

Physics with Top Quarks

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University of Virginia Physics Colloquium, 11/2/2007



*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

- Introduction
- Particle masses and the top quark
- The Energy frontier
- Tevatron: Top quark measurements
- LHC: Top as a tool
- Conclusions

- Simplified units:

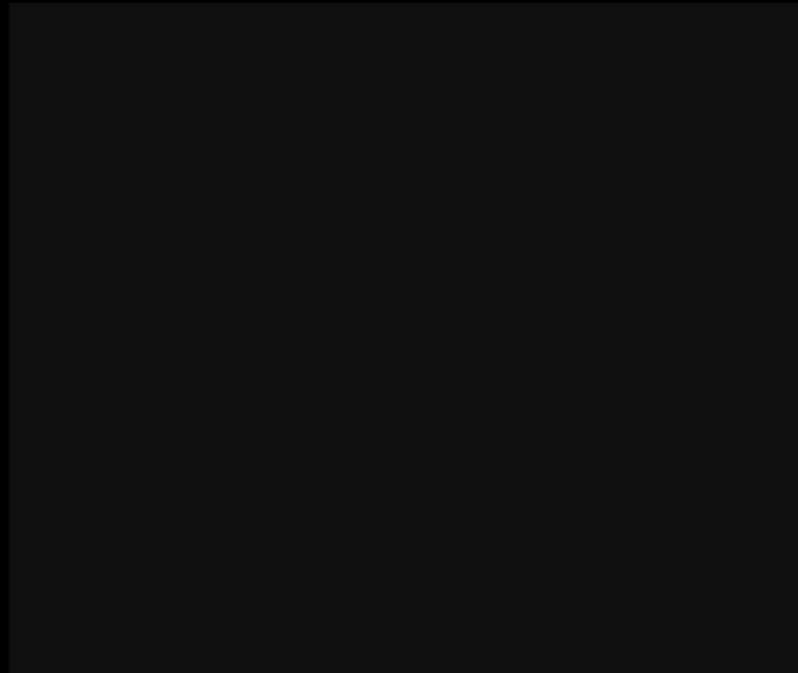
$c = 1$

→ 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?

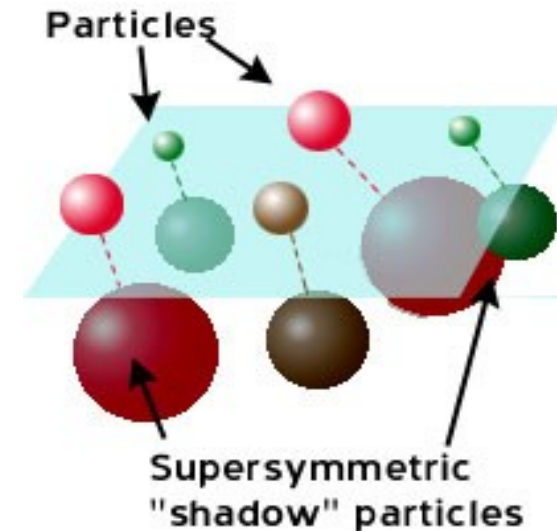
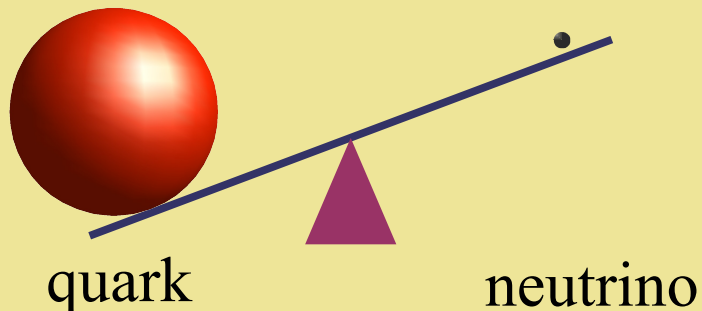
What is the universe made of?

What is dark matter?

What is dark energy?

What happened to anti-matter?

What makes quarks so heavy and neutrinos so light?



Supersymmetry? Extra spatial dimensions? ...

Particle masses

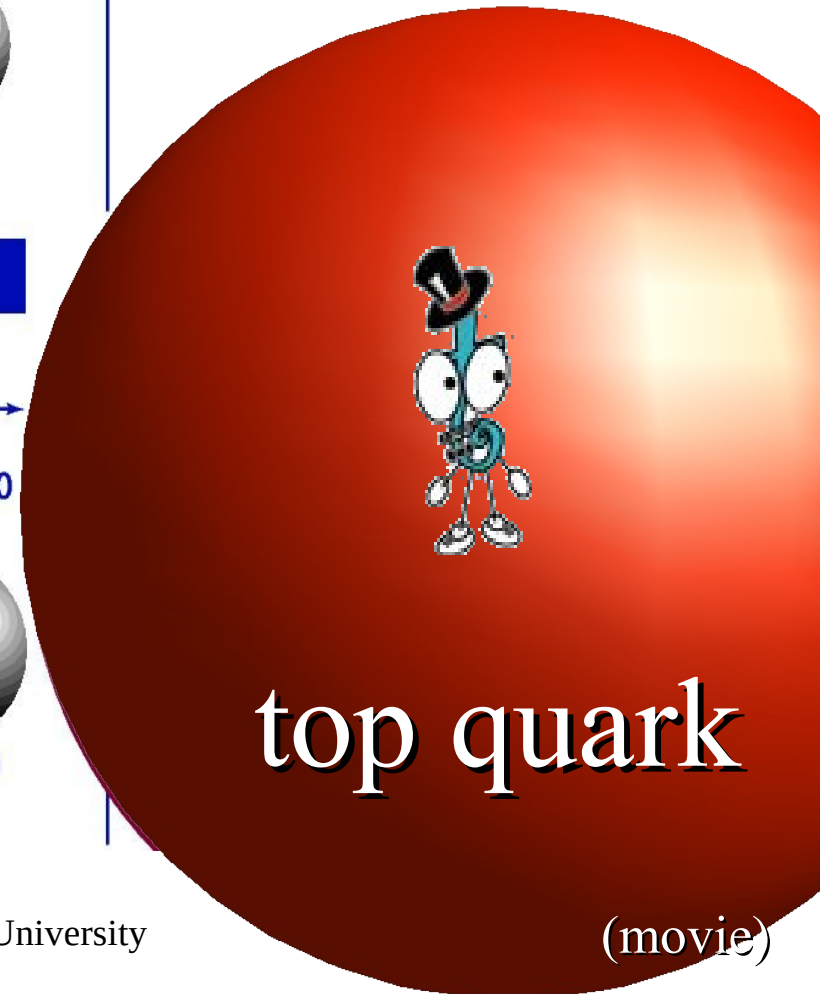
Electroweak symmetry breaking

Fermion masses

L E P T O N S			
Charge			
0	Electron neutrino Mass: 0?	Muon neutrino 0?	Tau neutrino 0?
-1	Electron .511	Muon 105.7	Tau 1,777
Q U A R K S			
Charge			
$+2/3$	Up Mass: 5	Charm 1,500	
$-1/3$	Down 8	Strange 160	Bottom 4,250

Fermion masses

L E P T O N S			
Charge			
0	Electron neutrino Mass: 0?	Muon neutrino 0?	Tau neutrino 0?
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Q U A R K S			
Charge			
$+2/3$	Up Mass: 5	Charm 1,500	Top ~180,000
$-1/3$	Down 8	Strange 160	Bottom 4,250



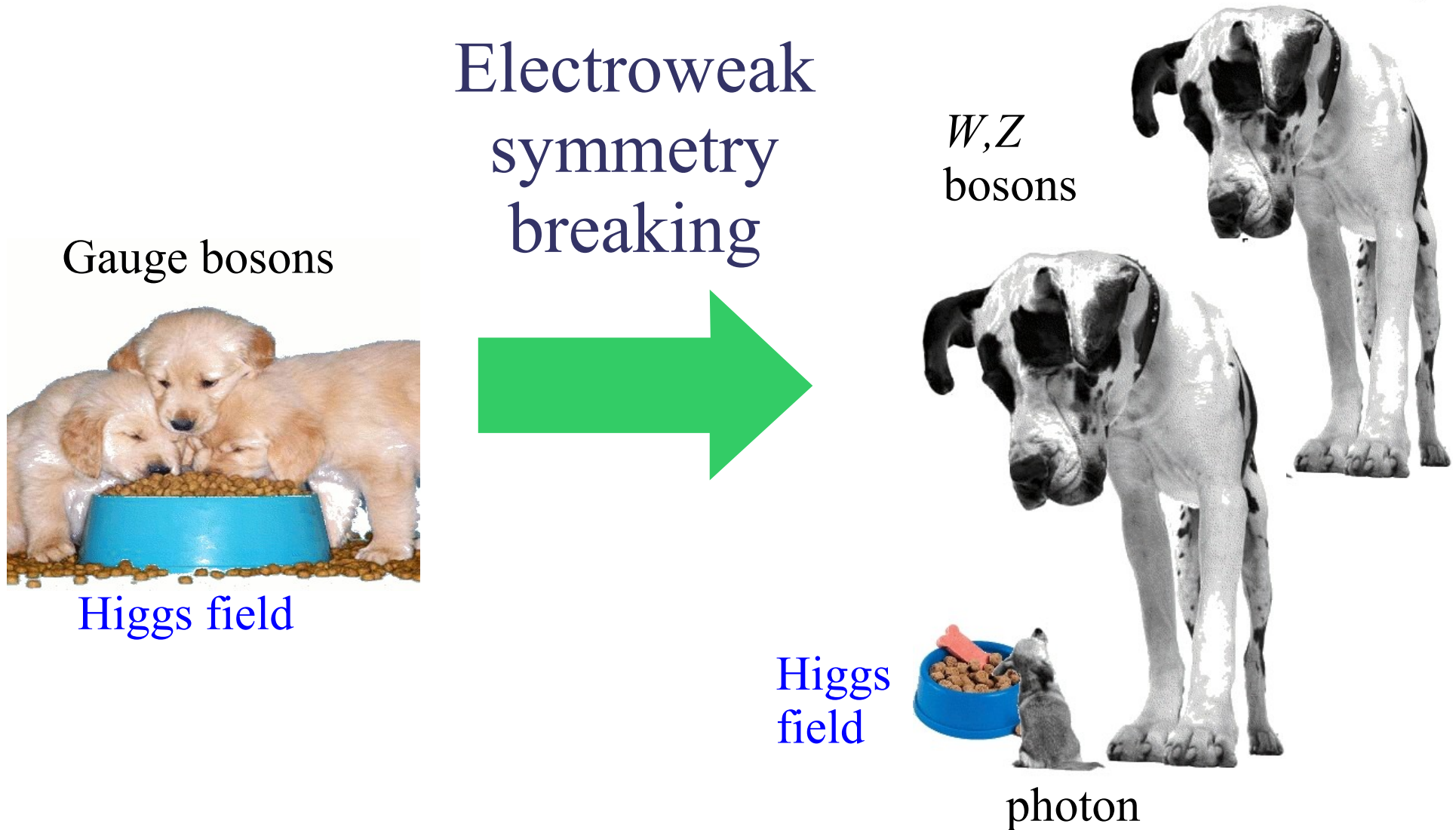
Higgs mechanism: Gauge boson masses in the SM

Gauge bosons



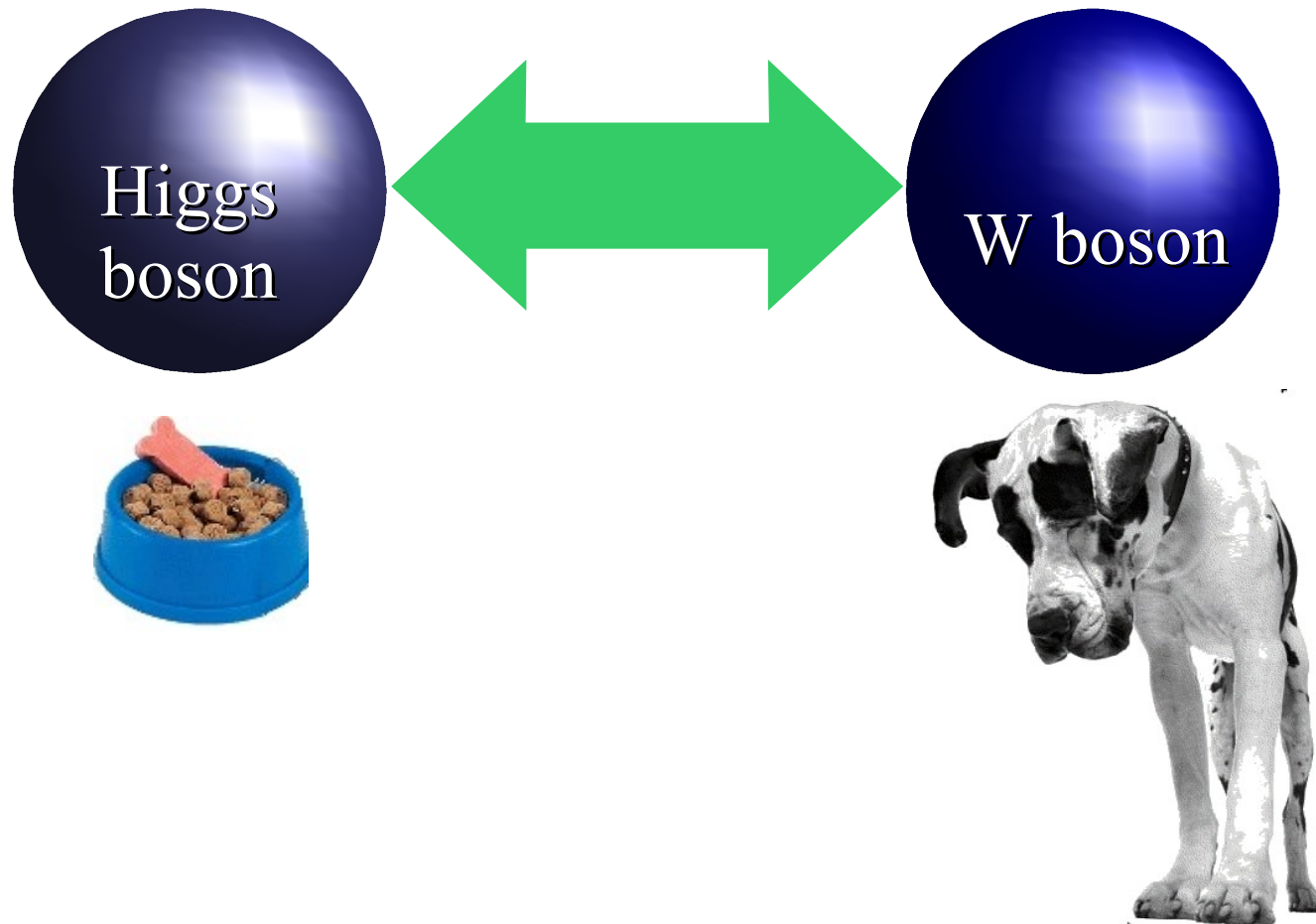
Higgs field

Higgs mechanism: Gauge boson masses in the SM



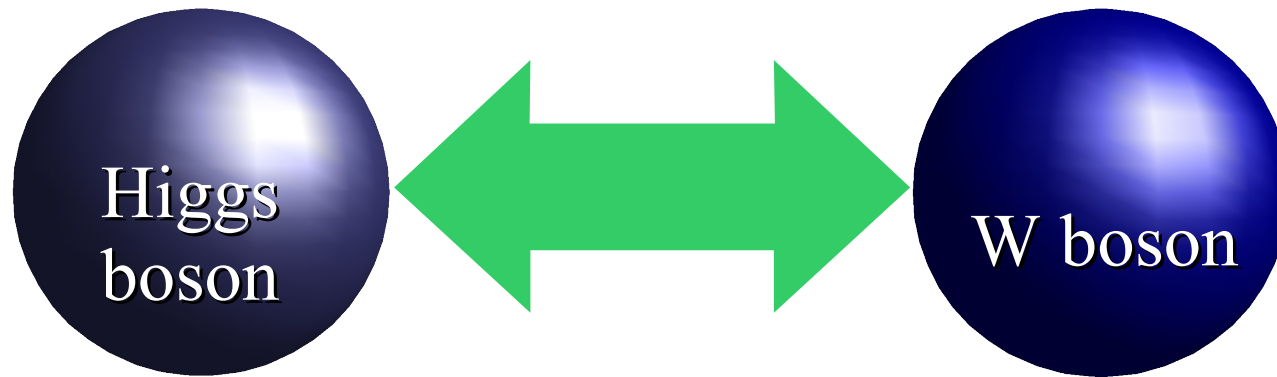
Electroweak symmetry breaking

Gauge boson coupling to Higgs field

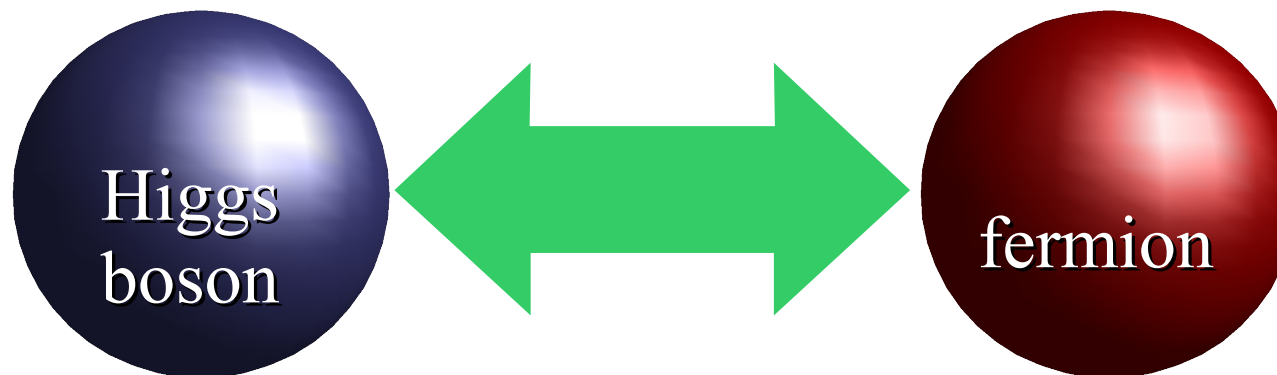


Electroweak symmetry breaking

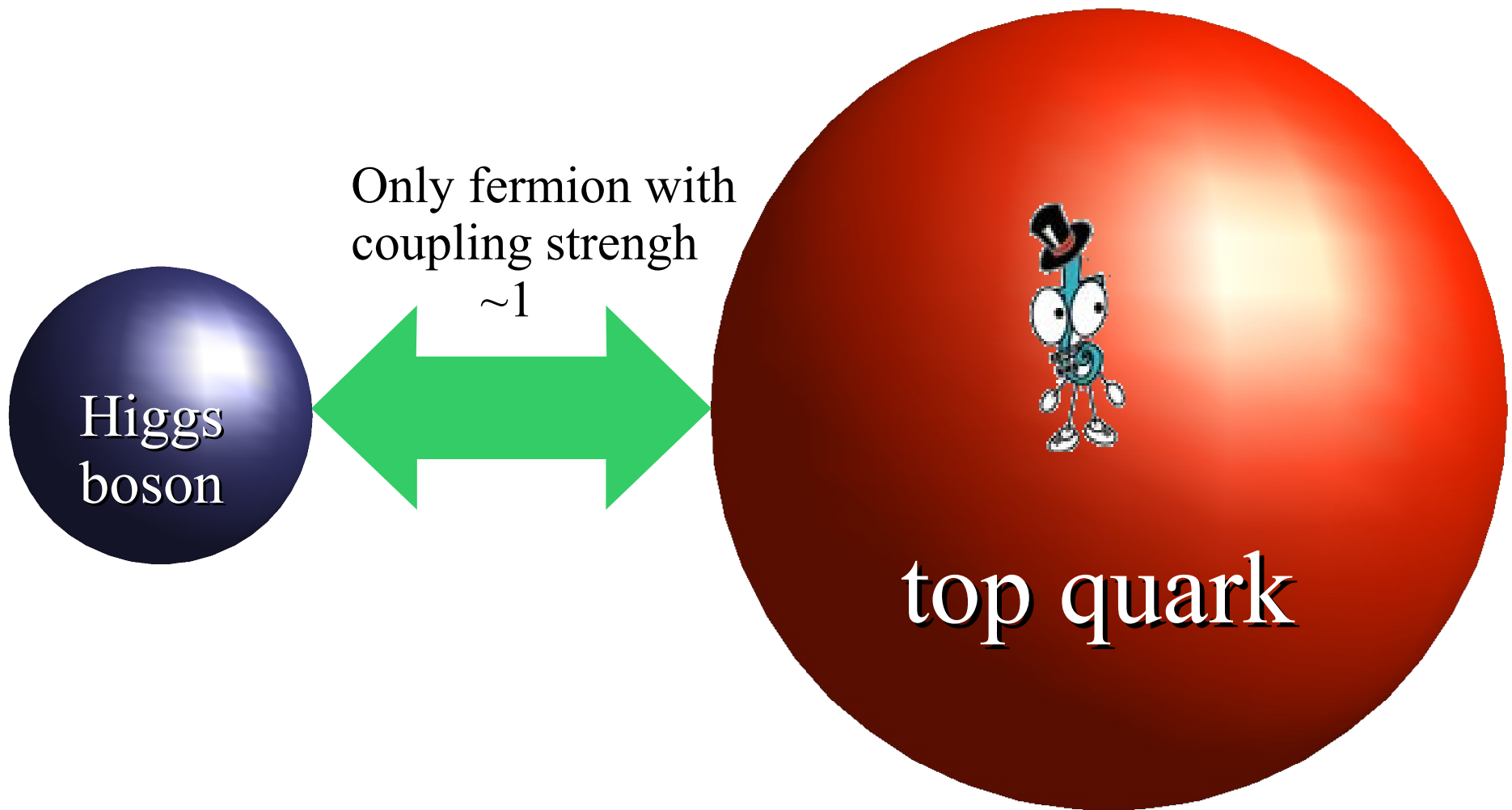
Gauge boson coupling to Higgs field



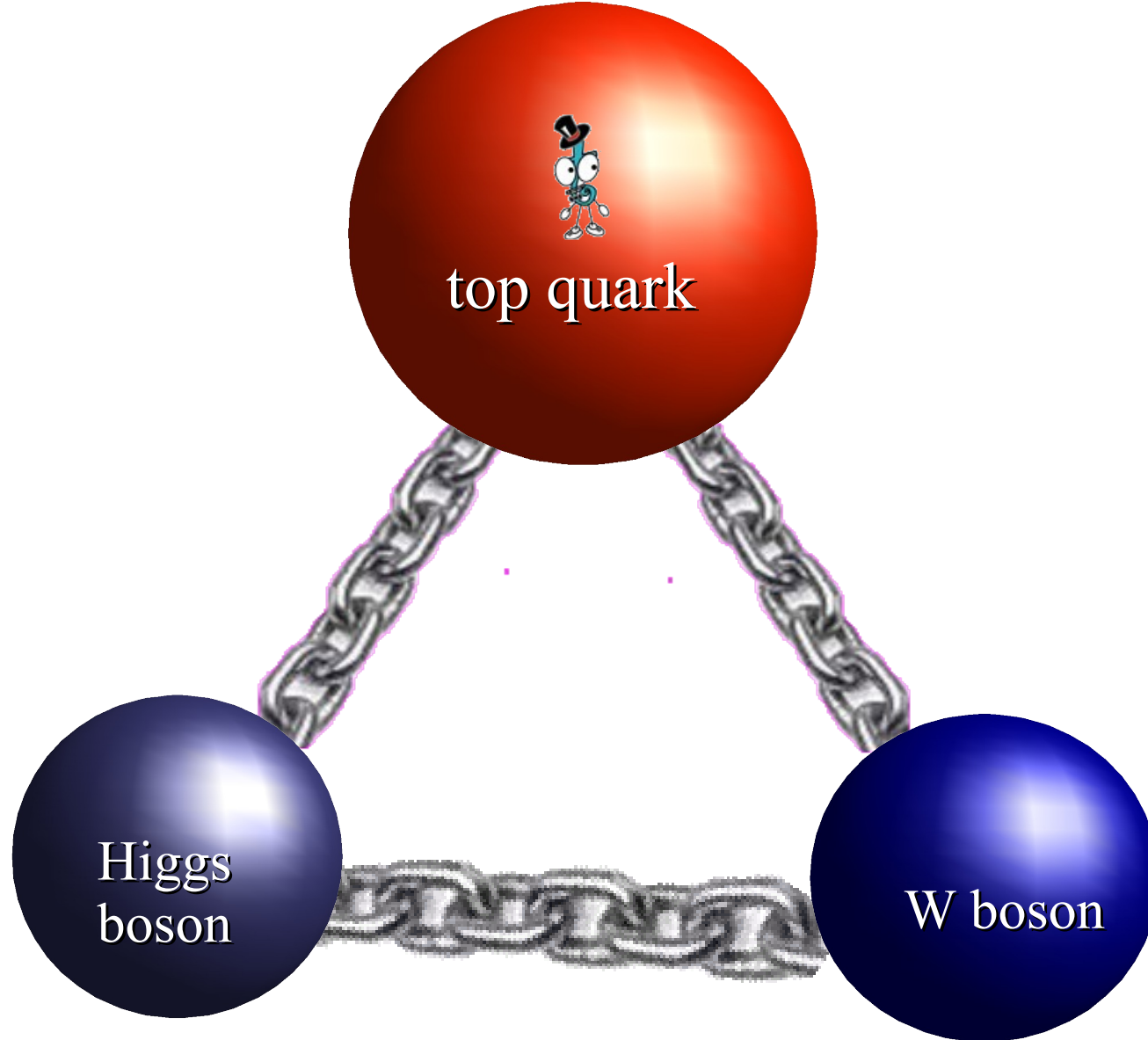
Fermions acquire mass through Higgs coupling



Top quark mass



Key to electroweak symmetry breaking

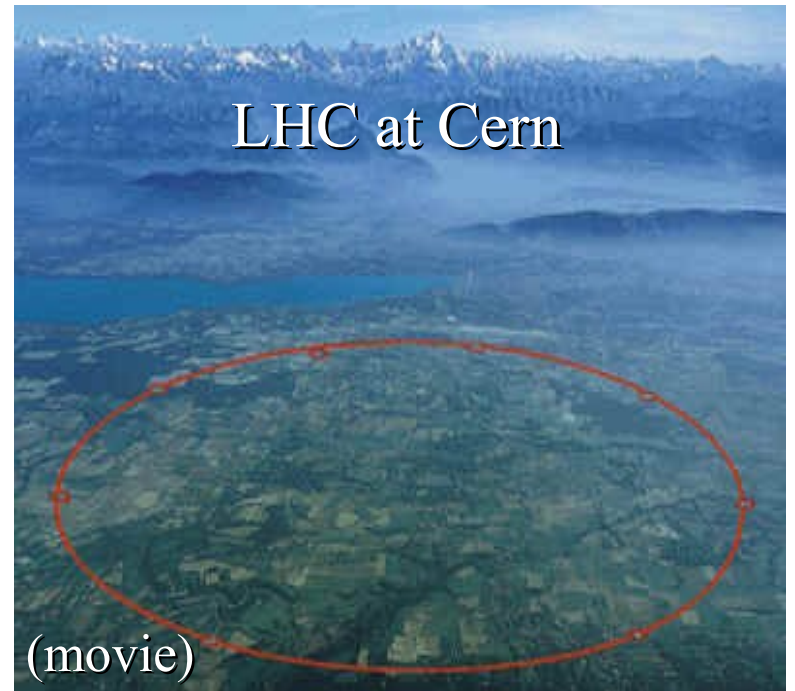
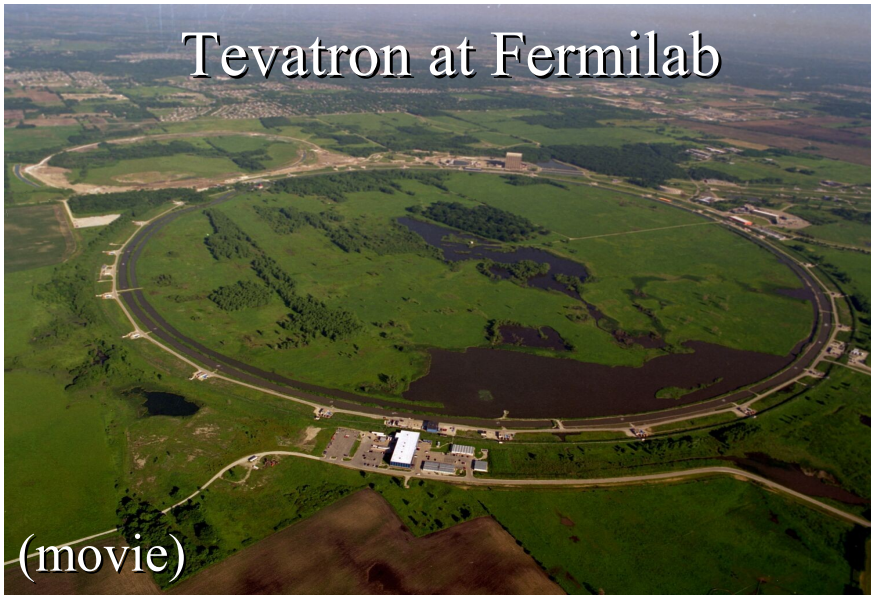
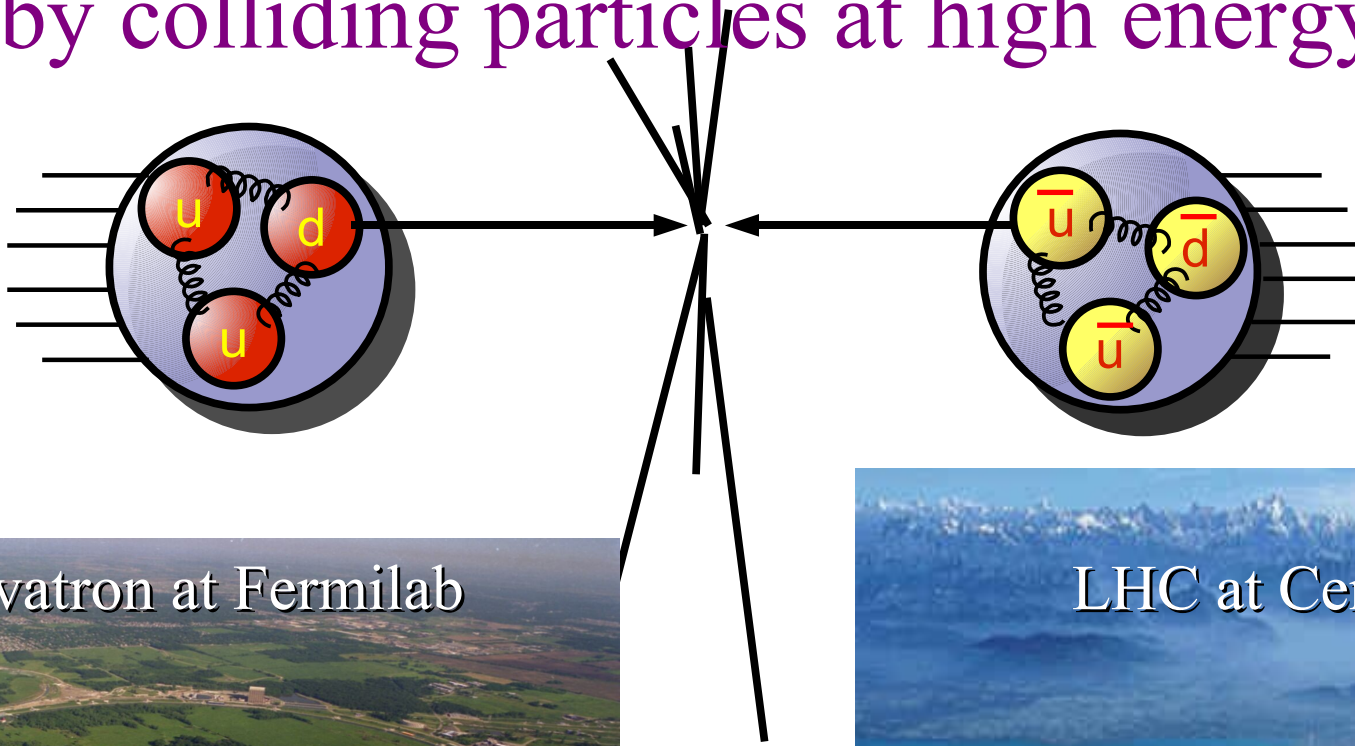


Experimental procedure

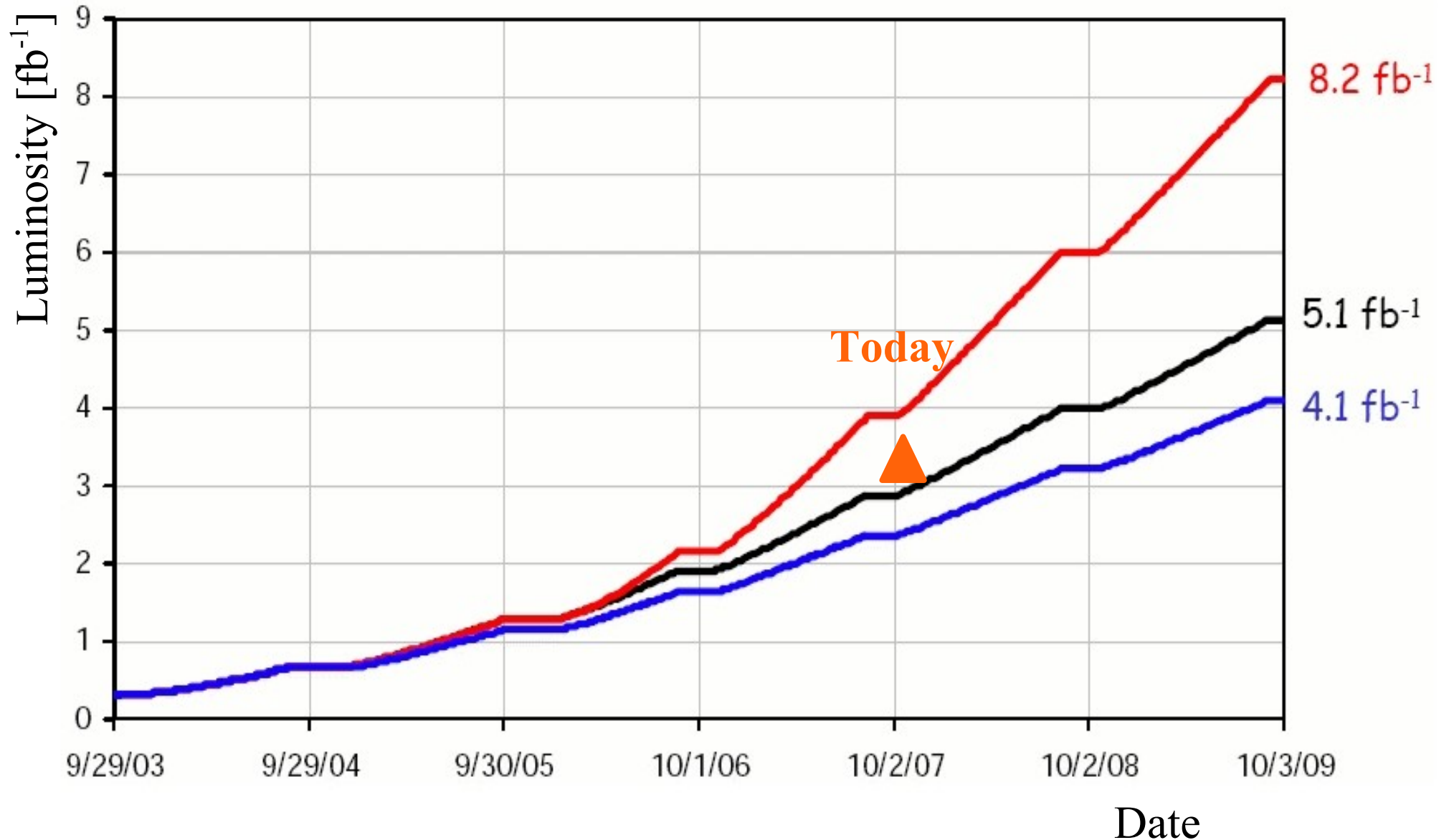
How do we find out?

The energy frontier

Probing physics at small distances
by colliding particles at high energy



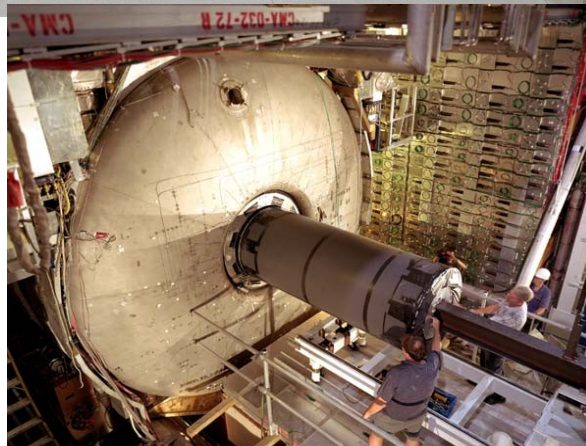
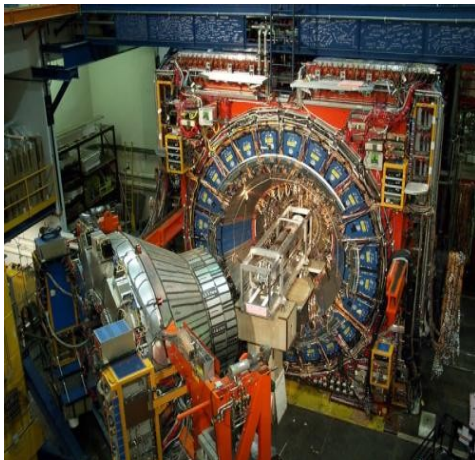
Tevatron luminosity



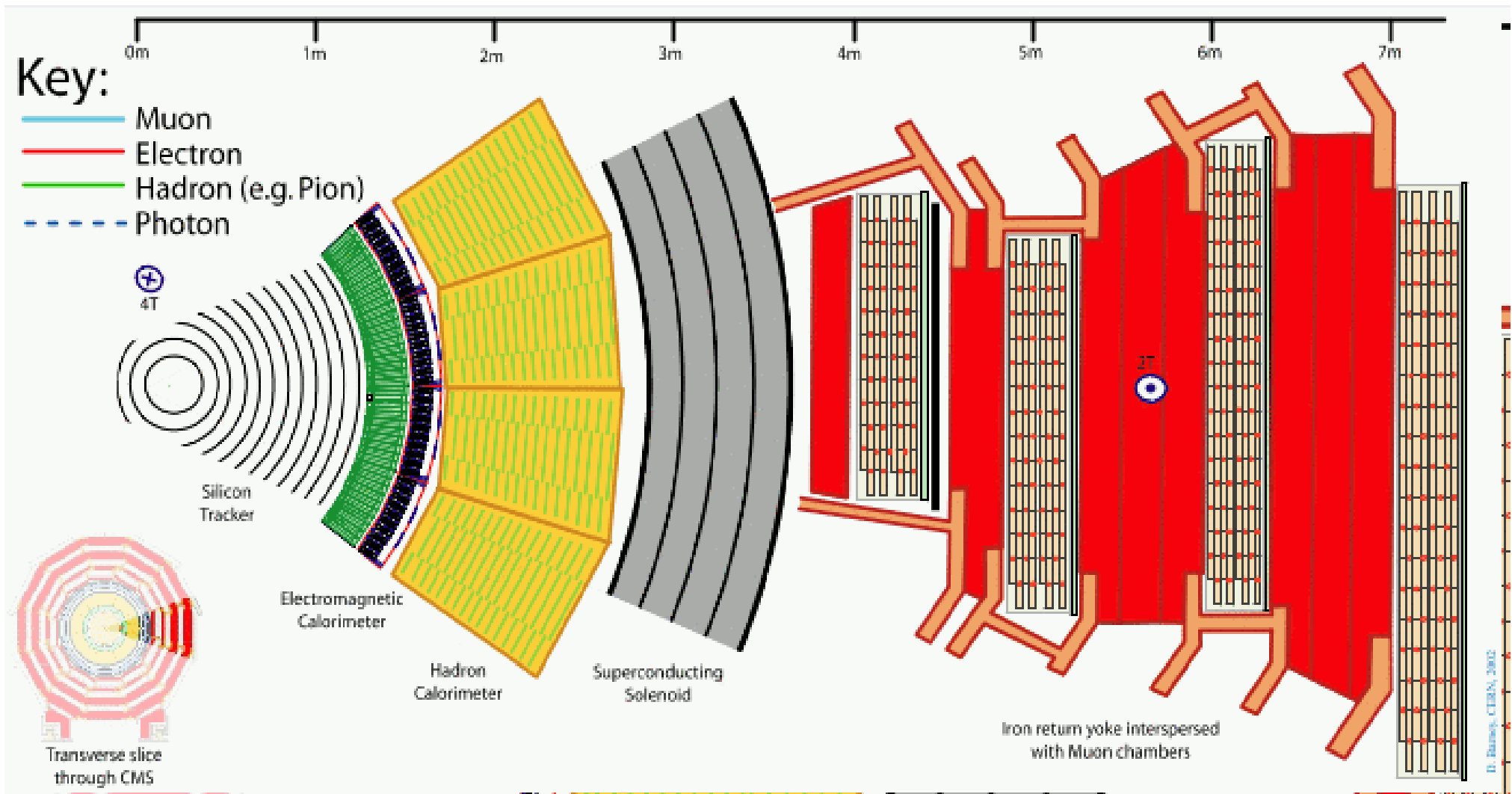
Tevatron collaborations



**Together
> 1400 physicists
from 21 countries**



Particles and detectors



Top quark known knowns



- Top quark produced in SM strong interaction
- Top quark decays before it hadronizes
 - Study bare quark
- Top quark usually decays to a W boson and b quark
- Top quark mass ~ 175 GeV

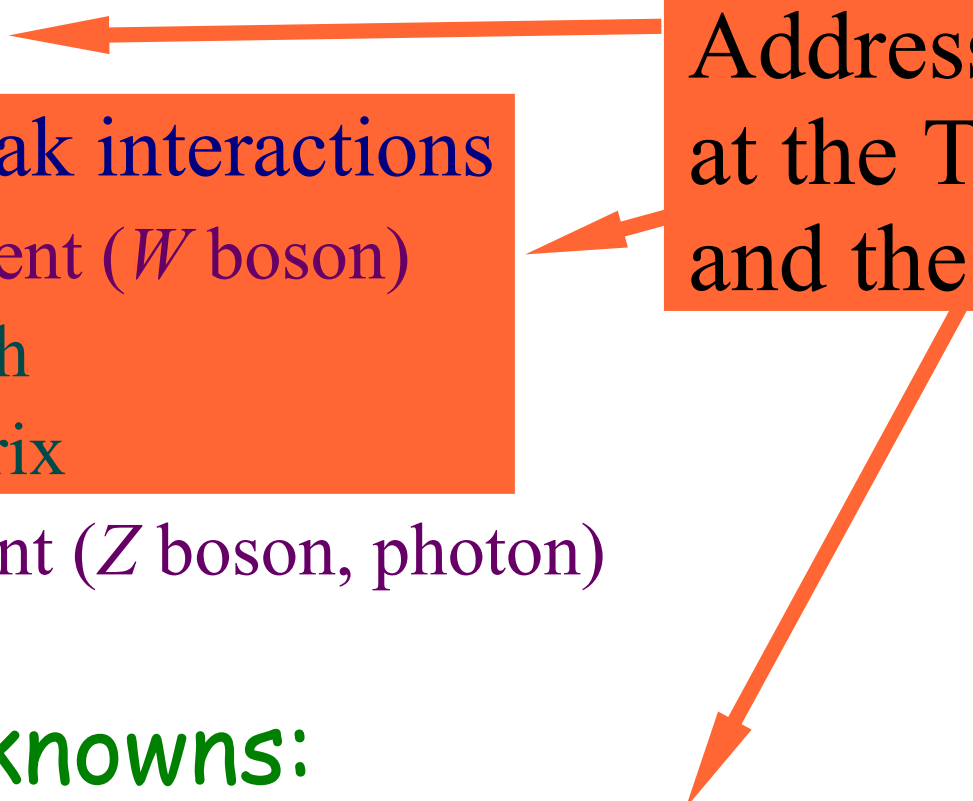
Top quark known unknowns:

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

Unknown unknowns:

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

Top quark known unknowns:

- Charge, Spin
 - SM electroweak interactions
 - Charged current (W boson)
 - Total width
 - CKM matrix
 - Neutral current (Z boson, photon)
- Address at the Tevatron and the LHC
- 

Unknown unknowns:

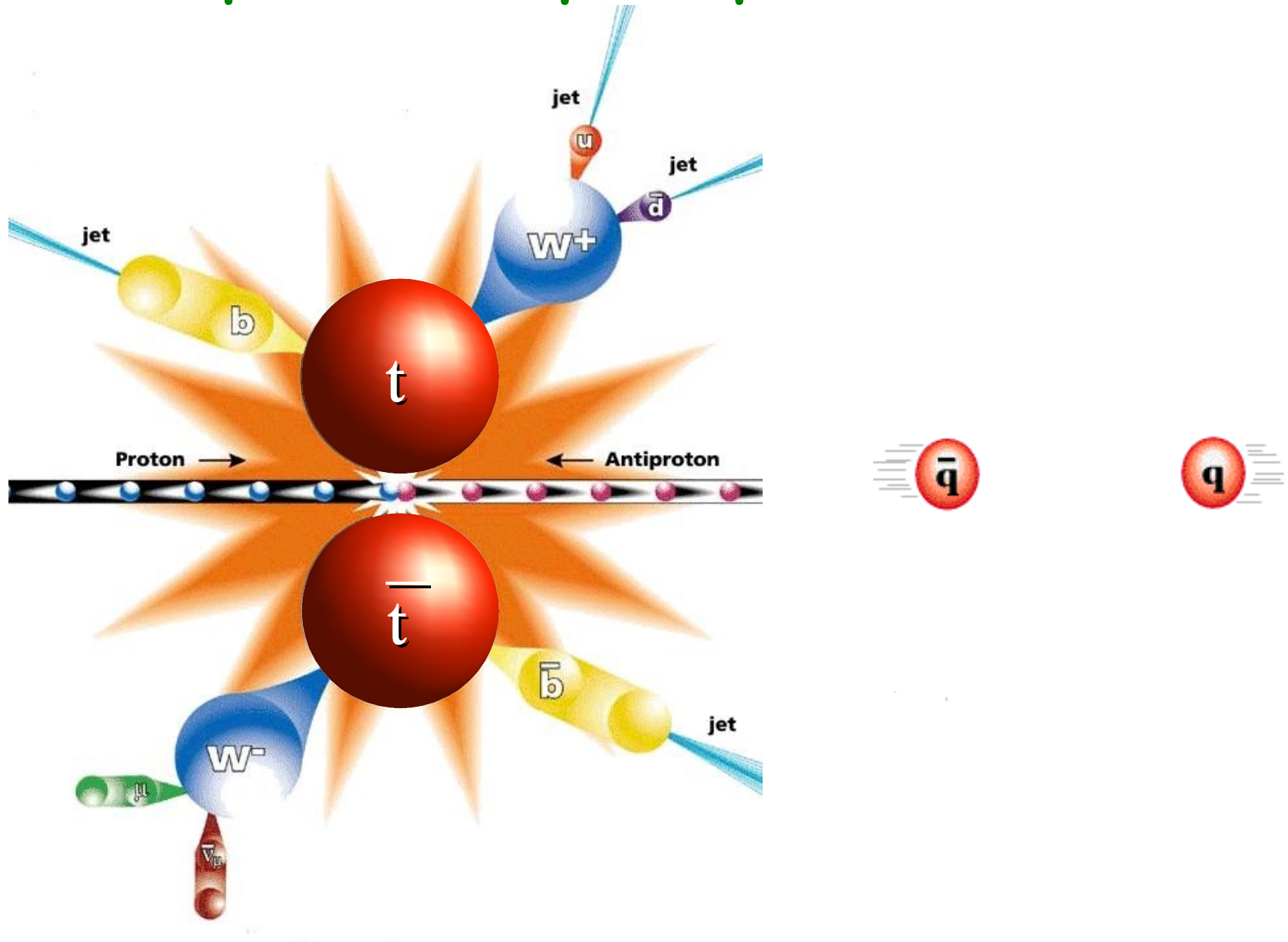
- Coupling to Higgs boson?
- Modified coupling to SM particles?
- New physics? New particle?

Recent results

*What have we learned about the
top quark?*

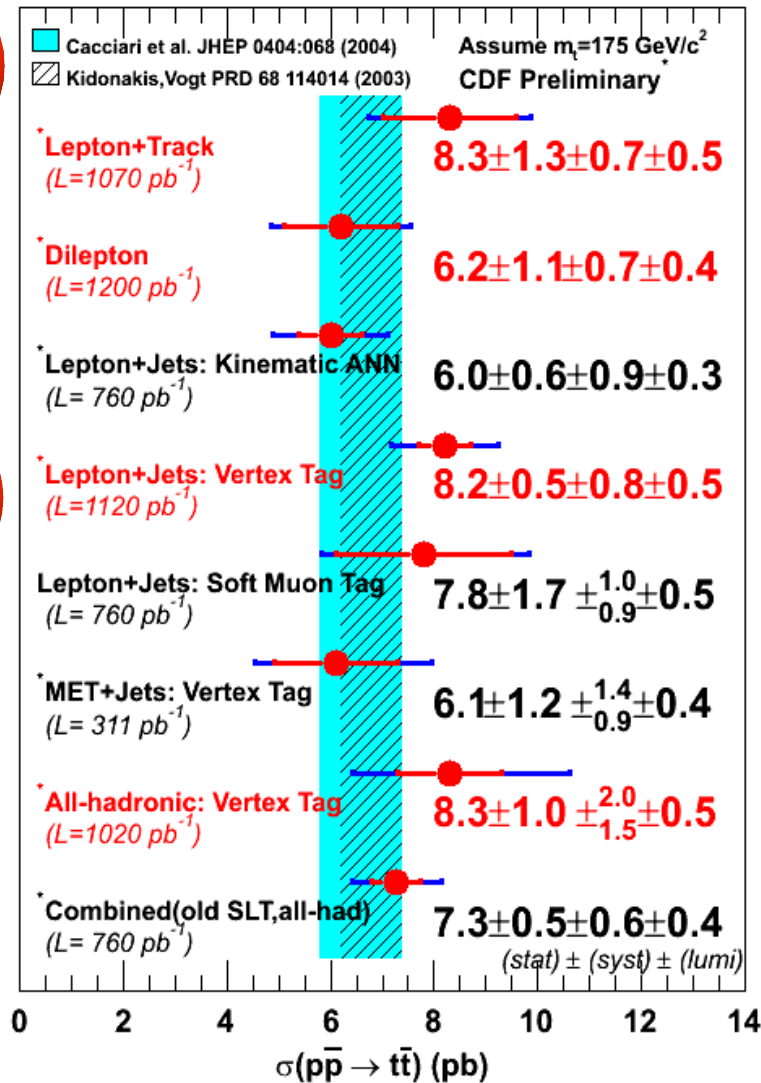
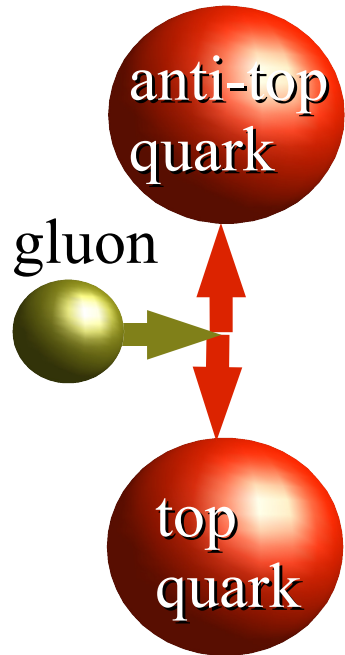
(at the Tevatron, the only place in the world making top quarks)

Top Quark pair production



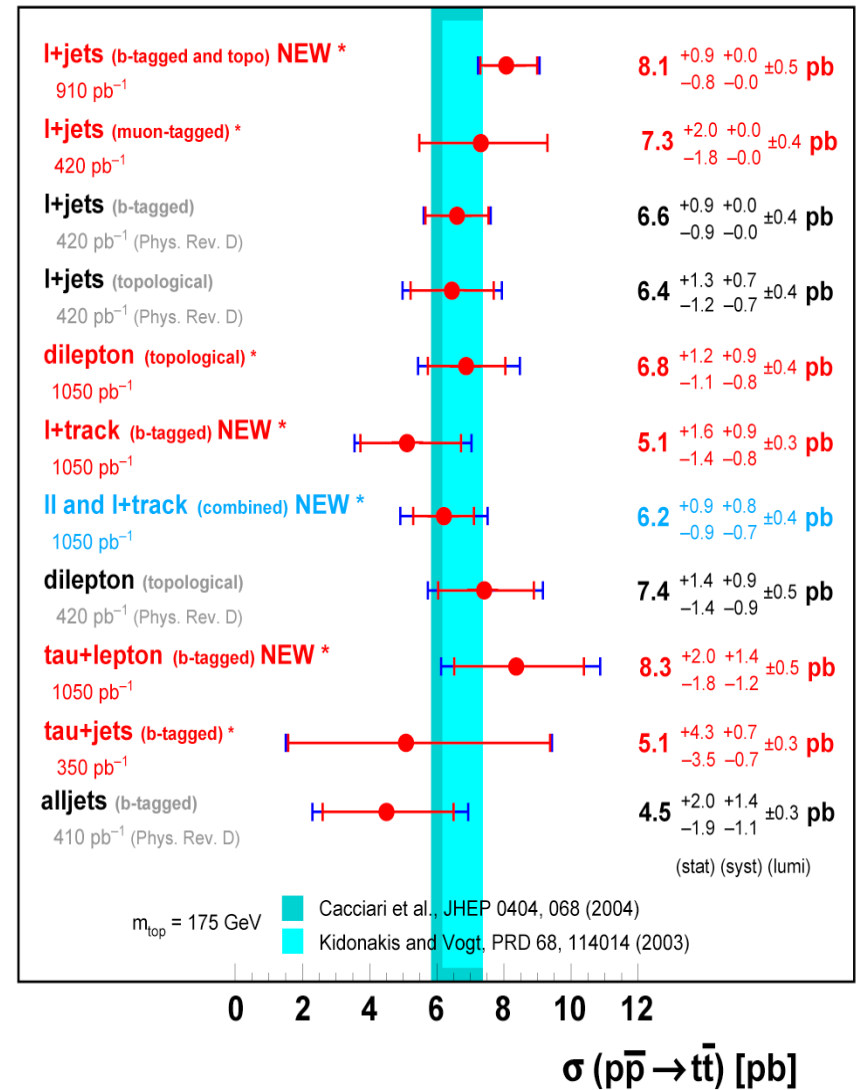
Top quark strong interaction –

Does it couple to gluons like a quark?



DØ Run II * = preliminary

Summer 2007

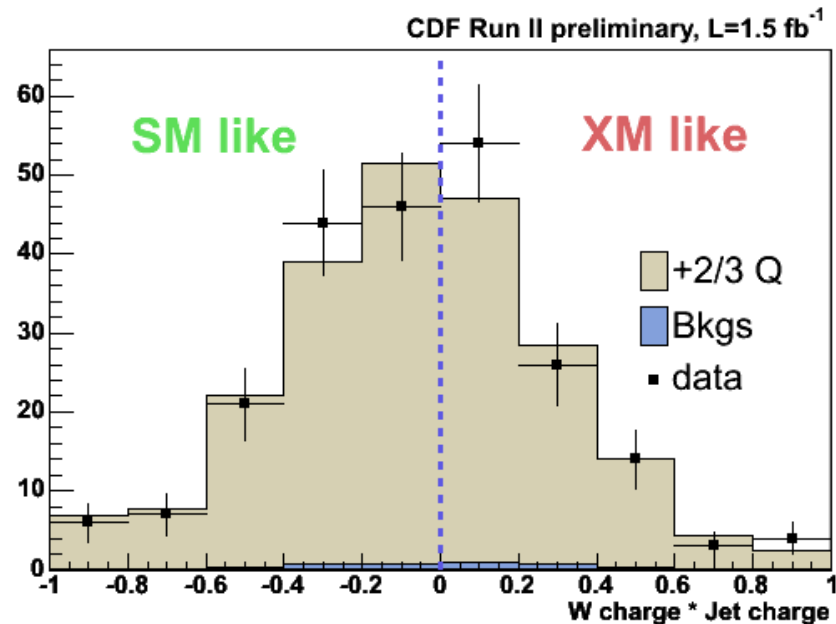
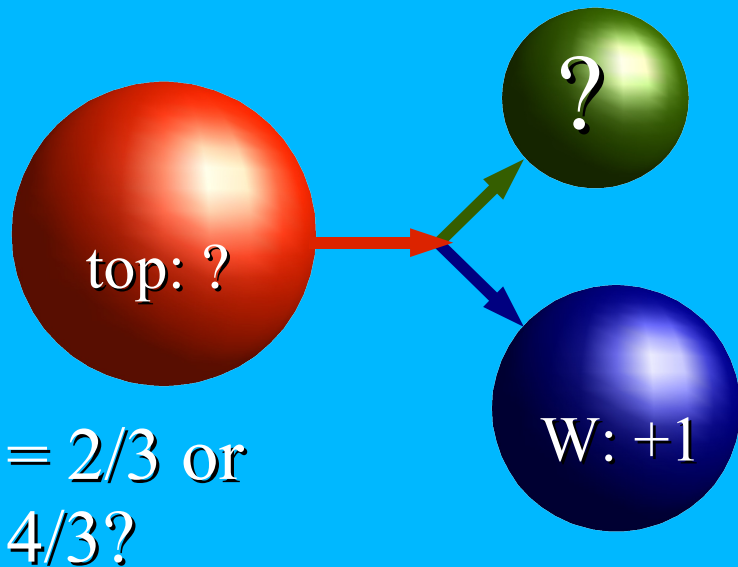


Result: SM strong interaction

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

Top quark charge

b ($-1/3$) or $\bar{b}$ ($+1/3$)?

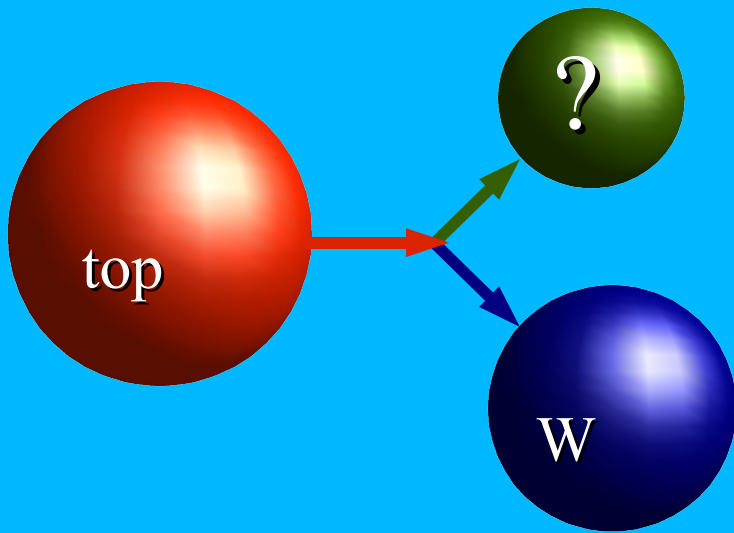


Result from both CDF and DØ:
charge=2/3
as expected in SM

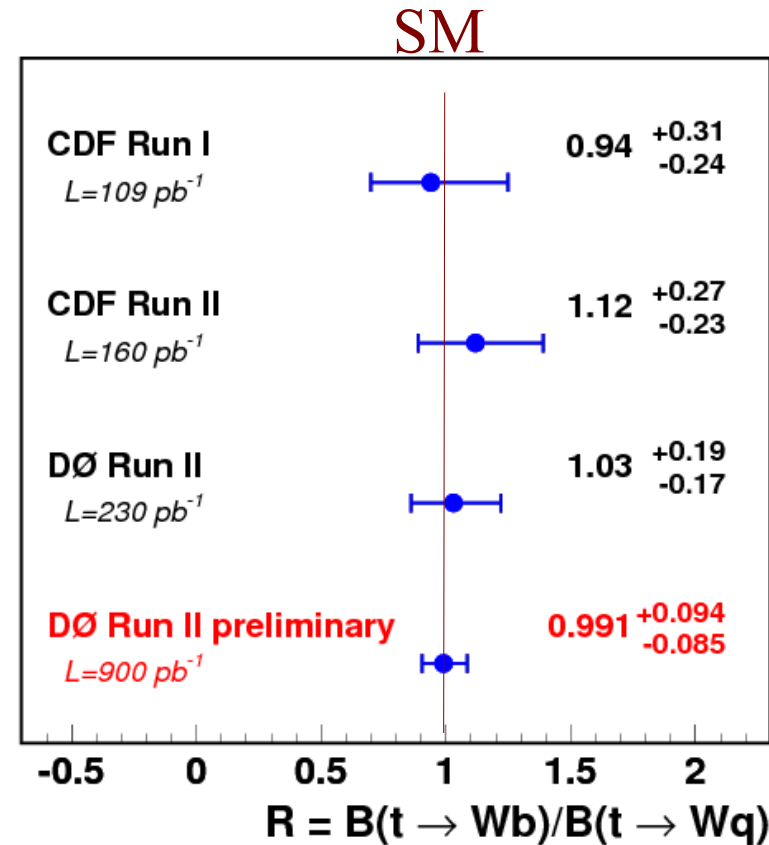
Top quark properties – *Is it the quark we think it is?*

Top quark decay

b or something else?



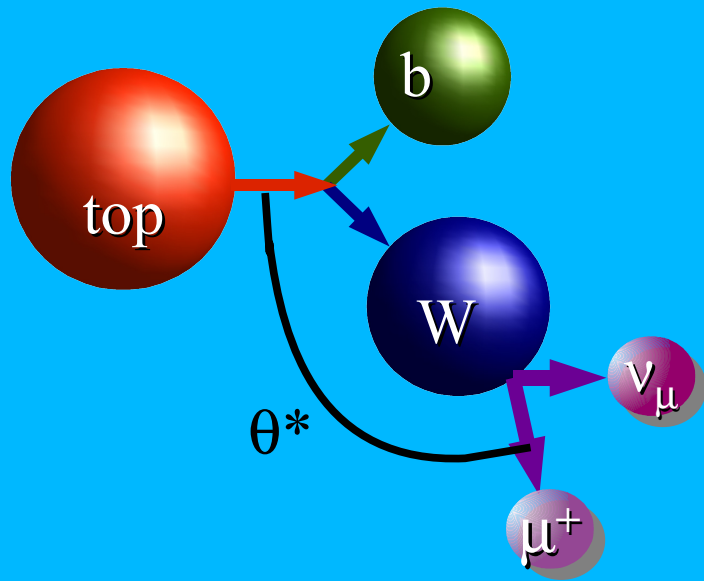
$$R = \frac{t \rightarrow W + b \text{ quark}}{t \rightarrow W + \text{any quark}}$$



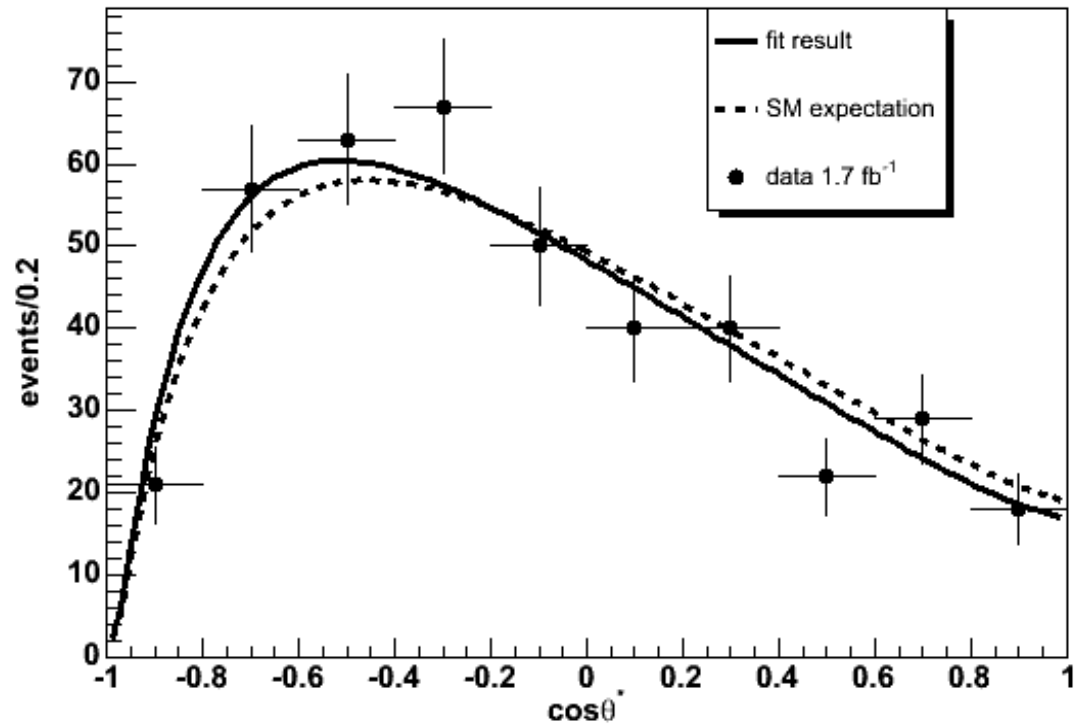
Result: $R \sim 1$ as expected in SM

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

Top quark decay
Helicity of the W boson



CDF Run II Preliminary



Result (CDF+DØ):
no right-handed W coupling
as expected in SM

Other top quark property measurements

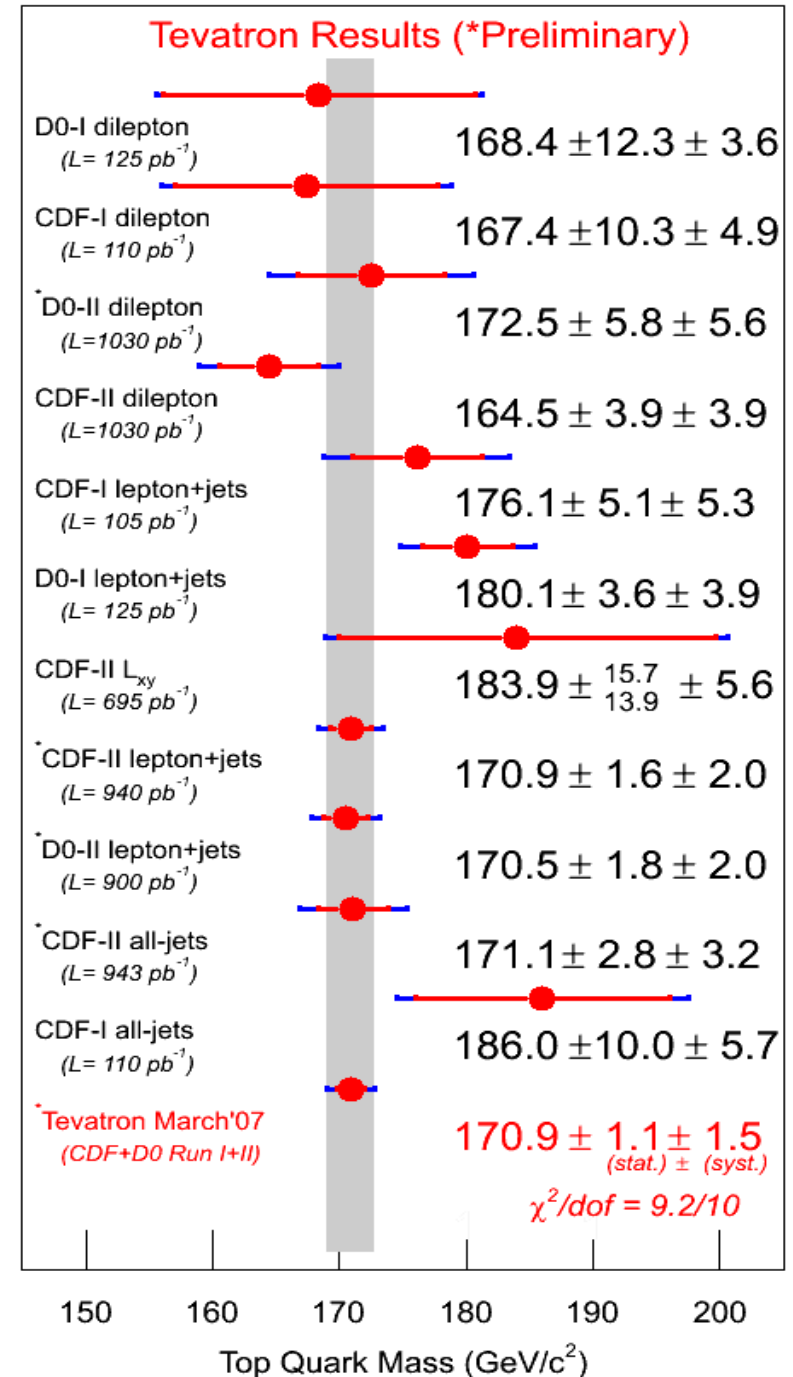
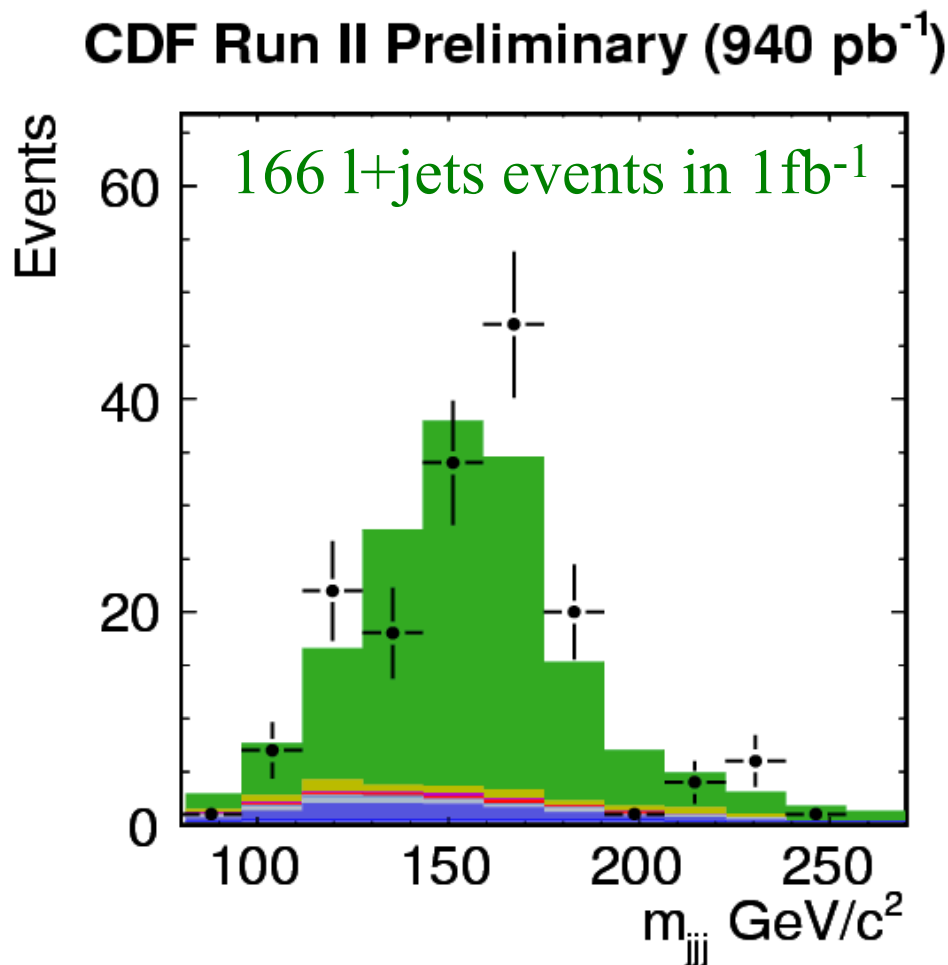
- Top quark production: tests of QCD
 - Forward-backward asymmetry
 - Quark-antiquark vs gluon-gluon annihilation
- Top quark width and lifetime
- Top quark decays to tau leptons



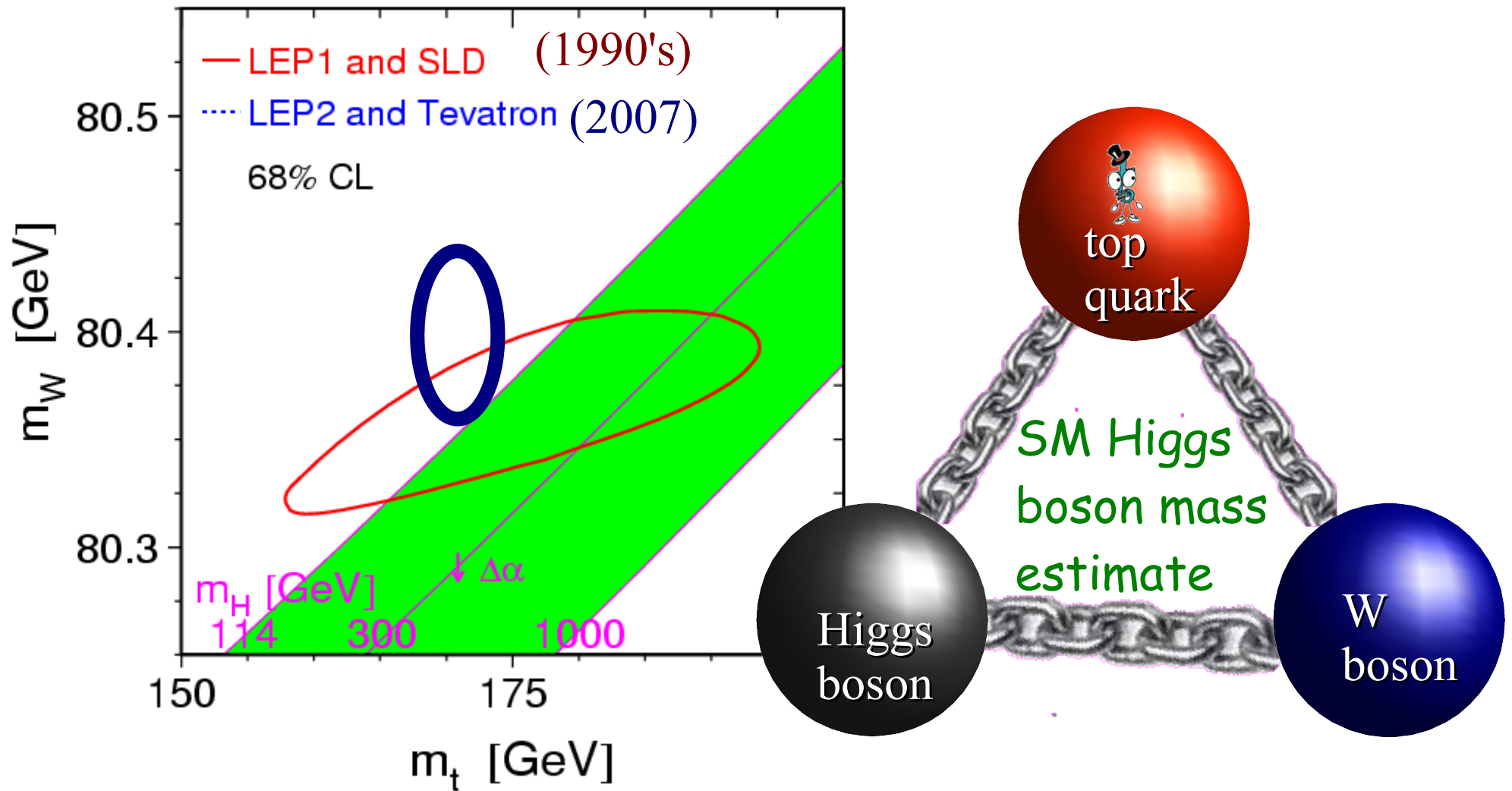
All properties measurements
are sensitive to new physics

Top quark mass determination

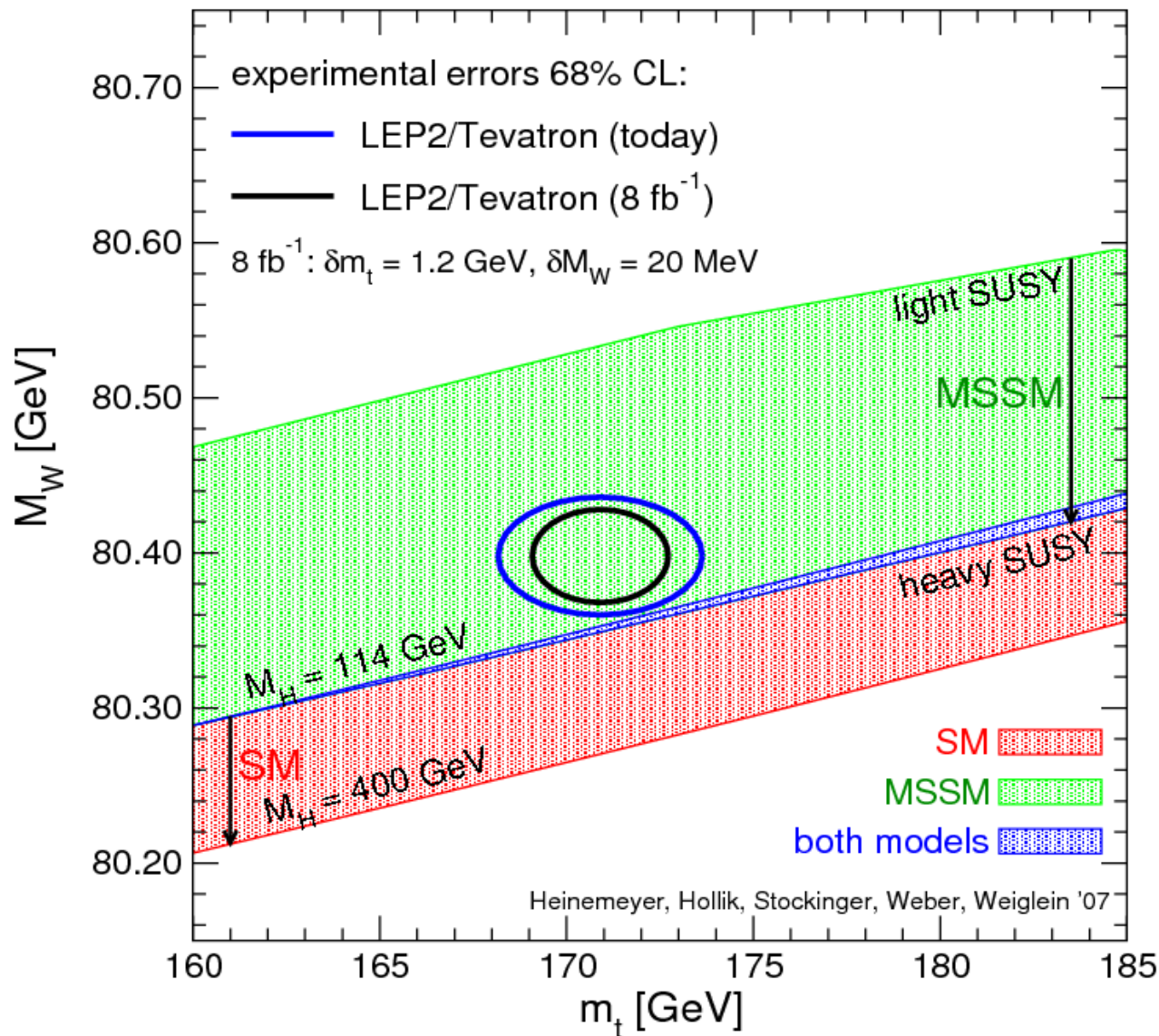
- Large sample of top quarks
 - $\sim 10^3$ events in 1 fb^{-1} per experiment
- Advanced analysis techniques
 - uncertainty $\sim 1\%$, close to decay width



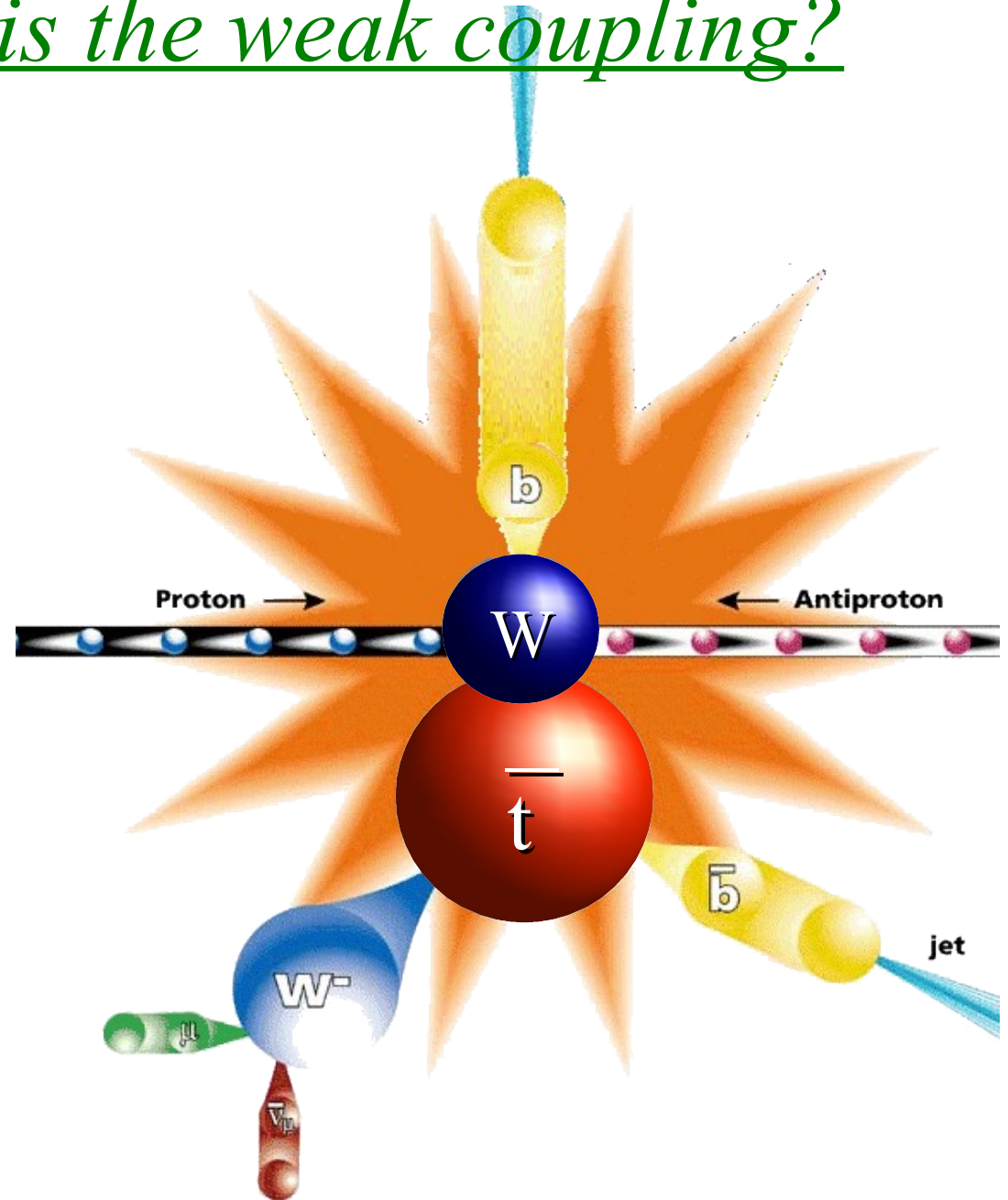
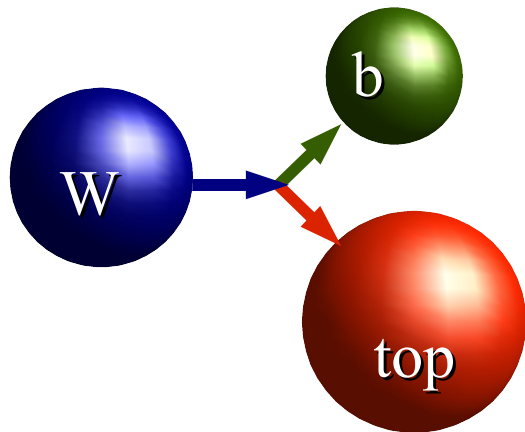
Top quark mass implications – *What can Top tell us about Higgs?*



Top quark mass implications – *What about top and supersymmetry?*

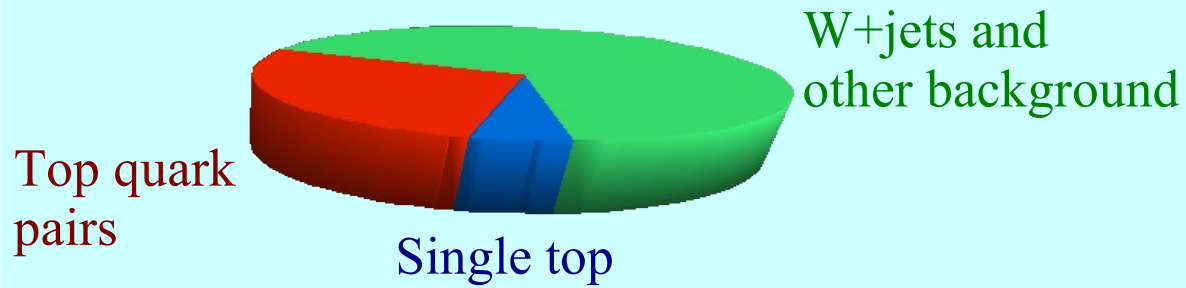


Electroweak top quark production – *How strong is the weak coupling?*



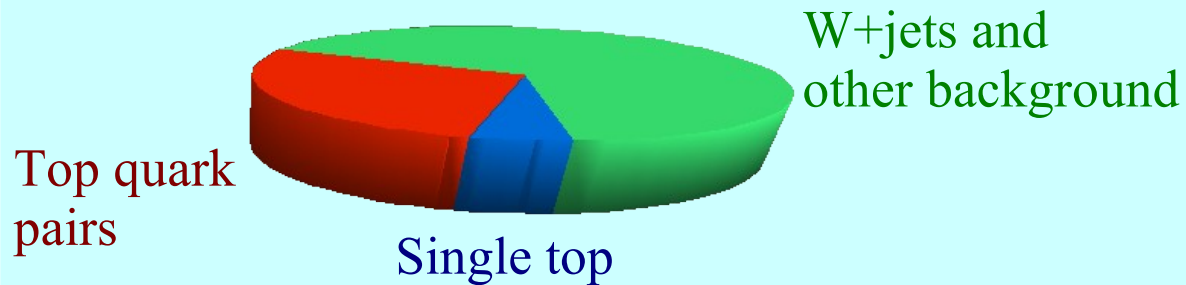
Single top quark search

Event Sample Composition



Single top quark search

Event Sample Composition



- Optimized event analysis

Input:

discriminating variables

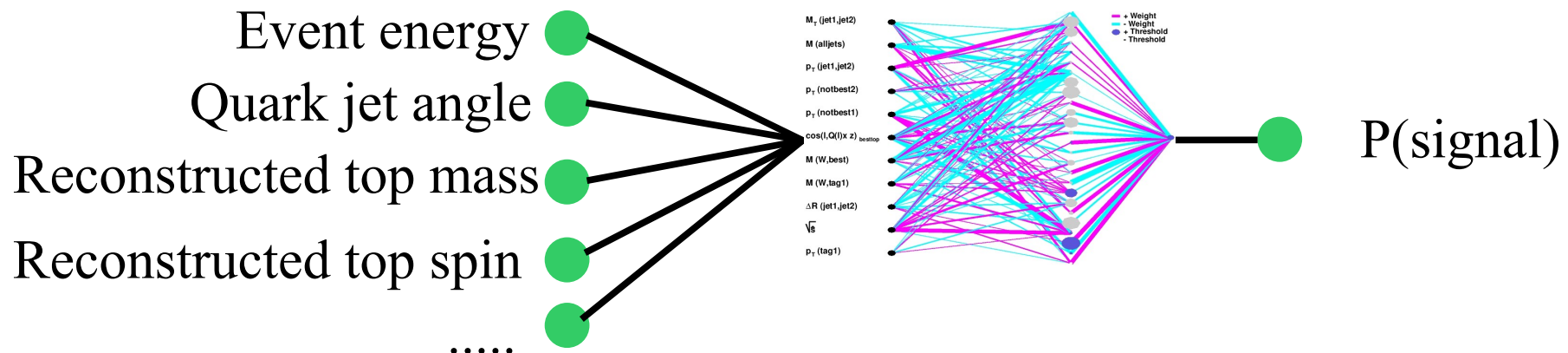
Method:

multivariate analysis

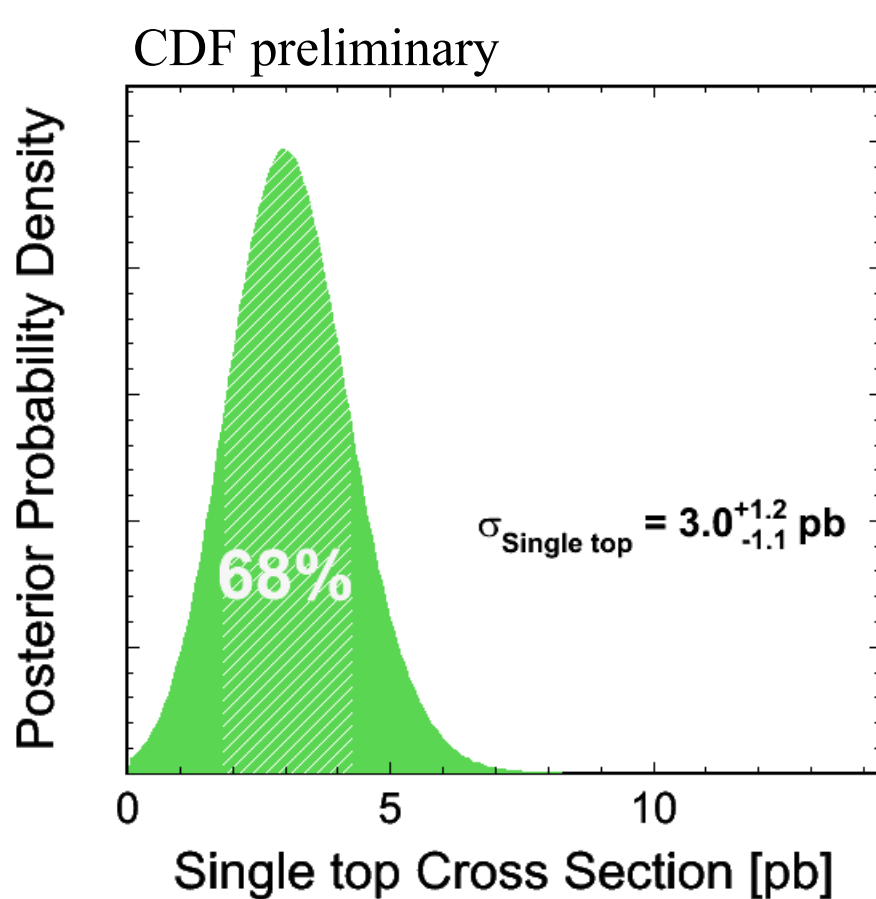
Bayesian Neural Networks,
boosted Decision Trees, etc

Output:

signal probability

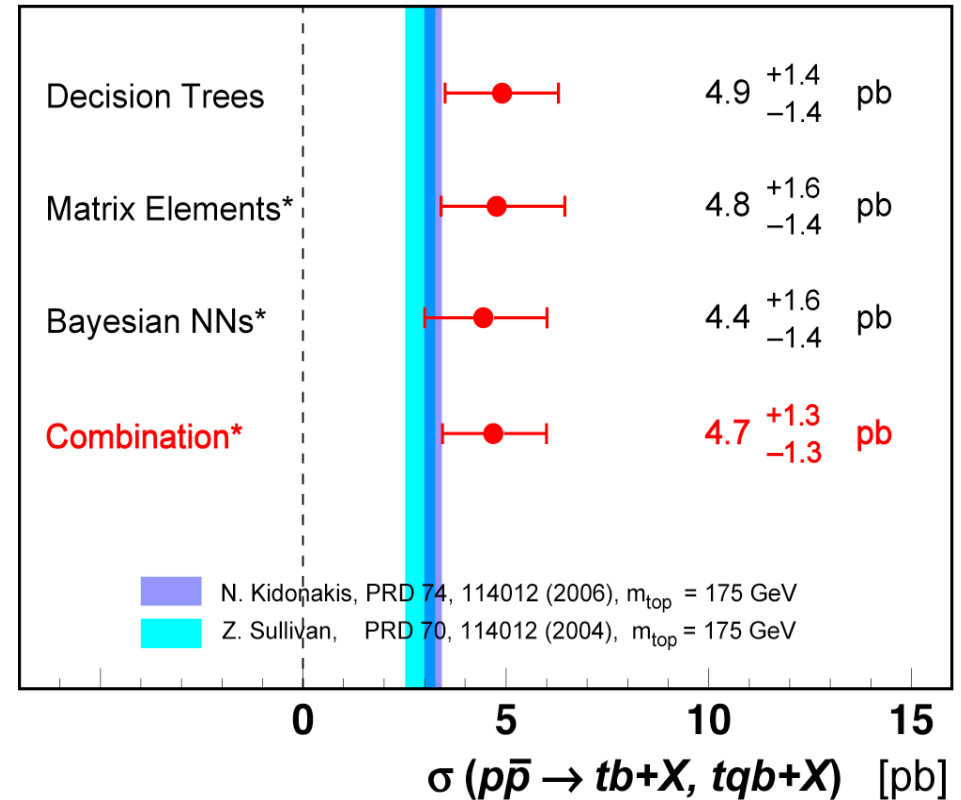


Single top quark search



DØ Run II * = preliminary

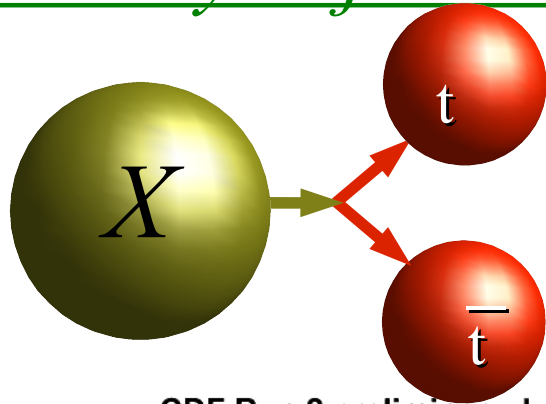
0.9 fb⁻¹



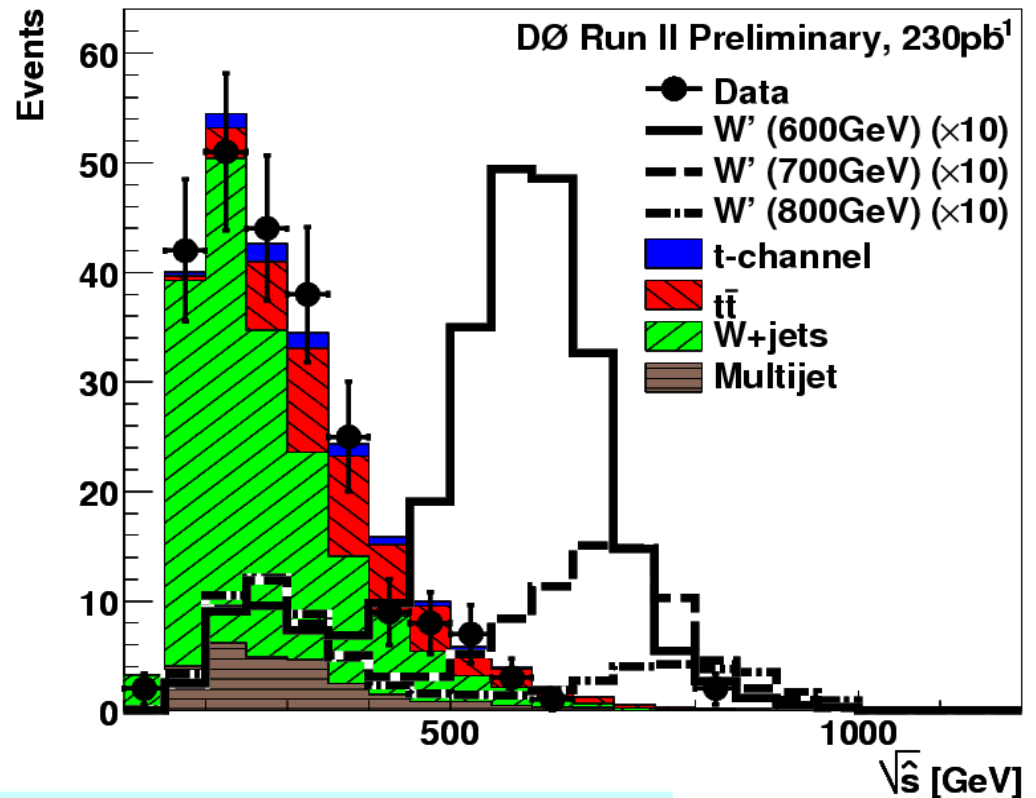
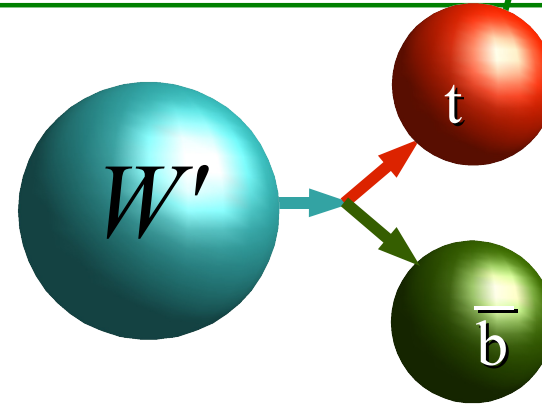
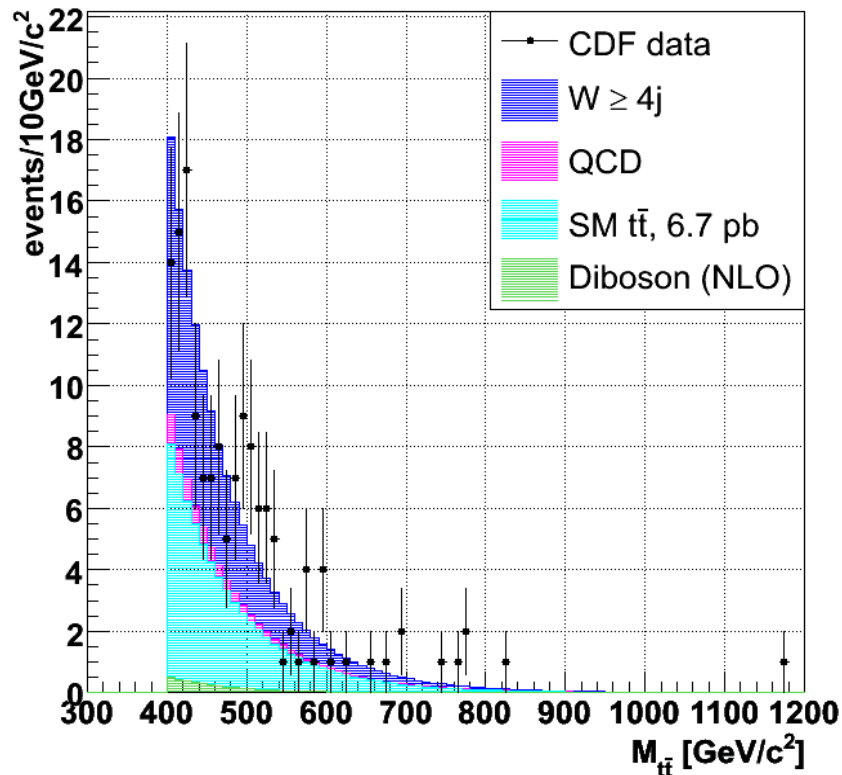
Result: consistent with SM

Top as a tool

New heavy objects decaying to one or more top quarks?

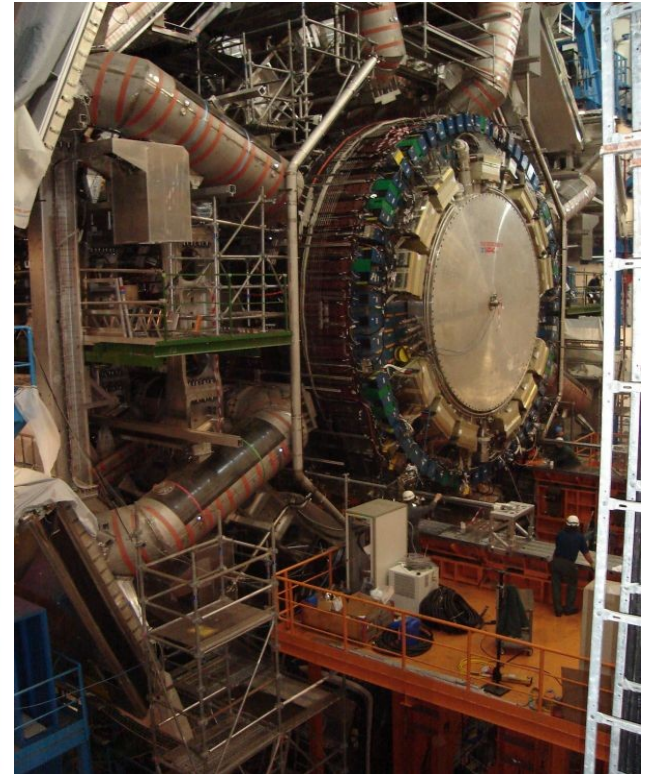
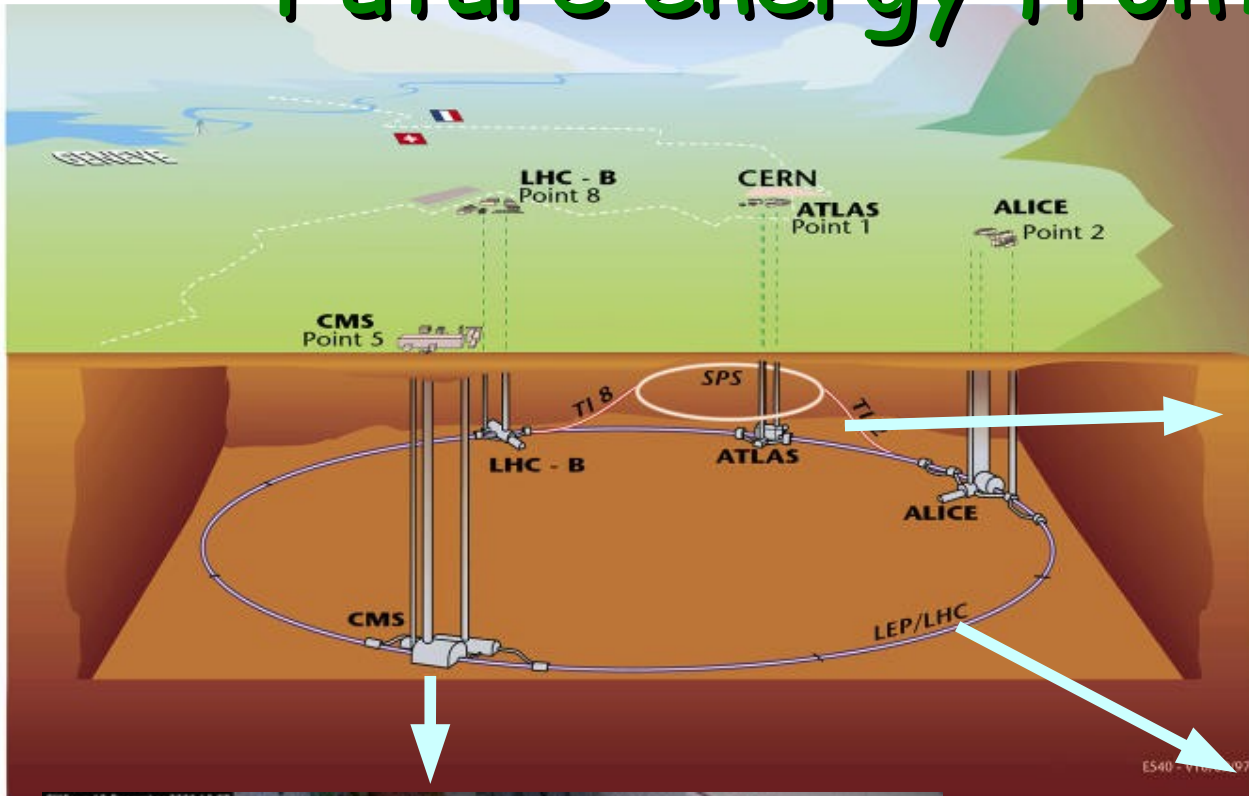


CDF Run 2 preliminary, $L=319\text{pb}^{-1}$



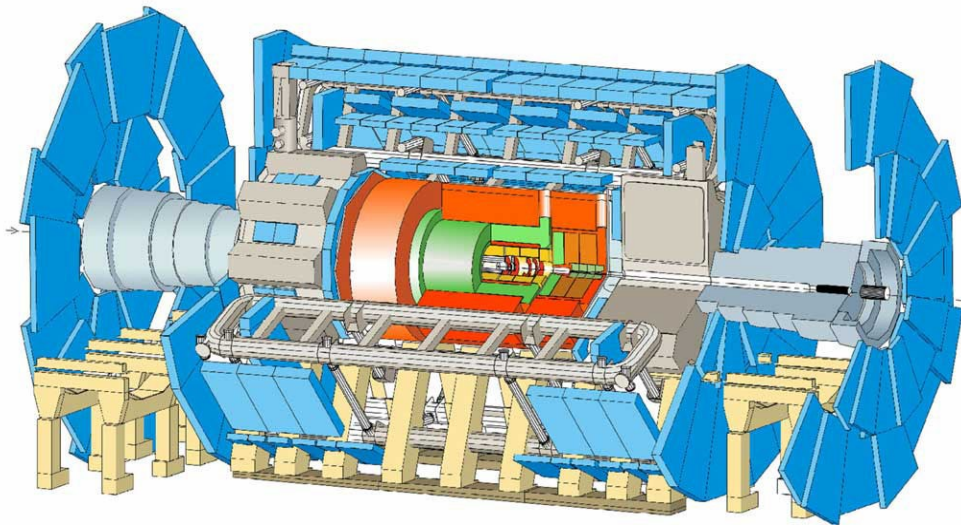
Result: no evidence for new heavy objects

Future energy frontier: LHC

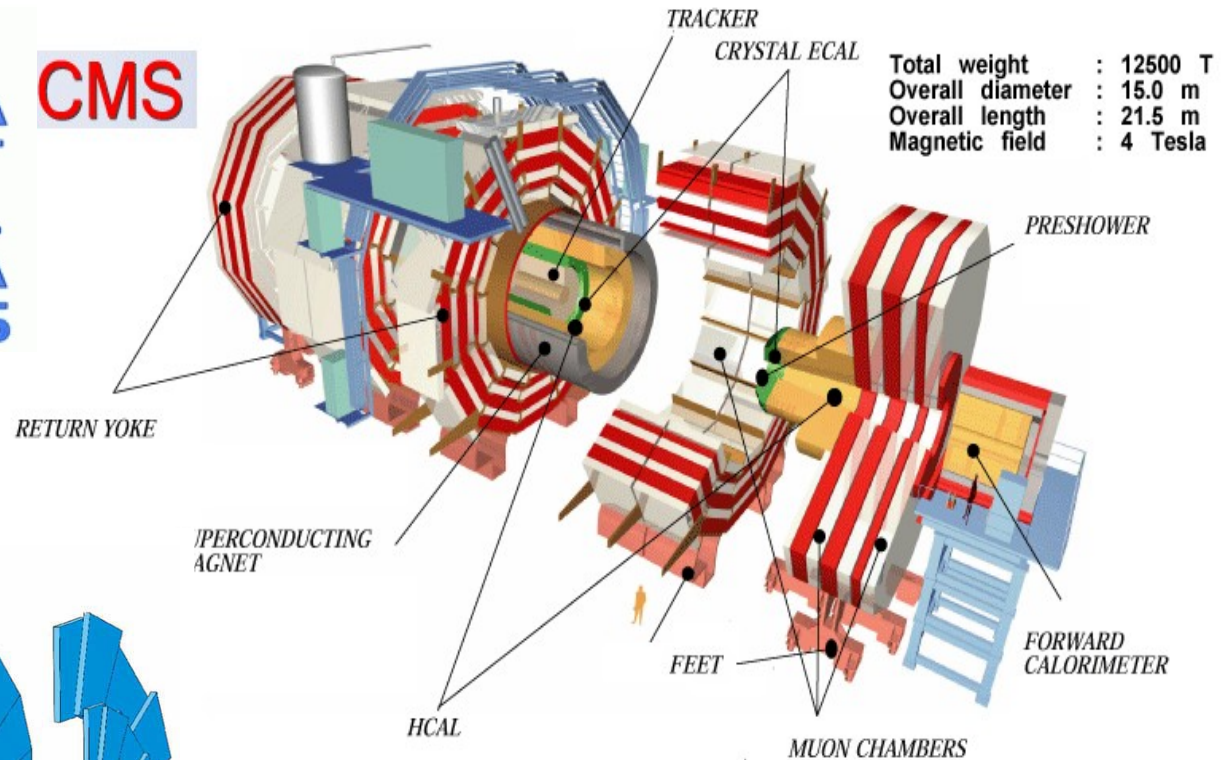


LHC detectors

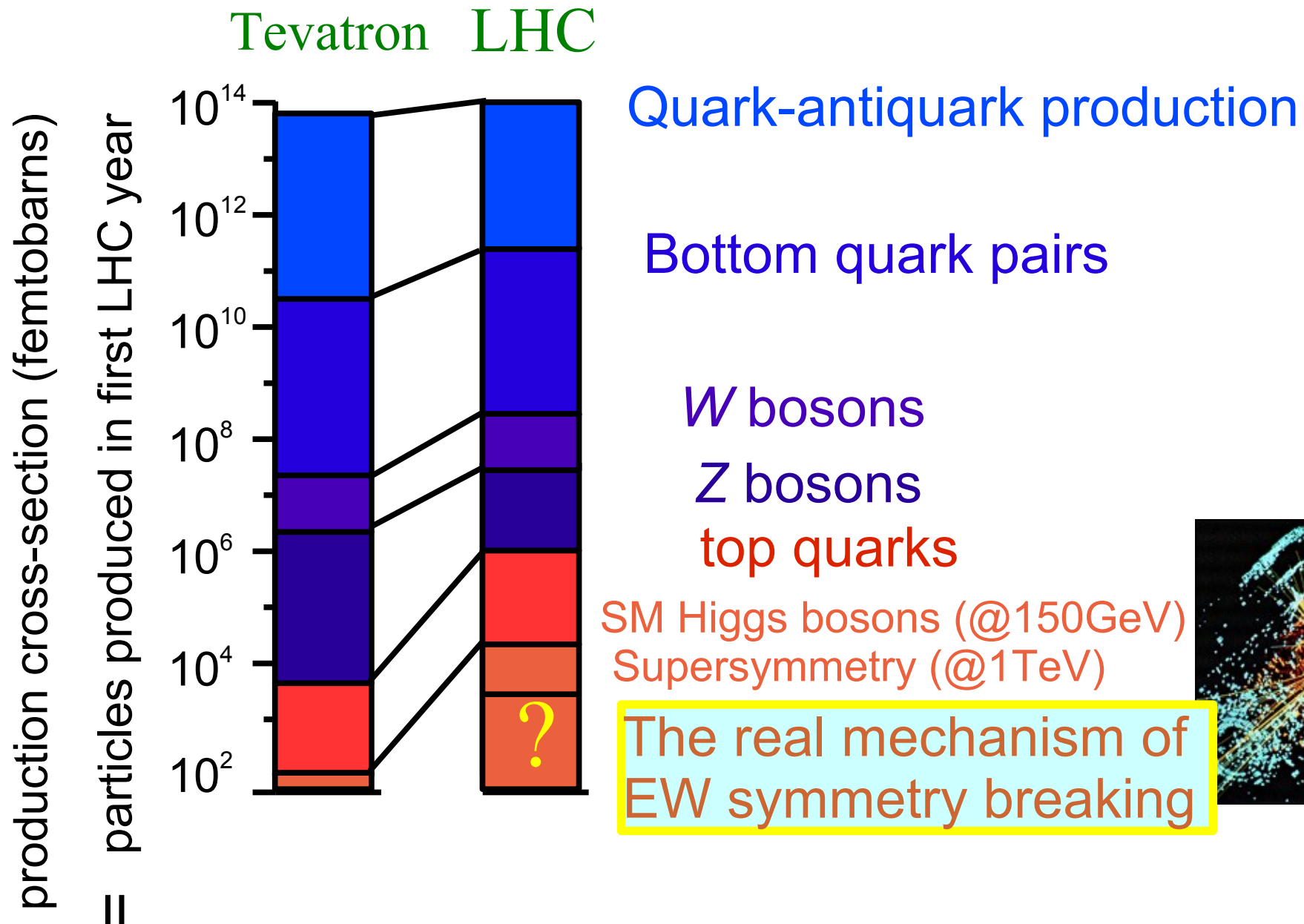
- Diameter 25 m
- Length : 46 m
- Barrel toroid length 26 m
- Overall weight 7 000 tonnes
- ~ 100 million electronic channels
- ~ 3 000 km of cables



CMS

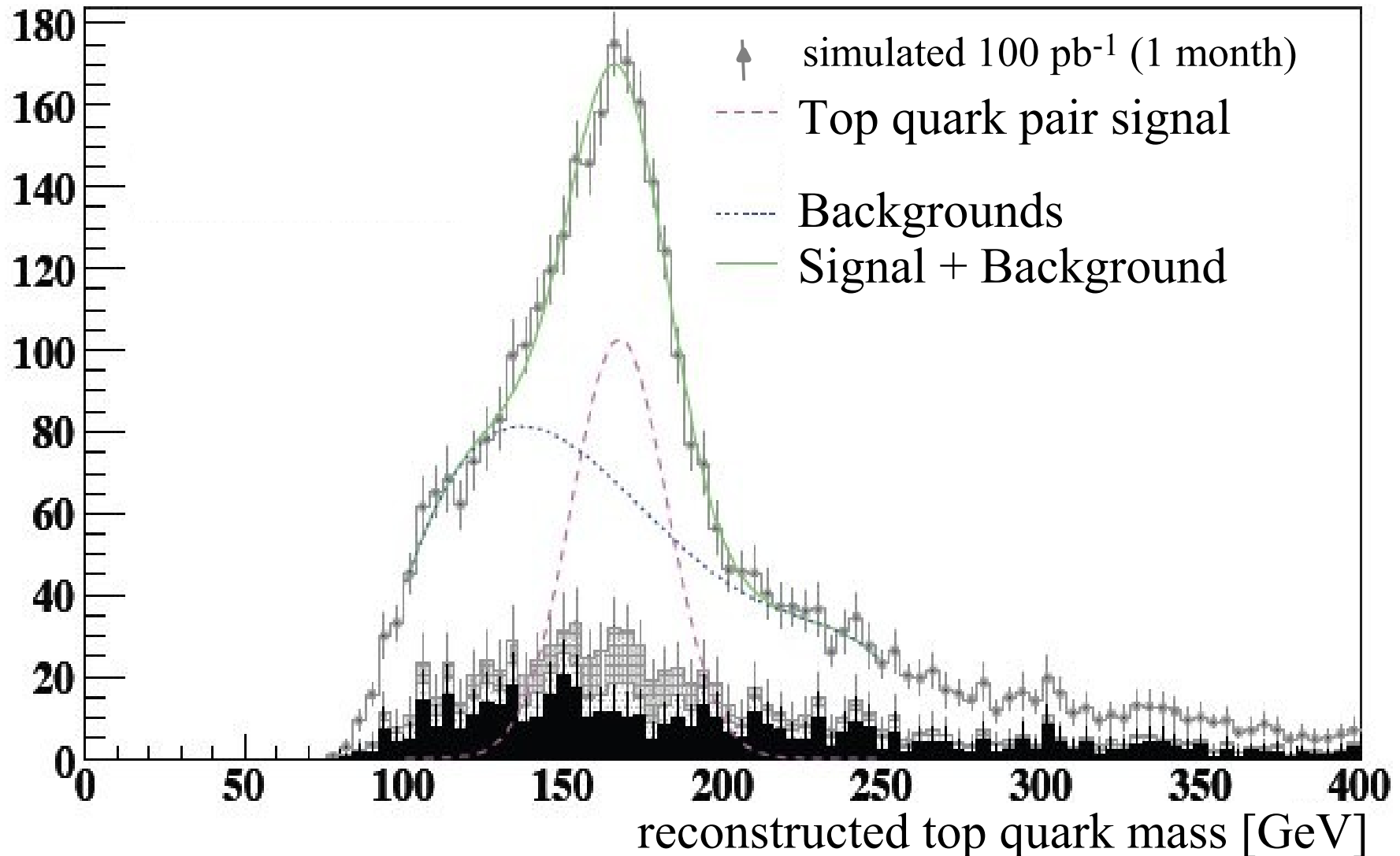


Particle production at the LHC



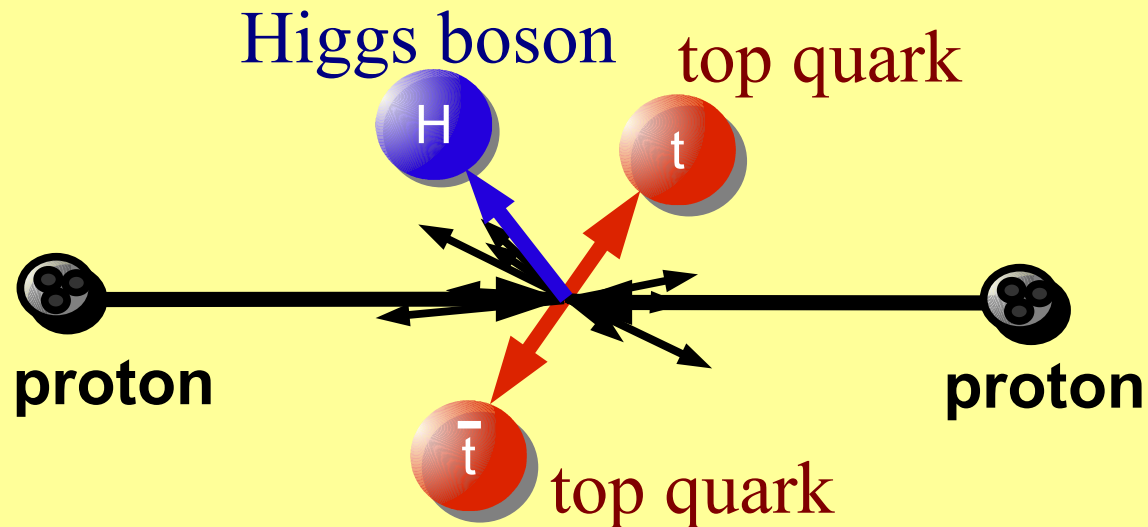
Top as a tool to calibrate the detector

- Large sample of top quarks (10^5 events/week)
- Calibrate energy measurement, tune b-quark tagging

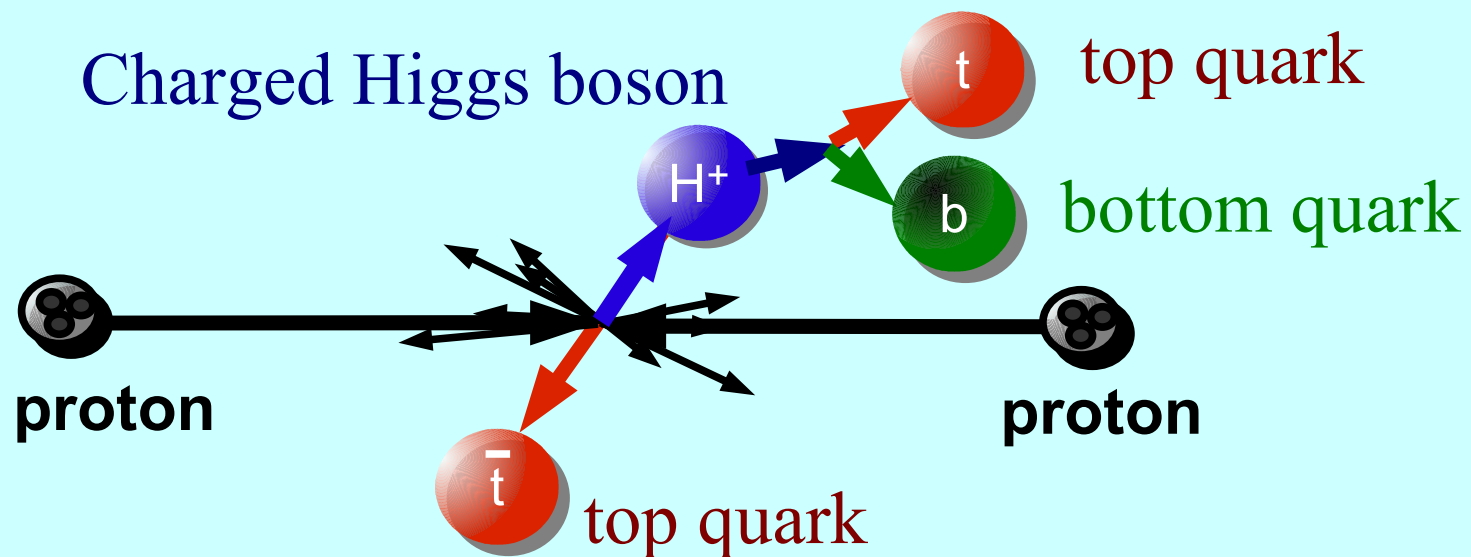


Top as the gateway to Higgs

Neutral SM Higgs



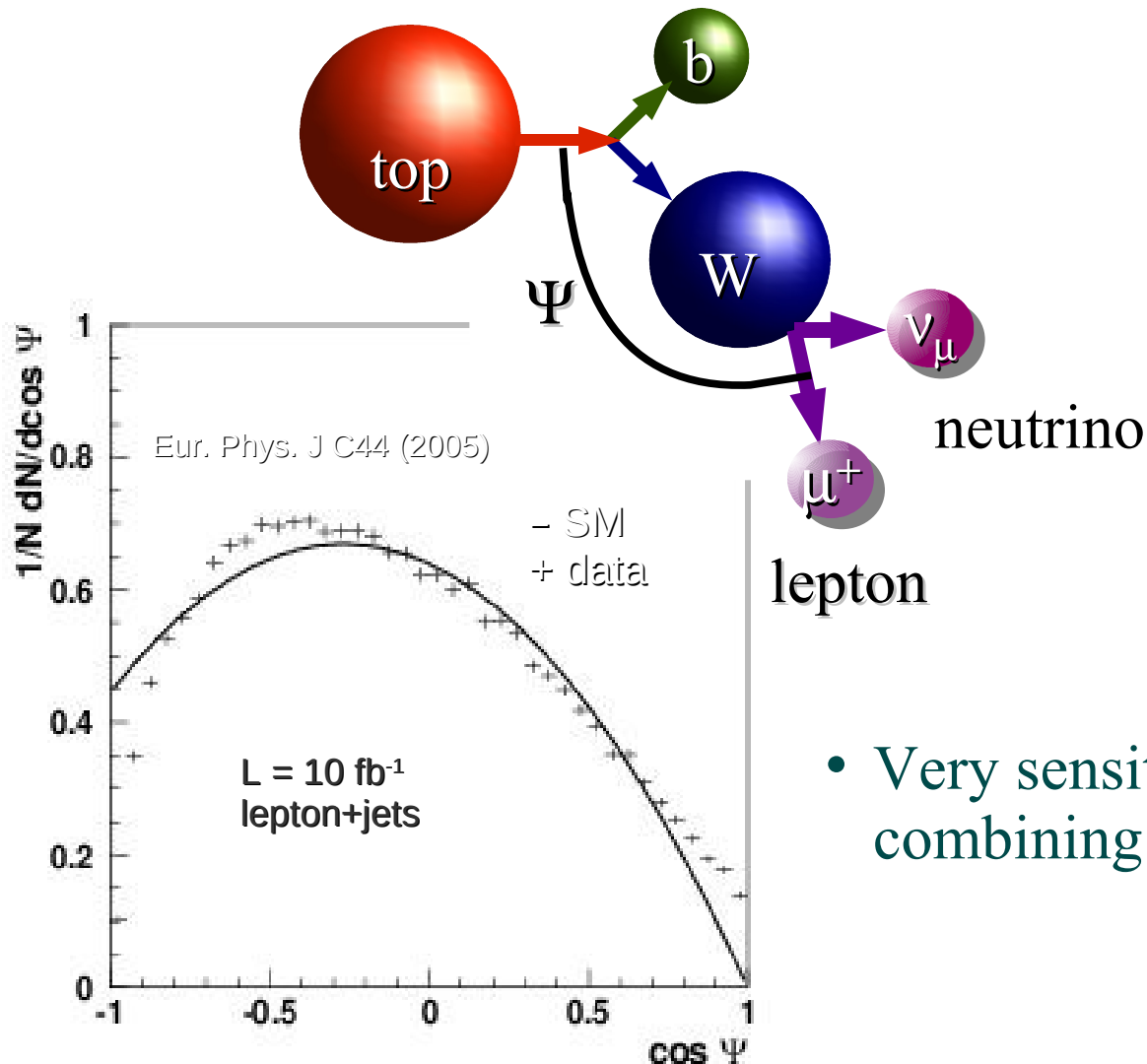
Supersymmetry: Charged Higgs



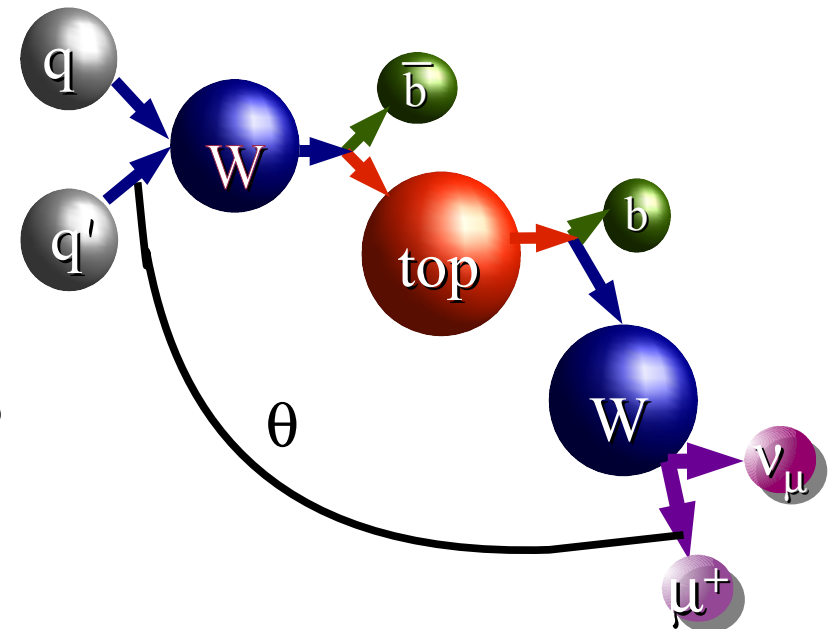
Precision top quark physics

- Example: top quark polarization probes higher-order couplings
 - Especially important if Higgs is not where expected

in the top quark decay



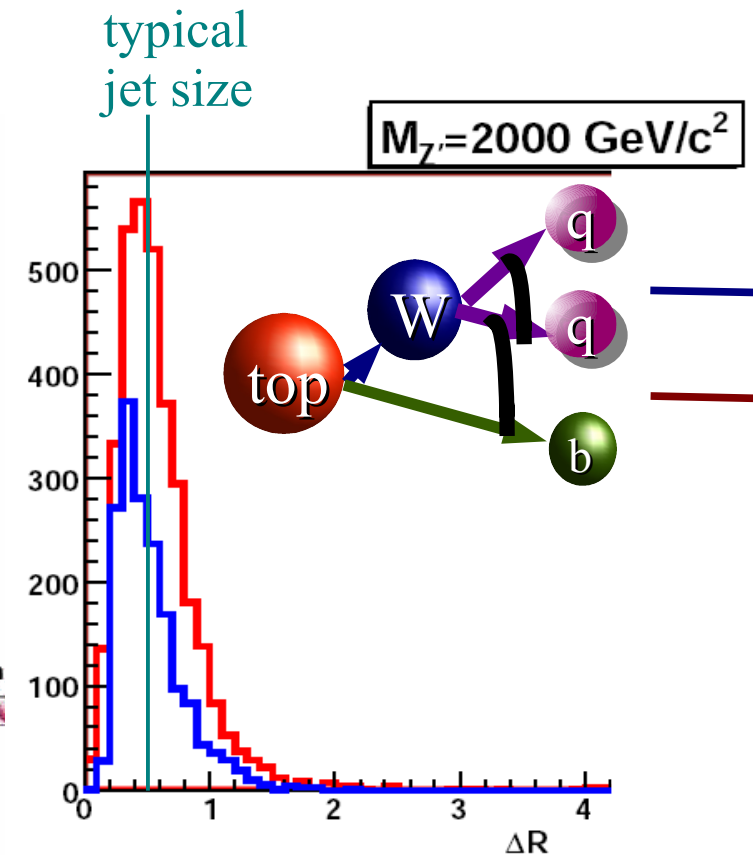
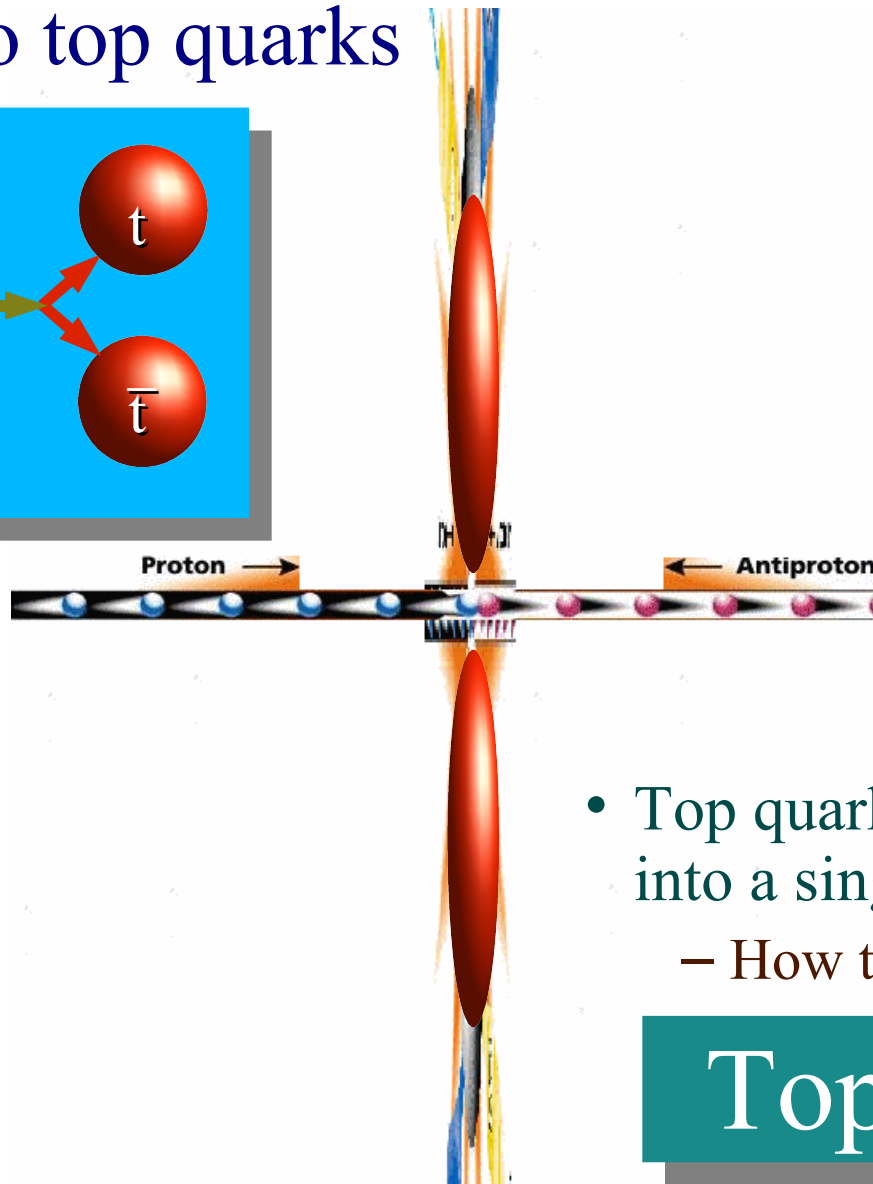
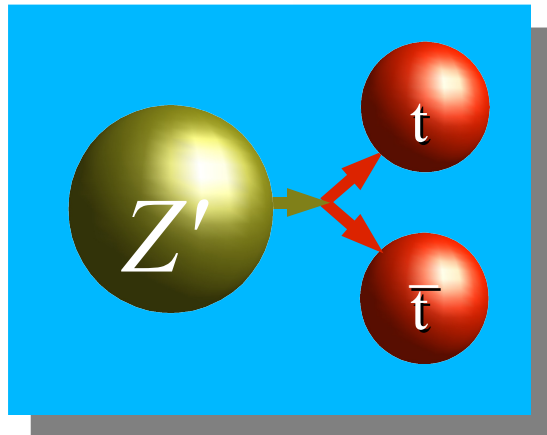
in single top production



- Very sensitive to new physics by combining different channels

New challenges

- A very heavy object decays to top quarks



- Top quark decay products merge into a single jet
 - How to reconstruct them?

Top jets



top quark



New physics

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

International Linear Collider

One is getting all the attention, but the other
one is the key to understanding our world



One is getting all the attention, but the other one is the key to understanding our world



Reinhard Schwienhorst, Michigan State University

Conclusions

- We have learned a lot about the top quark recently
 - Tevatron experiments measure mass, properties, electroweak coupling
- This is just the beginning
 - Tevatron will collect 5 times more data
 - LHC is just around the corner
 - We will measure the top quark coupling to new physics

We are close to revealing the origin of matter

and the top quark is the key player

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>