Physics in the Third Generation

Testing the Standard Model at the Energy Frontier

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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
- Exploring the top quark at the Tevatron
- The third generation points to the Future
- Conclusions

- Simplified units:
  $c = 1$
  - Energy, momentum, mass in GeV

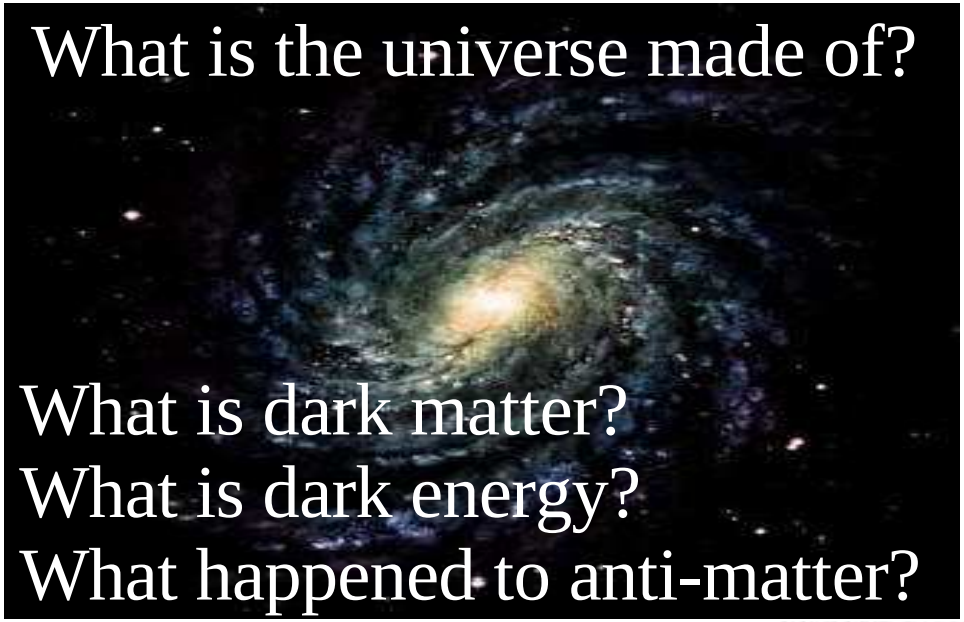
- Cross section in picobarn
  (1 barn = 10^{-24} cm^2)
  - Luminosity in $\frac{1}{\text{picobarn}}$

A fundamental question

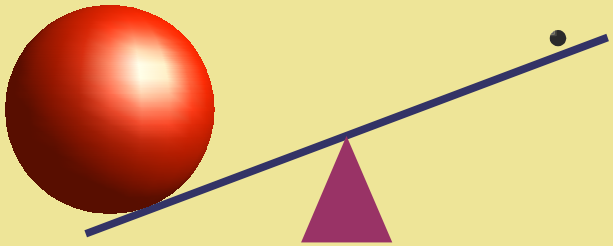
What is the origin of matter?

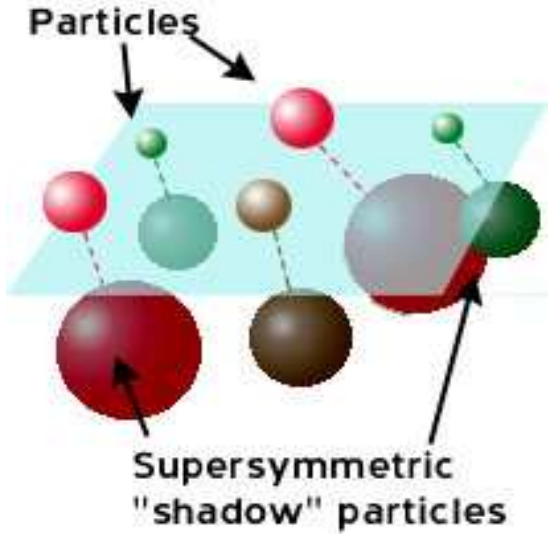
What is the origin of matter?

What gives mass to elementary particles?



What makes quarks so heavy and neutrinos so light?





Supersymmetry? Extra spatial 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

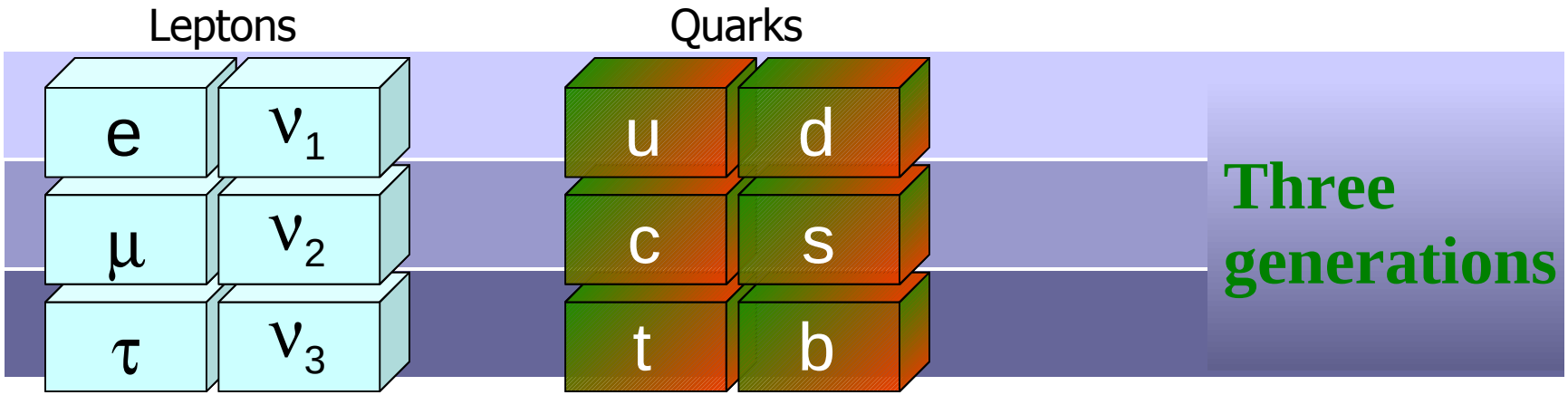
The minute particular

State of the art

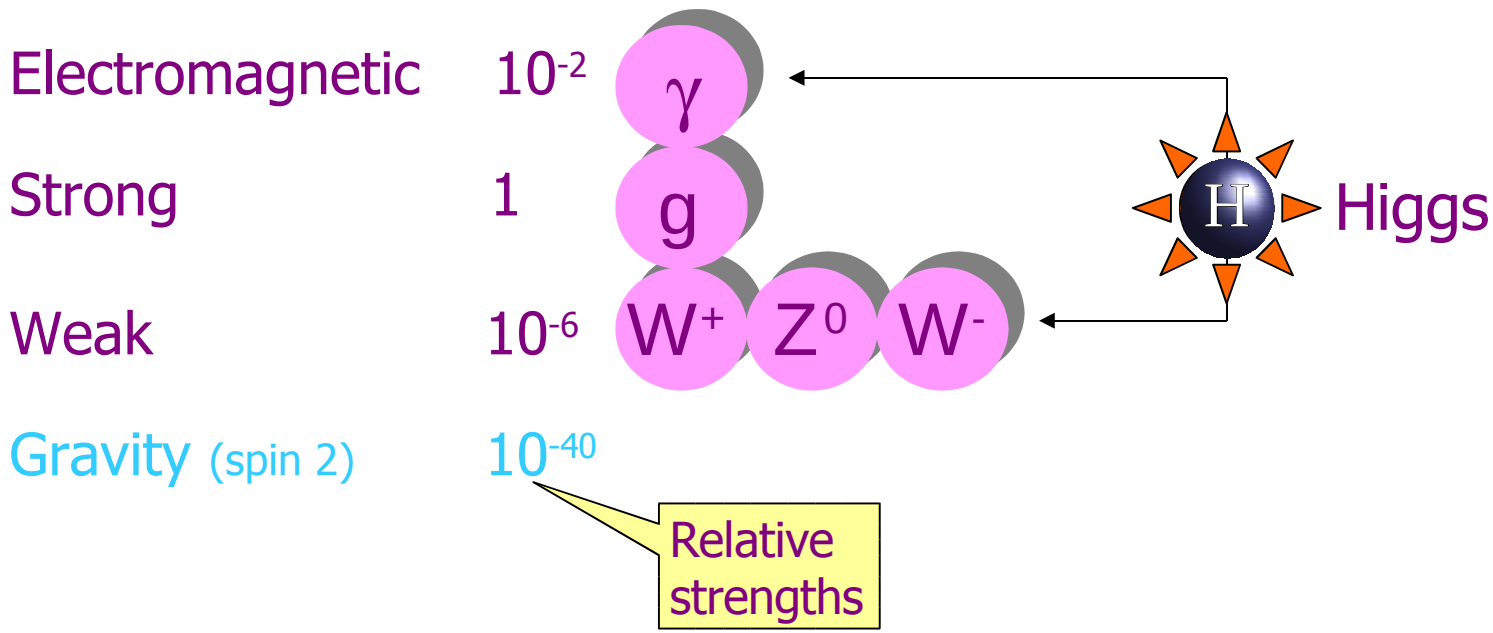
What do we know already?

Standard model of particles and forces

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

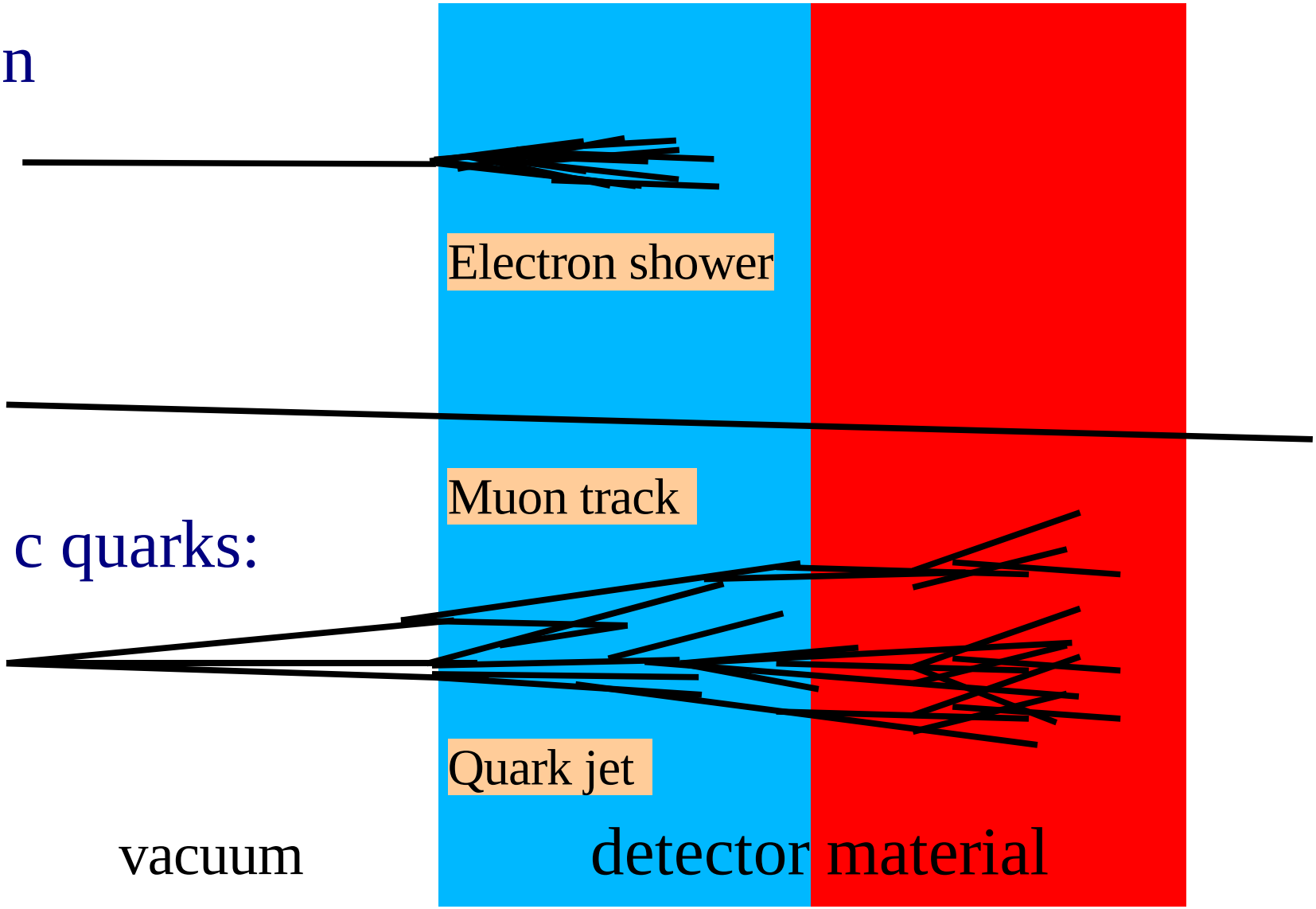


- Which interact by exchanging spin-1 vector bosons



The first two generations

- electron
- muon
- u, d, s, c quarks:



Electrons, muons, and quark jets are used as standard tool at the energy frontier

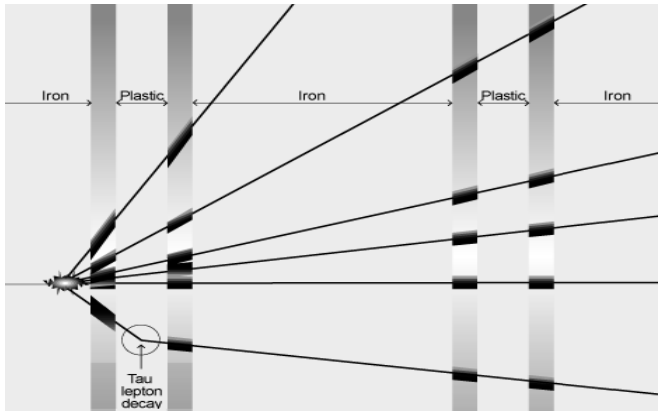
The third generation

Tau lepton

Discovered 1975 at SLAC

Tau neutrino

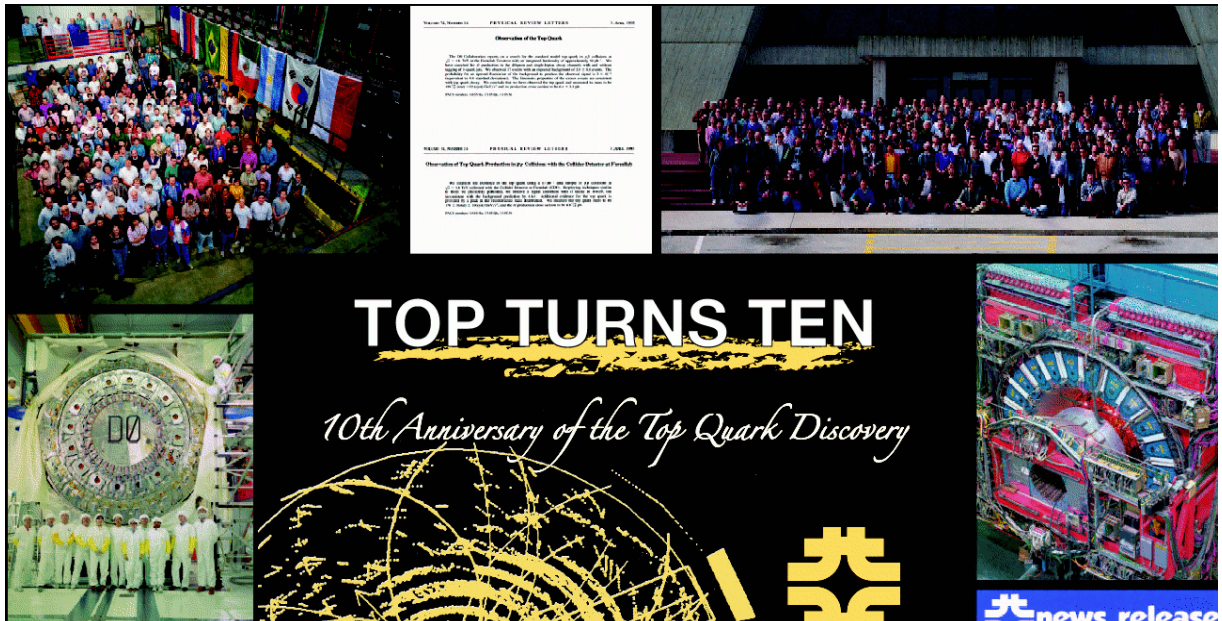
Discovered 2000 at Fermilab



bottom quark

Discovered 1978 at Fermilab

top quark



Gauge boson masses in the SM

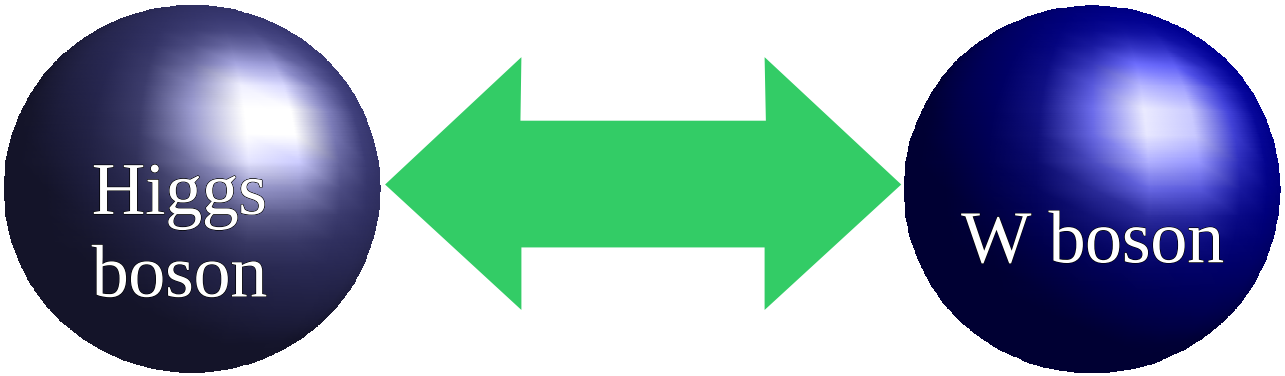
Gauge bosons

Higgs field

Electroweak symmetry breaking

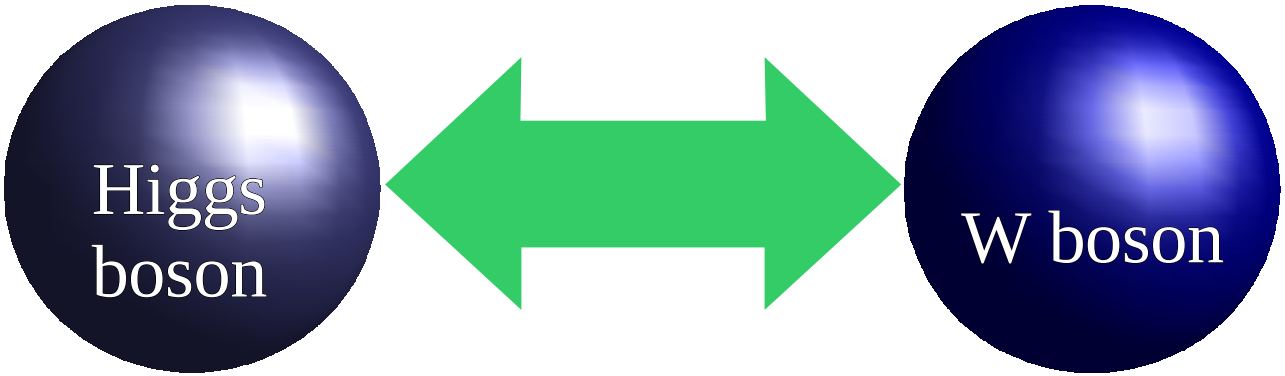
Electroweak symmetry breaking

Gauge boson coupling to Higgs field

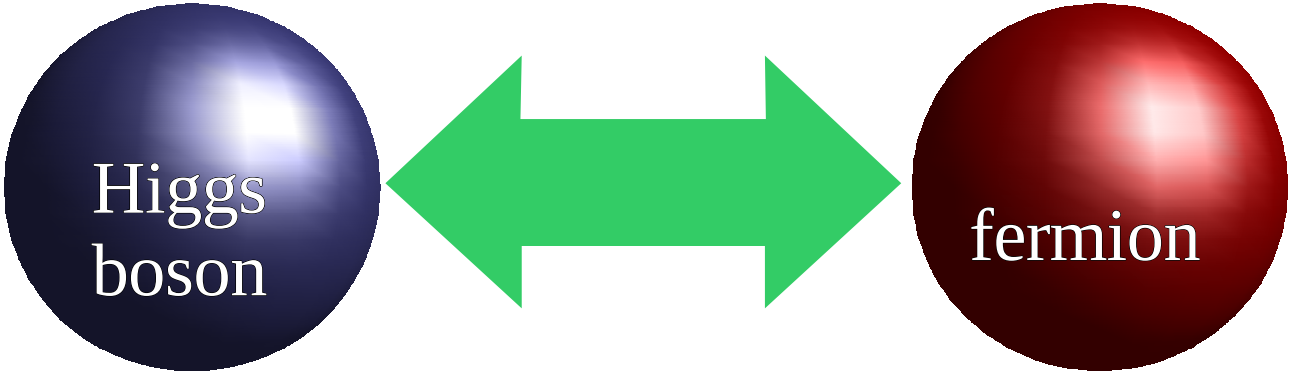


Electroweak symmetry breaking

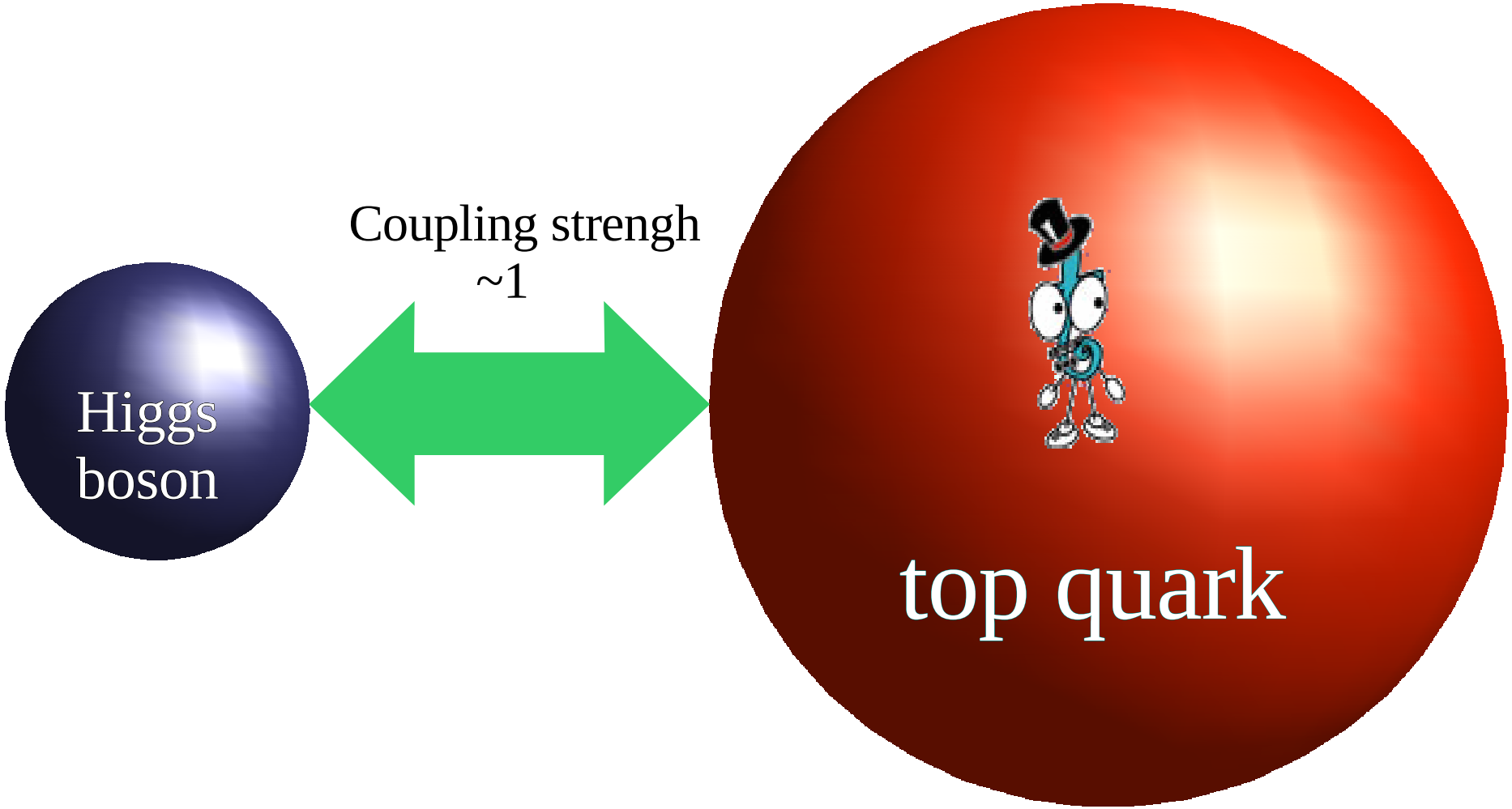
Gauge boson coupling to Higgs field



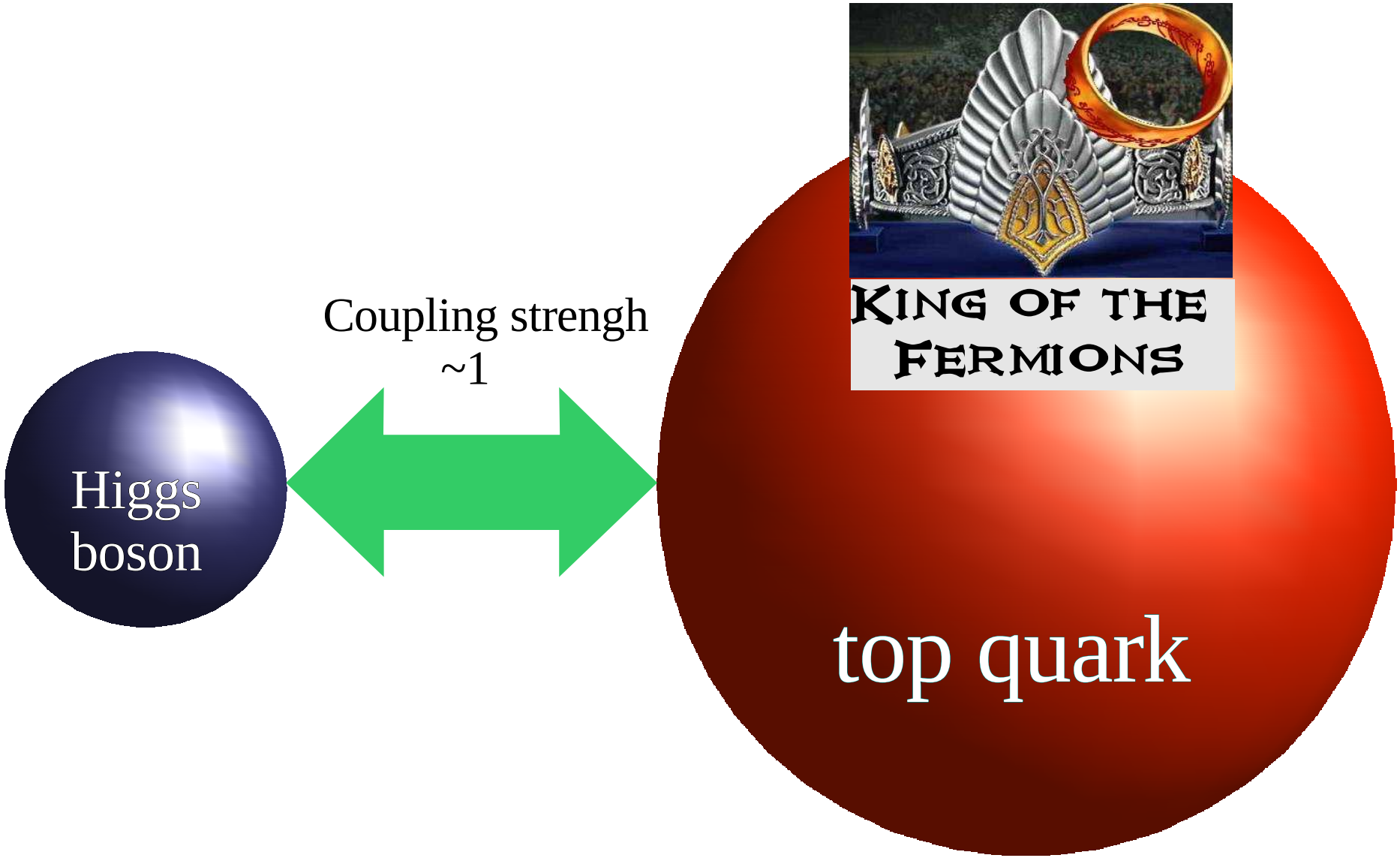
Fermions acquire mass through Higgs coupling



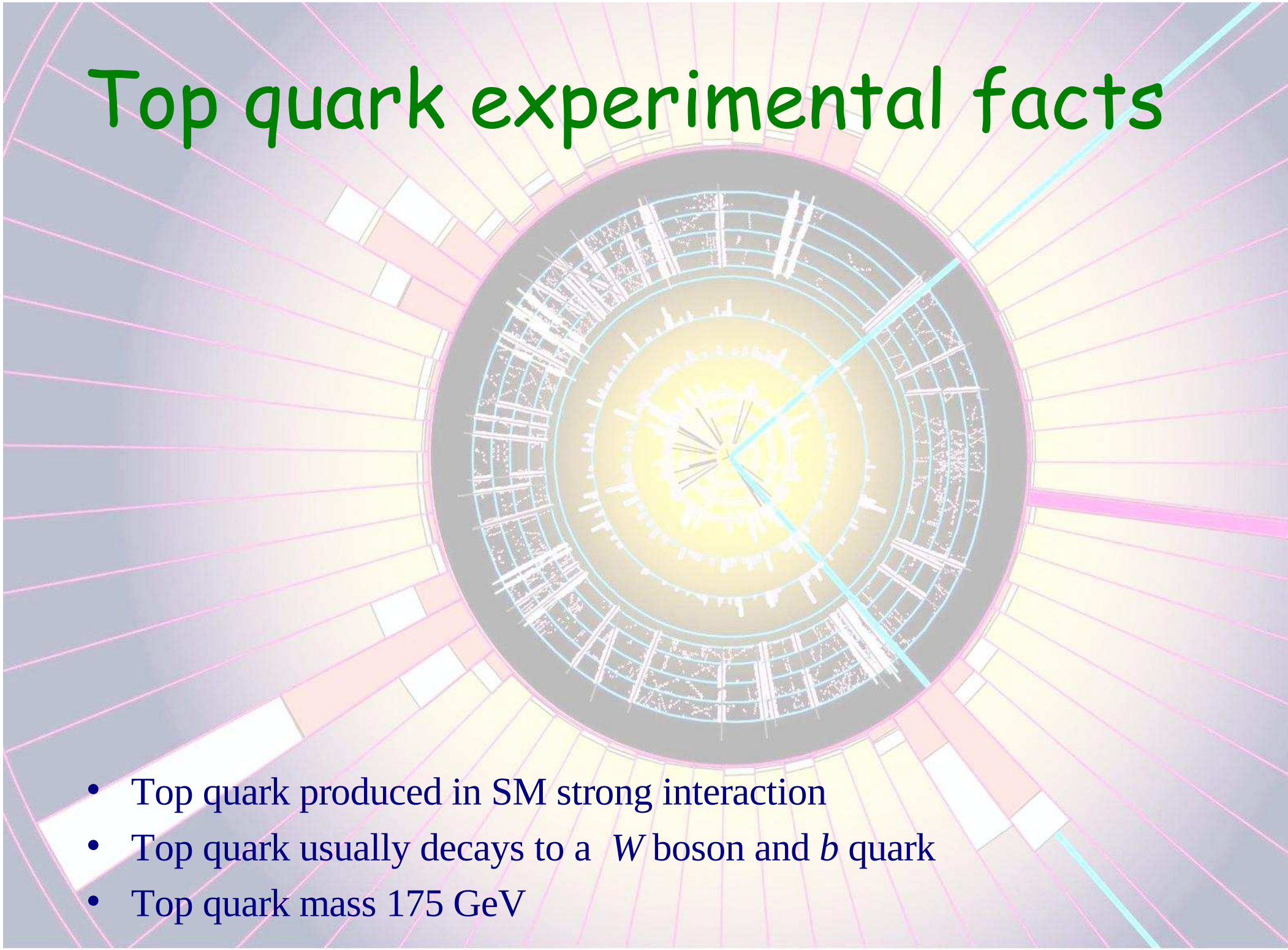
Top quark mass



Top quark mass



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

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
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Address in RunII at the Tevatron

We really don't know:

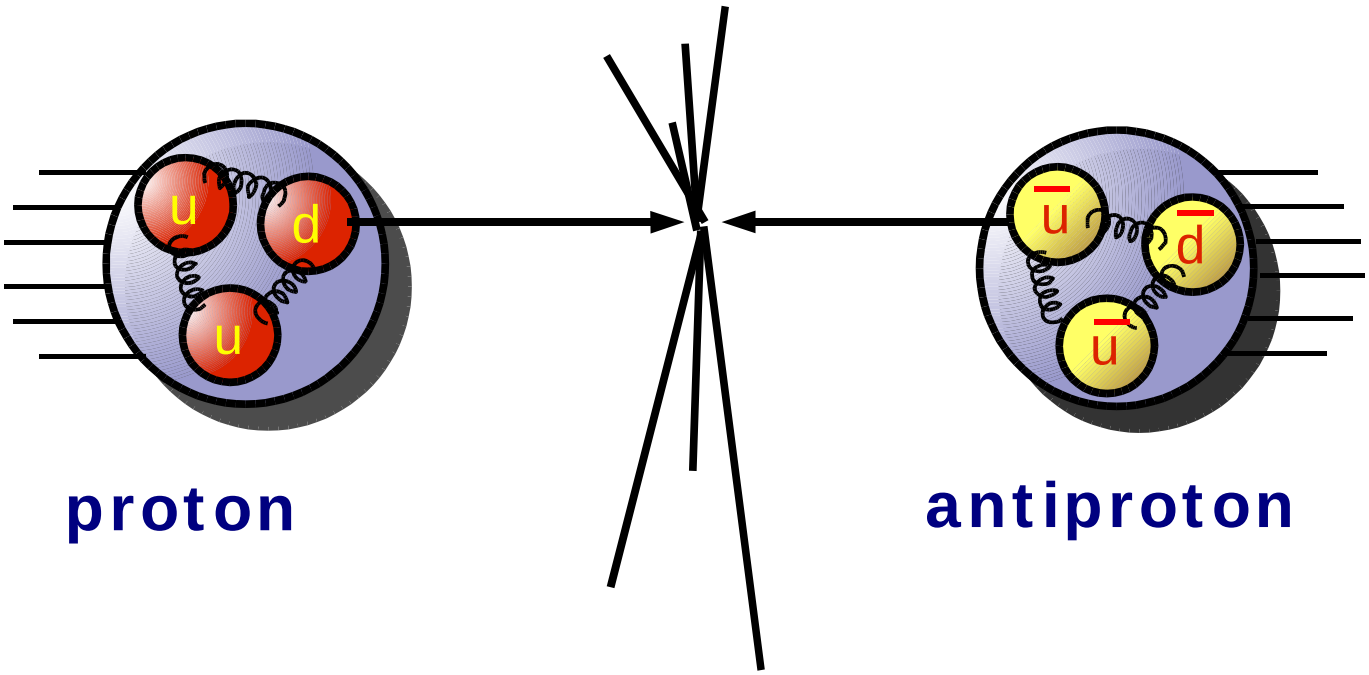
- Coupling to Higgs boson?
- Modified coupling to SM particles?
- New physics? New particle?

Experimental procedure

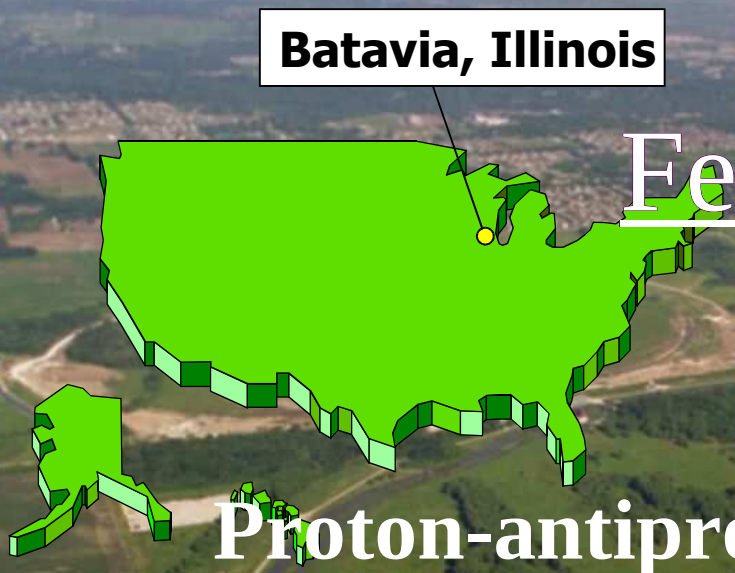
How do we find out?

The energy frontier

Probe physics at small distances
by colliding particles at high energy



Experimental setup: Fermilab Tevatron in Run II



Proton-antiproton collider

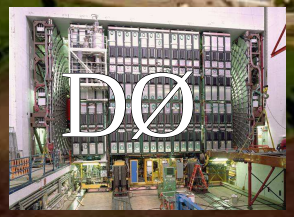
CM energy 1960 GeV

→ ***Energy frontier***

Instantaneous luminosity >160E30 cm^{-2}s^{-1}

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

→ ***Luminosity frontier***



Experimental setup: detector configuration

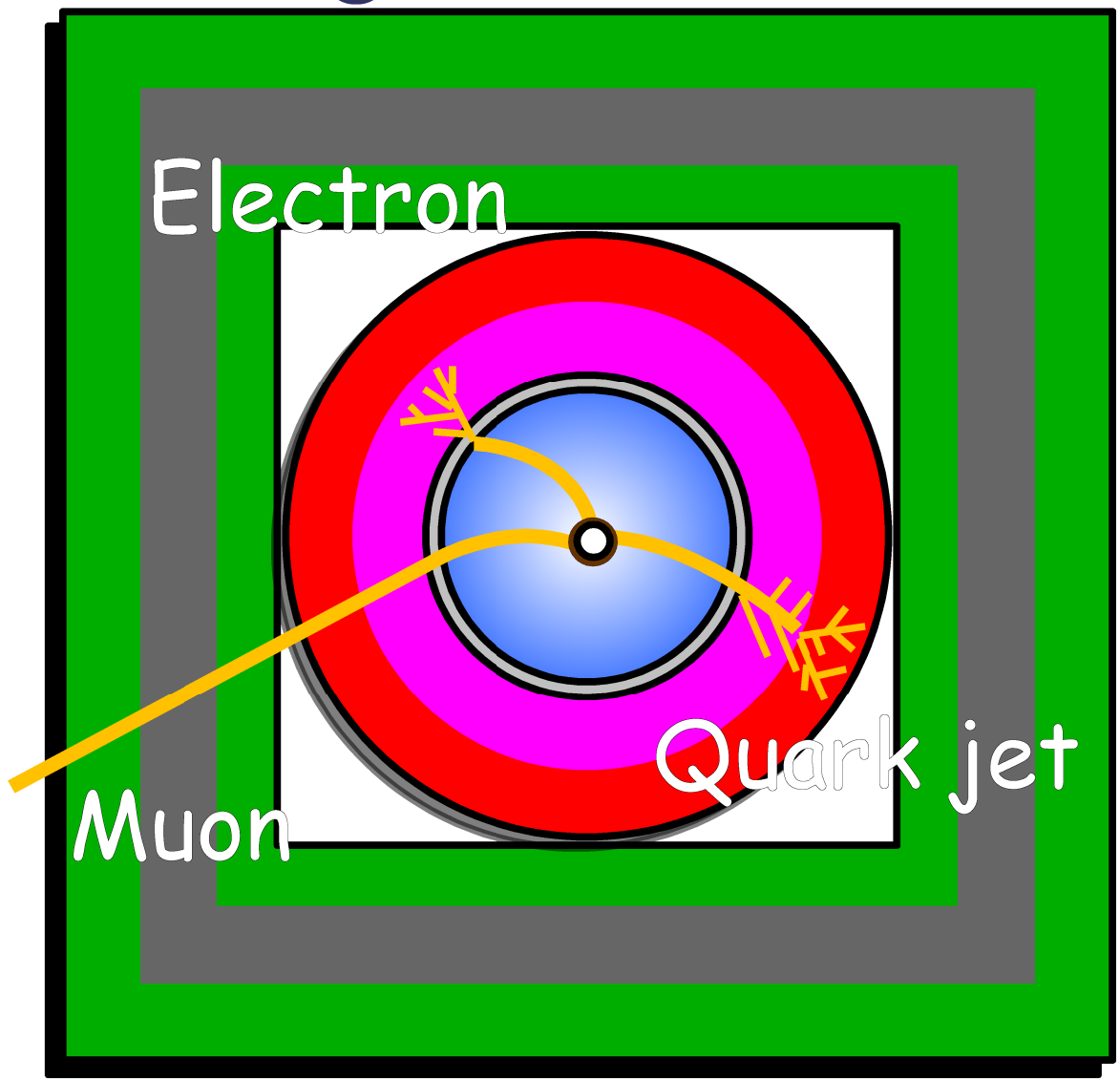
Beam pipe

Tracking detector

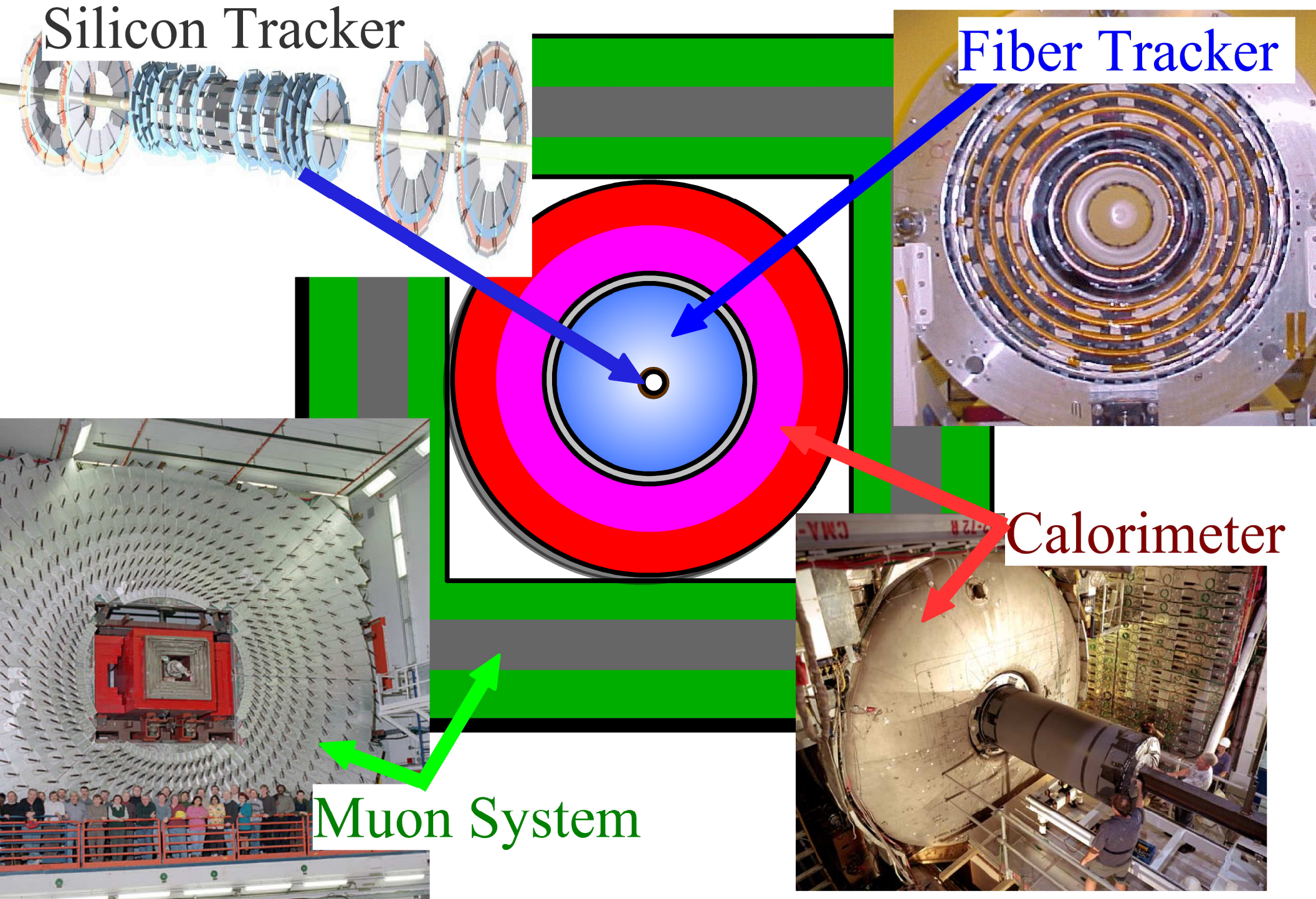
Magnet

Calorimeter:
EM and hadronic

Muon detectors
surrounding
another magnet



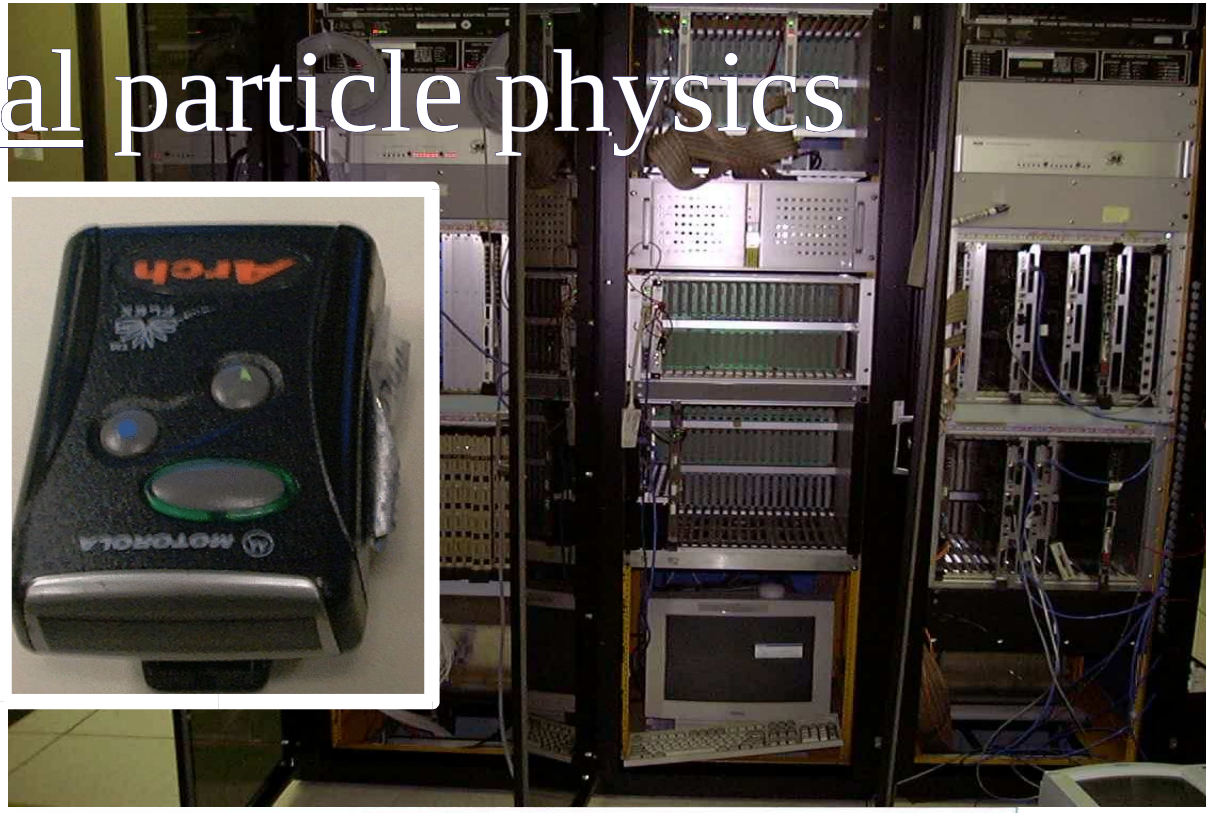
Apparatus: Run II DØ Detector

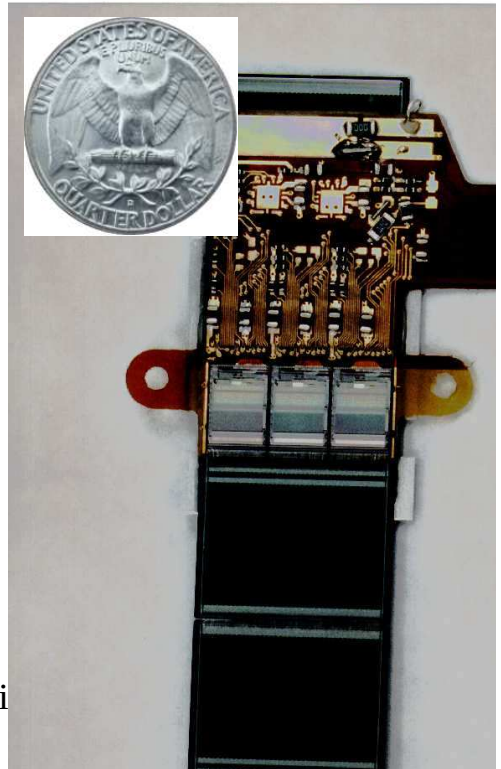


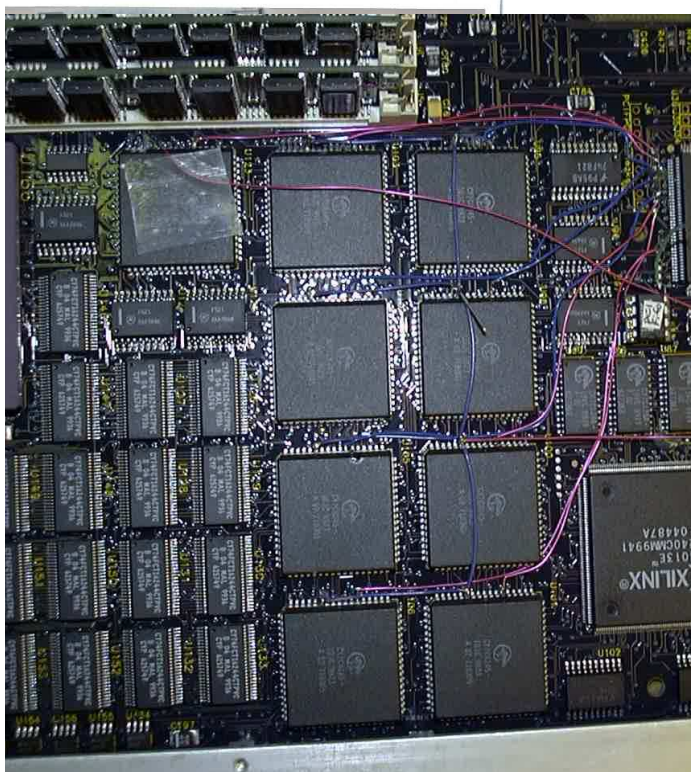
Experimenters

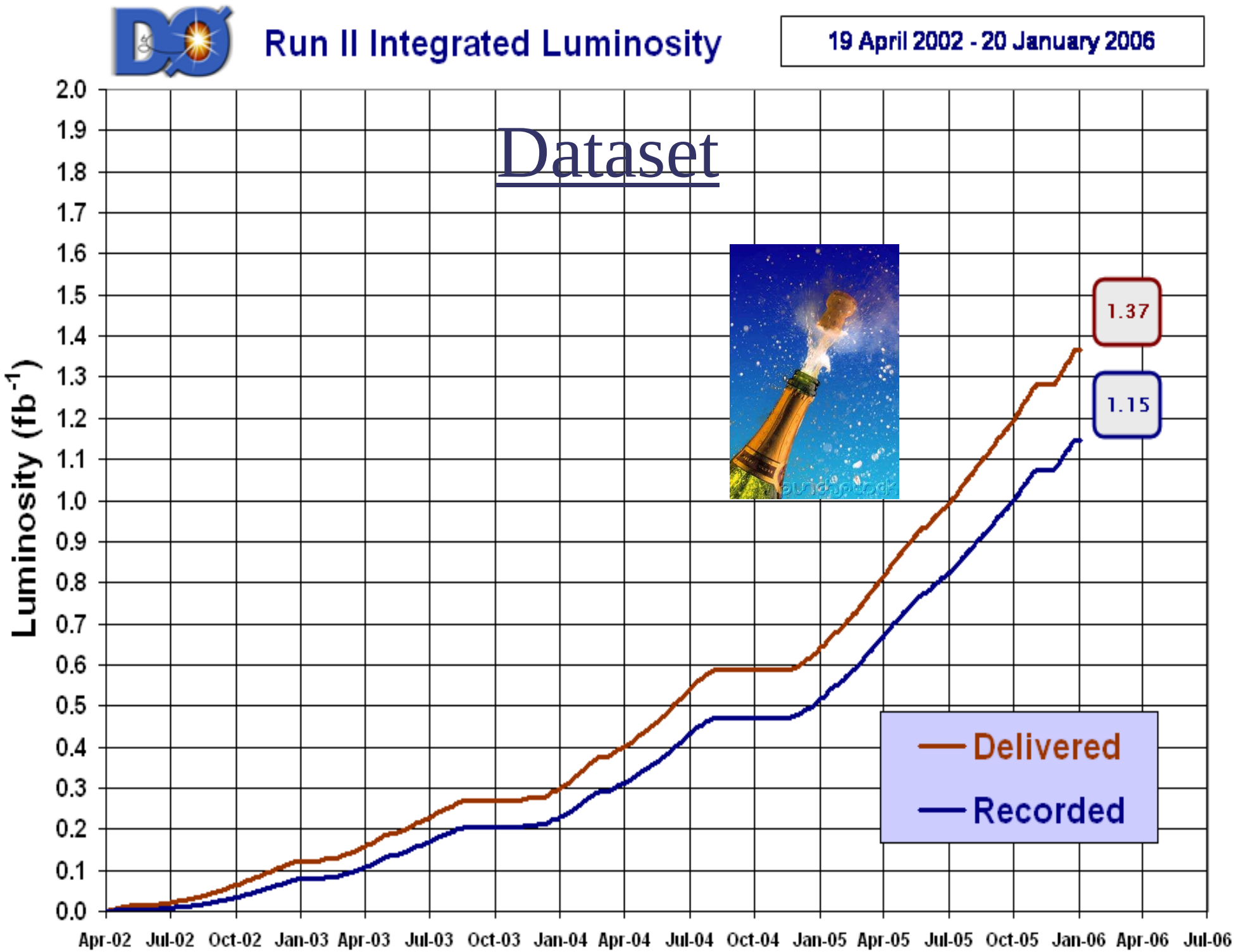
Together
> 1400 physicists
from 21 countries

Experimental particle physics

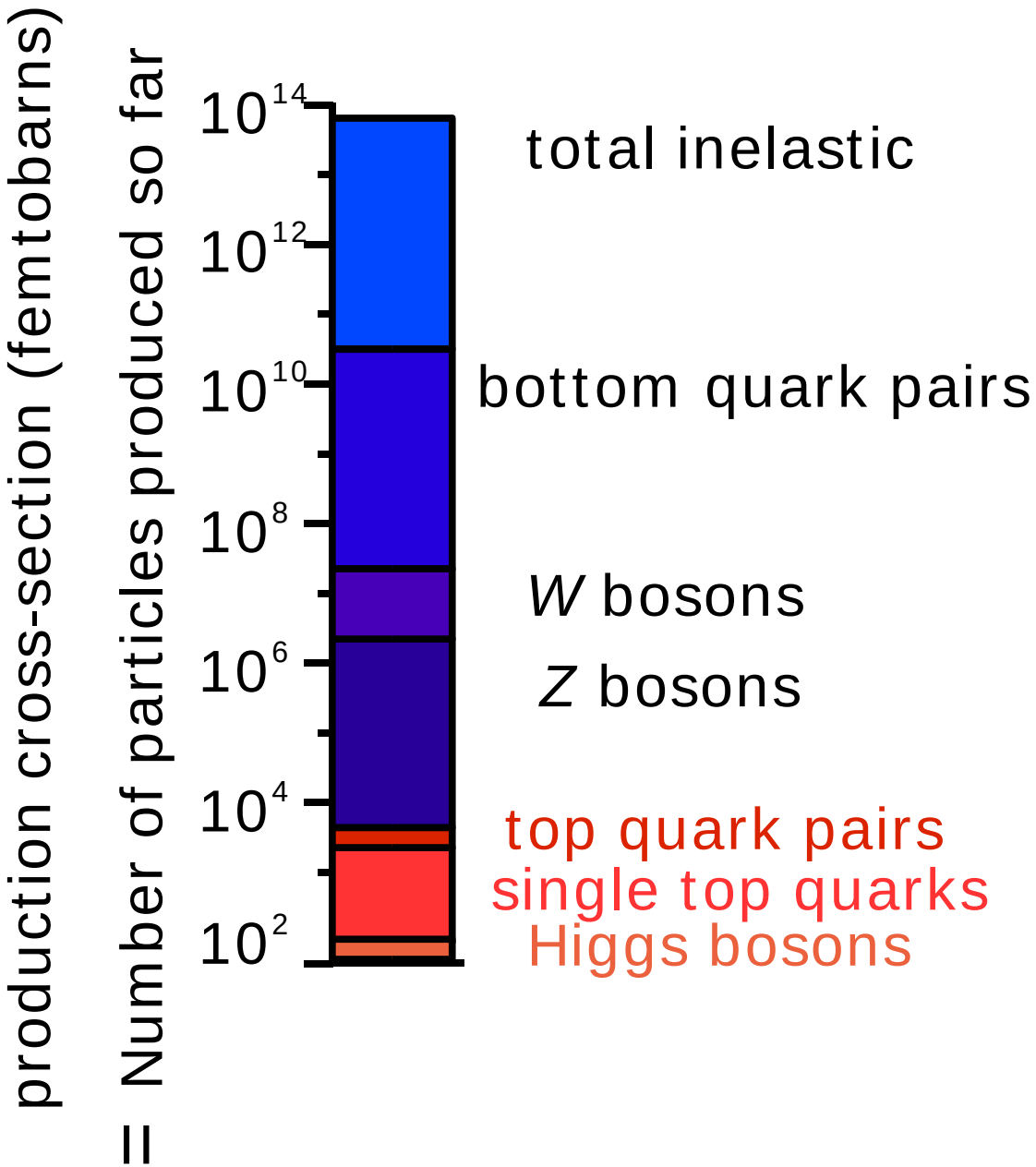




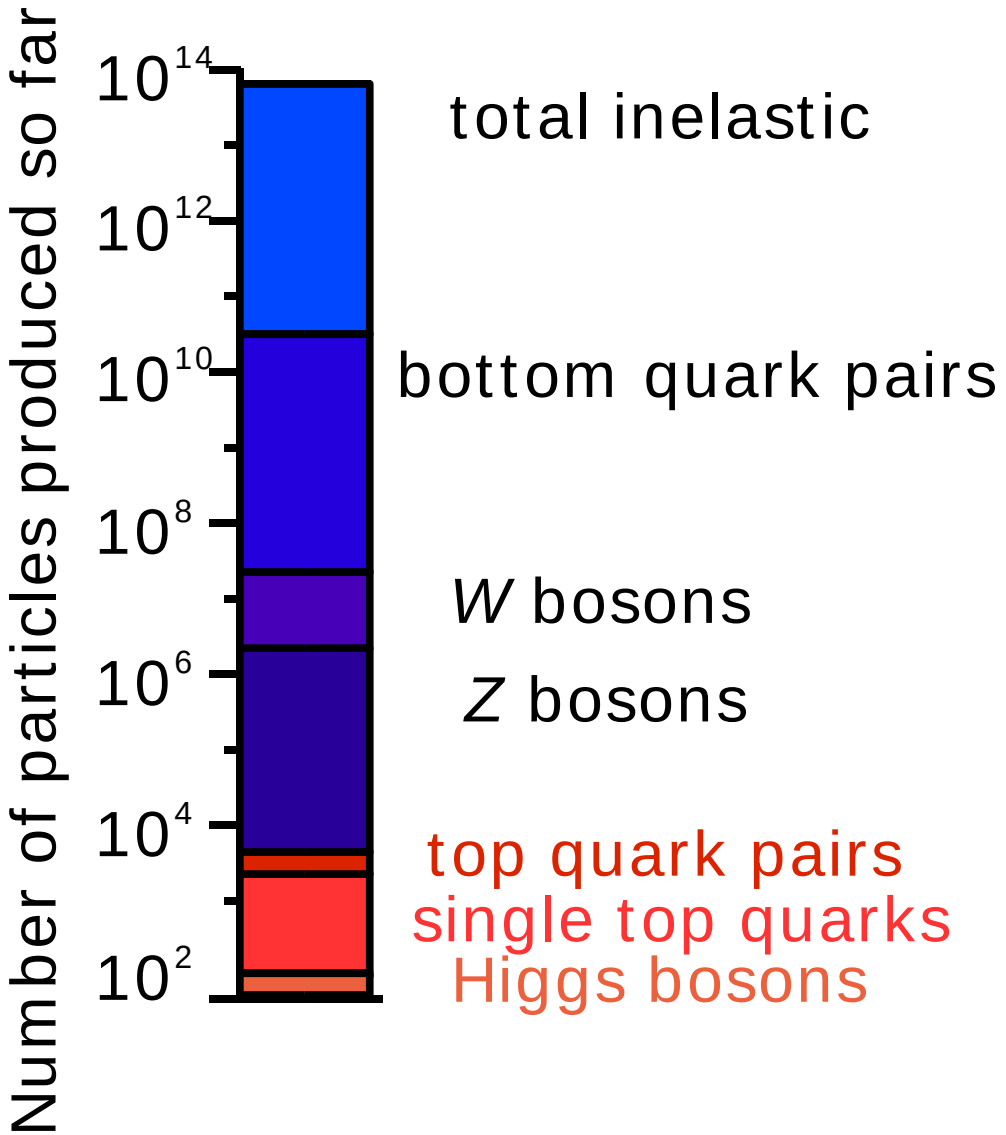



Run II Integrated Luminosity
19 April 2002 - 20 January 2006
Dataset
Luminosity (fb^{-1})
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Apr-02
Jul-02
Oct-02
Jan-03
Apr-03
Jul-03
Oct-03
Jan-04
Apr-04
Jul-04
Oct-04
Jan-05
Apr-05
Jul-05
Oct-05
Jan-06
Apr-06
Jul-06
1.37
1.15
Delivered
Recorded

Particle production at the Tevatron



Tevatron physics program



Precision quark jet physics

Bottom quark physics

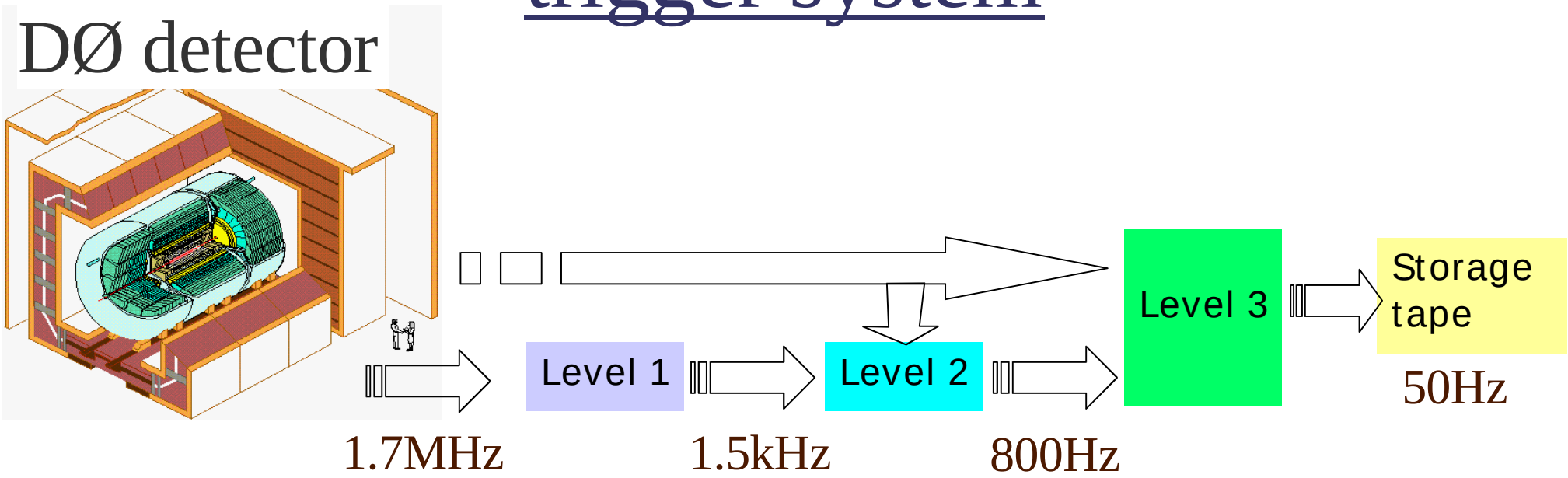
Precision electroweak physics

Top quark measurements

Searches for new physics

Higgs boson searches

Collecting interesting events: trigger system

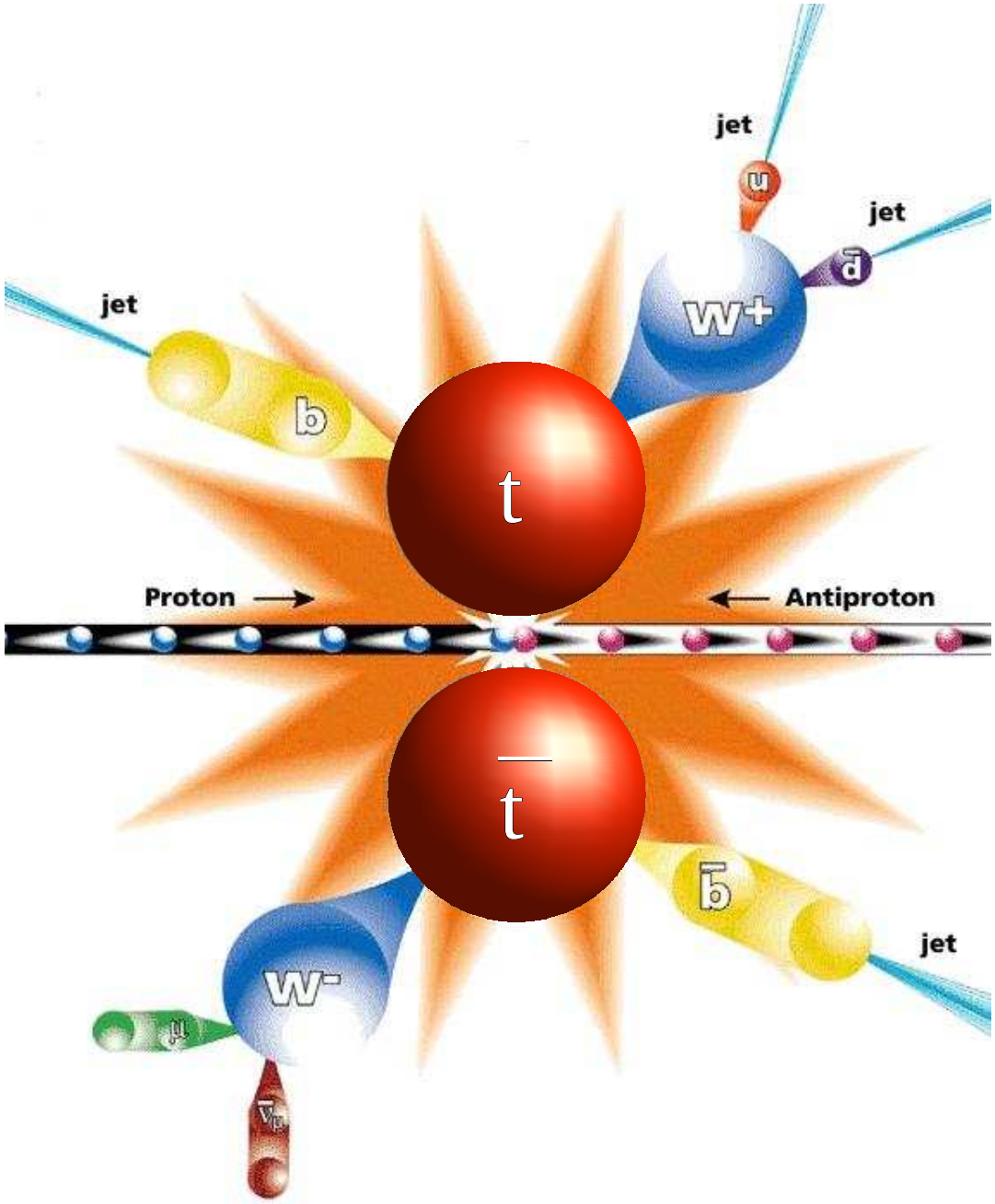


- Reduce rate of interactions (inelastic collisions) to manageable level that can be stored
- Record "interesting" events → trigger system
  - Select events containing high-energy final state objects
    - Electrons, muons, quark jets

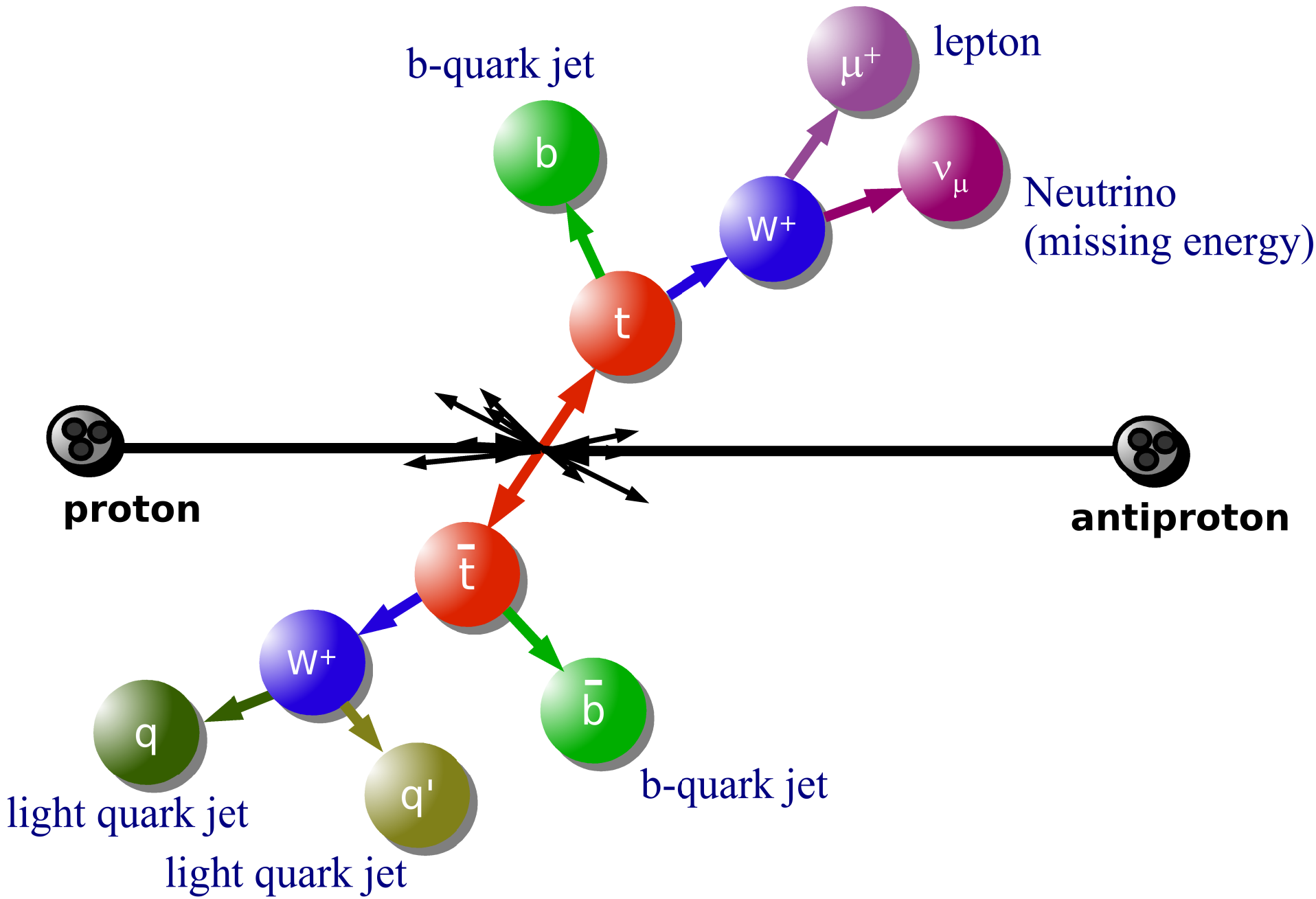
Event Selection

How do we find top quarks?

Top Quark pair production



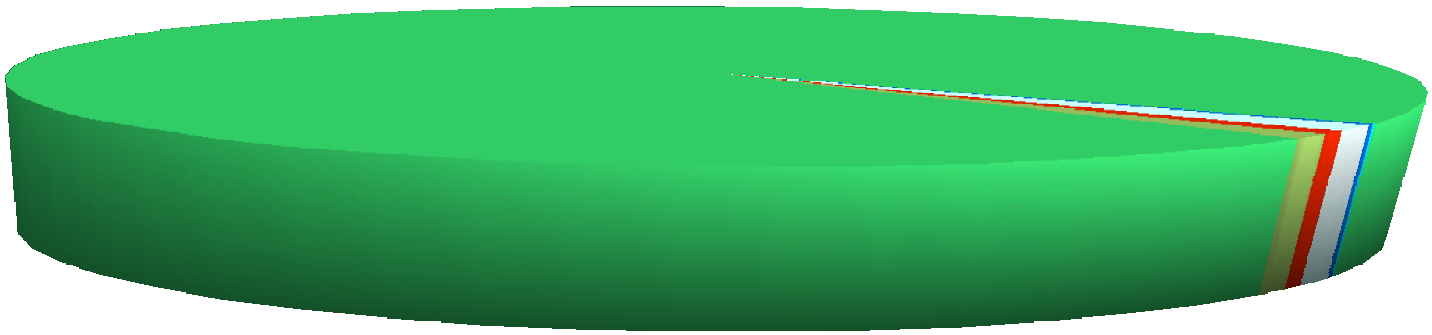
Top quark pair selection: lepton+jets



Event selection result

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

expect ~250 top quarks



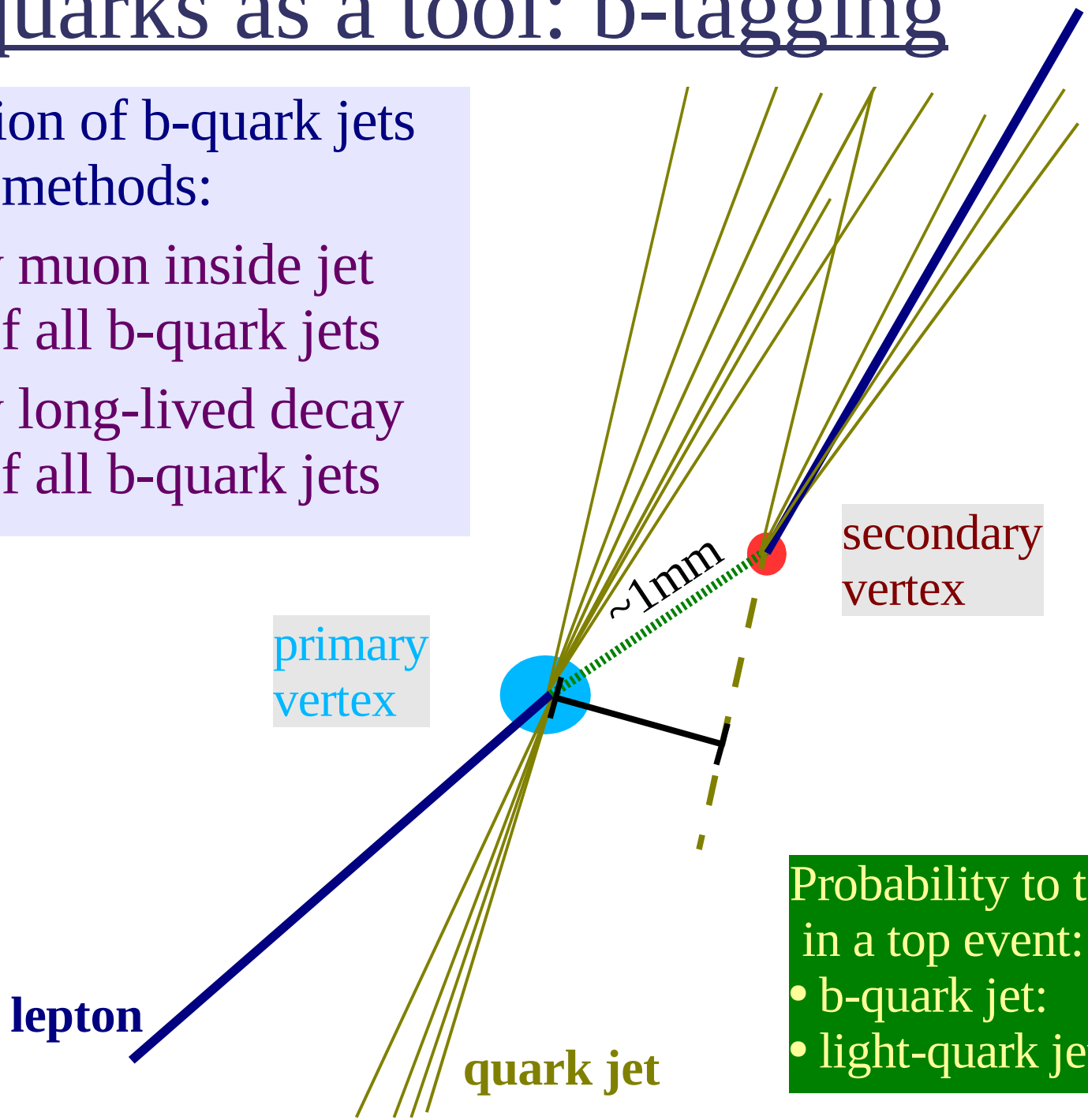
Top quark pairs

Backgrounds

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

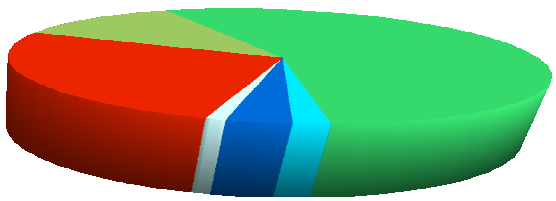
with lepton, neutrino, ≥ 2 jets

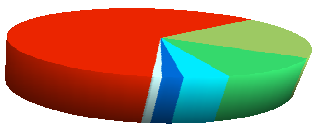
=1 b-tag:

367 events

=2 b-tags:

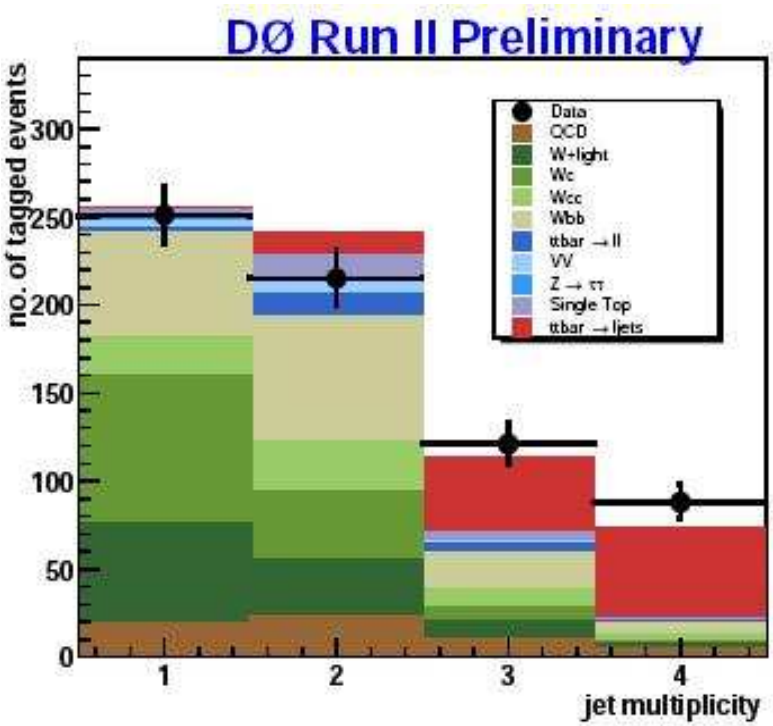
76 events

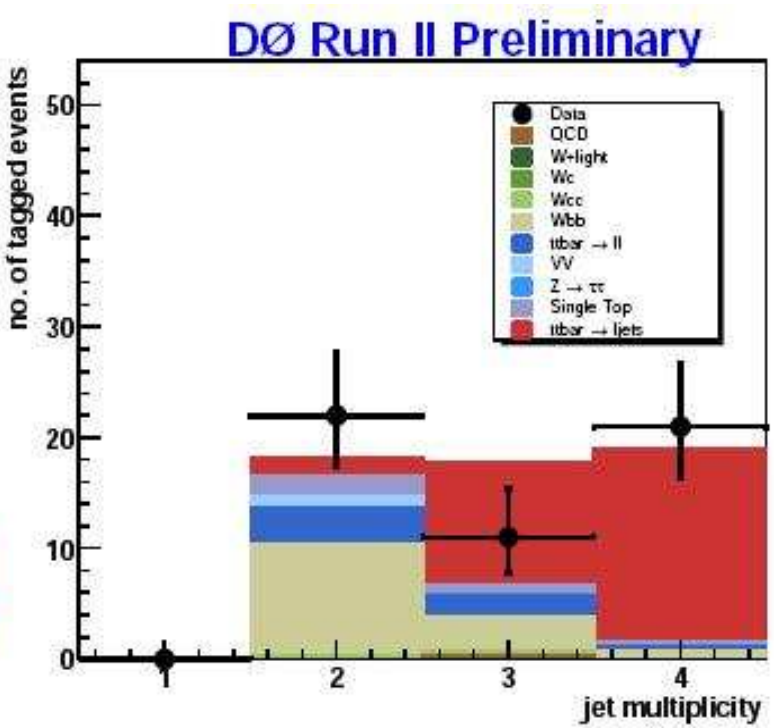




Top quark pairs

Backgrounds



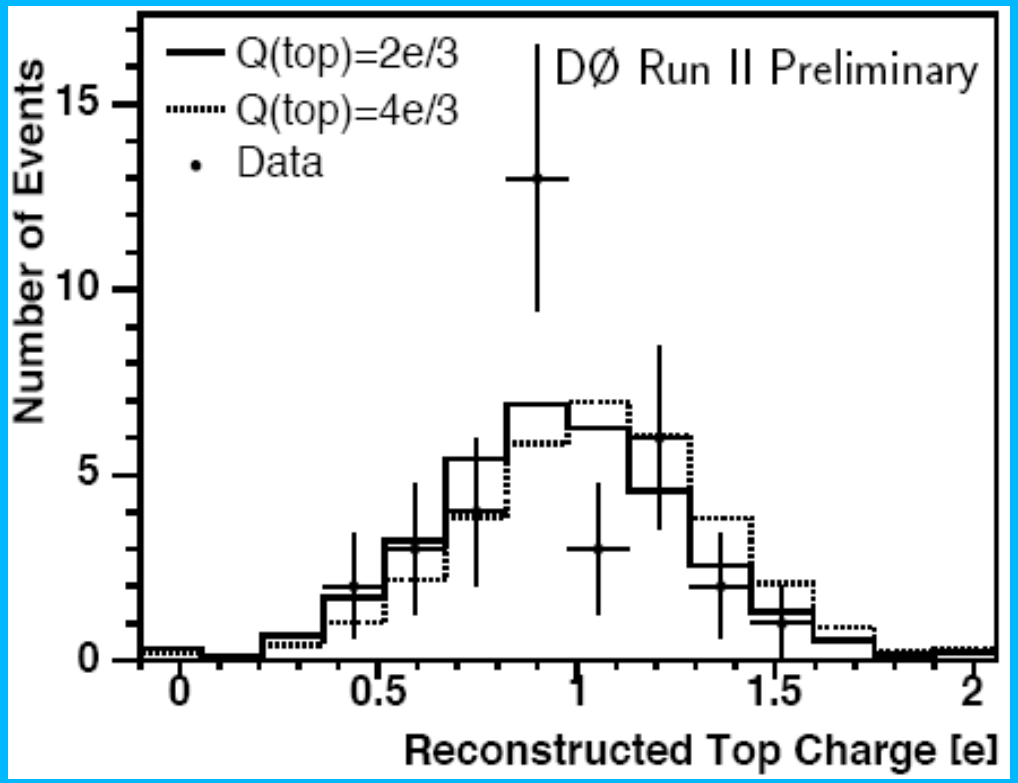


Current Results

What have we learned about the top quark?

Top quark properties –
Is it the quark we think it is?

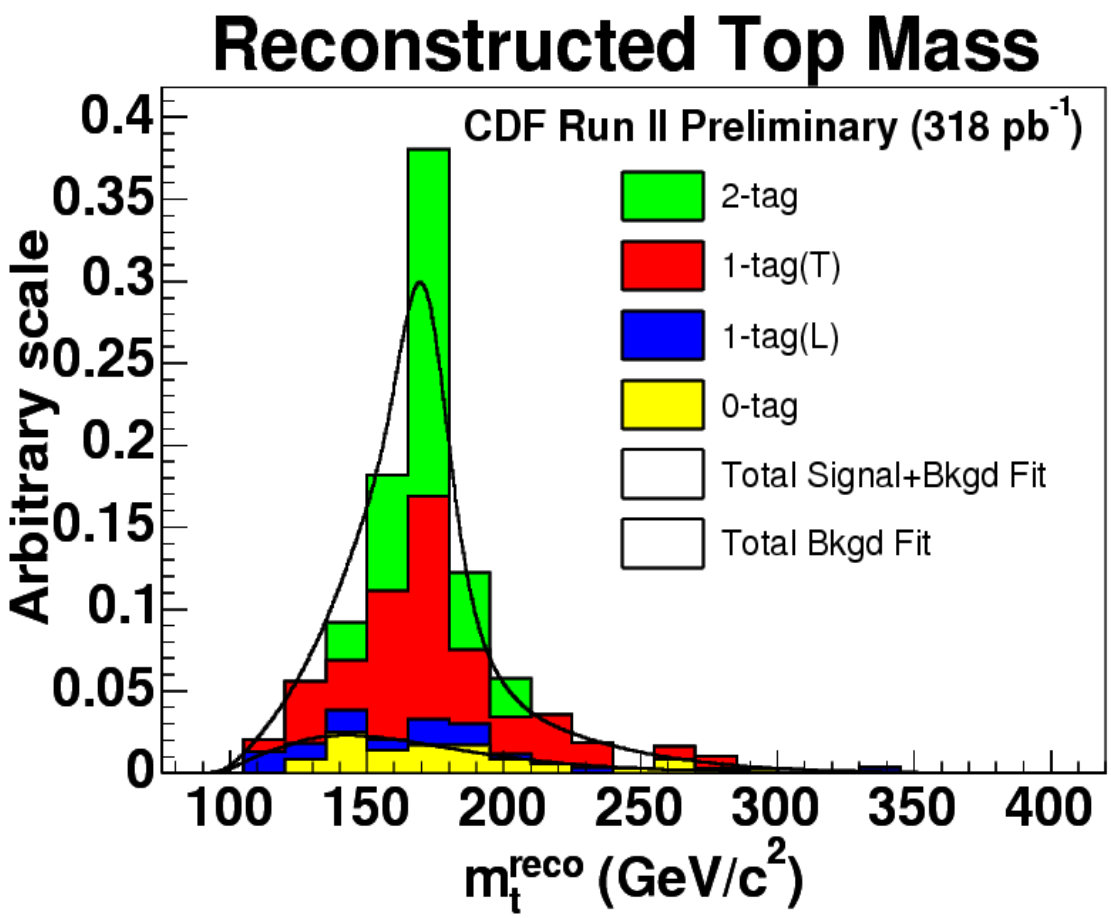
Top quark charge = 2/3 or 4/3?

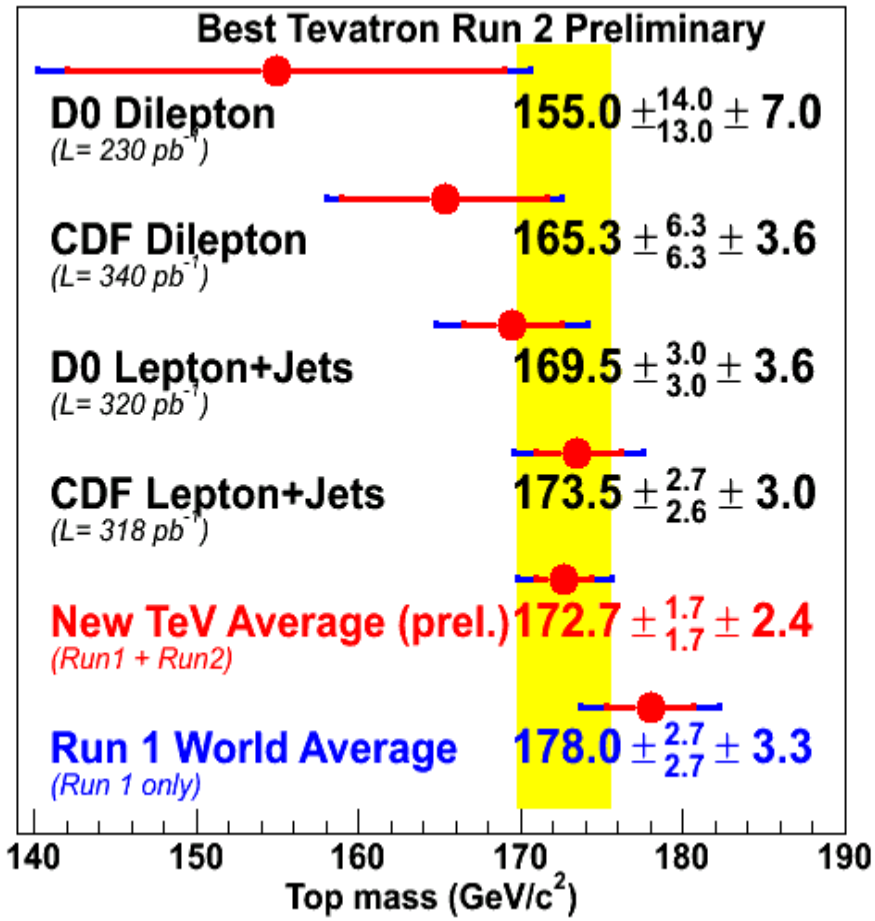


Result: charge=2/3

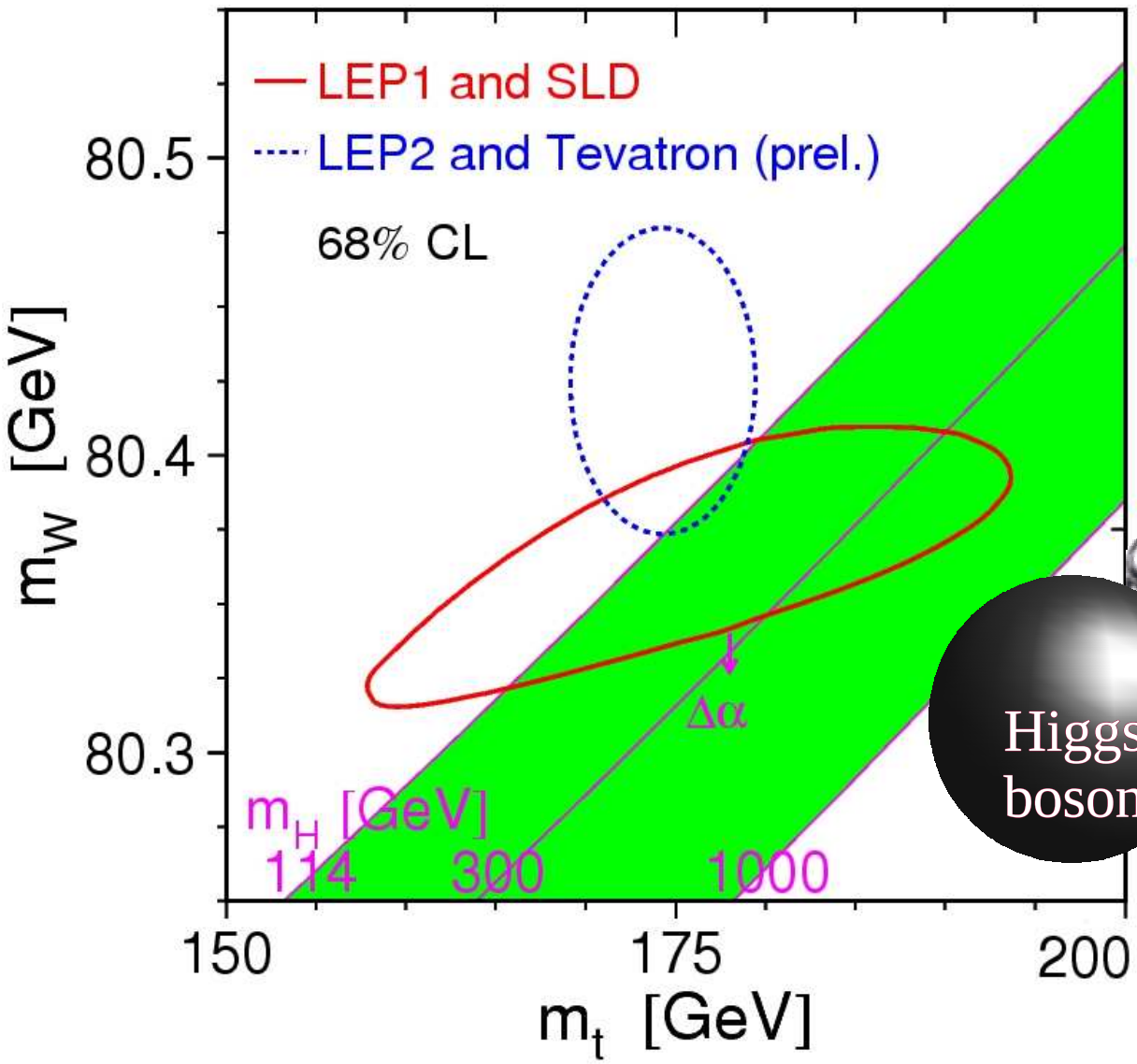
Top quark mass determination

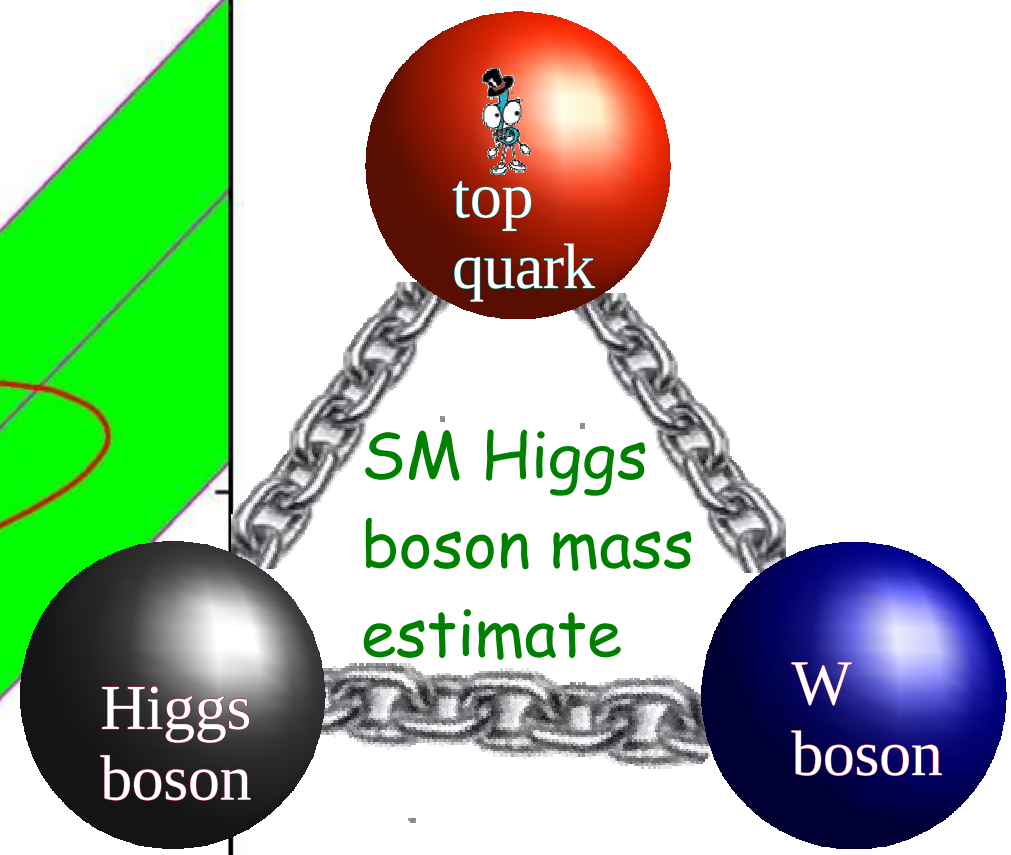
- Large sample of top quarks
- Advanced analysis techniques
  - ➔ Measurement uncertainty dominated by systematic effects





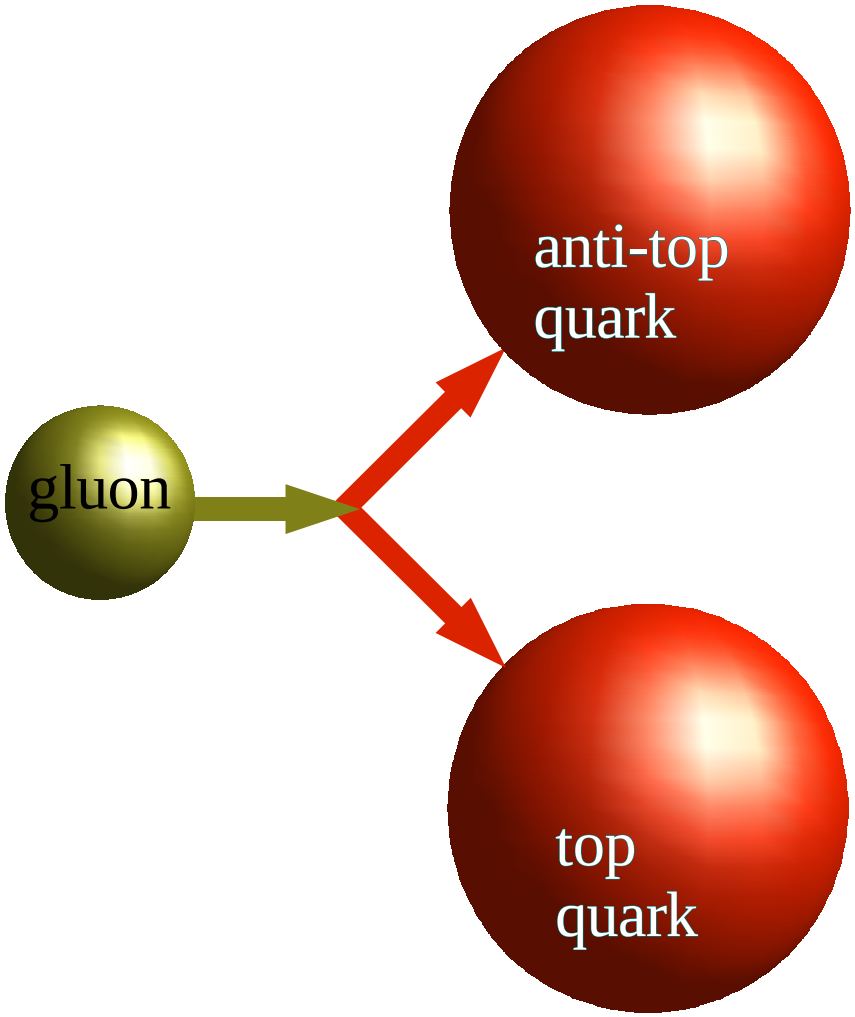
Top quark mass implications –
What can Top tell us about Higgs?

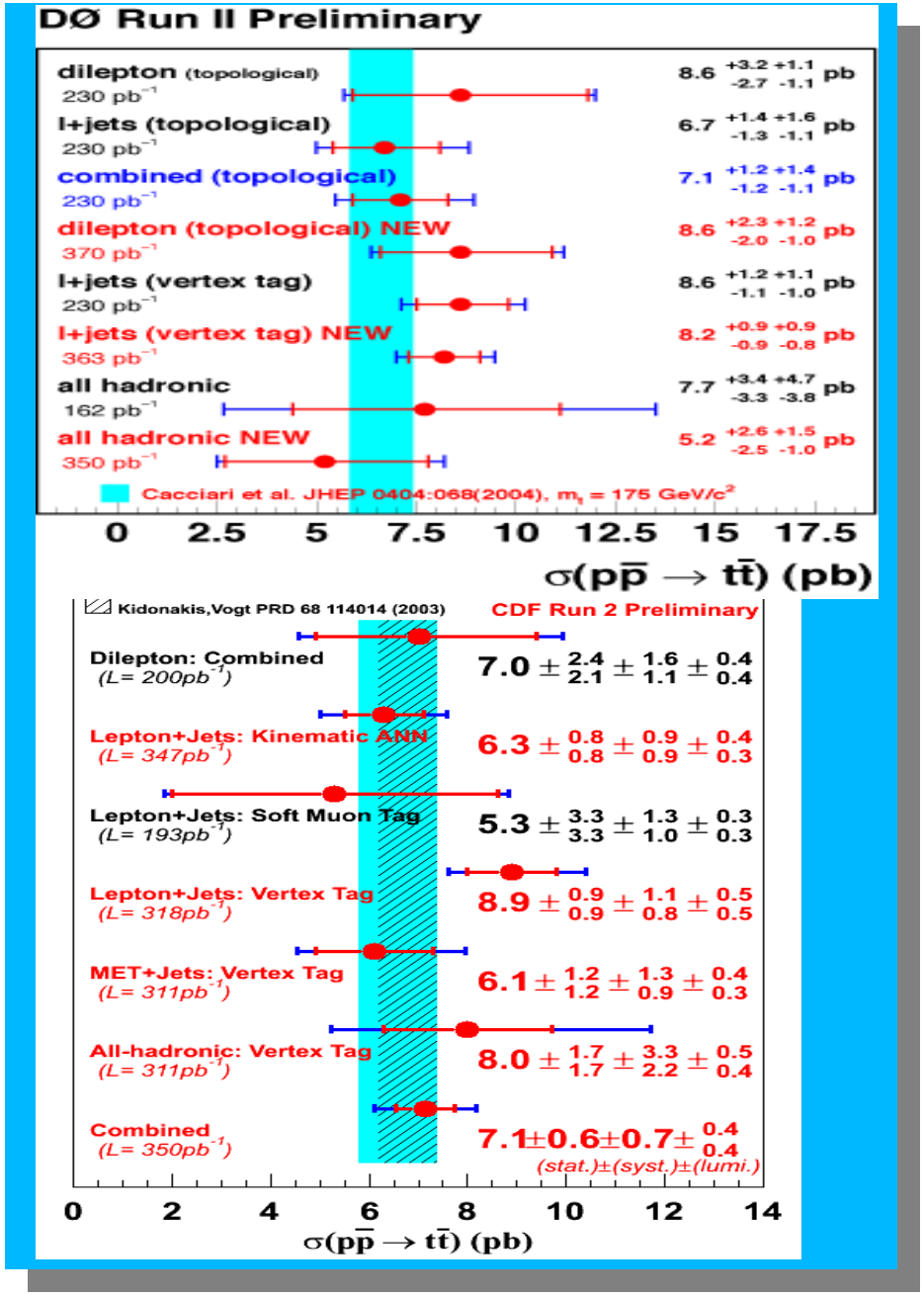




Top quark strong interaction –

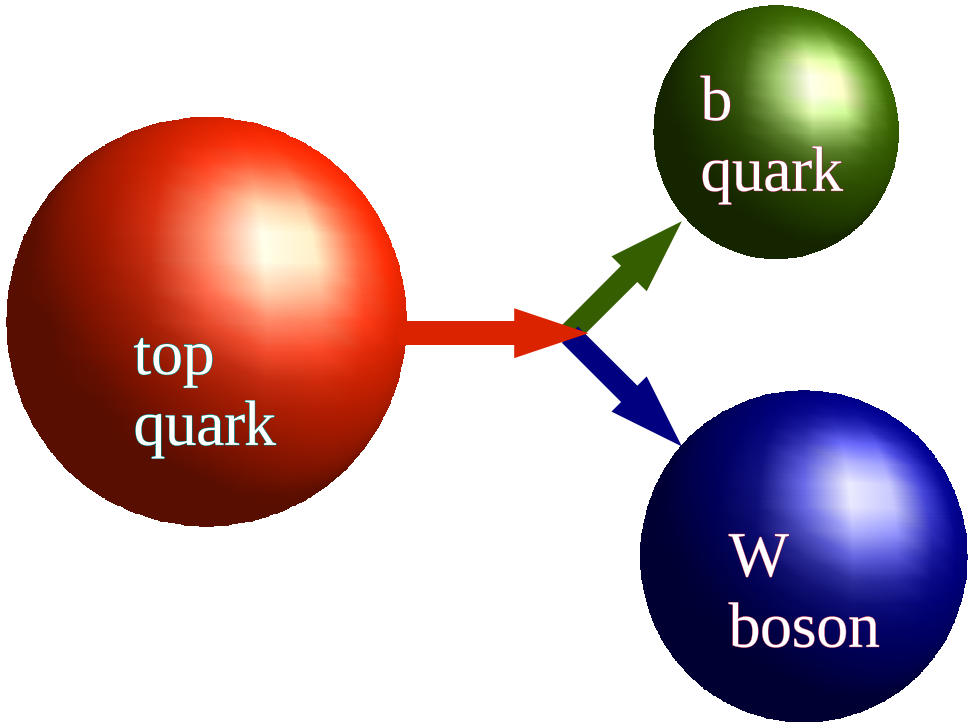
Does it couple to gluons like a quark?





Result: SM strong interaction

Top quark electroweak charged current interaction

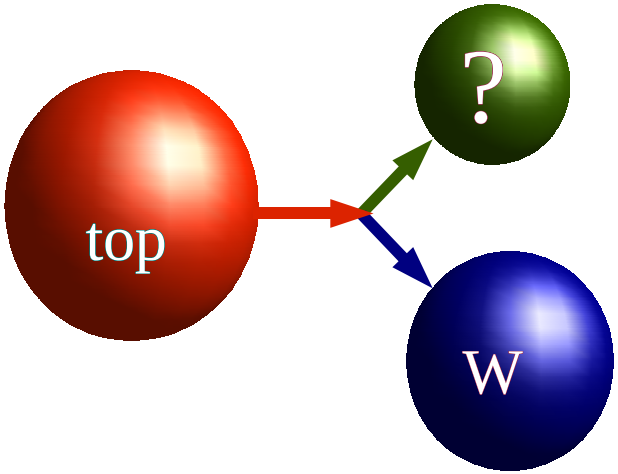


Top quark decay

Top quark decay –

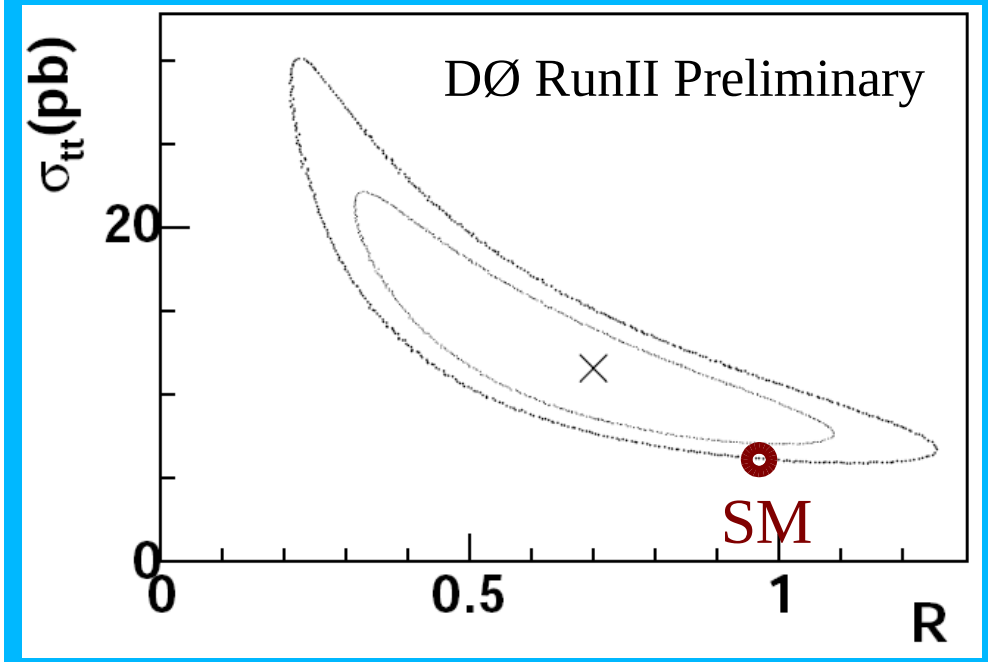
Does it decay to the particles we expect?

b quark or other flavor?



$$R = \frac{t \rightarrow W + b\ \text{quark}}{t \rightarrow W + \text{any quark}}$$

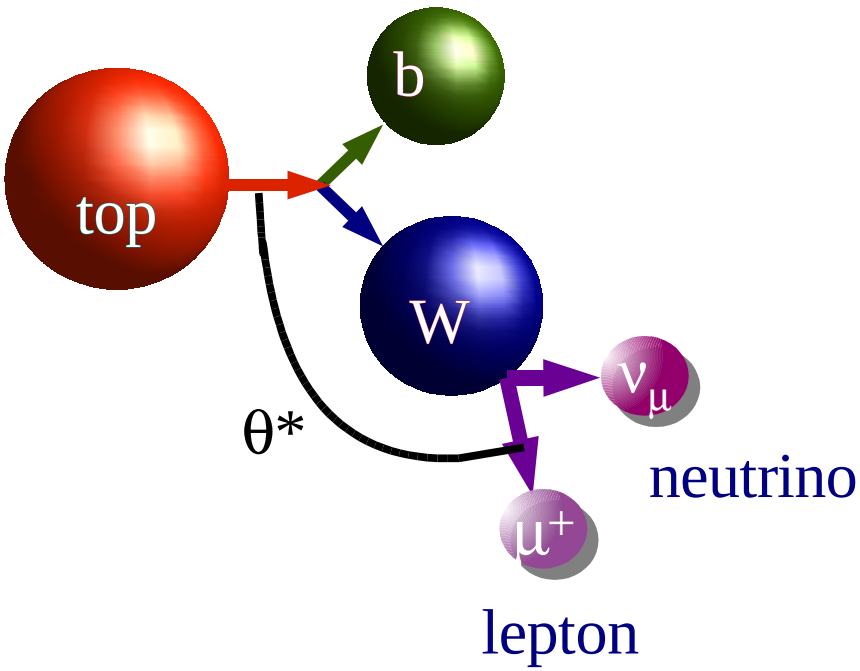
CDF: R>0.61 at 95%CL



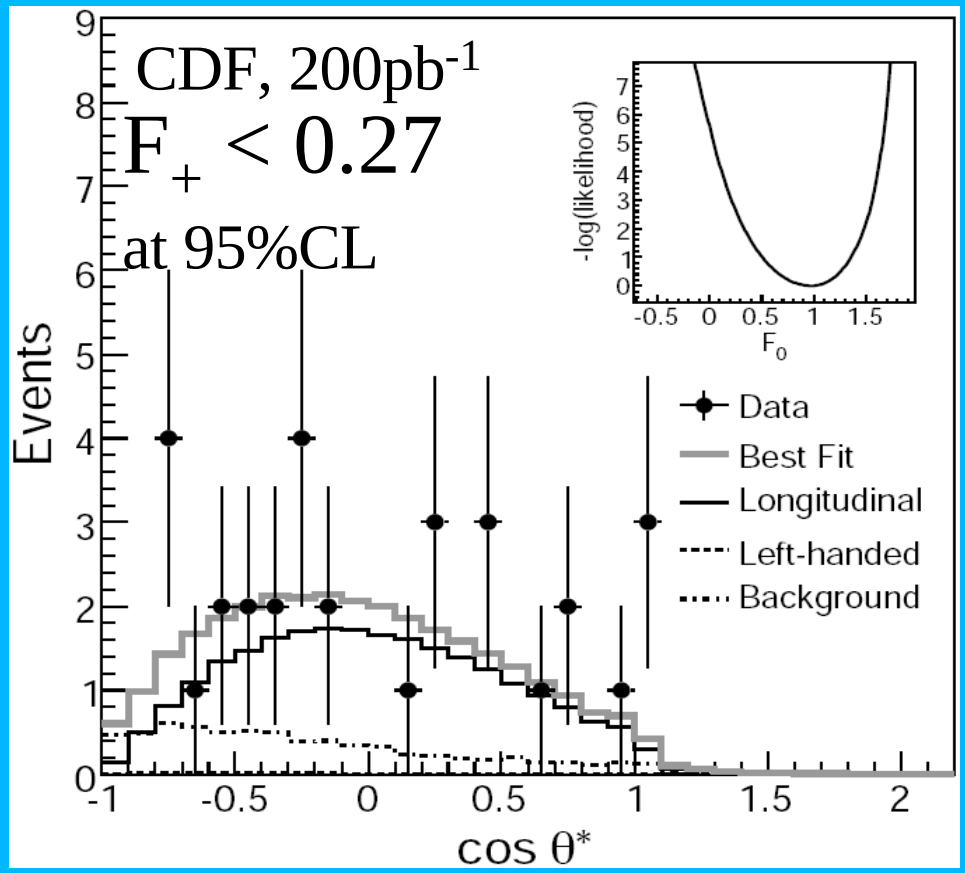
Result: decays to *W* and b-quark, as expected in SM

Top Quark Decay –

Does it follow the SM weak decay rules?



Angular correlation of decay *W*

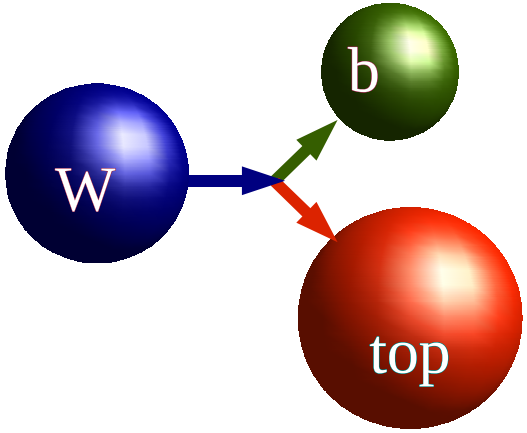


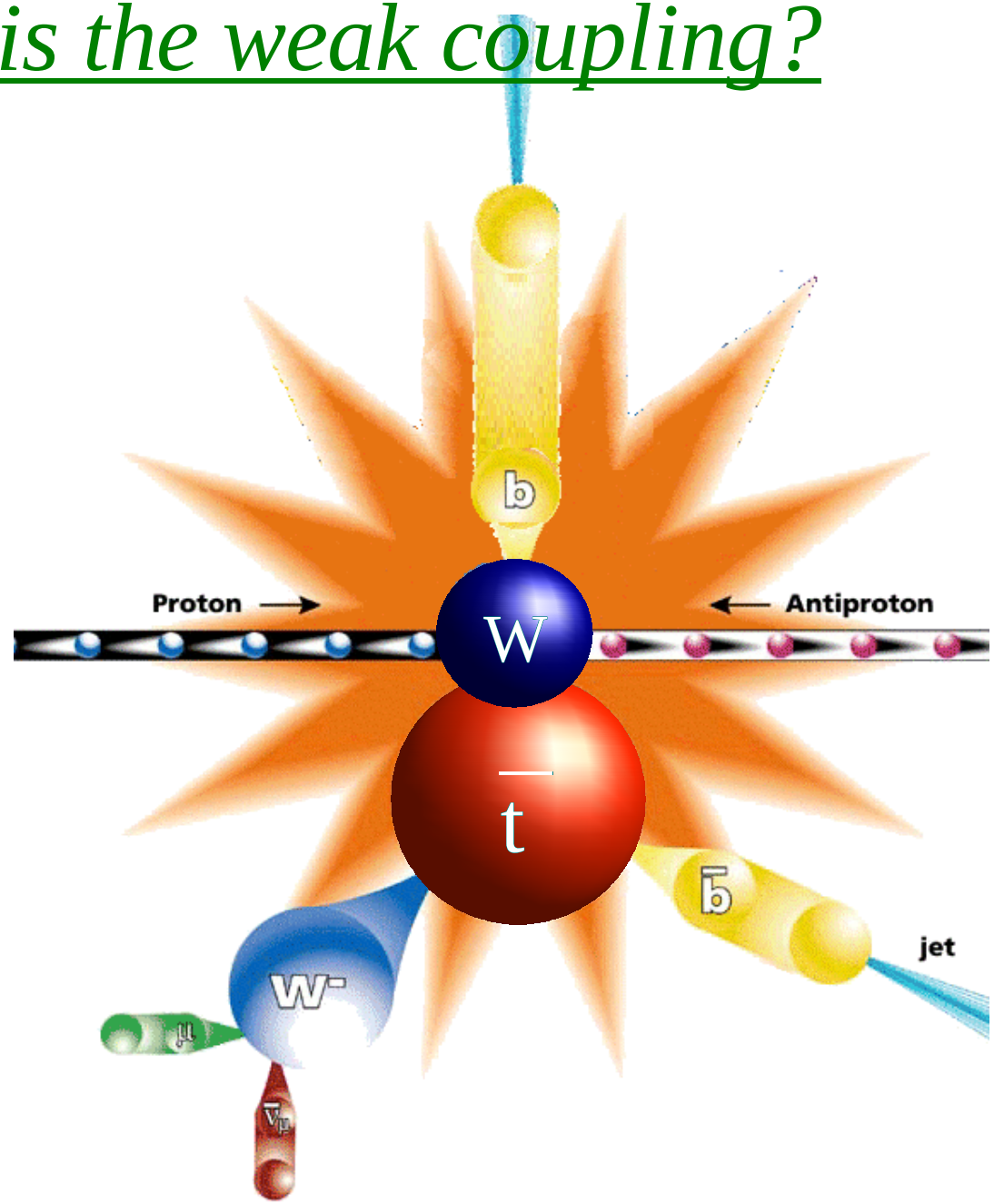
DØ: $F_+ < 0.25$ at 95%CL

Result: decay interaction is mostly left-handed, as expected in SM

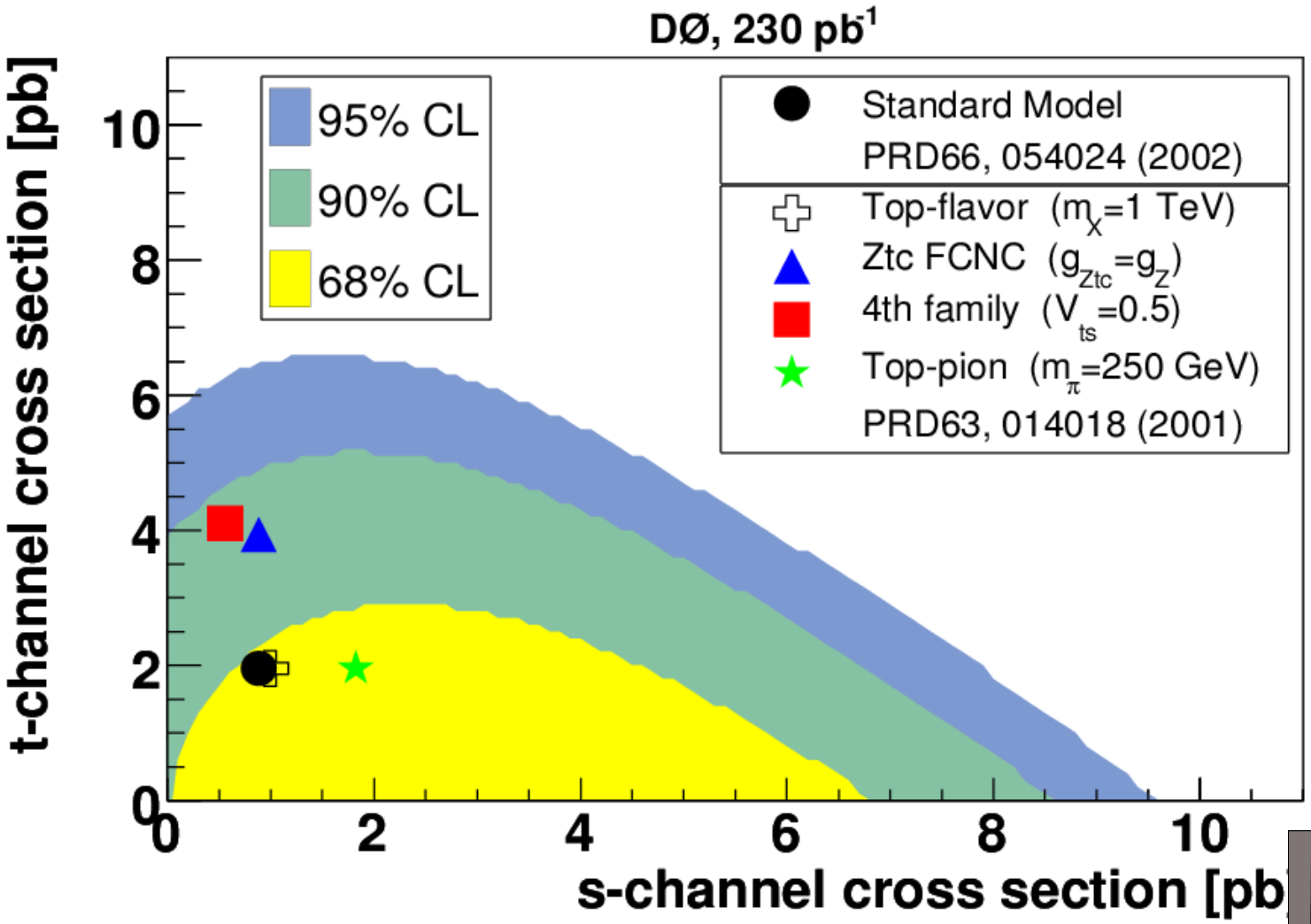
Electroweak top quark production –

How strong is the weak coupling?





Single top search status

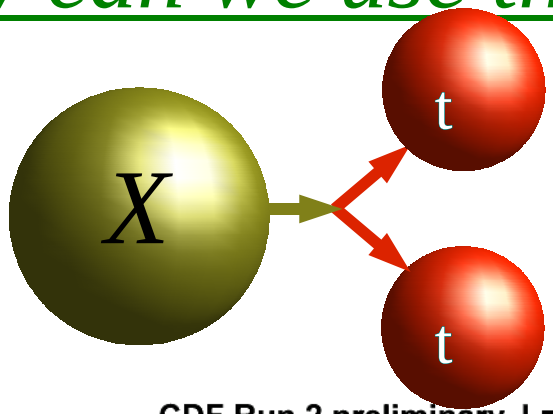


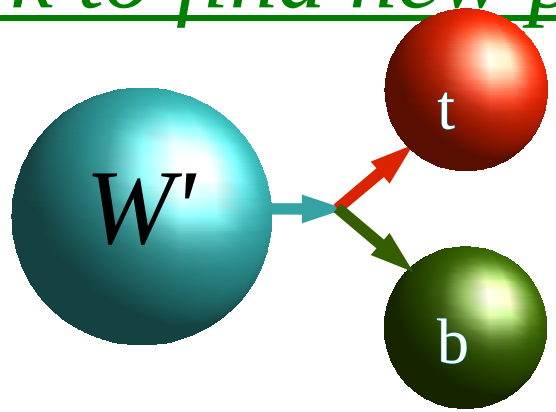
Result: electroweak production consistent with SM

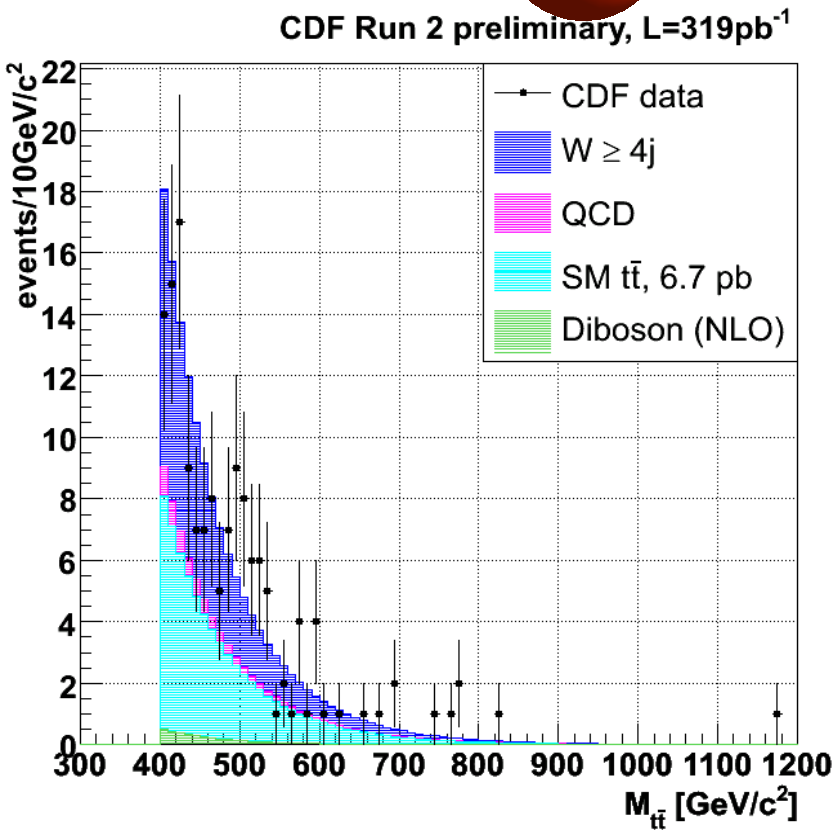
DØ collaboration, PLB 622, 265 (2005)

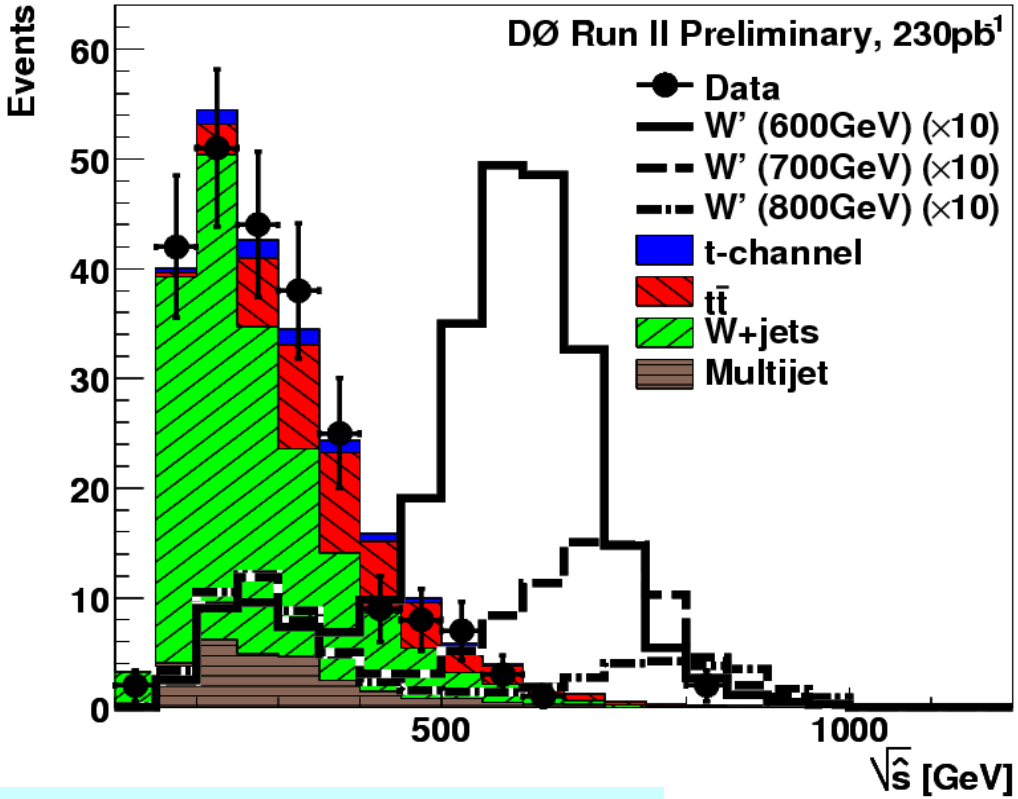
Top as a tool

How can we use the top quark to find new physics?





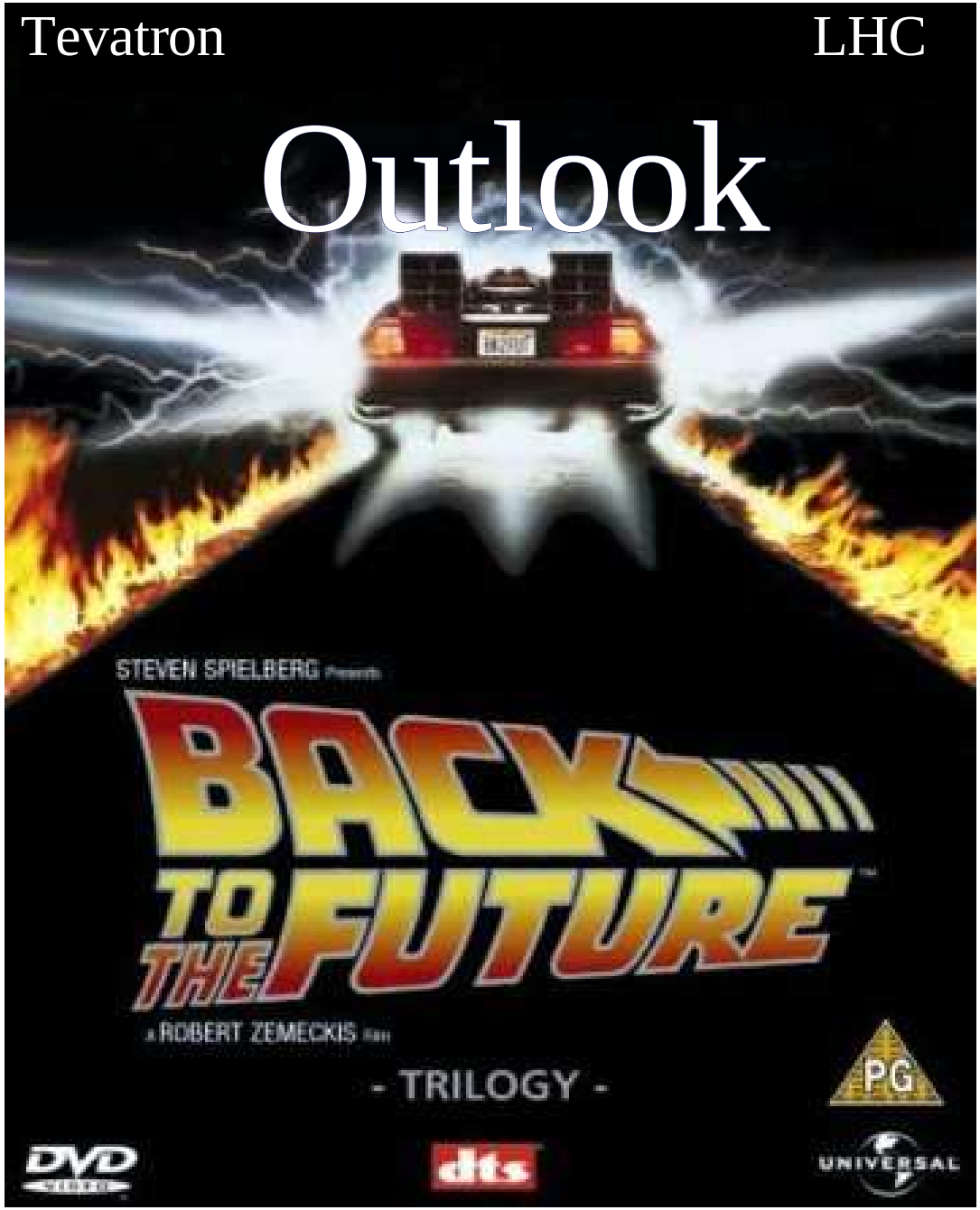




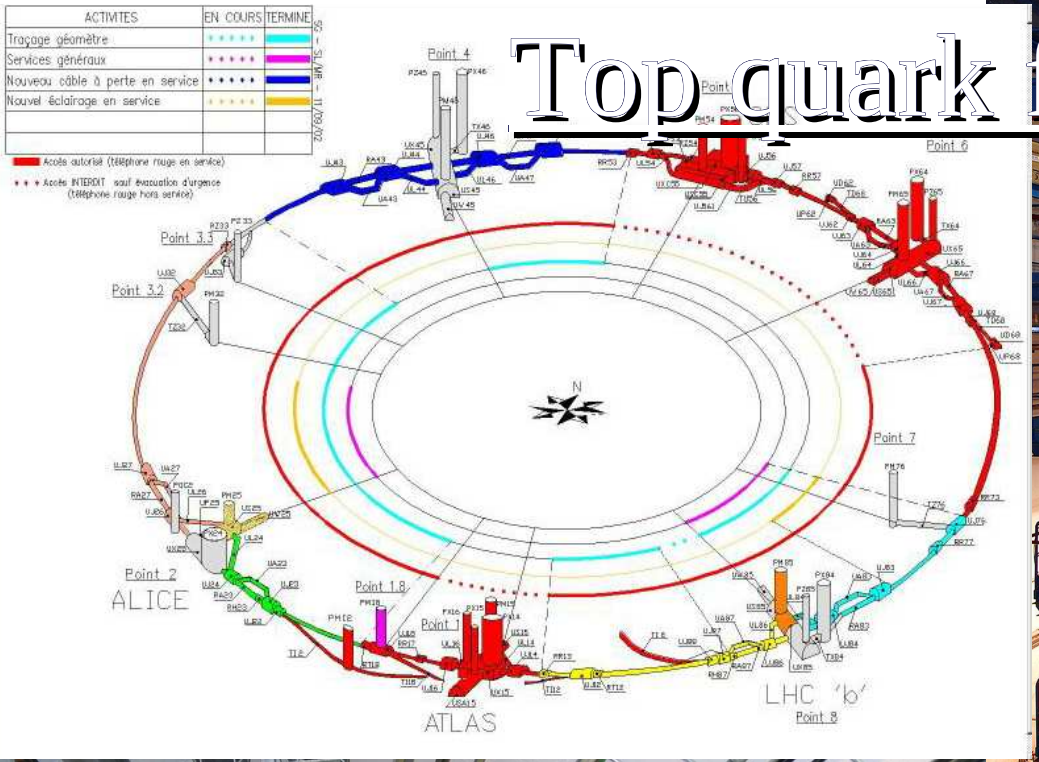
Result: no evidence for new heavy objects

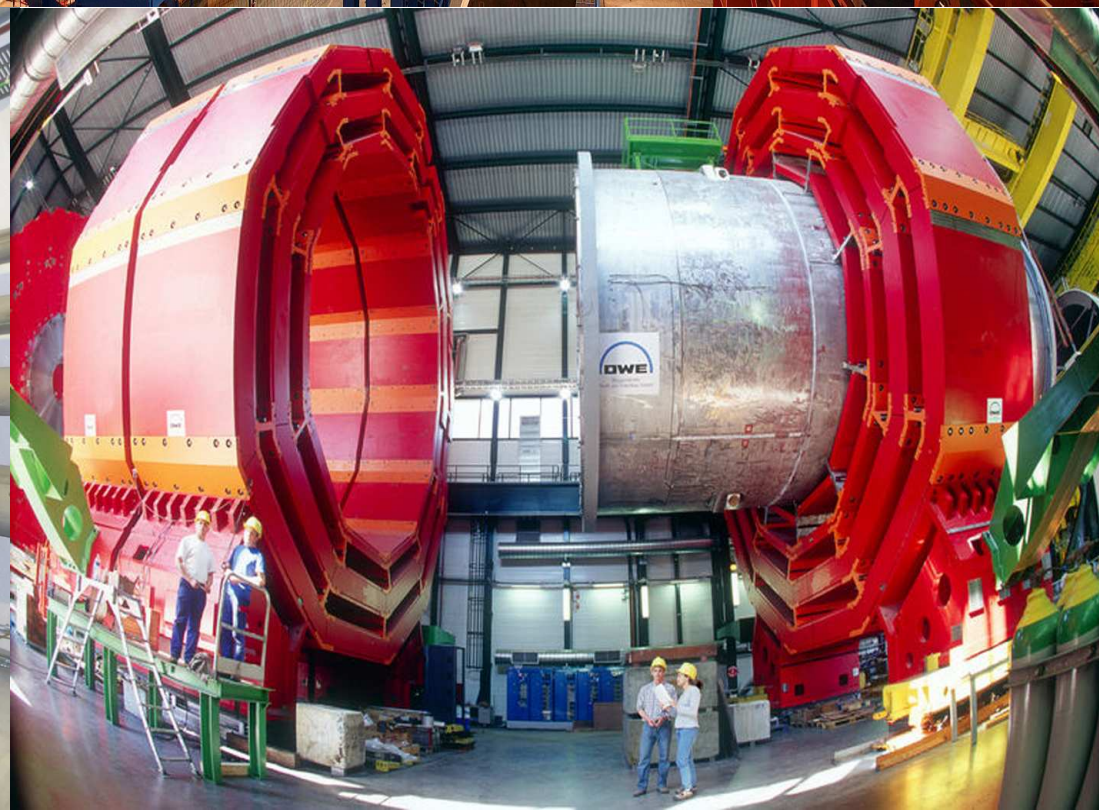
Tevatron LHC

Outlook

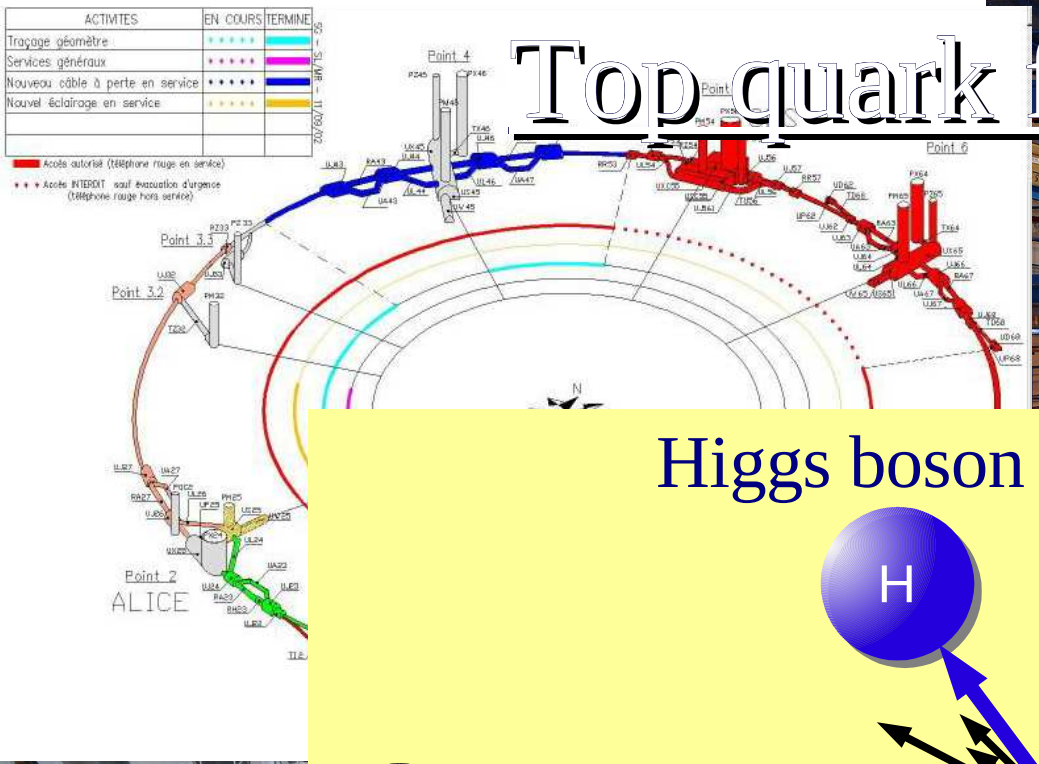


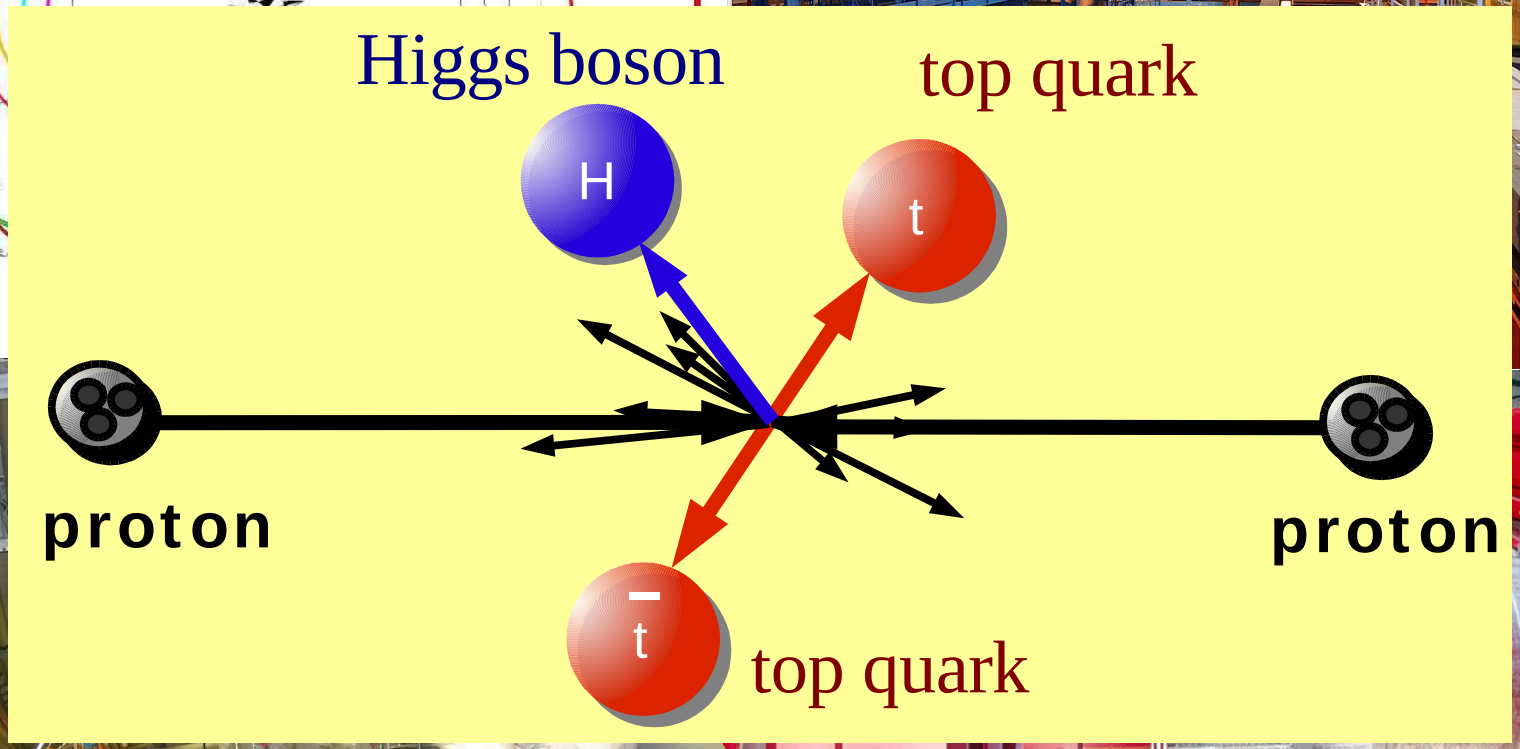
Top quark future: LHC



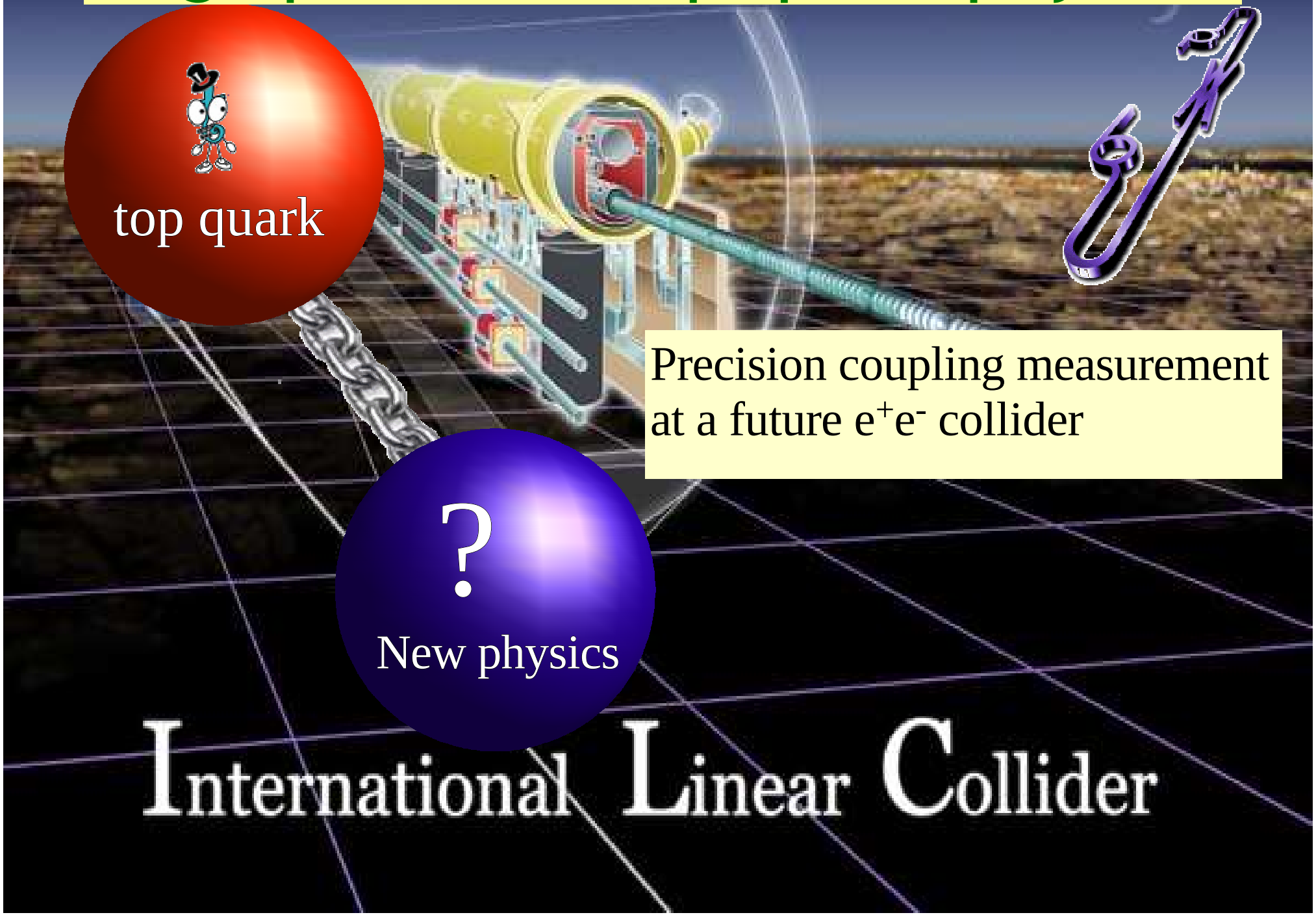


Top quark future: LHC





High precision top quark physics



Precision coupling measurement at a future e^+e^- collider

Conclusions

- The top quark is a key to understanding the mechanism that generates particle mass
- We have learned a lot about the top quark recently
  - 25 top-quark related papers from Tevatron RunII already
- This is just the beginning
  - Tevatron dataset will increase ×20 in next 4 years
  - LHC is just around the corner
- We are close to revealing the origin of matter

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