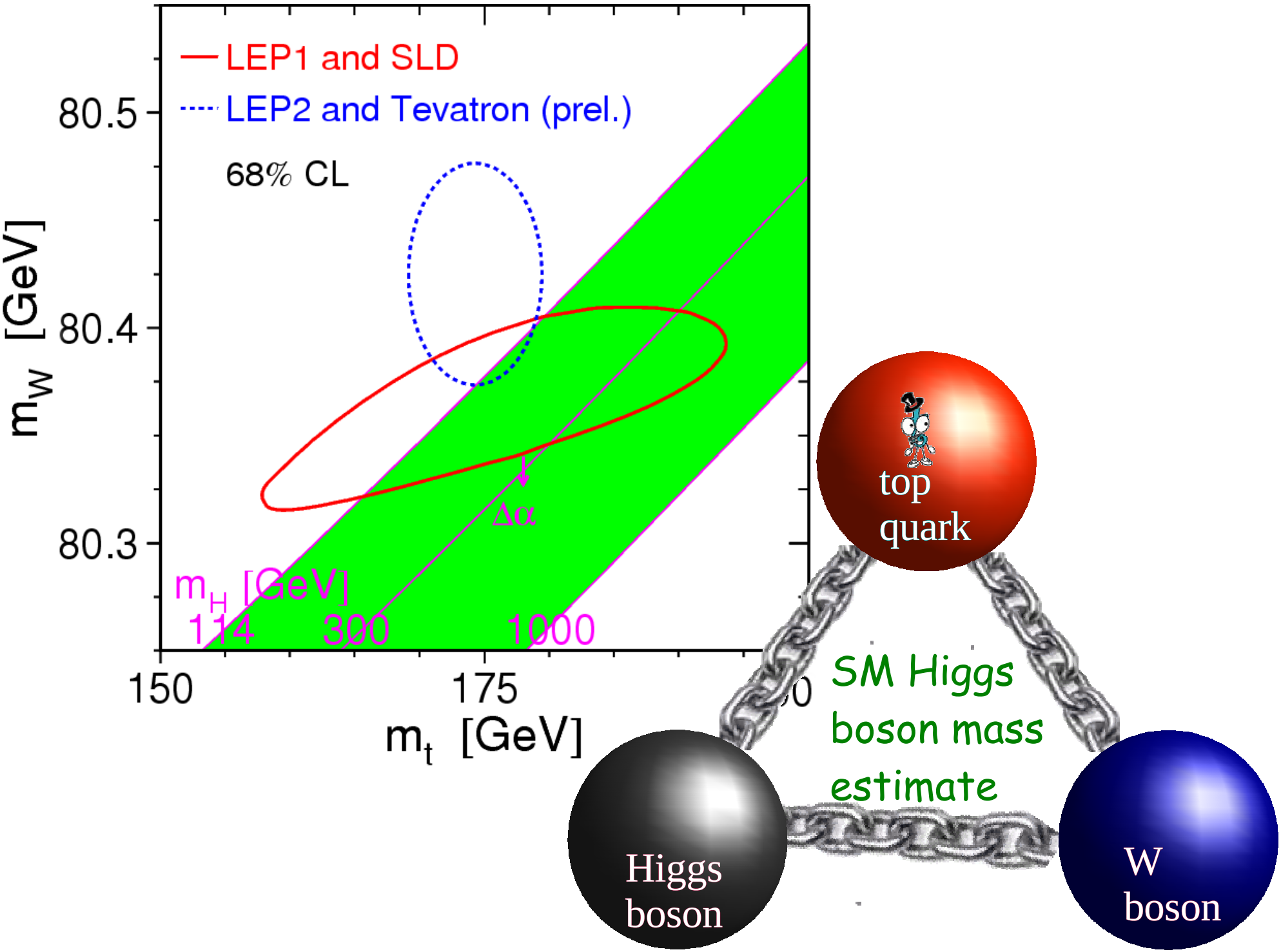


Top Quark Mass Determination

- Large sample of top quarks
- Advanced analysis techniques
  - ➔ Measurement uncertainty dominated by systematic effects

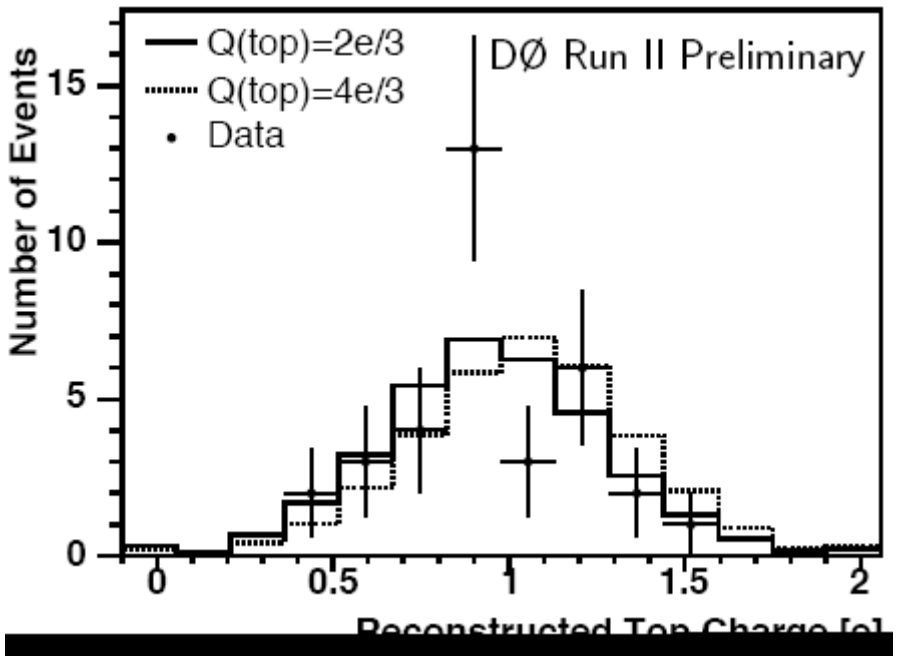





LEP1 and SLD
LEP2 and Tevatron (prel.)
68% CL
80.5
80.4
80.3
m_W [GeV]
$\Delta\alpha$
m_H [GeV]
114
300
1000
150
175
m_t [GeV]
top quark
SM Higgs boson mass estimate
Higgs boson
W boson

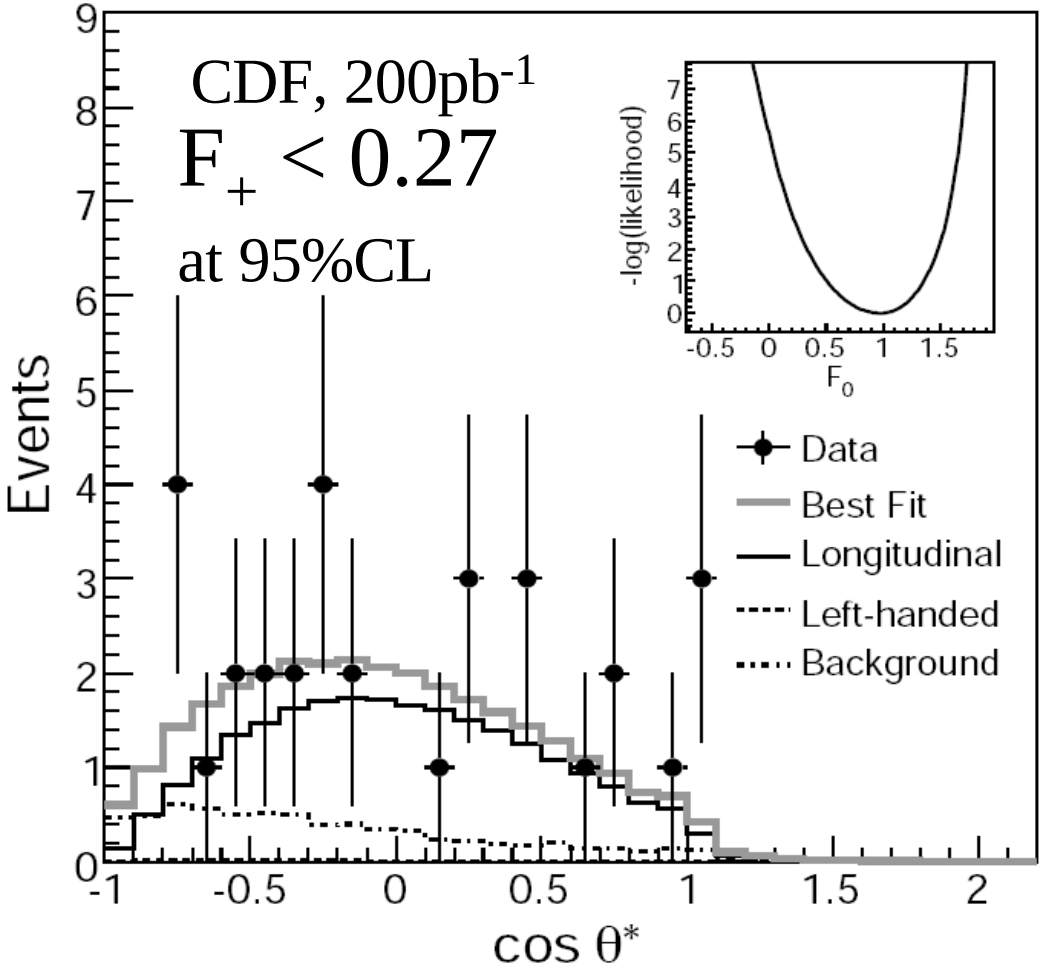
Other top quark properties

Top quark charge = 2/3 or 4/3?



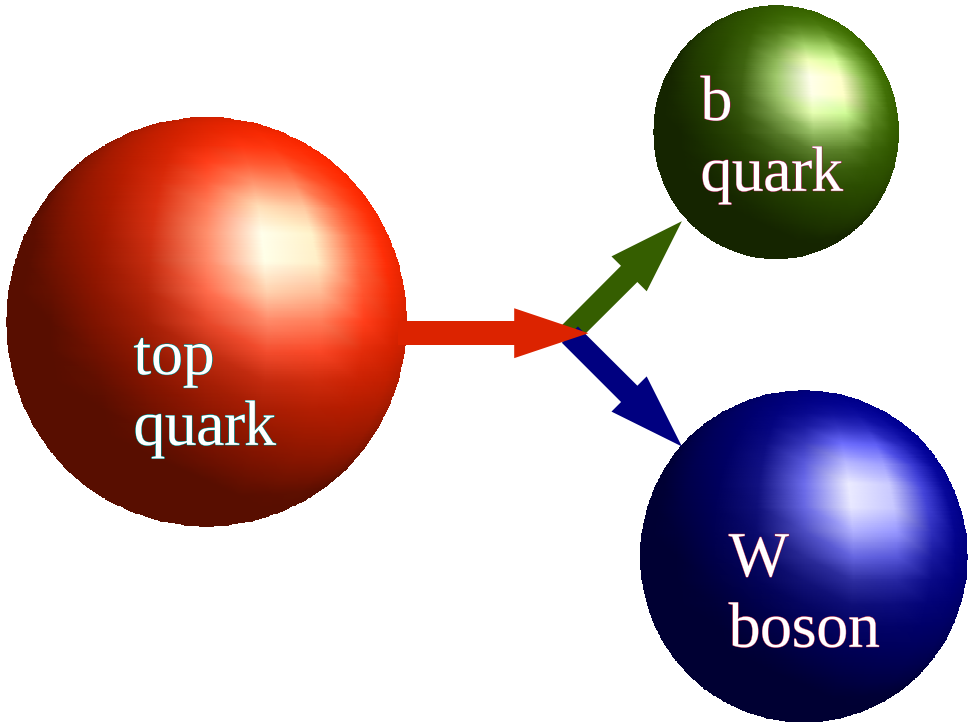
Result: charge=2/3

Structure of the interaction? According to SM?



DØ: $F_+ < 0.25$ at 95%CL

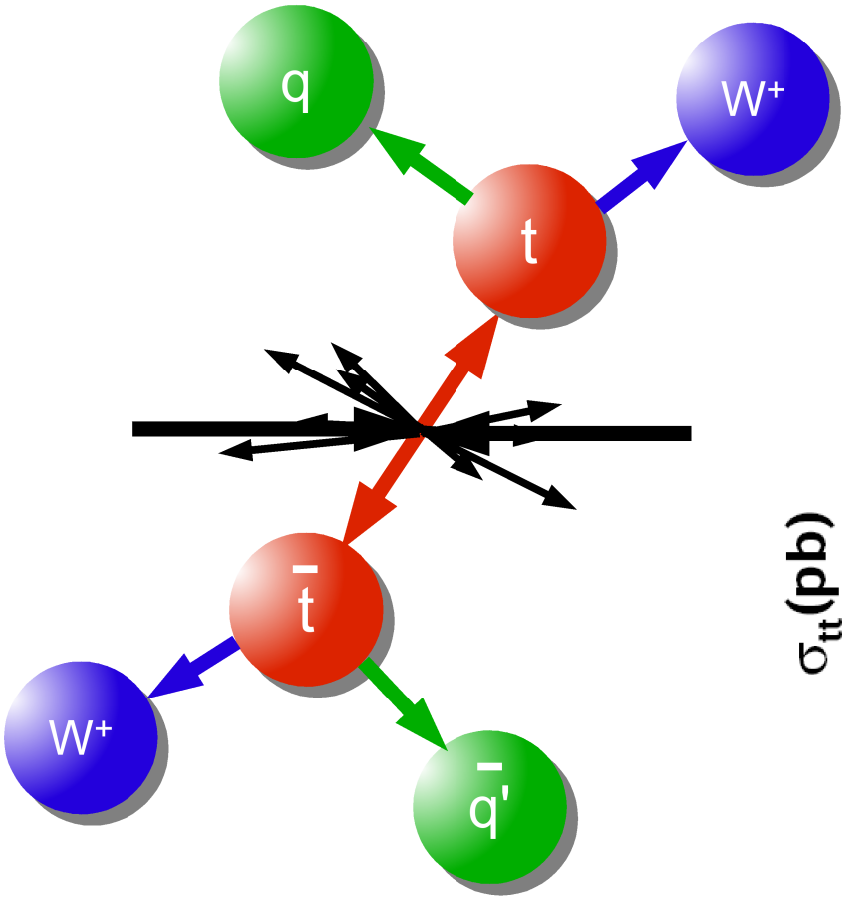
Top quark electroweak charged current interaction



Top quark decay

Top quark decay branching ratios

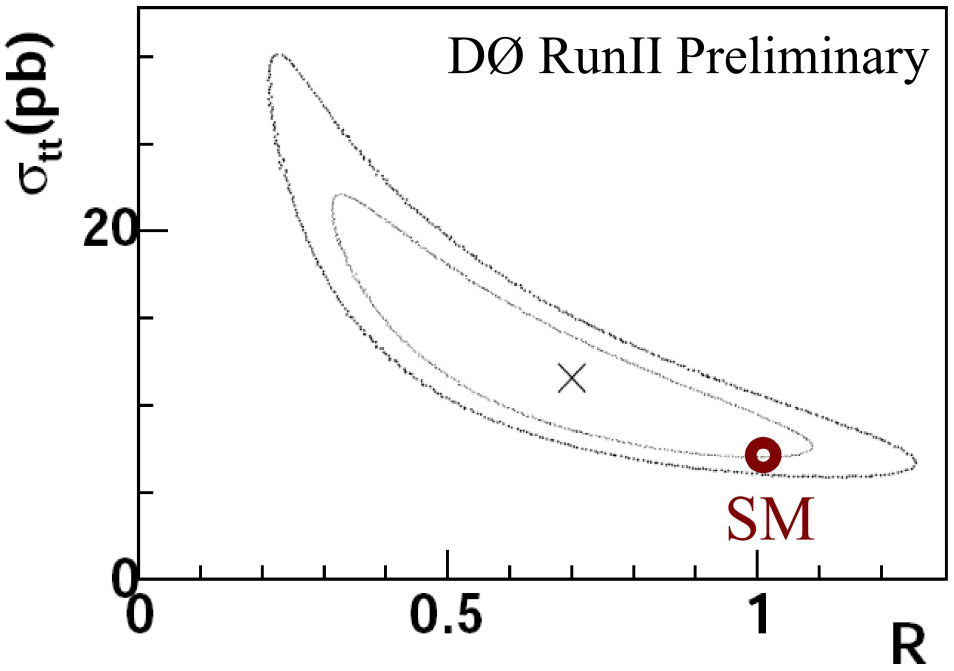
b quark or other flavor?



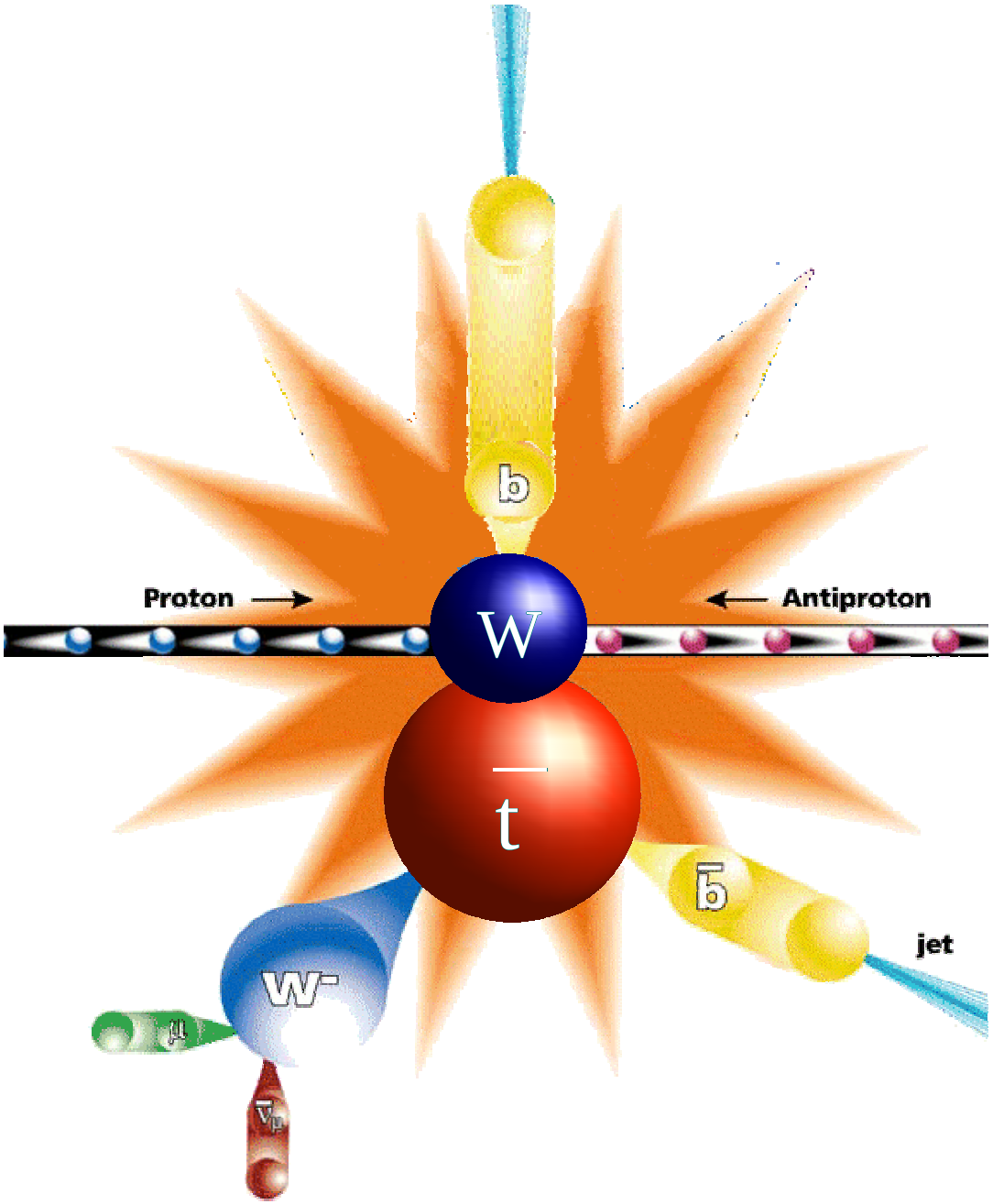
b quark or other flavor?

$$R = \frac{t \to W + b\ \text{quark}}{t \to W + \text{any quark}} \sim \frac{\#\ \text{with 2 b-tagged jets}}{\#\ \text{with 1 b-tagged jets}}$$

CDF: R>0.61 at 95%CL



Single top quark production

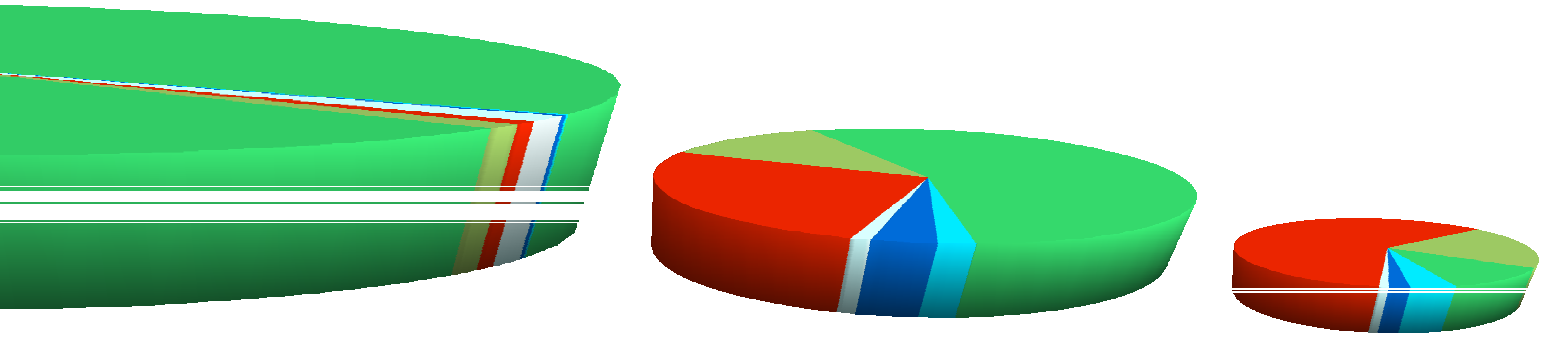


Top Quark Events

All: 10,000 events

=1 b-tag: 367 events

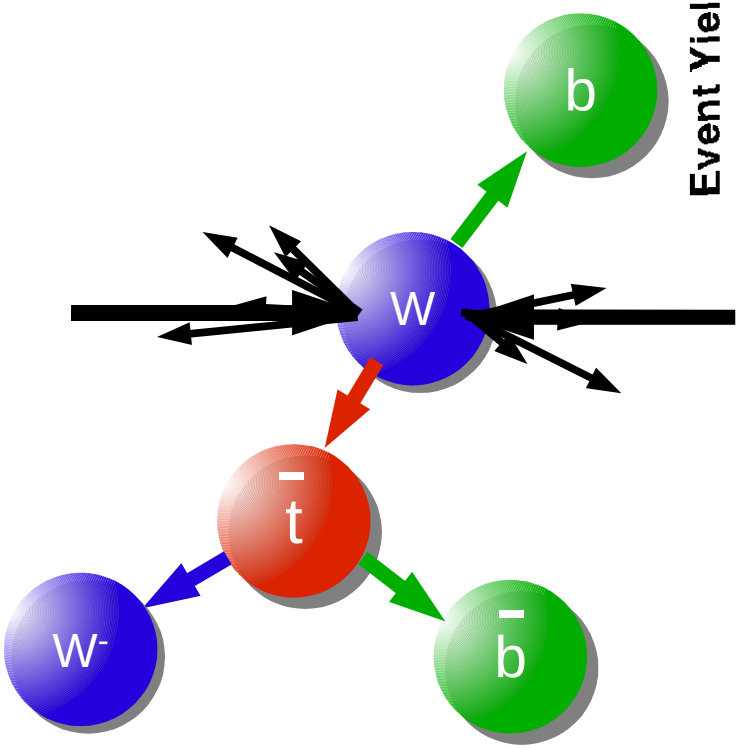
=2 b-tags: 76 events

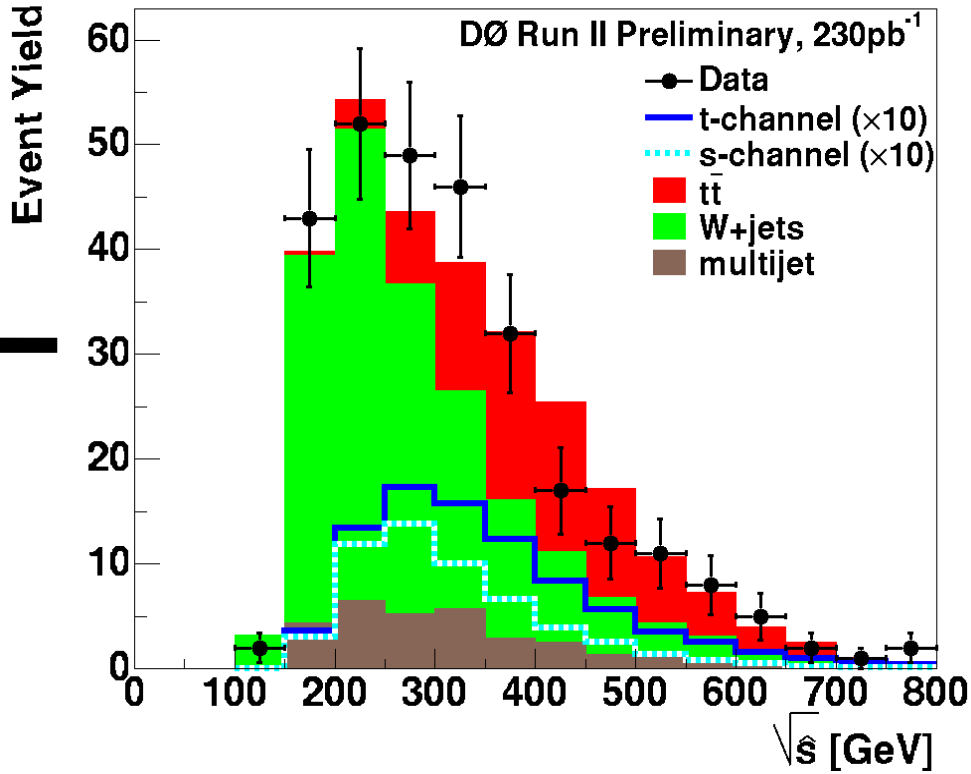


Top quark pairs

Backgrounds

Single top

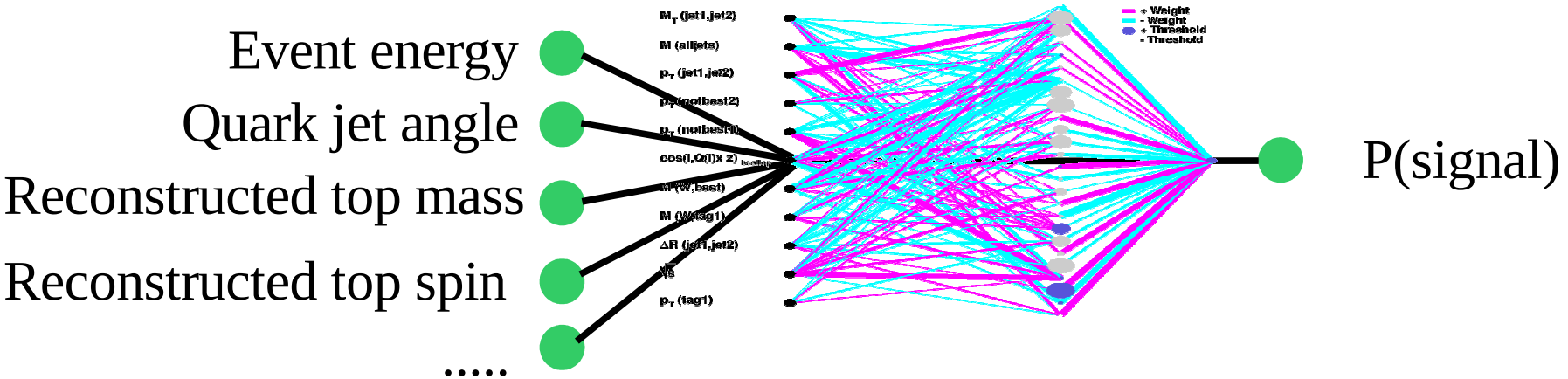




Separating Signal from Backgrounds

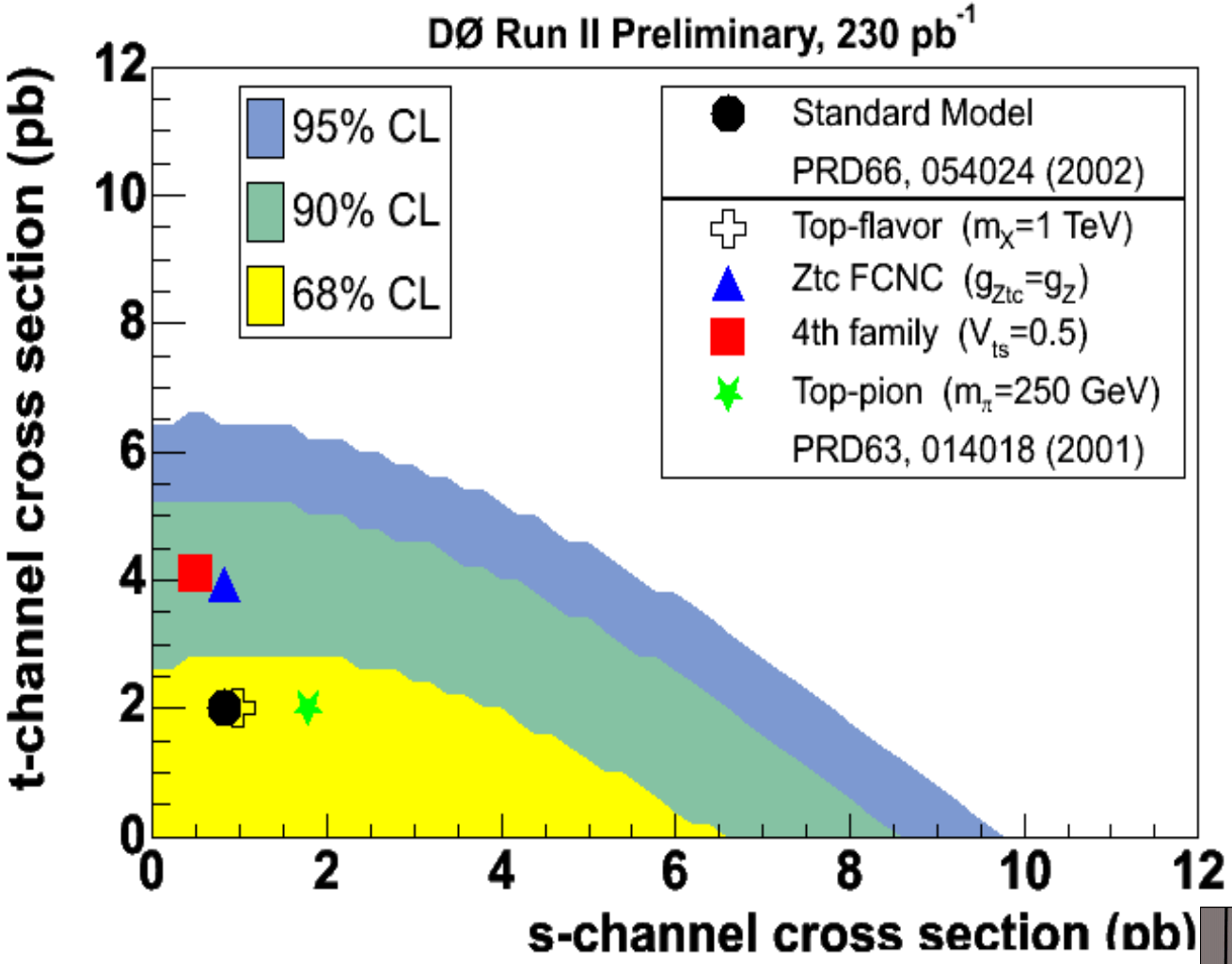
- Optimized event analysis

Input:	Method:	Output:
discriminating variables	multivariate analysis Neural Networks, Decision Trees, etc	signal probability



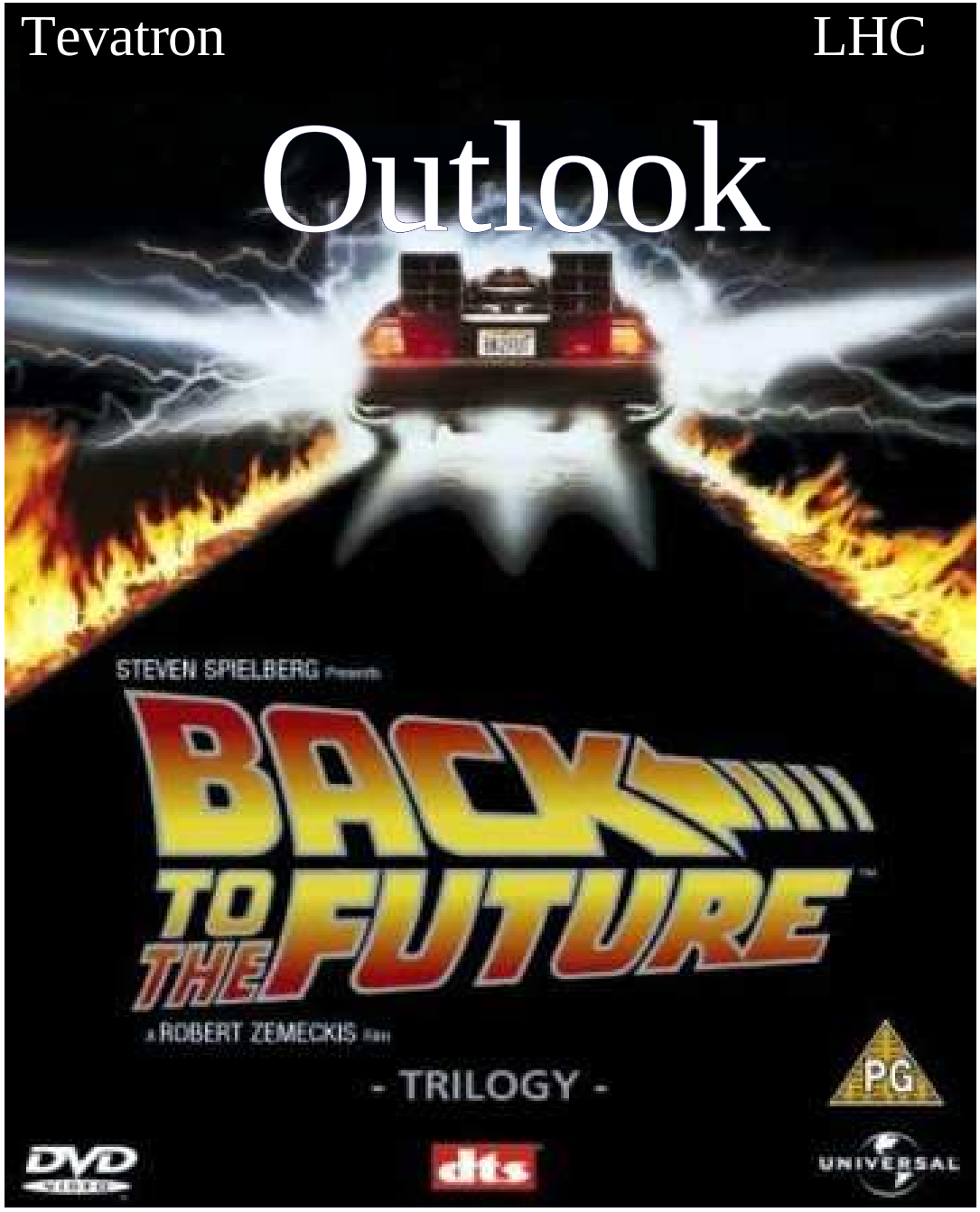
Single top search status

using only muon channel data



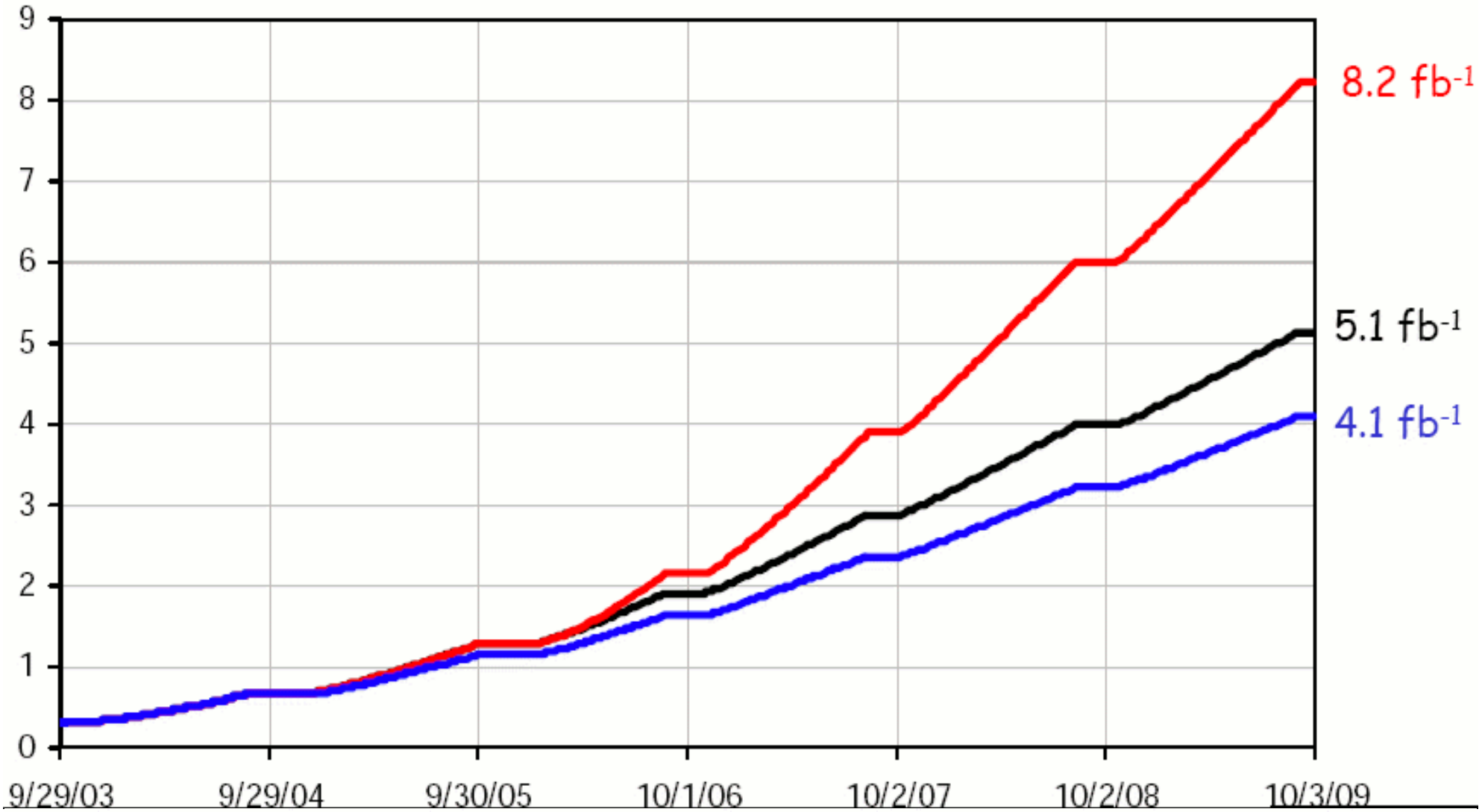
using only electron channel data

DØ collaboration, PLB 622, 265 (2005)

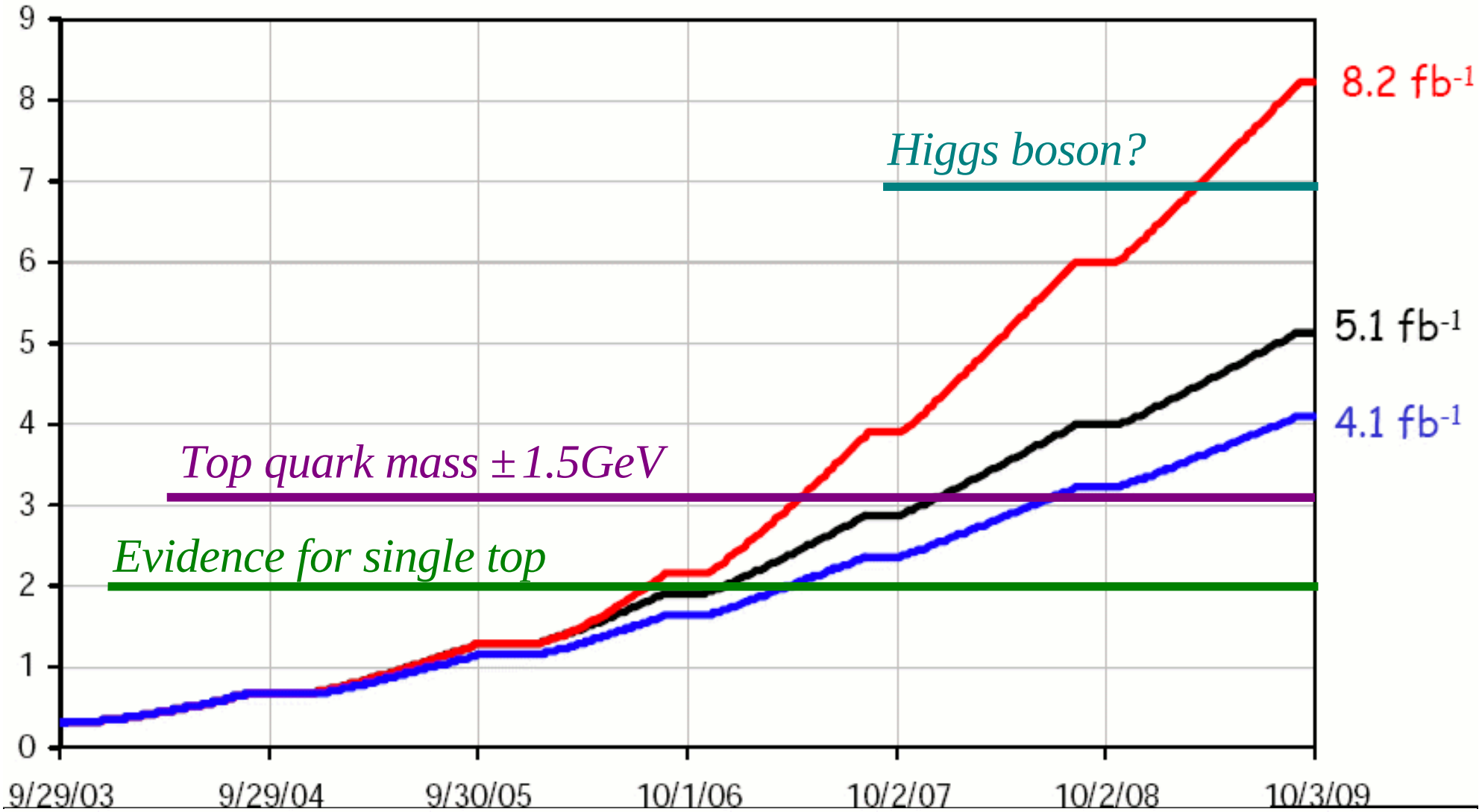


I never think of the future. It comes soon enough.
Albert Einstein

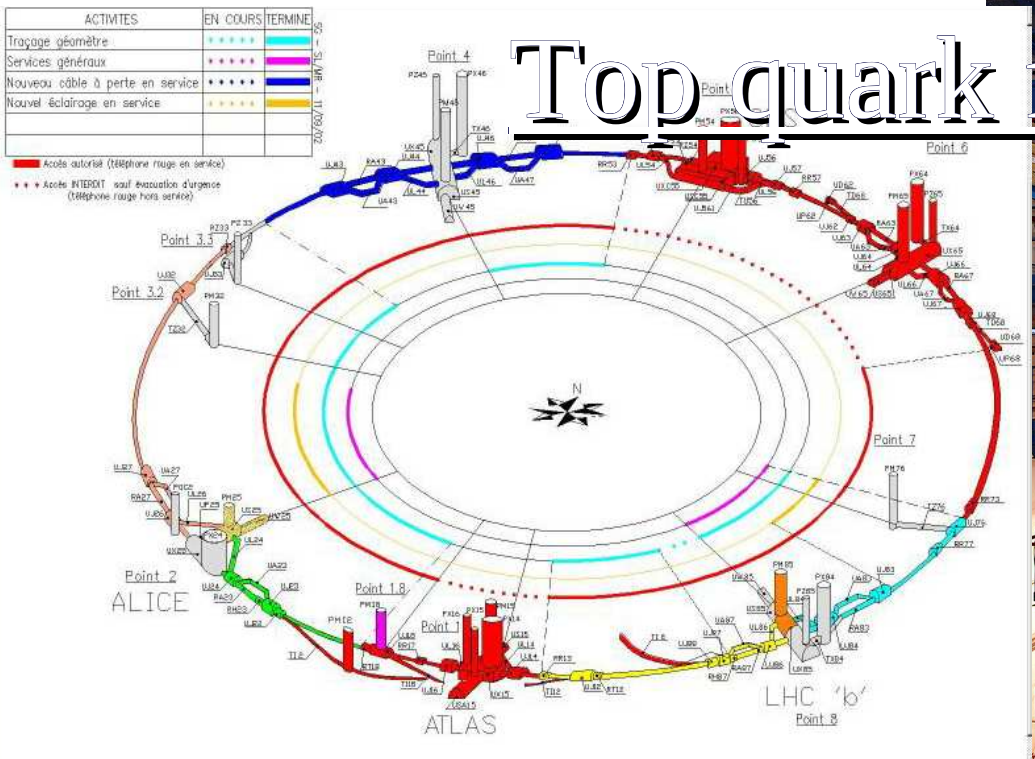
Tevatron luminosity projection

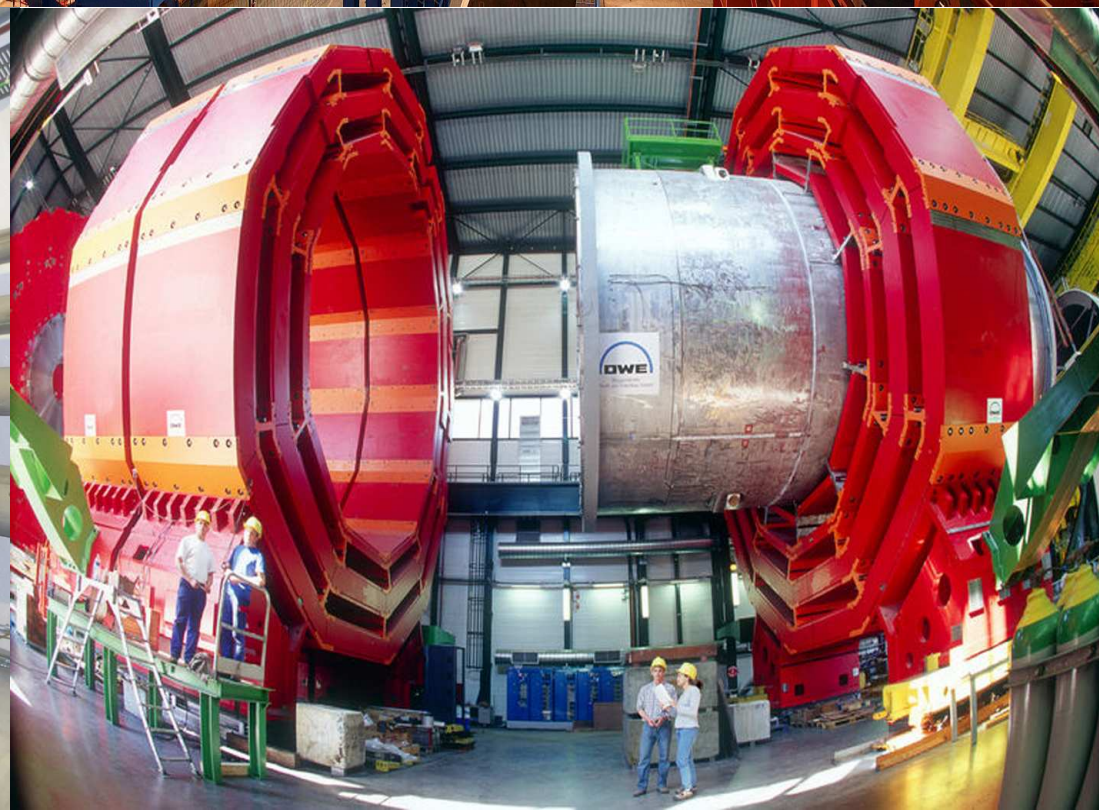


Tevatron luminosity projection

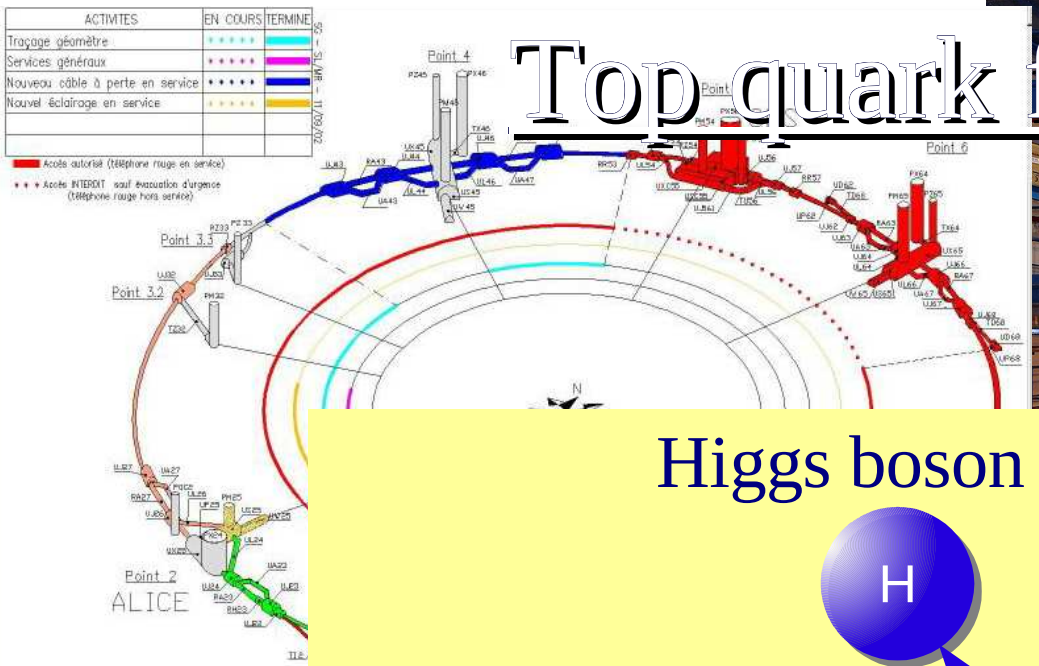


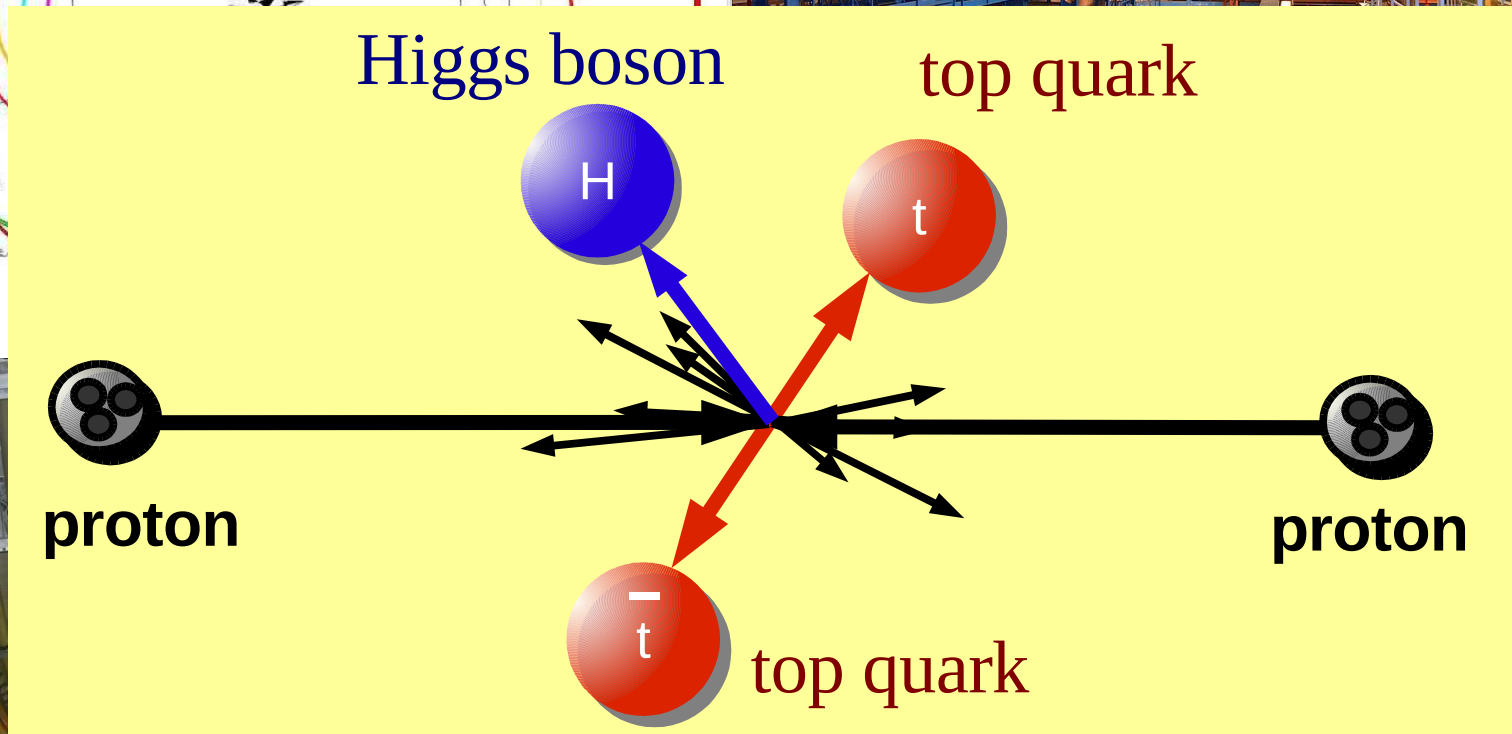
Top quark future: LHC



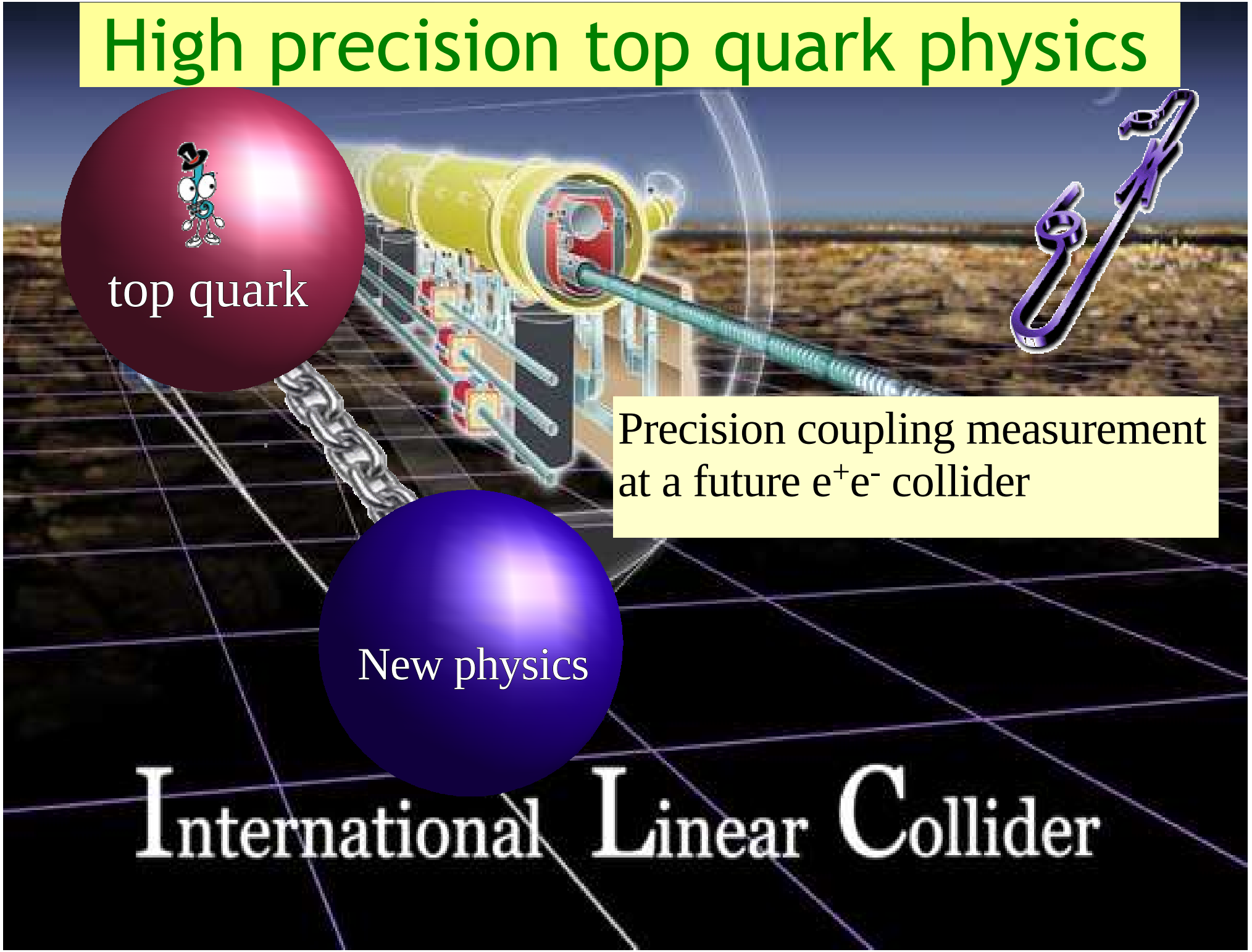


Top quark future: LHC





High precision top quark physics



2005 2006 2007 2008 2010 2013 20??

First top results

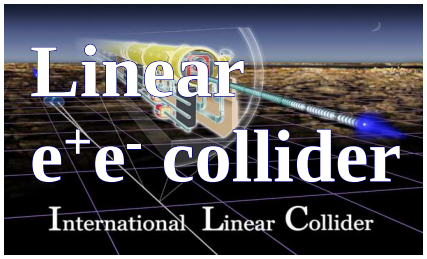
Single top observation

Top mass ± 1.5GeV

First top results

Single top, top mass

New top couplings



Precision top measurements

Conclusions

- The Tevatron Run II is now producing many results
  - Precision measurements with a large dataset
  - Excellent results due to advanced analysis techniques
- The top quark is a central focus at the Tevatron
  - Measuring mass, branching ratio, helicity, ...
  - Discovering new top quark production modes
- This is just the beginning
  - Analyzing ×3 dataset now
  - LHC is just around the corner
- We are getting very close to understanding the origin of matter

Dawn of Discoveries

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
- DØ
  http://www-d0.fnal.gov
- Cern
  http://www.cern.ch

Credits

- Thanks to the many people that have helped me put this talk together
  - Including Brigitte Vachon, John Womersley, Dugan O'Neil
- Some of the material was adopted from the web pages listed on the previous page
- The latest CDF results can be found at http://www-cdf.fnal.gov/physics/physics.html
- The latest DØ results can be found at http://www-d0.fnal.gov/Run2Physics/WWW/results.htm