What can obese quarks tell us about weak forces?

Reinhard Schwienhorst

MICHIGAN STATE UNIVERSITY

Ball State Physics Colloquium, 2/21/2008

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

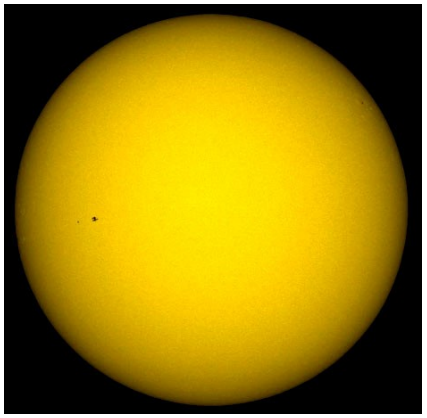
- The sun, particle masses and all that
- Top quark
- Energy frontier
- Tevatron: Top quark measurements
- LHC: Top as a tool
- Conclusions

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

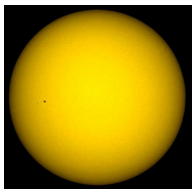
- Cross section in picobarn
  (1 barn = 10^{-24} cm^2)
  - Luminosity in $\frac{1}{\text{picobarn}}$

Age of the Earth Controversies

2008:  vs 

1860:  vs 

The Older Age of the Earth Controversy



- The "Helios"
  - e.g. Hermann von Helmholtz, Simon Newcomb
  - (Incorrectly) argued that there was no way the sun could shine longer than 10-20 million years
    - The earth can be no older than the sun

- The "Geos"
  - e.g. Charles Darwin, George Darwin
  - (Correctly) argued that features on the earth indicated that it was older than several hundred million years
    - The earth must be at least as old as any feature on it

Where does the sun get its energy?

- Helmholtz et al. related the gravitational potential energy of the sun to its luminosity (dE/dt)
  - This gives ~10-15 million years

$$t \approx \frac{GM_{\odot}^2}{R_{\odot}} \frac{1}{L_{\odot}}$$

- We know today that the energy source of the sun isn't gravity: it's nuclear fusion
  - Has ~1000x as much energy as gravity

$$4p \rightarrow {}^4\mathrm{He} + 2e + 2\nu$$

But why does the sun burn longer, not just brighter?

The sun and the LHC

- Nuclear fusion is a weak interaction process

$$4p \rightarrow {}^4\mathrm{He} + 2e + 2\nu$$

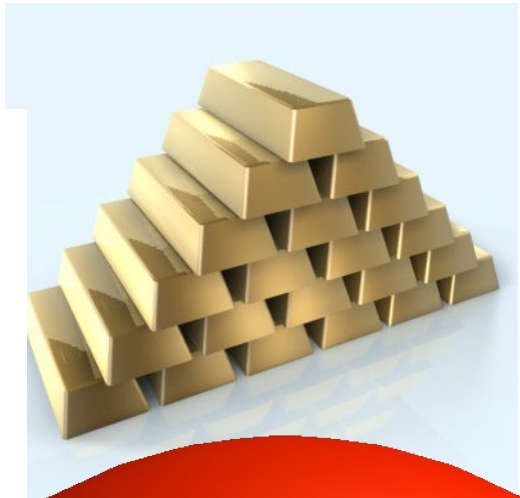
  - Carried by the W boson
  - Which has mass
  - The rate is suppressed by $(E/M_W)^4$
    - $\sim 10^{-32}$ for the sun
    - This is why it's called "weak" interaction
    - And this is why the sun shines for so long

But why does the weak boson have a mass?

This is what we expect to answer at the LHC!

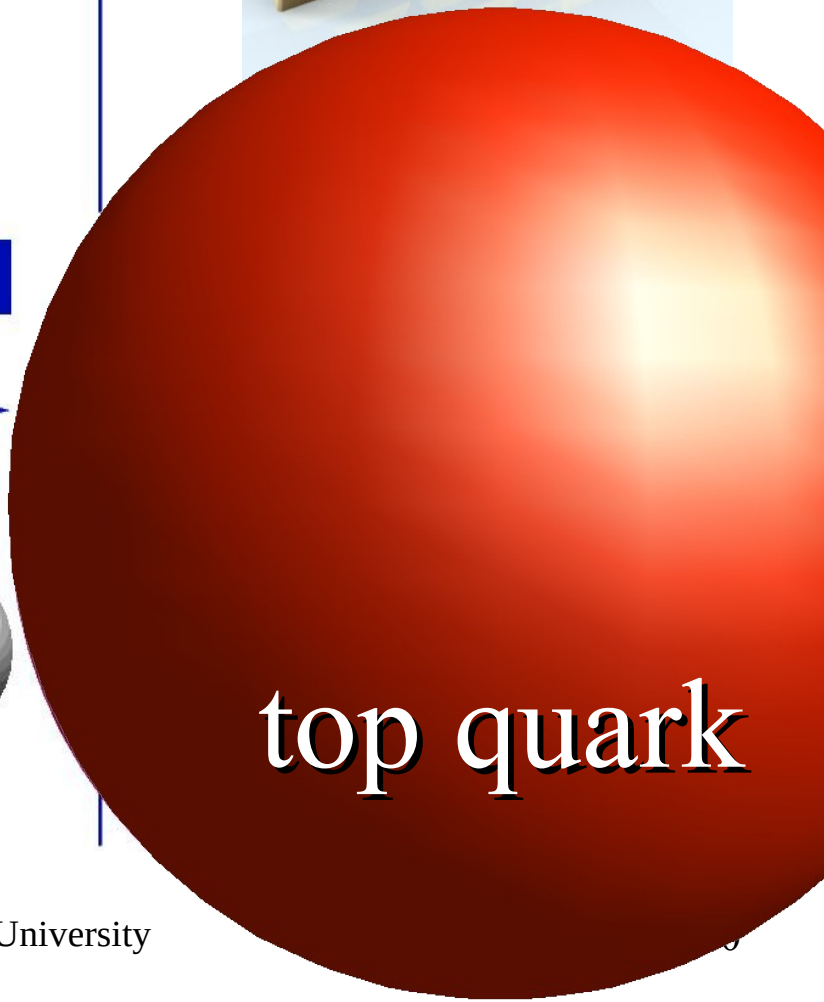
Fat Bastard

Fat Quark



LEPTONS			
Charge			
0	Electron neutrino Mass: 0?	Muon neutrino 0?	Tau neutrino 0?
-1	Electron .511	Muon 105.7	Tau 1,777

QUARKS			
Charge			
+2/3	Up Mass: 5	Charm 1,500	Top ~180,000
-1/3	Down 8	Strange 160	Bottom 4,250



Higgs mechanism:
Standard explanation for the W boson mass

Gauge bosons

Higgs field

Higgs mechanism:
Standard explanation for the W boson mass

Gauge bosons

Higgs field

Electroweak symmetry breaking

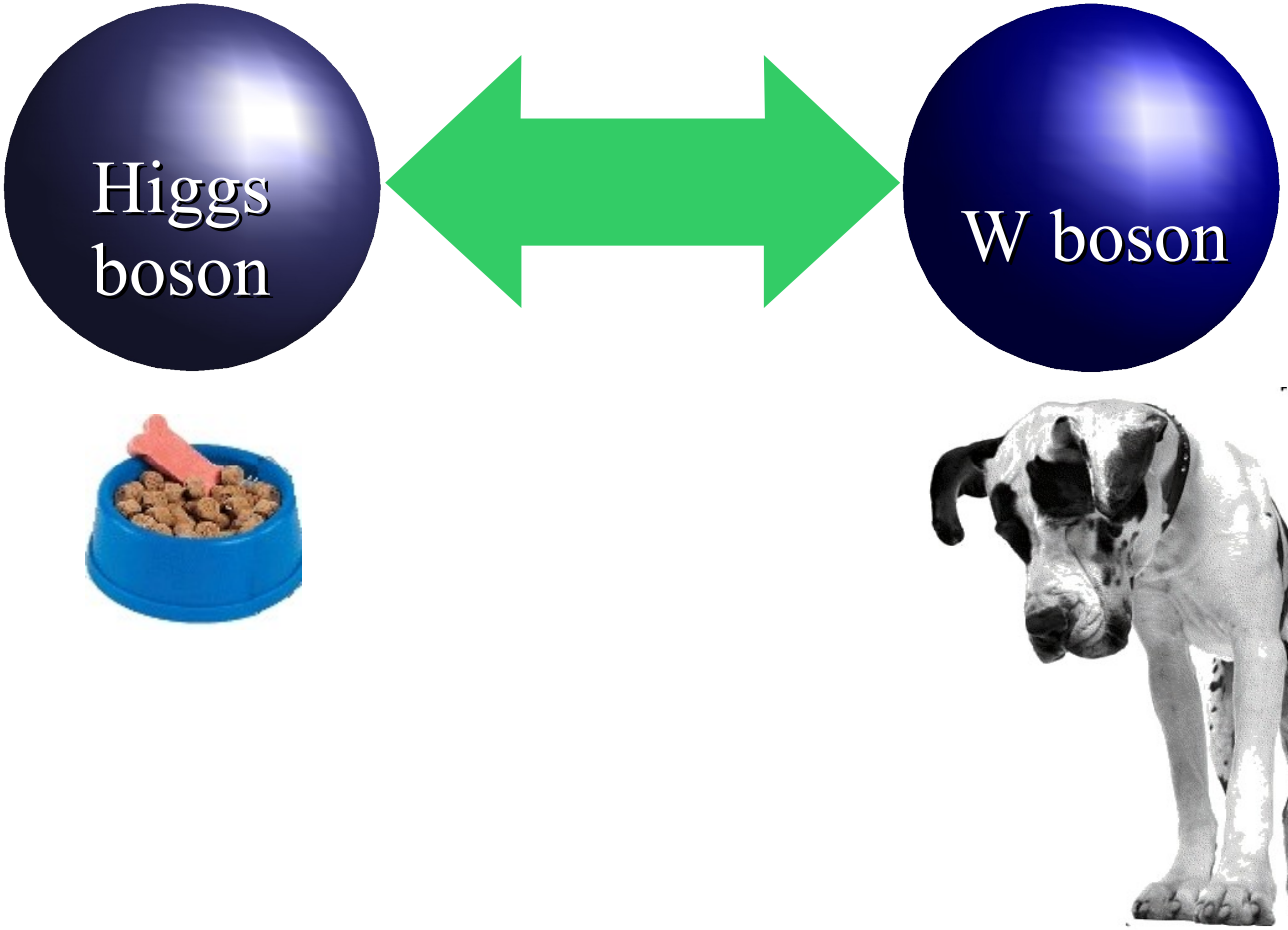
W,Z bosons

Higgs field

photon

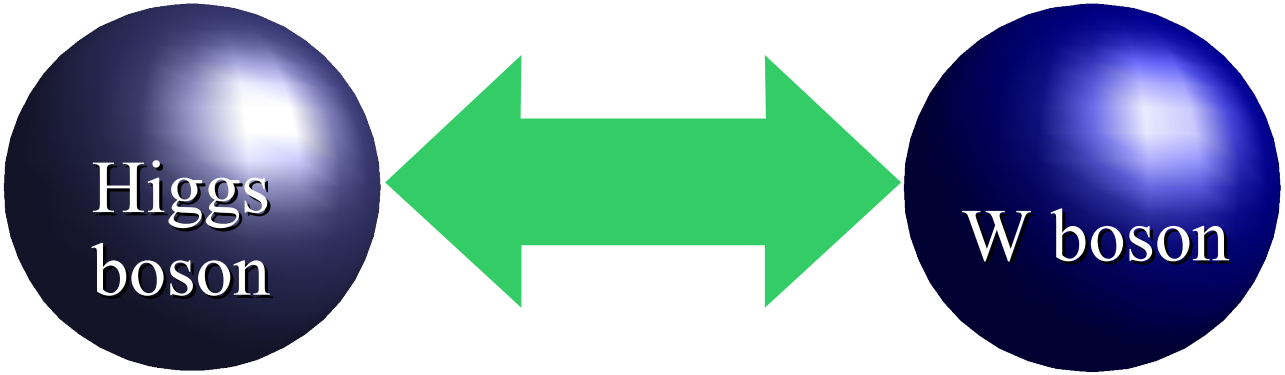
Electroweak symmetry breaking

Gauge boson coupling to Higgs field

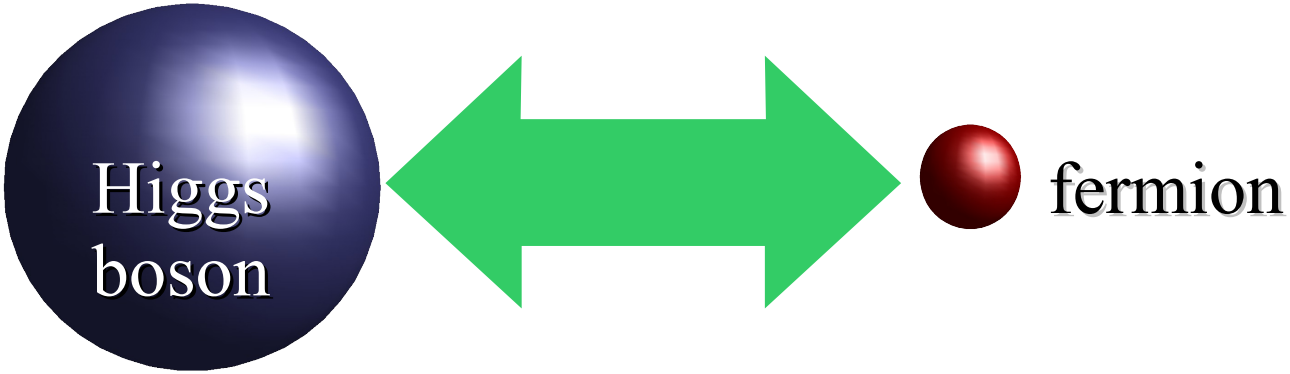


Electroweak symmetry breaking

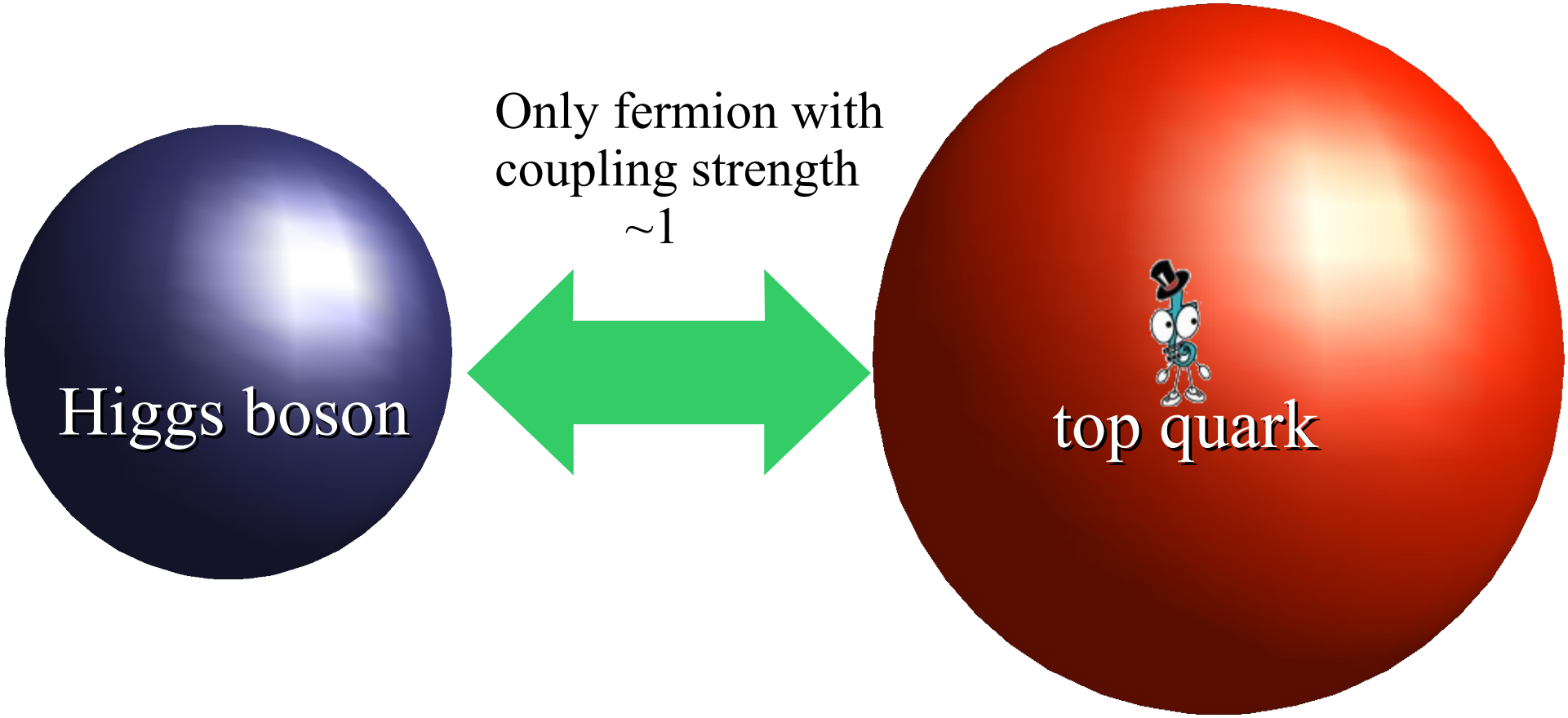
Gauge boson coupling to Higgs field



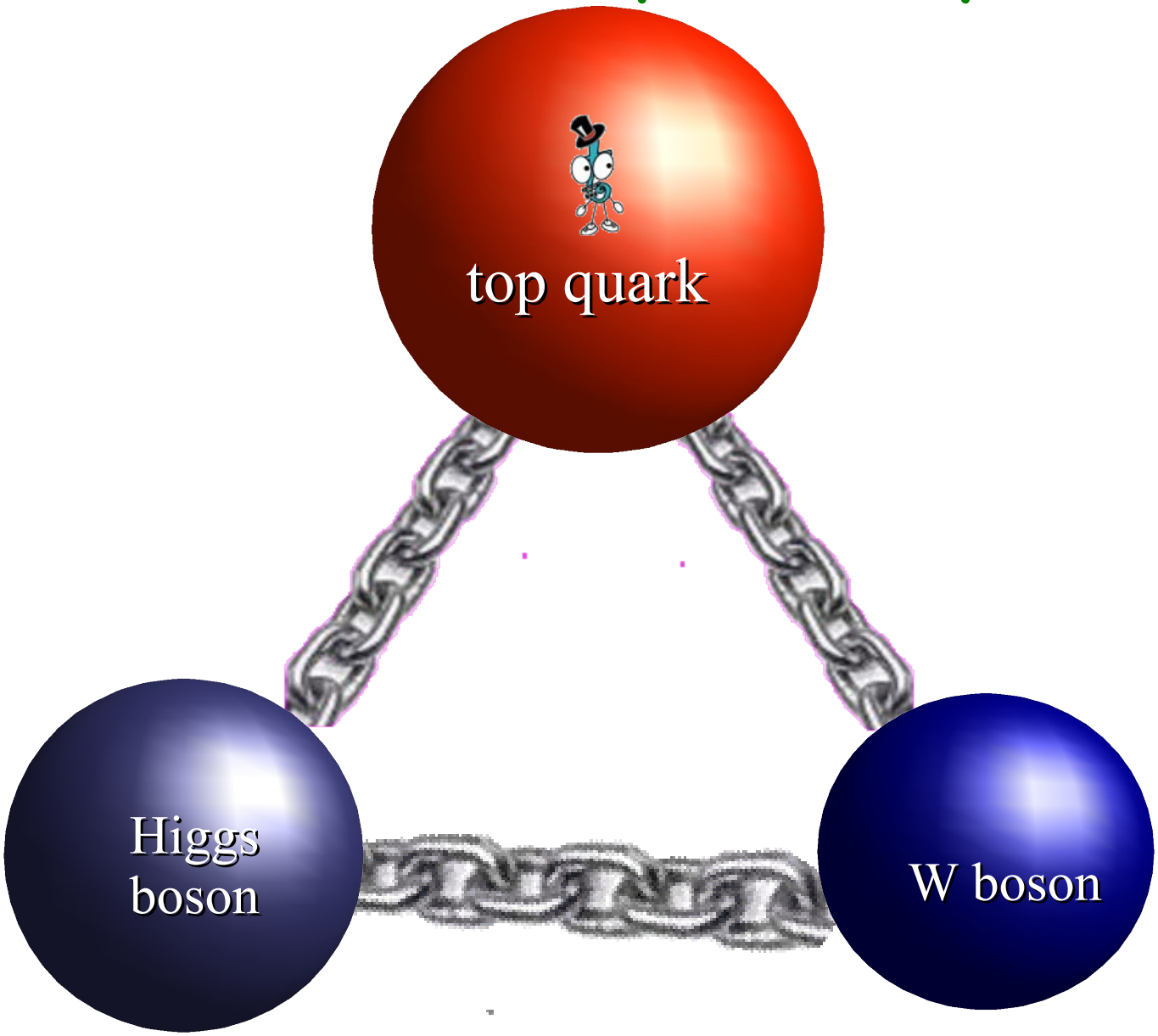
Fermions acquire mass through Higgs coupling



Top quark mass

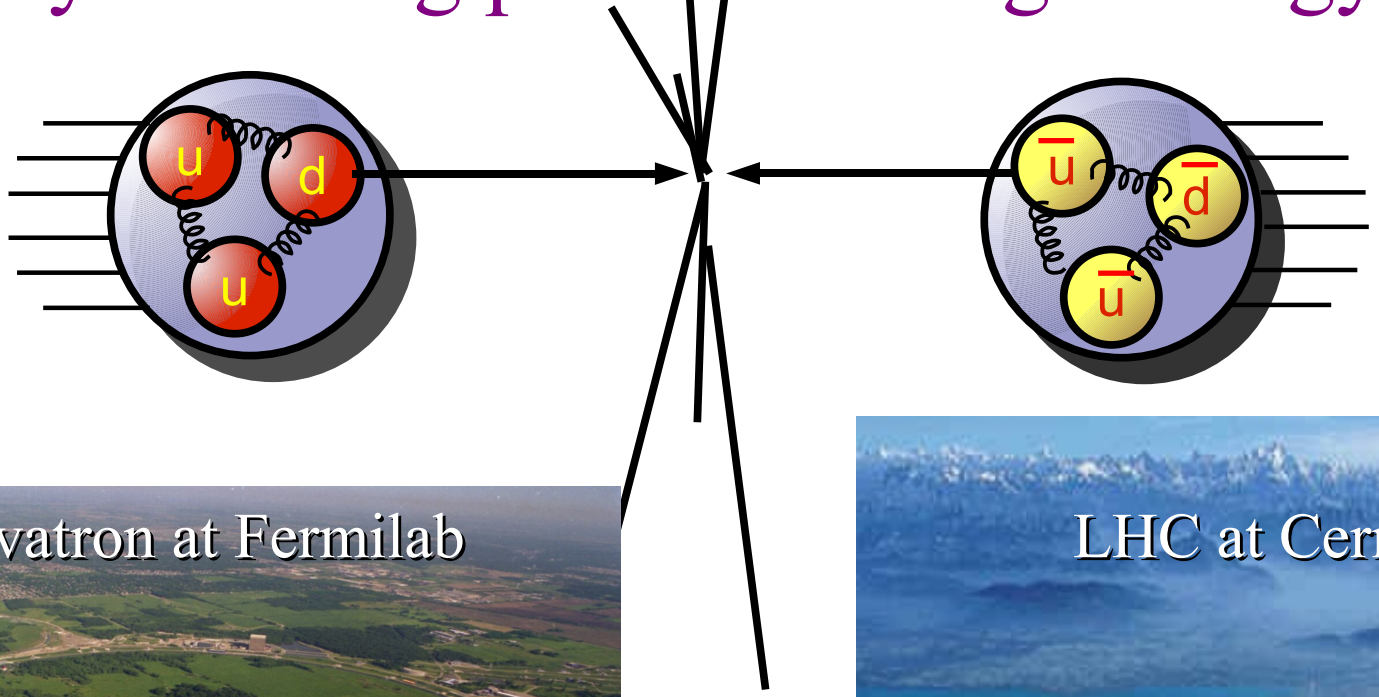


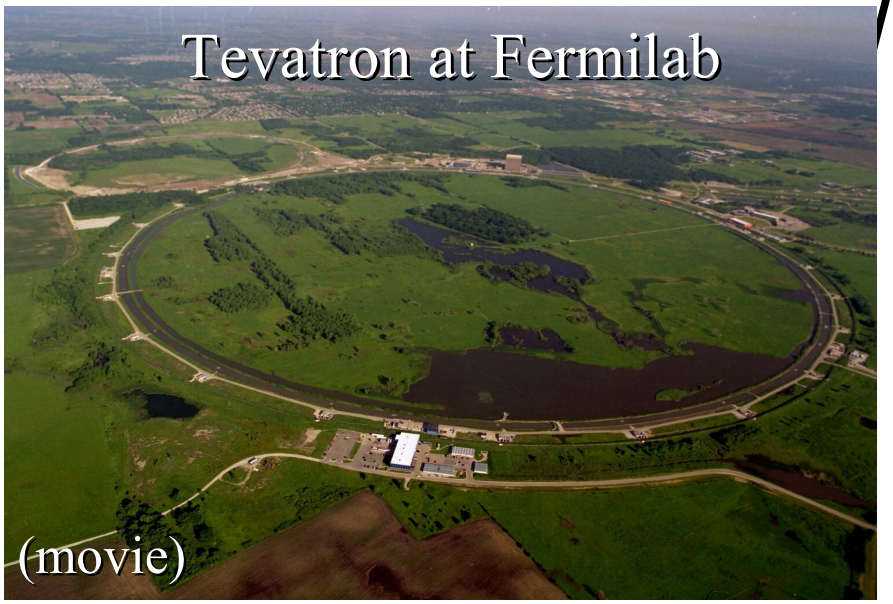
Key to electroweak symmetry breaking

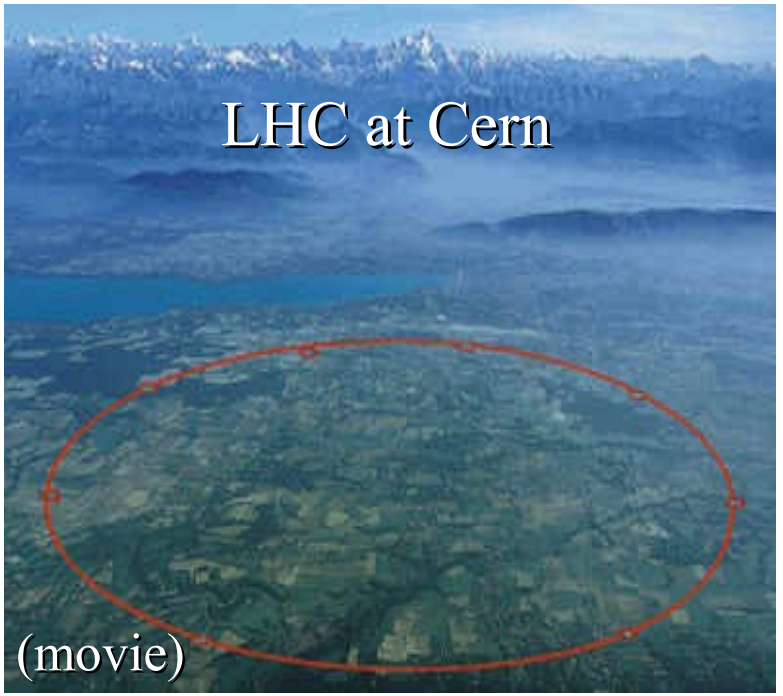


Experimental procedure

Probing physics at small distances by colliding particles at high energy

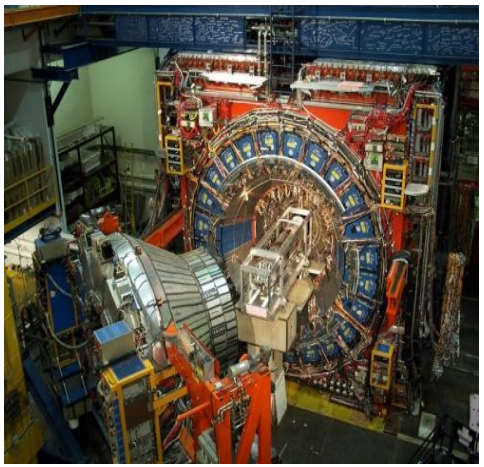


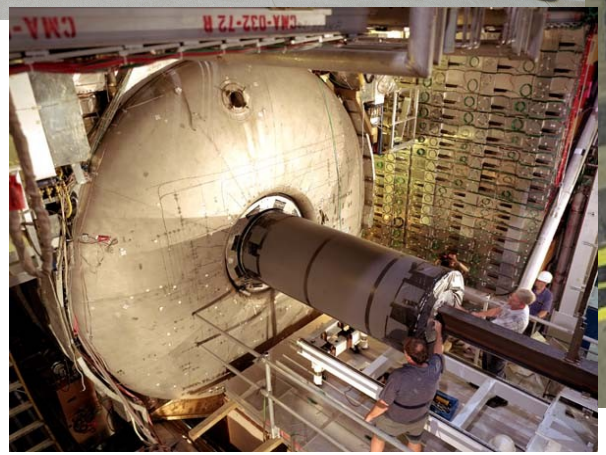




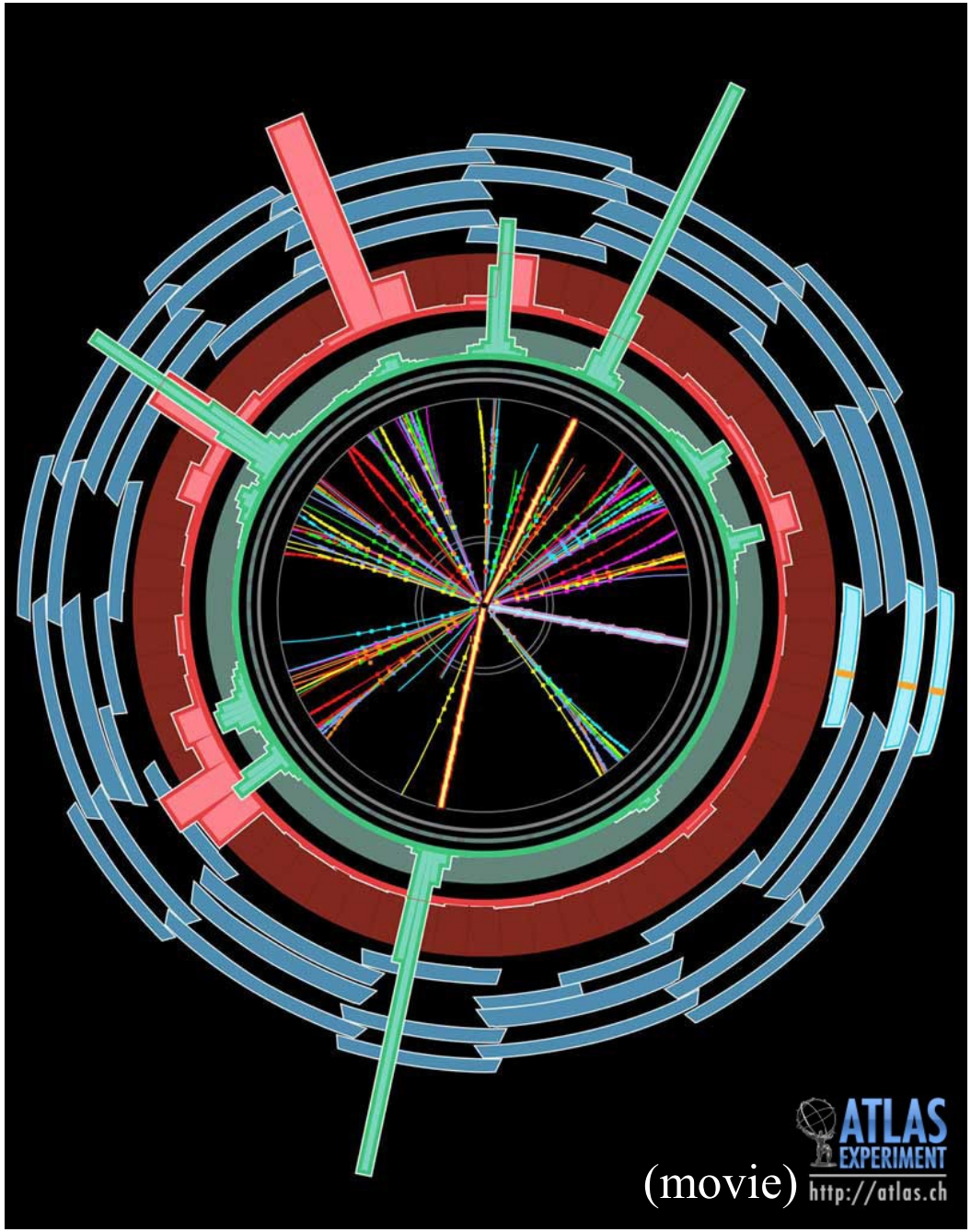
Tevatron collaborations

Together
> 1400 physicists
from 21 countries





Particles and detectors



(movie)

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:

- Electric 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:

- Electric 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:

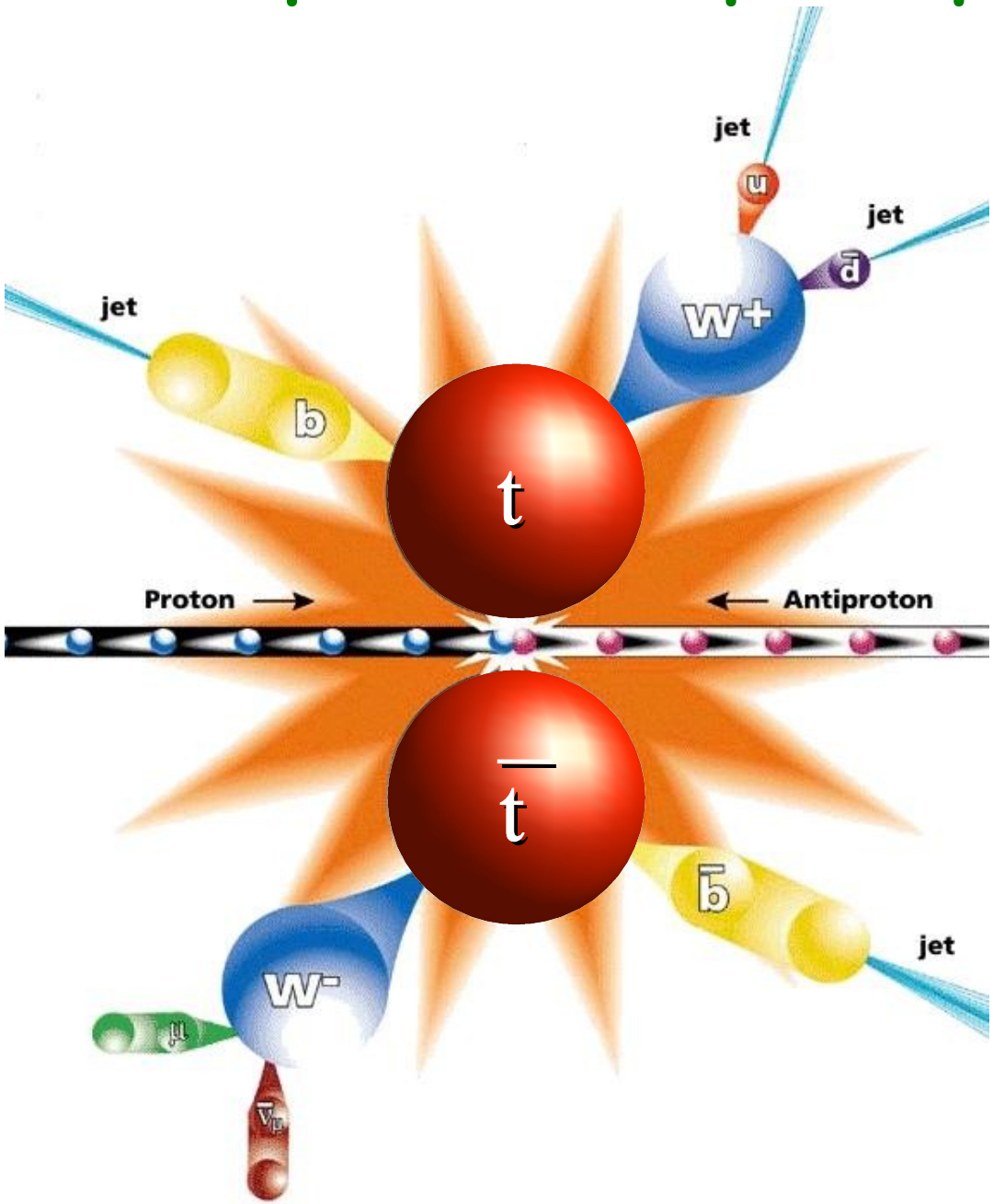
- Coupling to Higgs boson?
- Modified coupling to SM particles?
- New physics? New particle?

Recent results

What have we learned about the top quark?

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

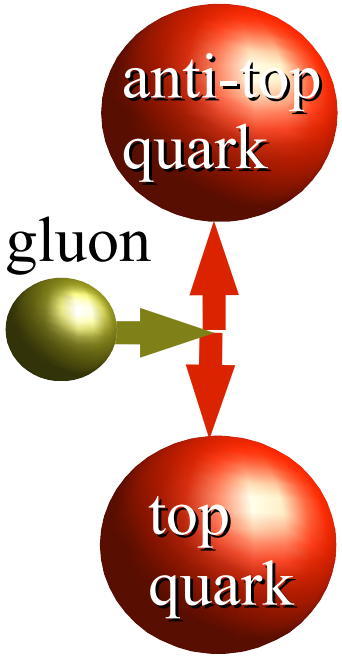
Top Quark pair production

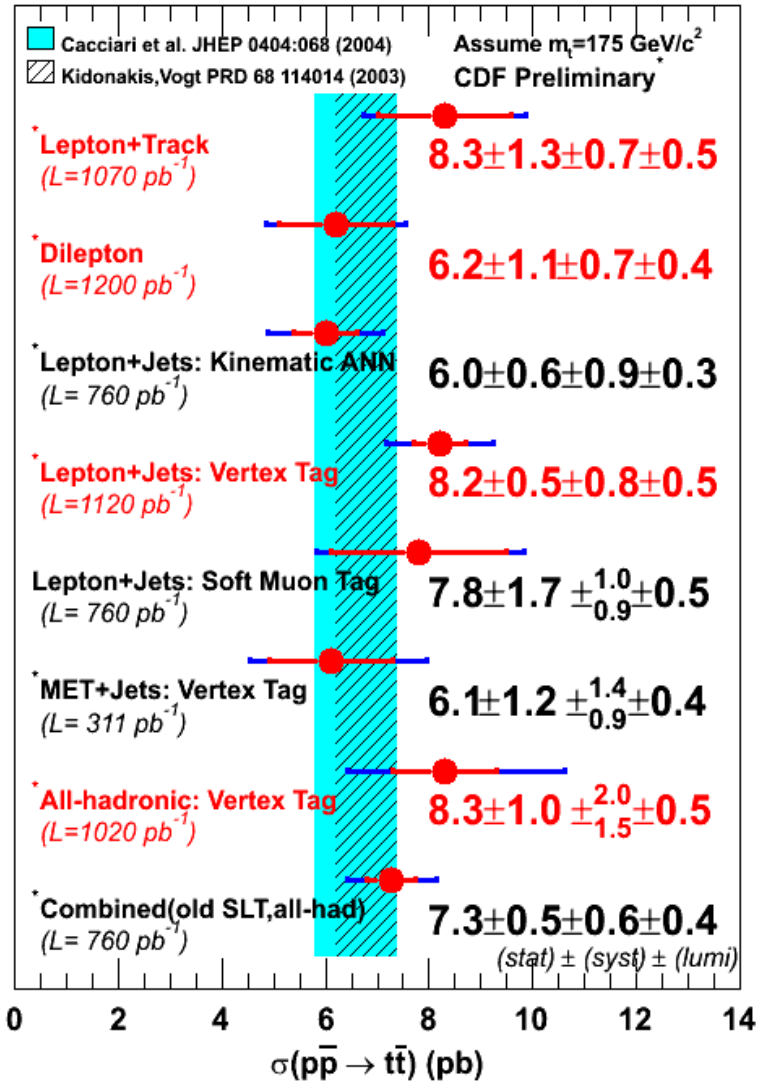


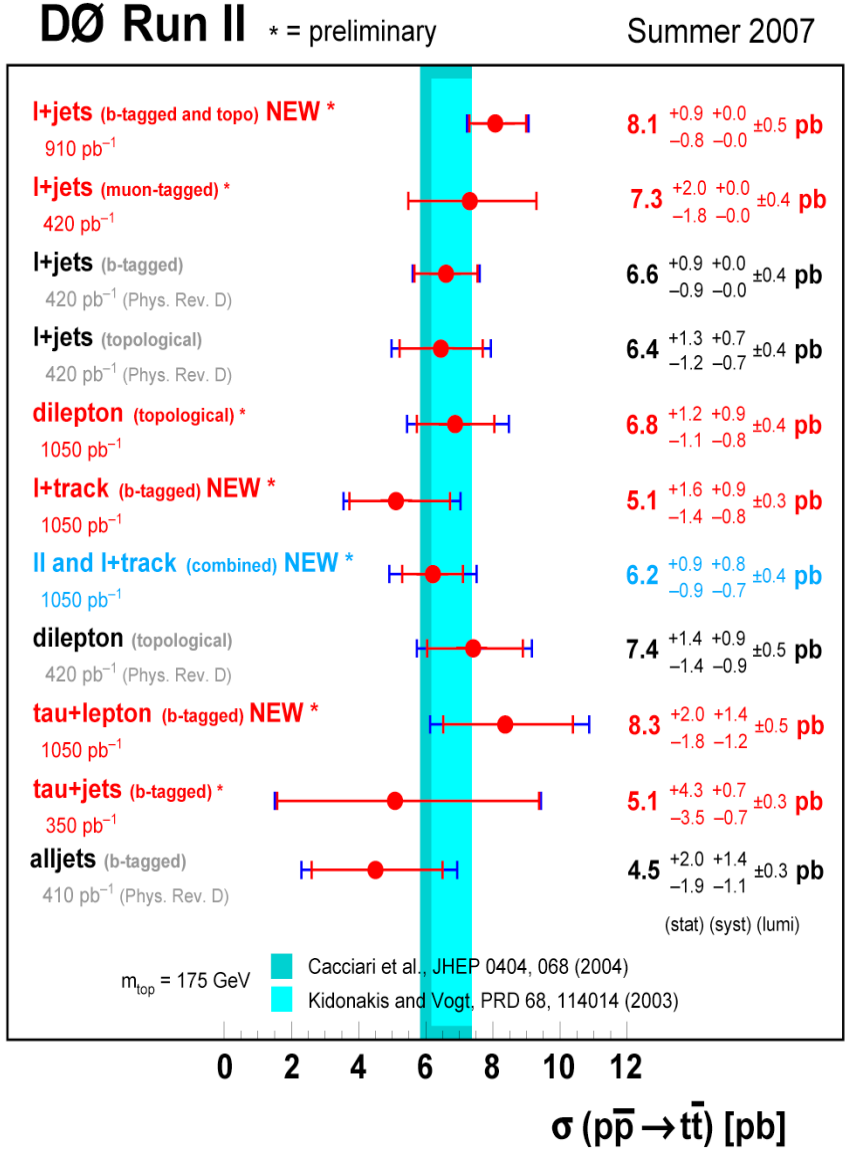
(movie)

Top quark strong interaction –

Does it couple to gluons like a quark?



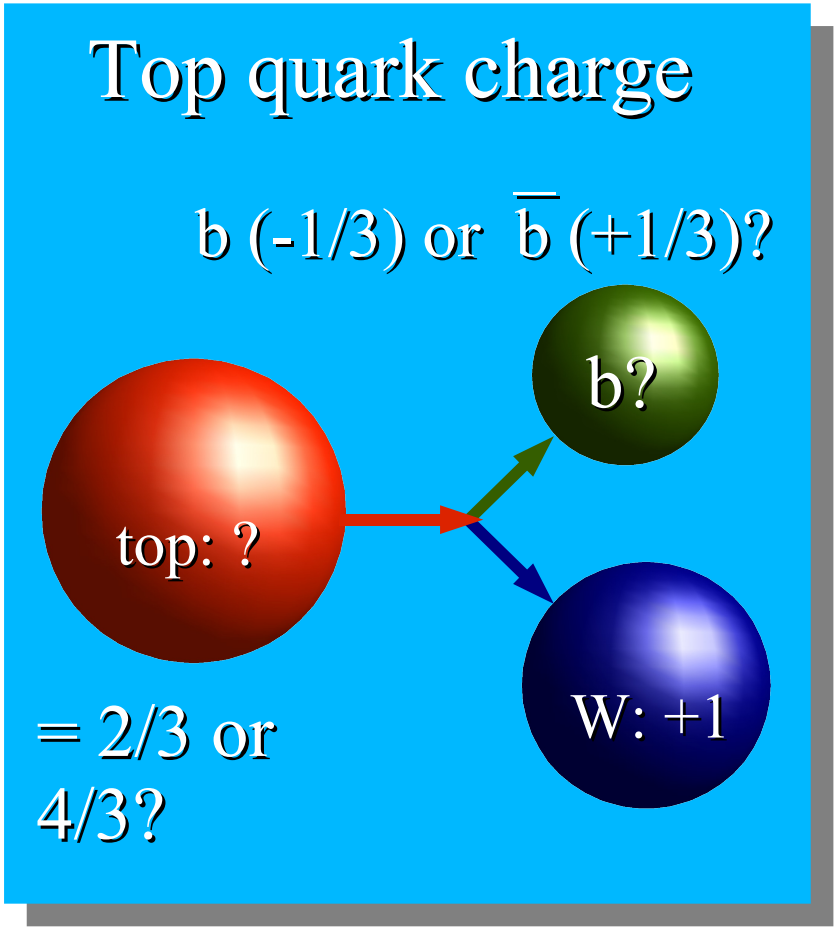


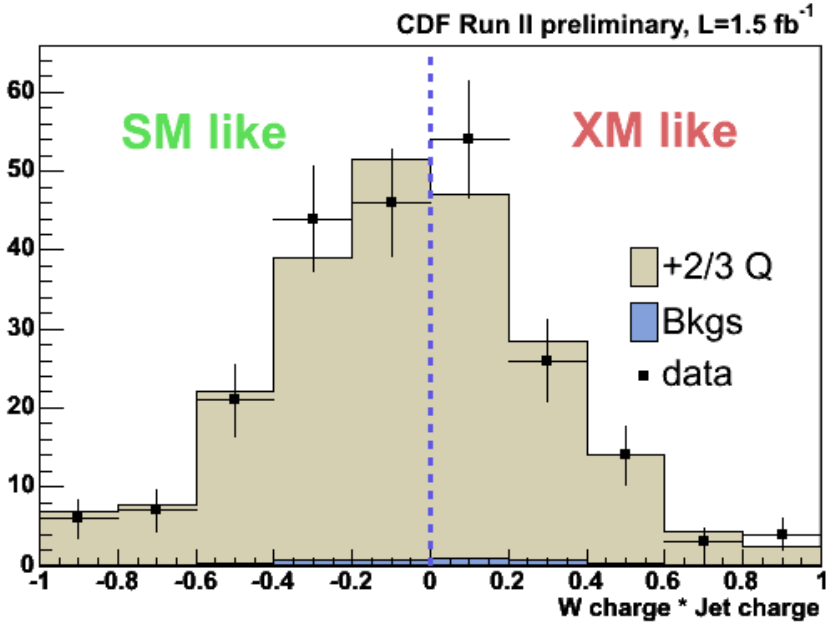


Result: SM strong interaction

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

Electric charge

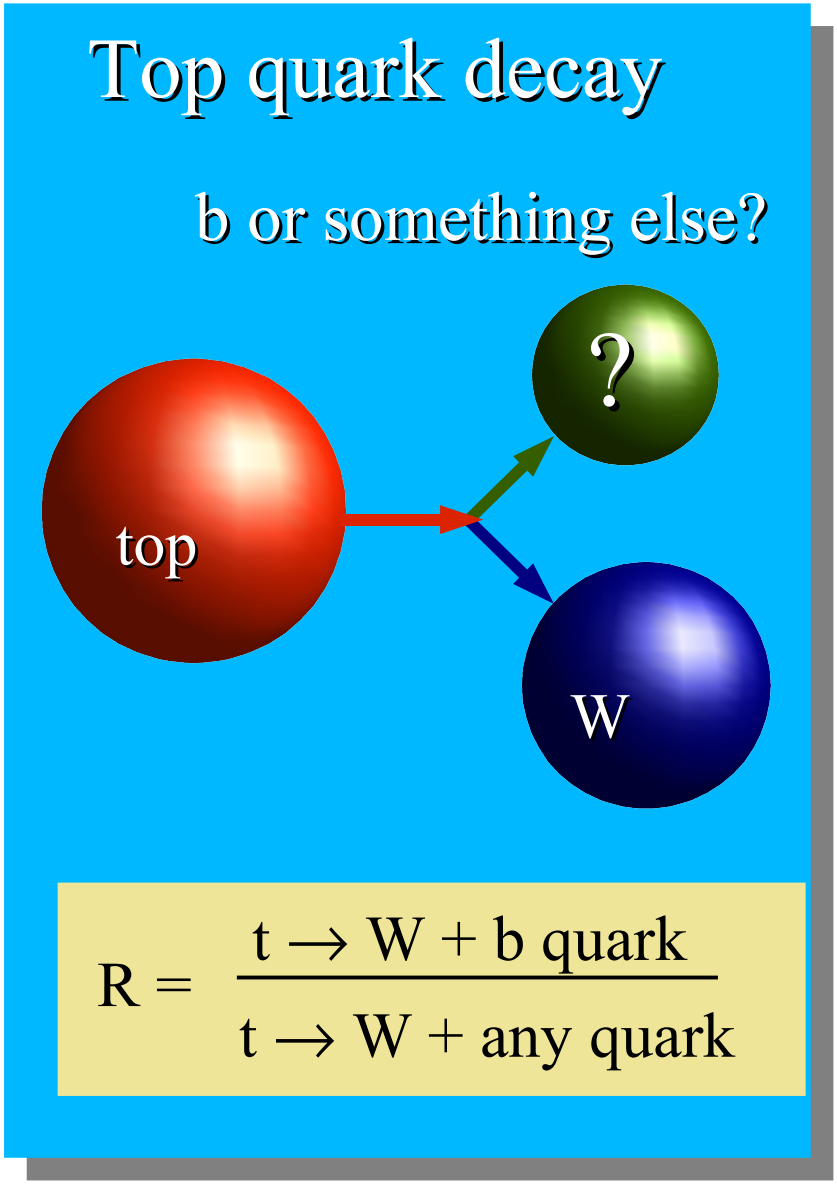


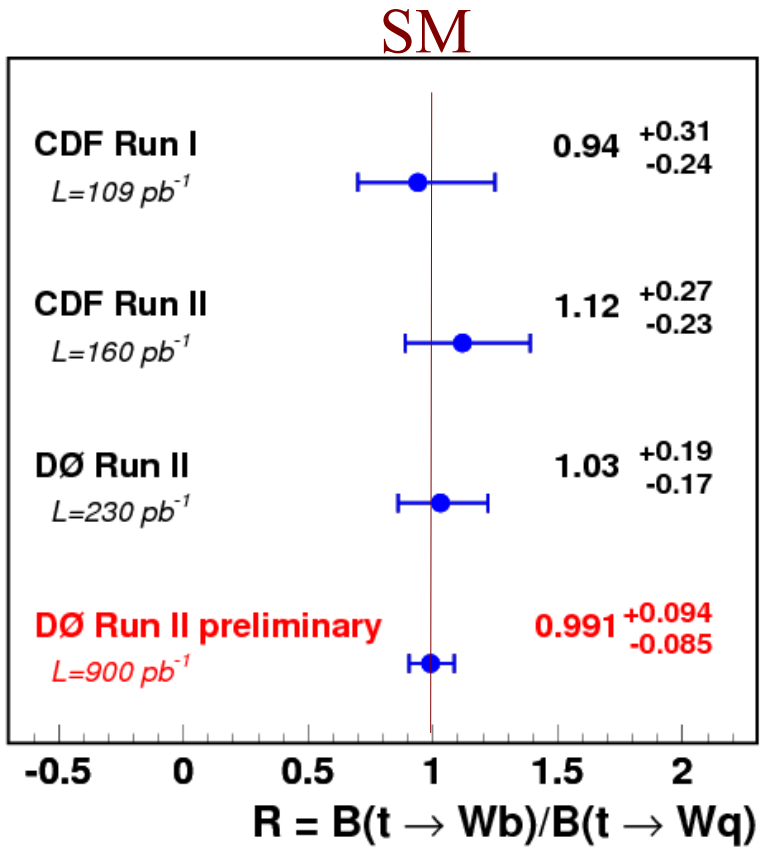


Result from both CDF and DØ: charge=2/3
as expected in SM

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

Decay branching ratio

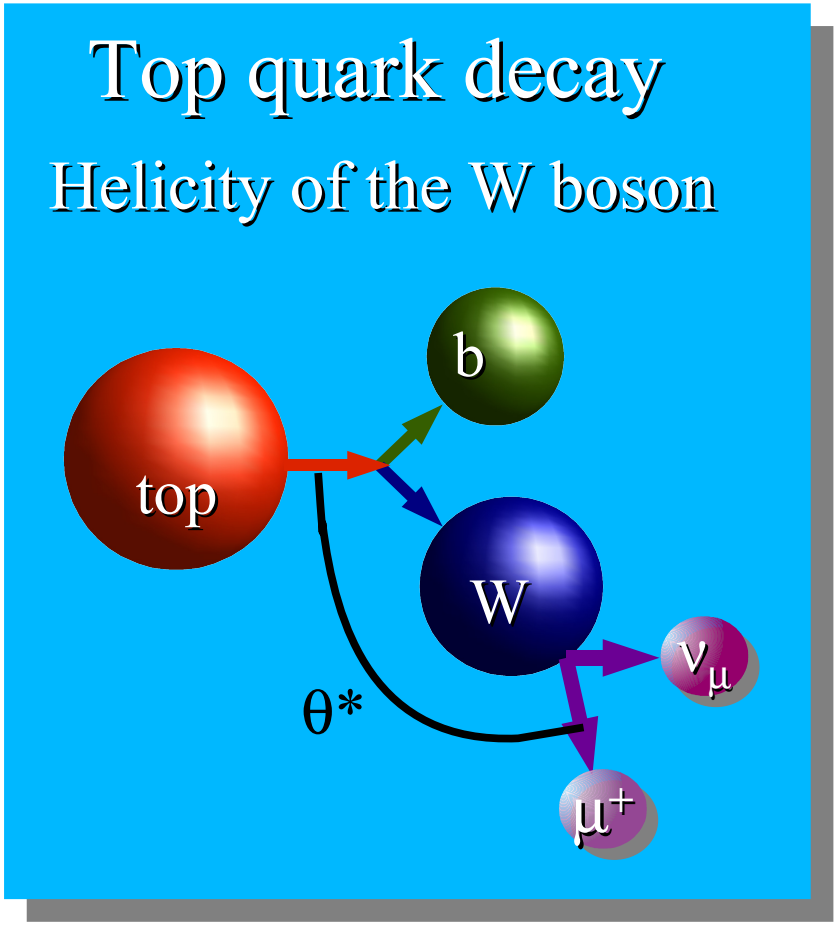


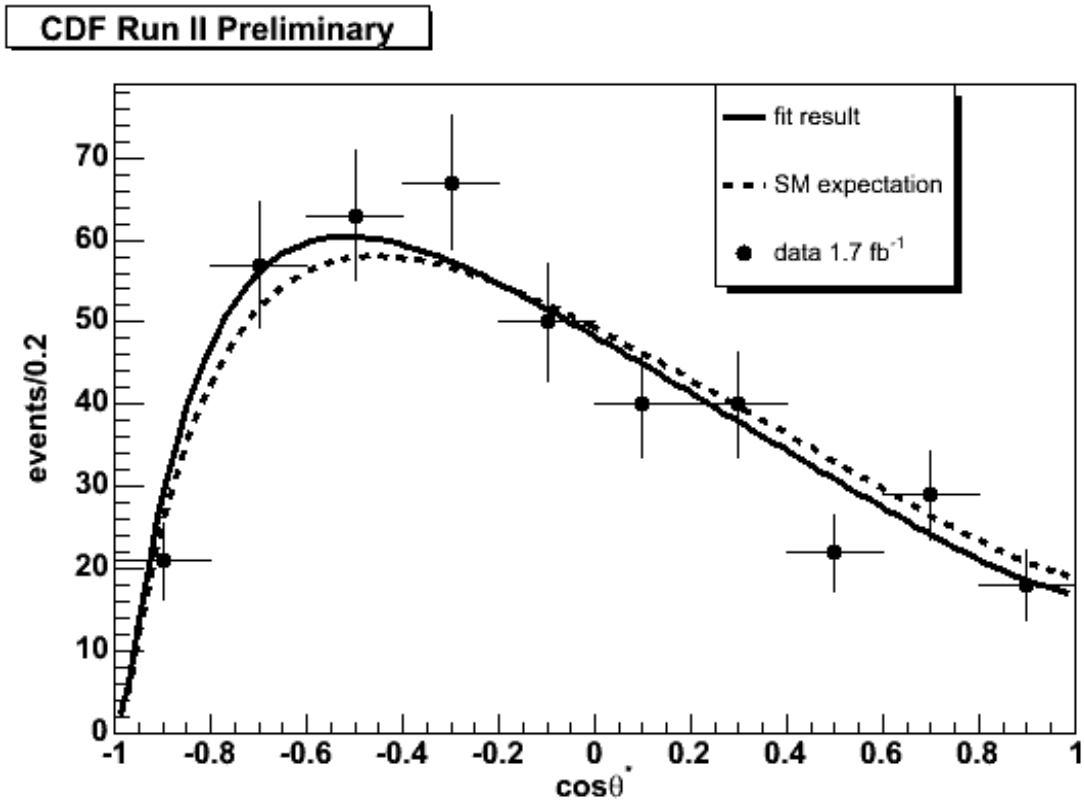


Result: R~1 as expected in SM

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

Helicity of the weak decay





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

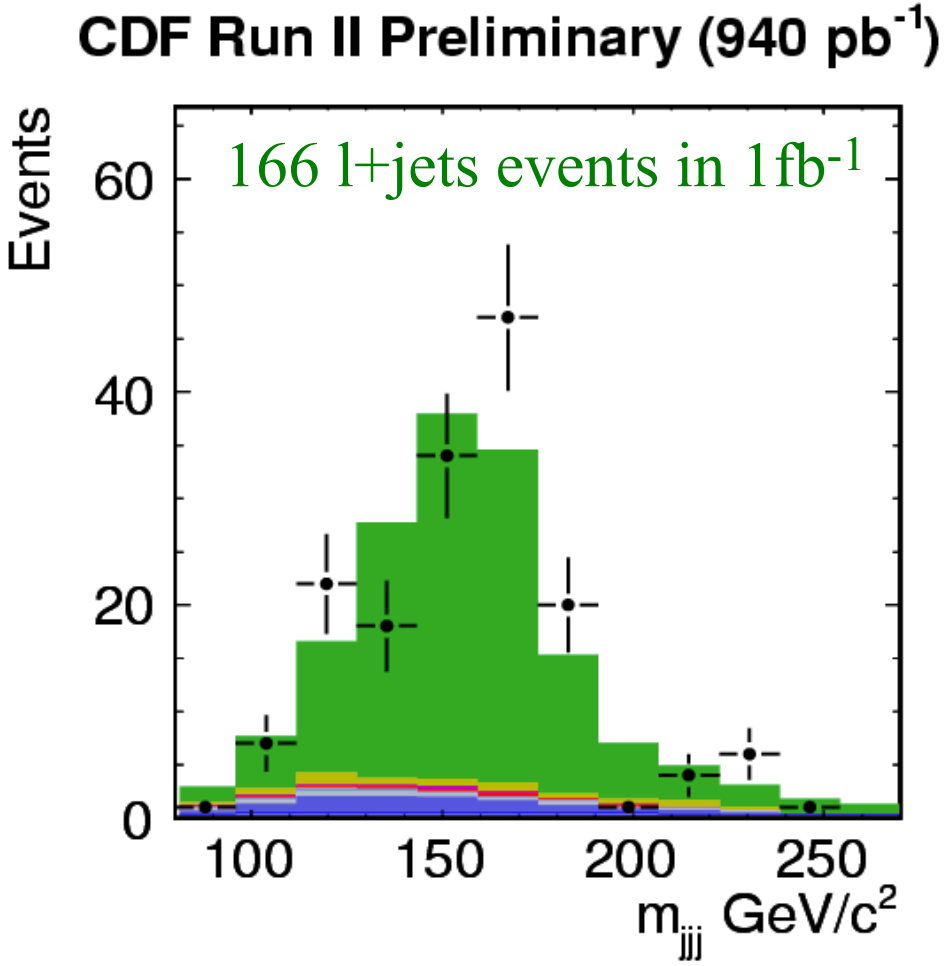
Other top quark property measurements

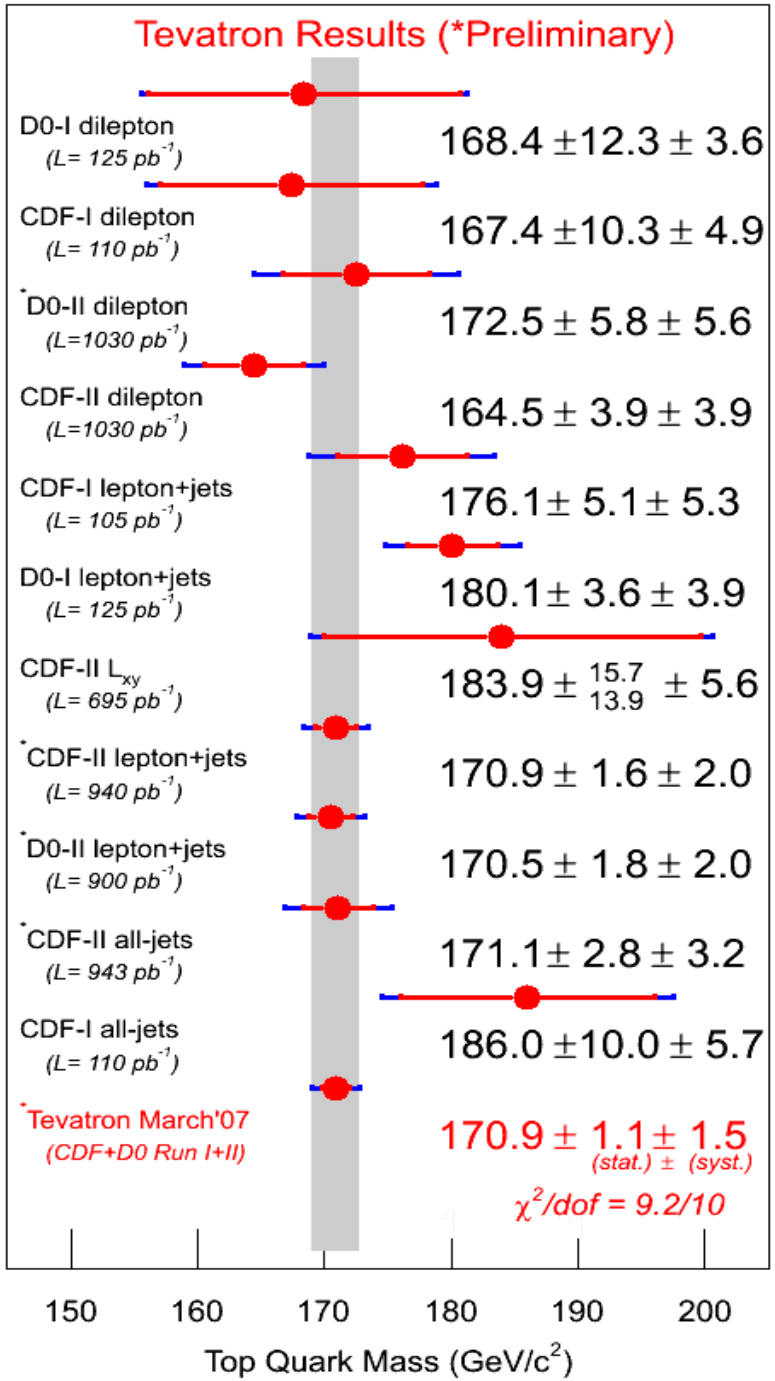
- Top quark production: tests of QCD
  - Forward-backward asymmetry
  - Quark-antiquark vs gluon-gluon annihilation
- Top quark width and lifetime
- Top quark decays to tau leptons

All properties measurements are sensitive to new physics

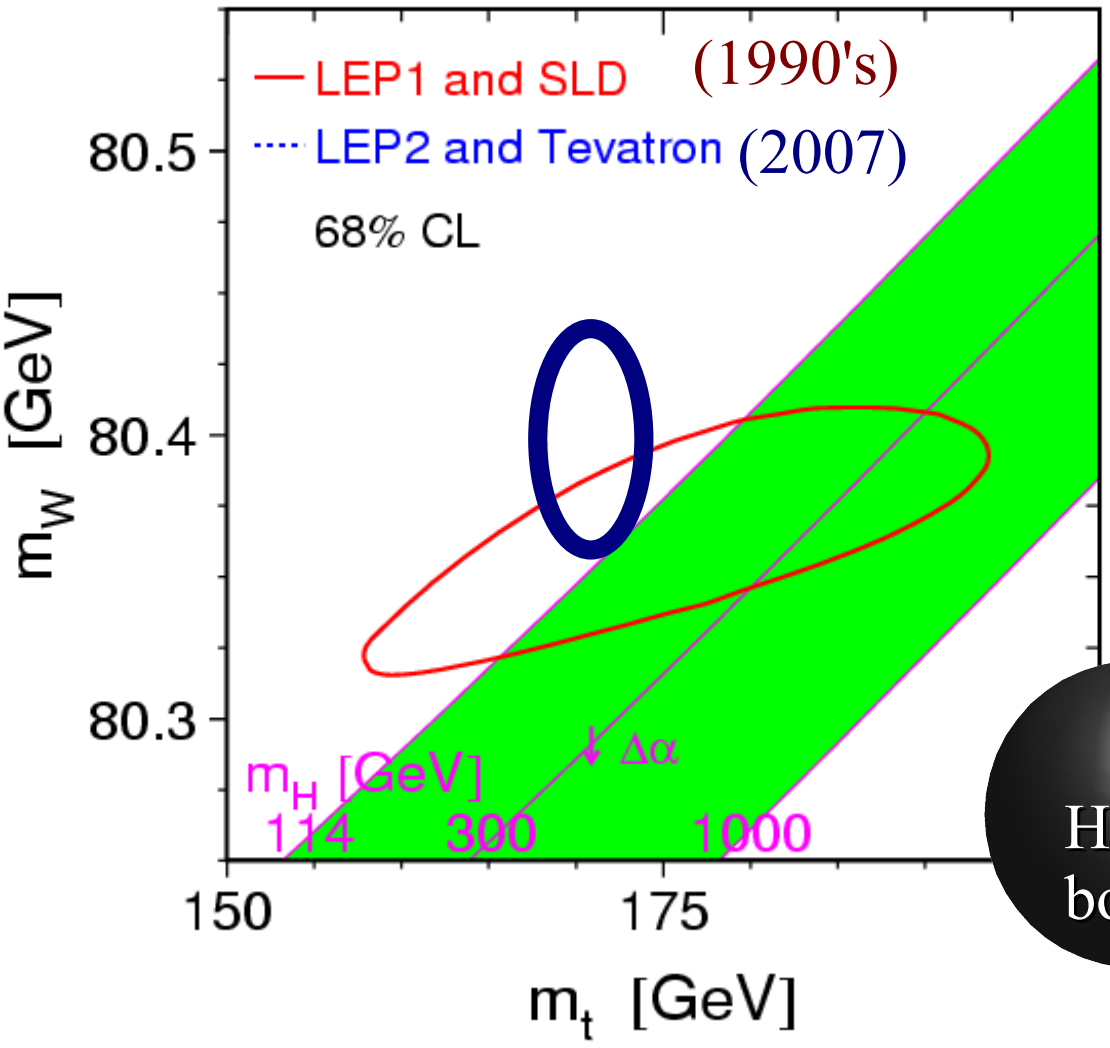
Top quark mass determination

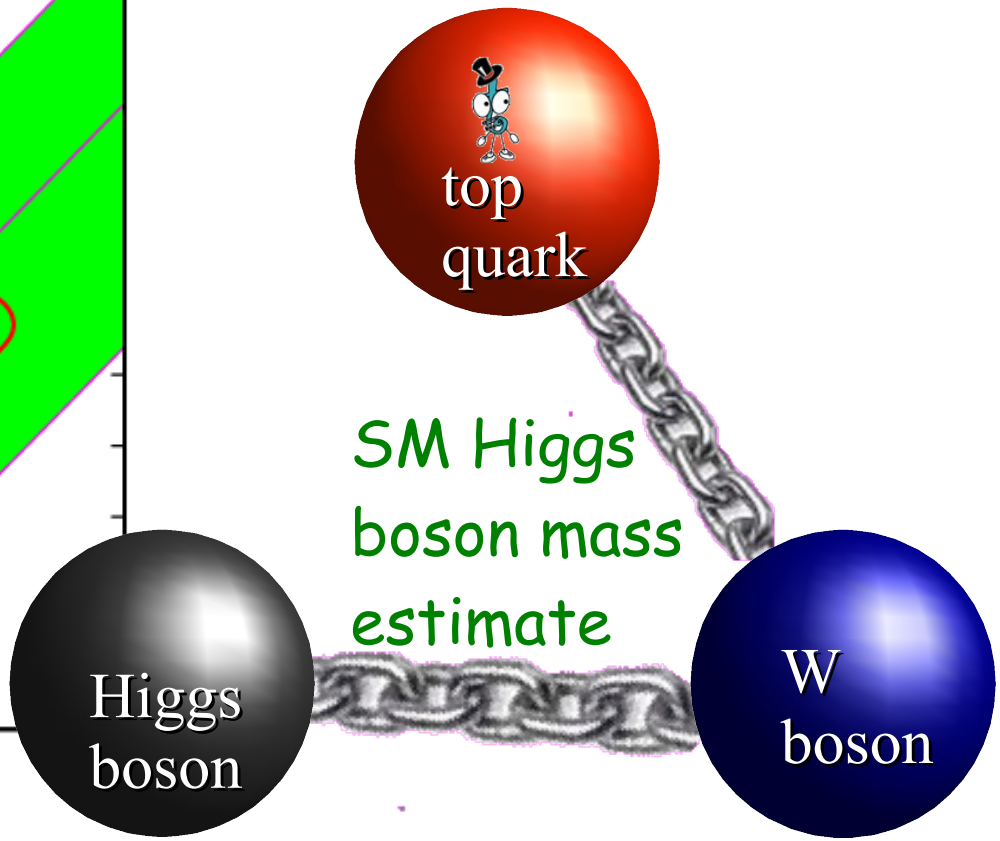
- Large sample of top quarks
  - ~10^3 events in 1 fb^{-1} per experiment
- Advanced analysis techniques
  - uncertainty ~1%, close to decay width





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

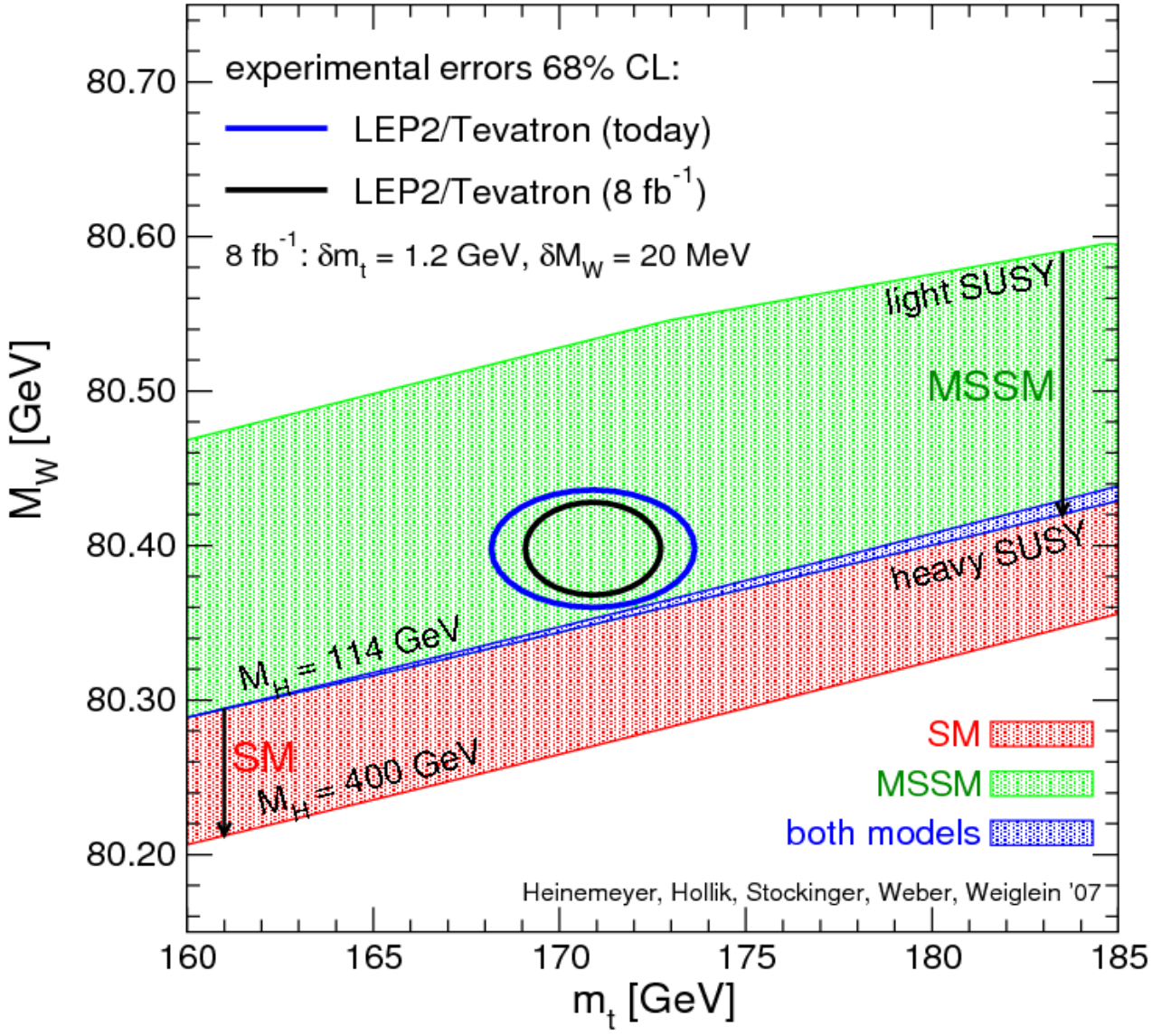




$$m_W = m_W^0 + const \times m_t^2 + const \times \ln(m_H) + \ldots$$

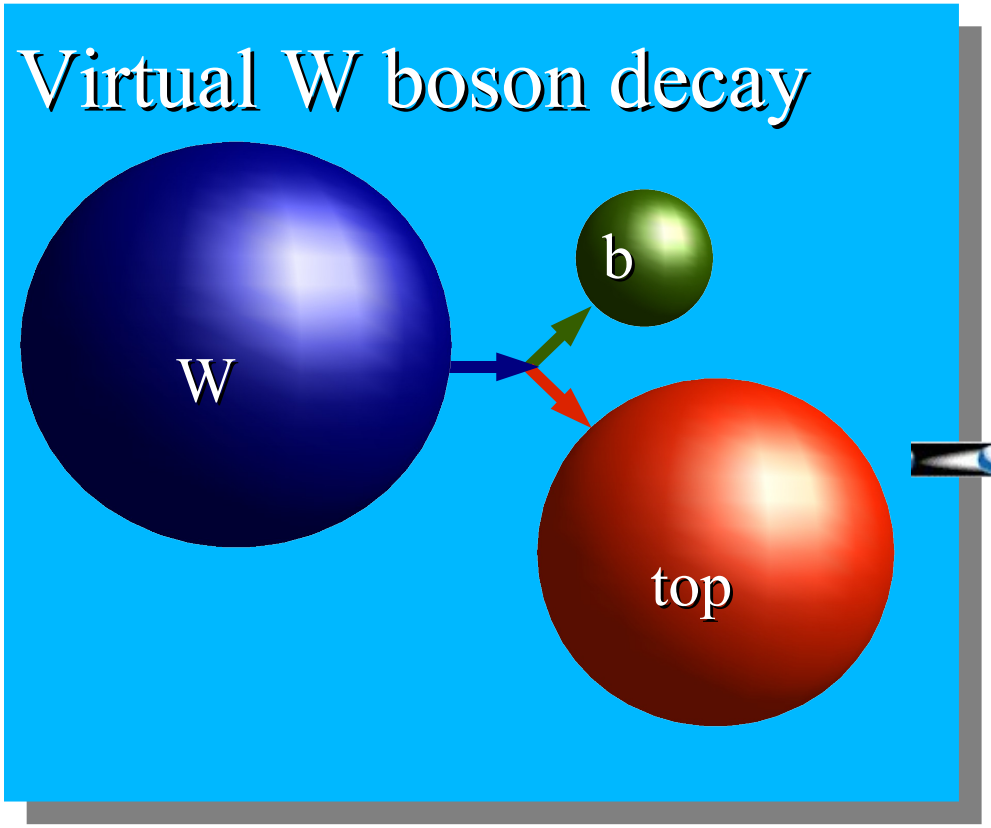
Top quark mass implications –

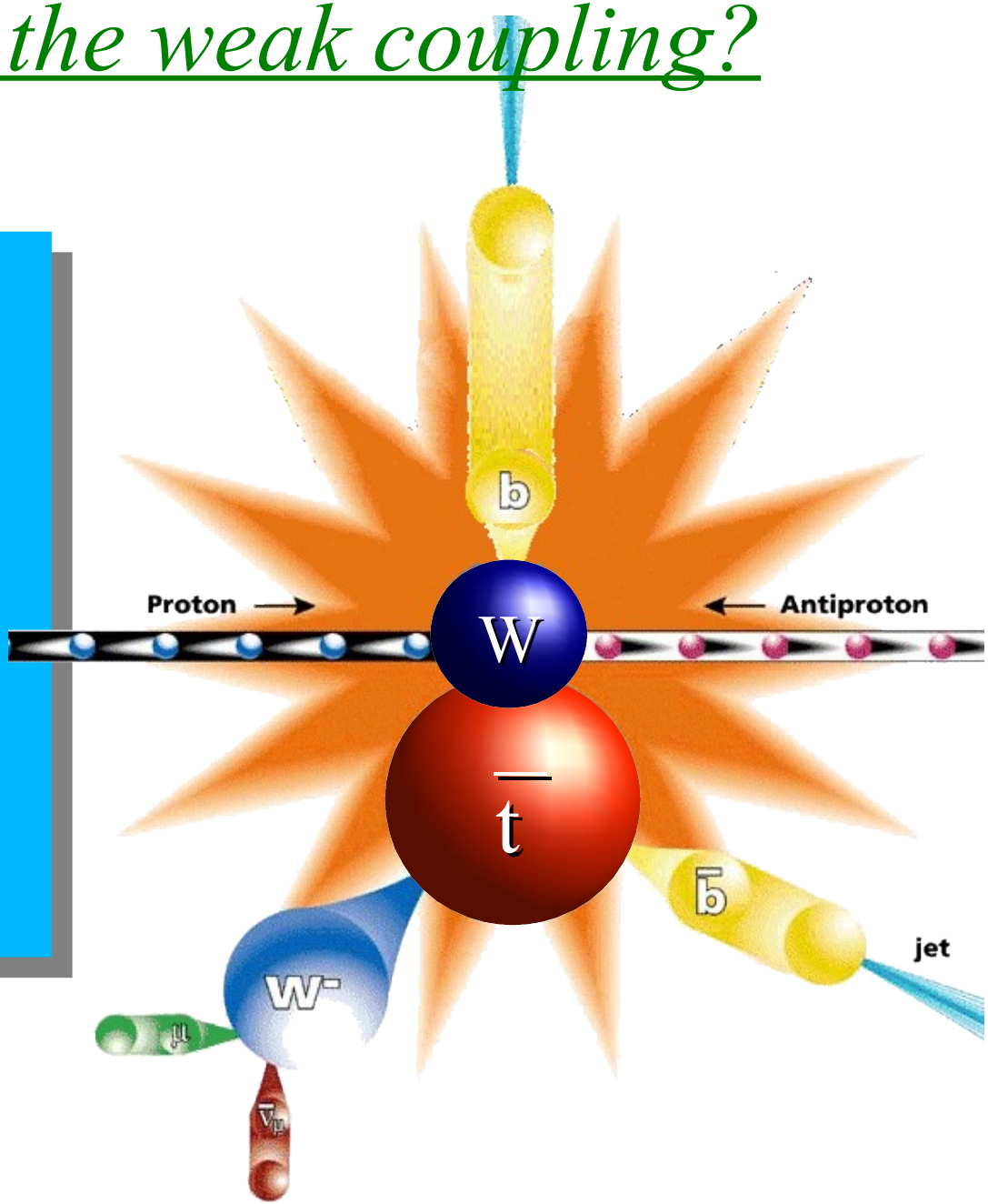
What about top and supersymmetry?



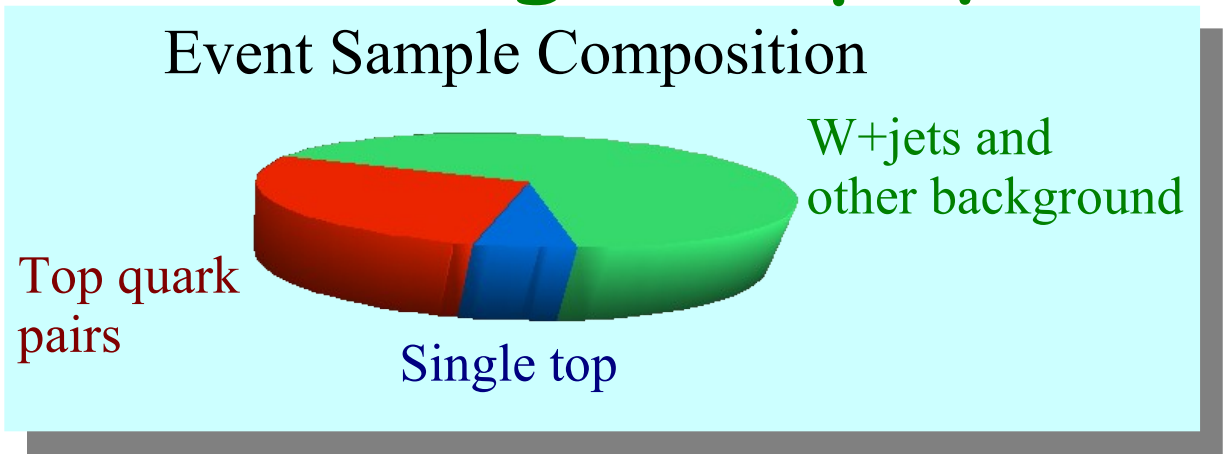
Electroweak top quark production –

How strong is the weak coupling?

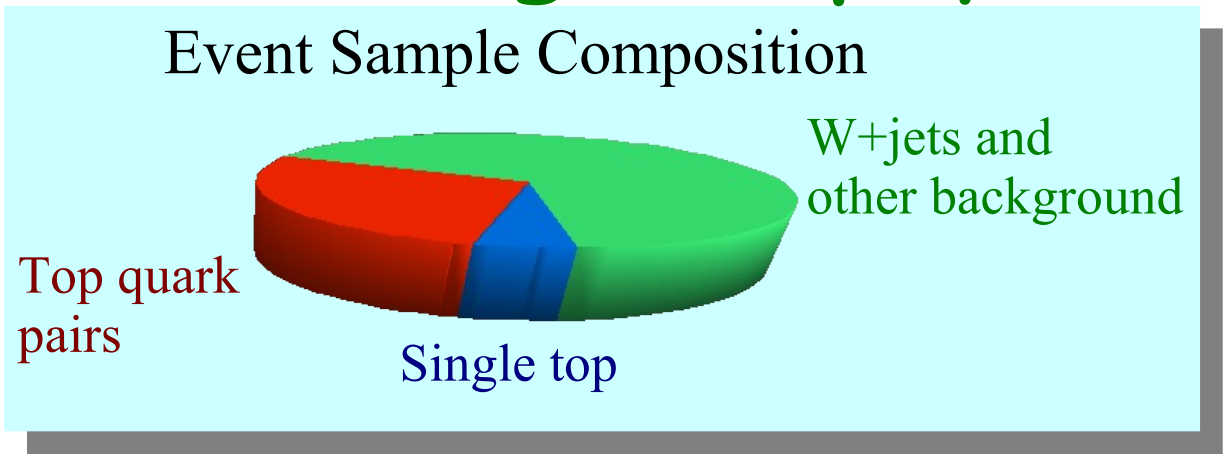




Single top quark search



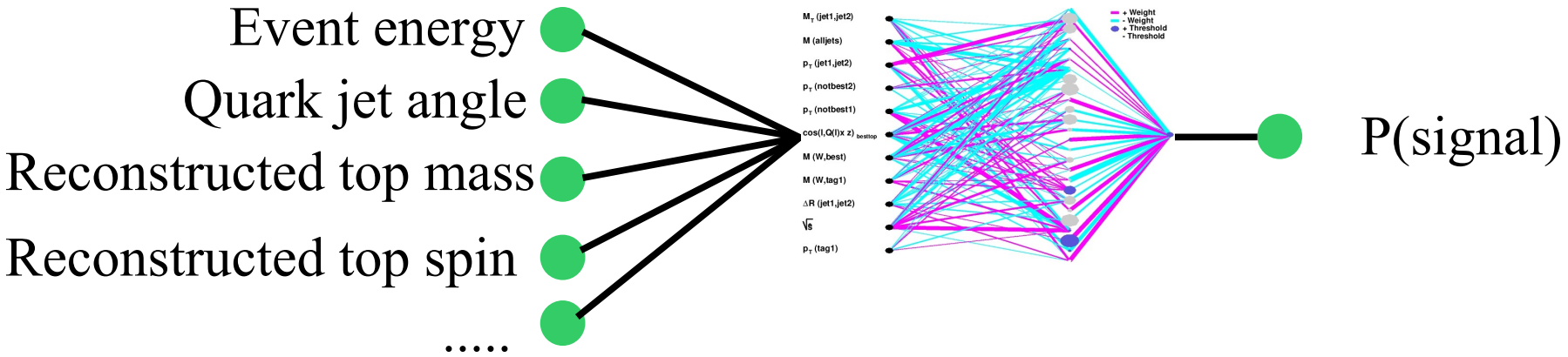
Single top quark search



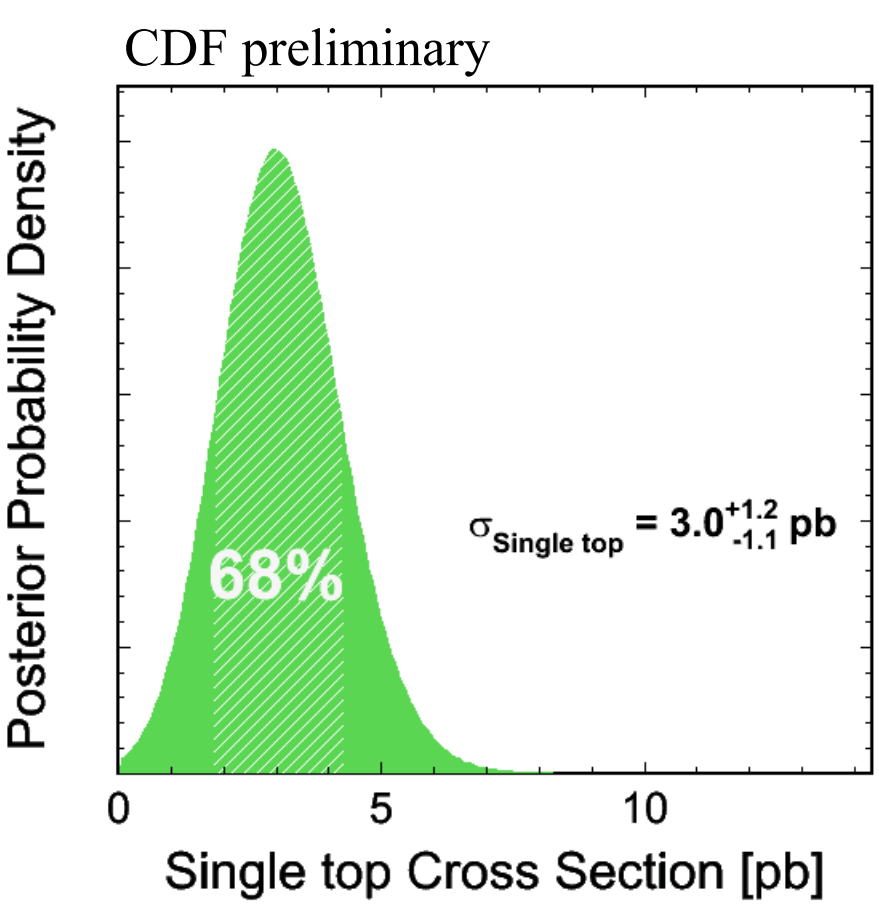
- Optimized event analysis

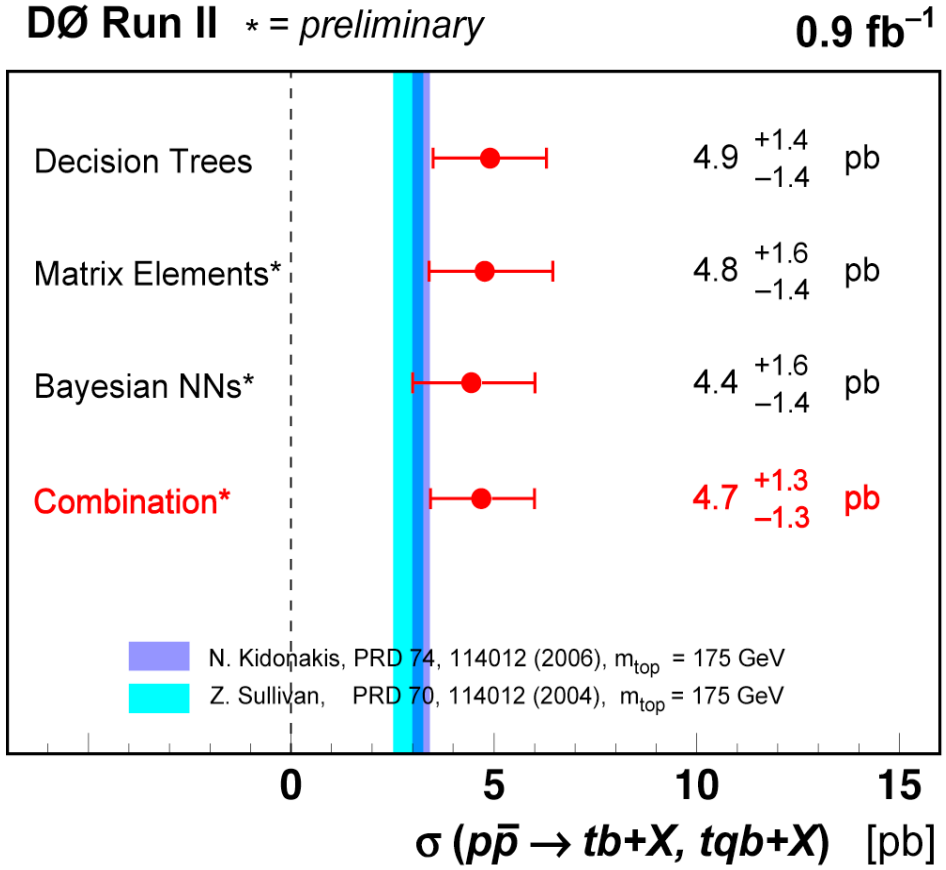
Input:	Method:	Output:
discriminating variables	multivariate analysis	signal probability

Bayesian Neural Networks,
boosted Decision Trees, etc



Single top quark search

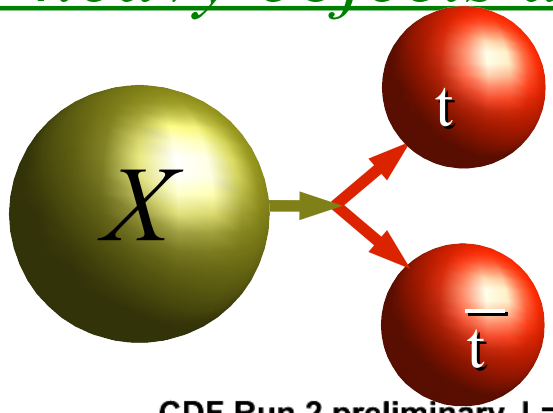


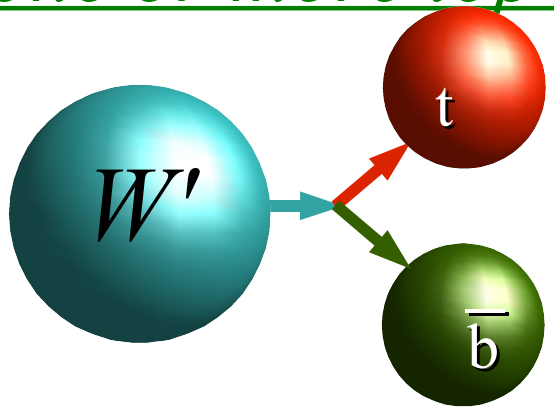


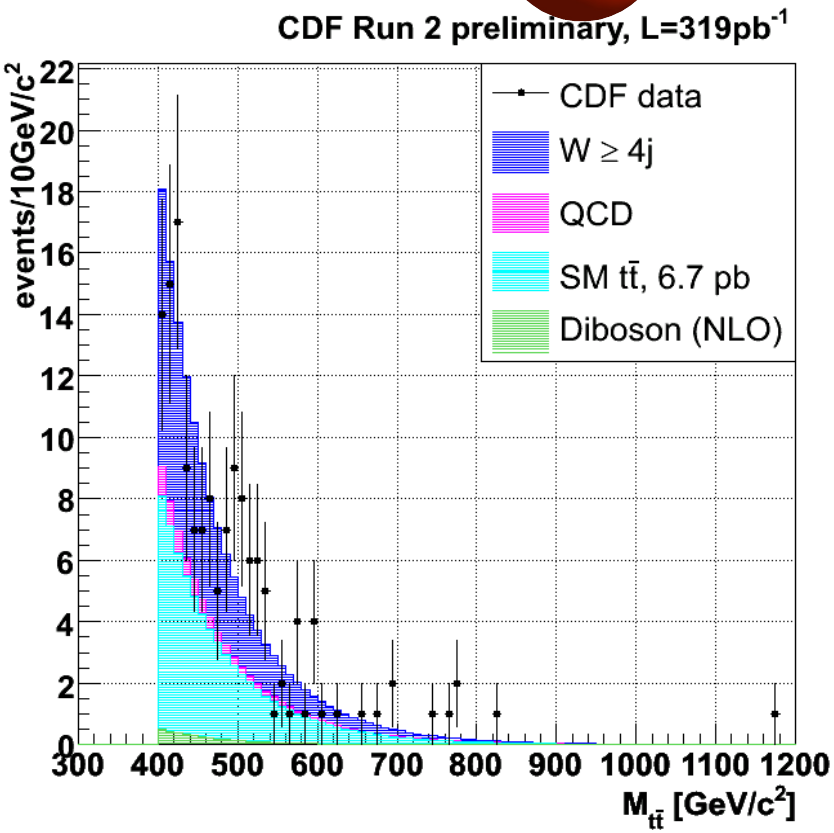
Result: consistent with SM

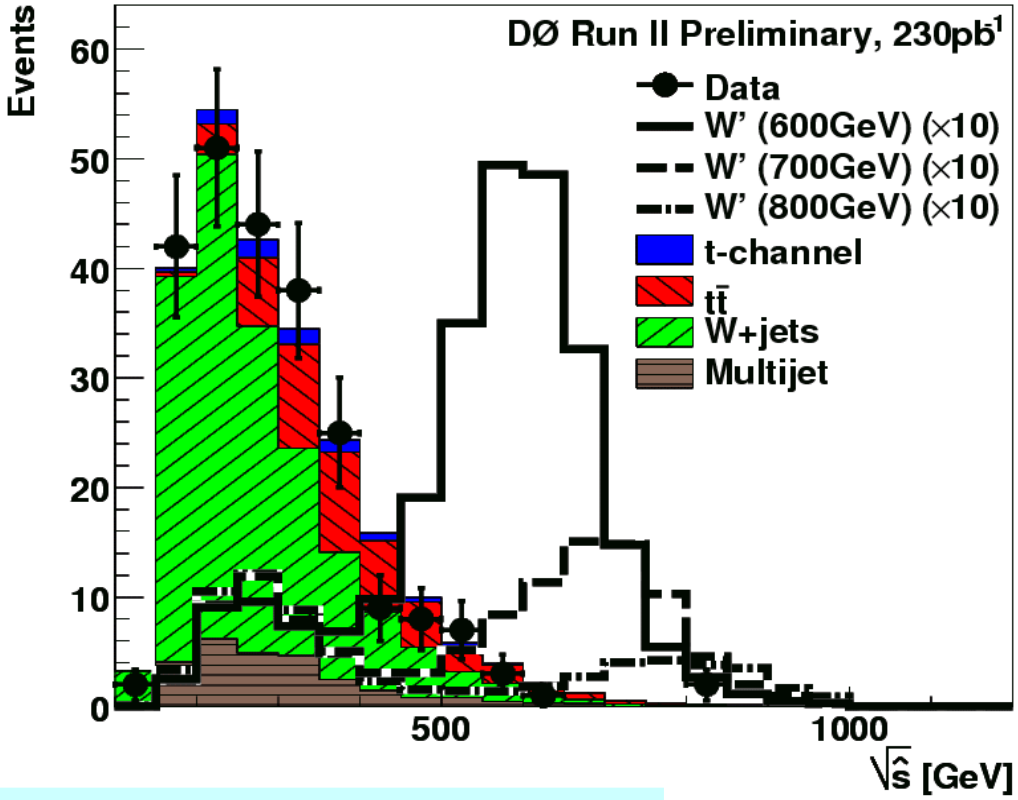
Top as a tool

New heavy objects decaying to one or more top quarks?



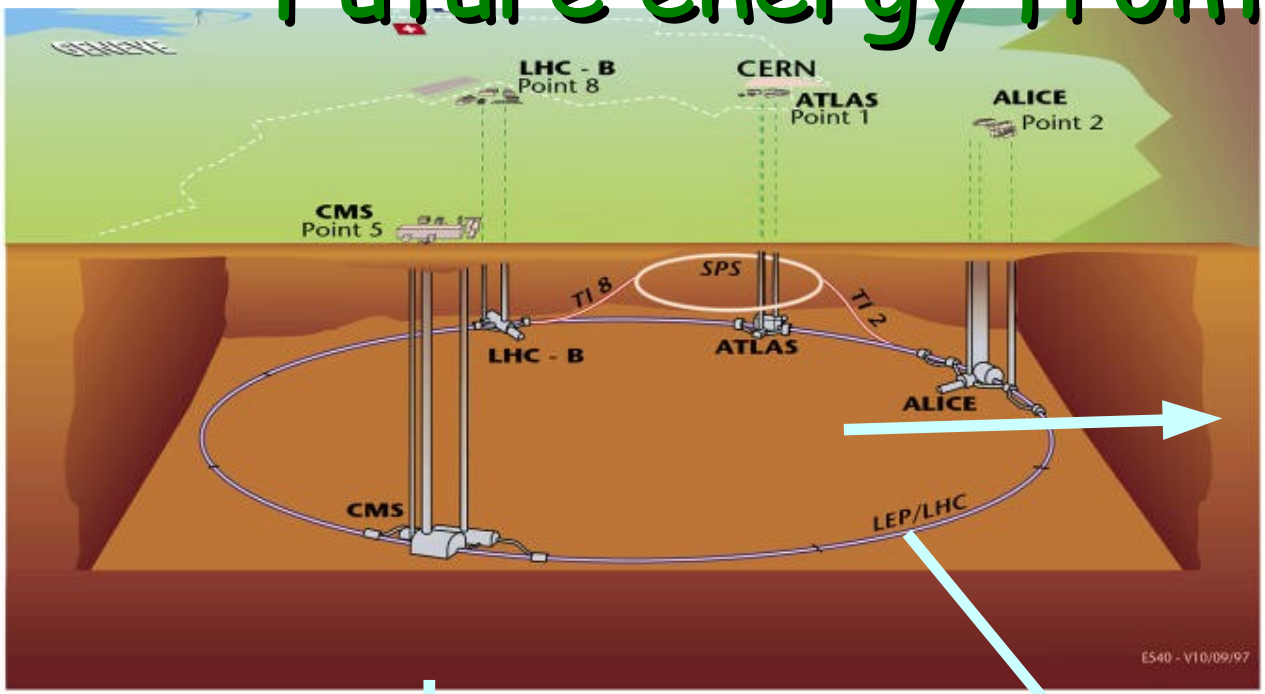


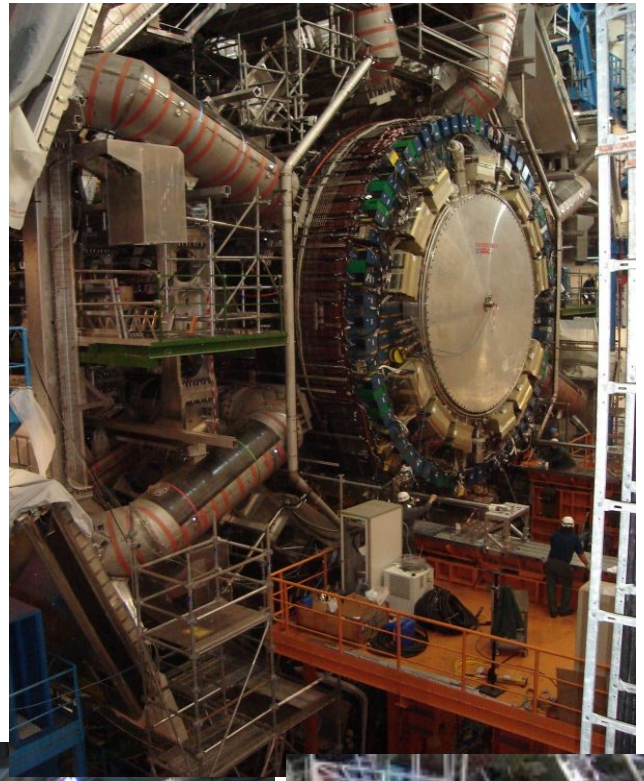


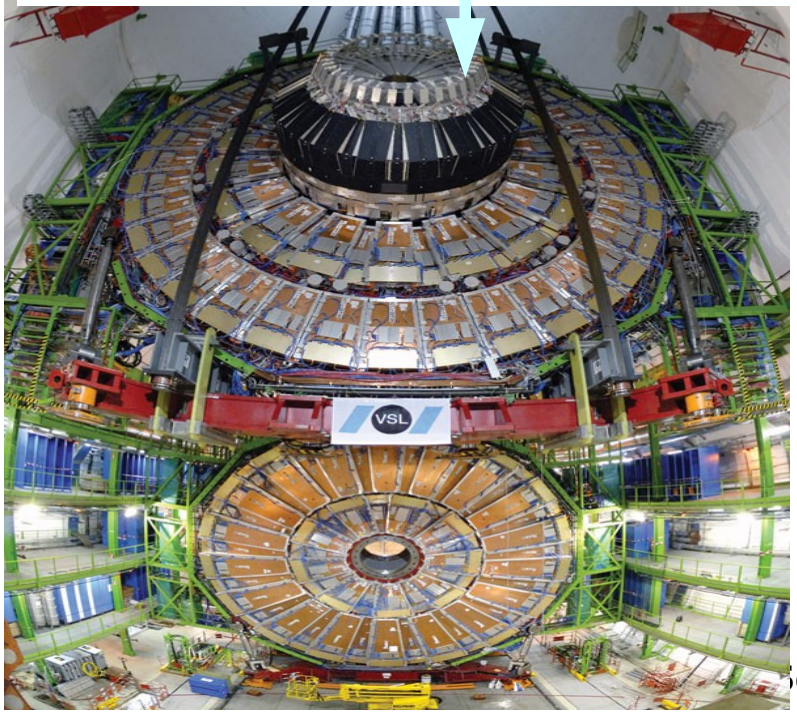


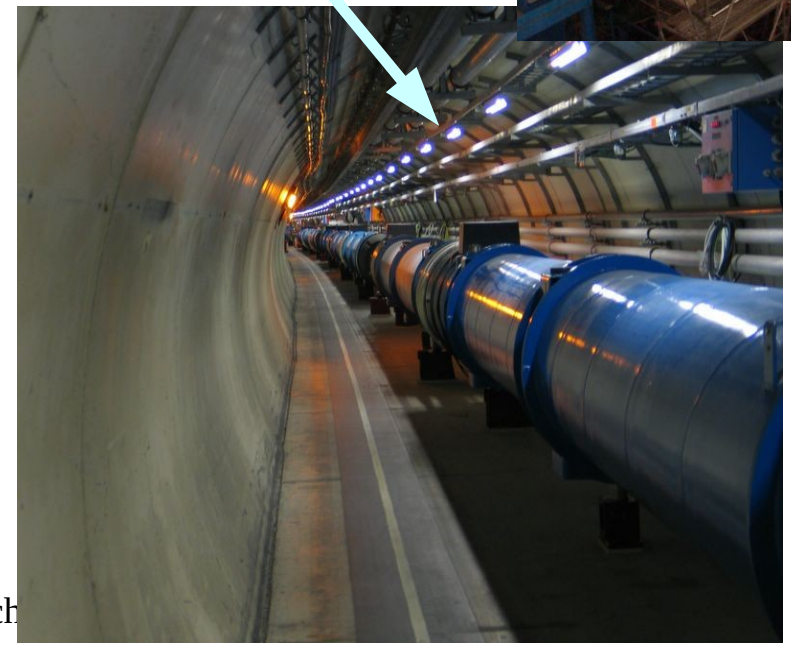
Result: no evidence for new heavy objects

Future energy frontier: LHC





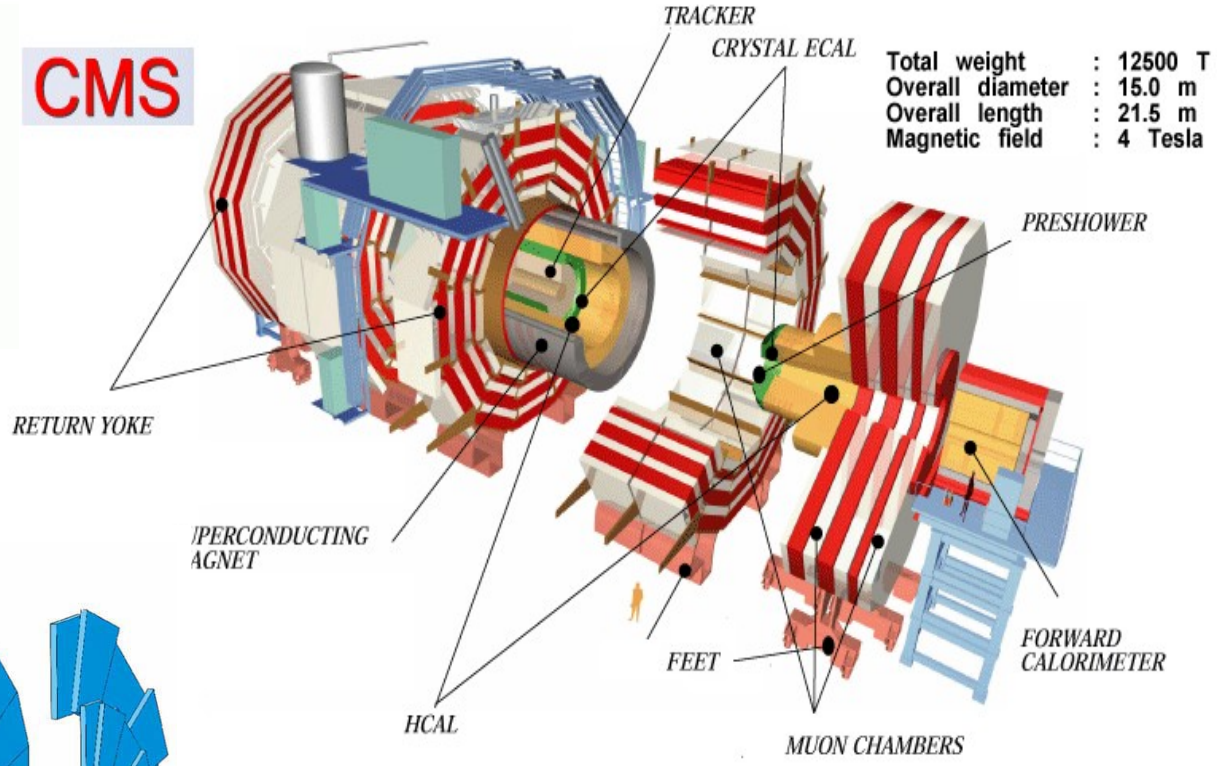


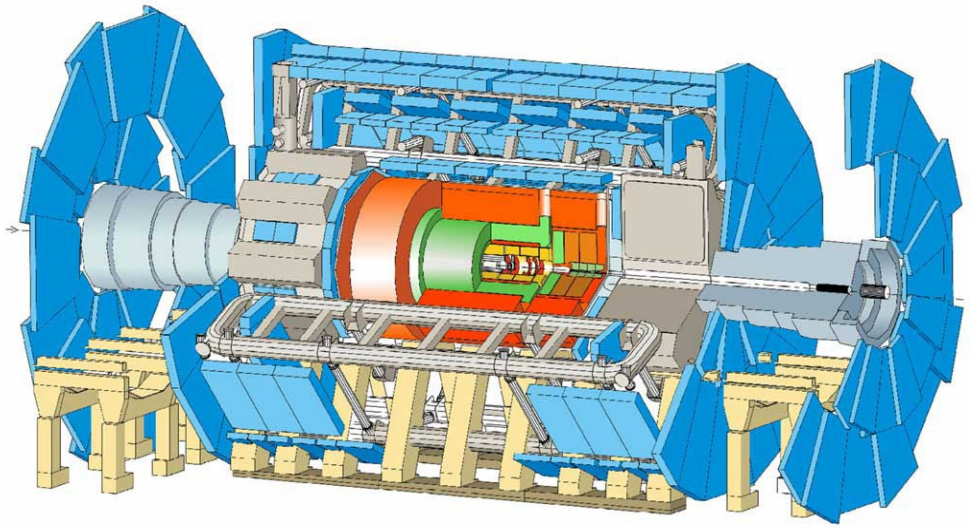


LHC detectors

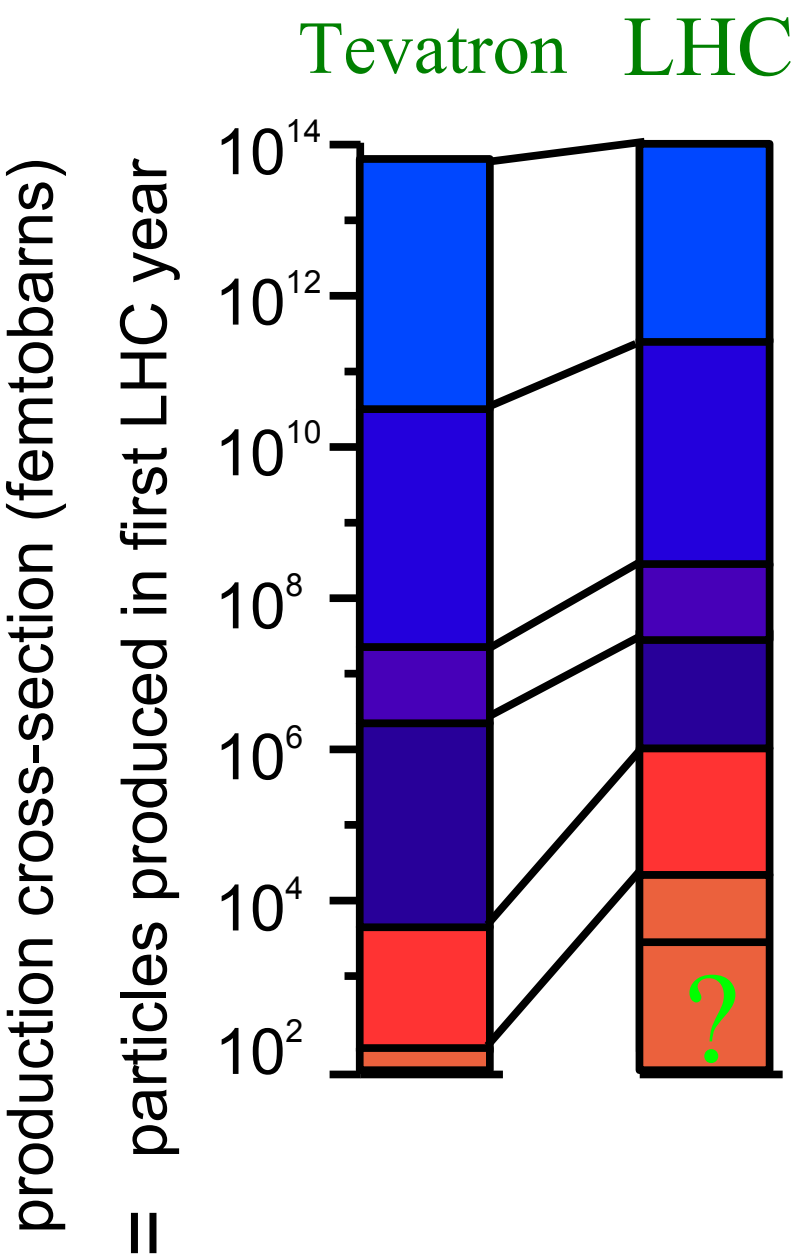
- Diameter 25 m
- Length : 46 m
- Barrel toroid length 26 m
- Overall weight 7 000 tonnes
- ~ 100 million electronic channels
- ~ 3 000 km of cables

CMS





Particle production at the LHC



Quark-antiquark production

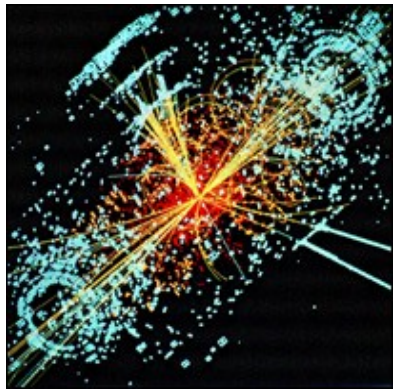
Bottom quark pairs

W bosons

Z bosons

top quarks

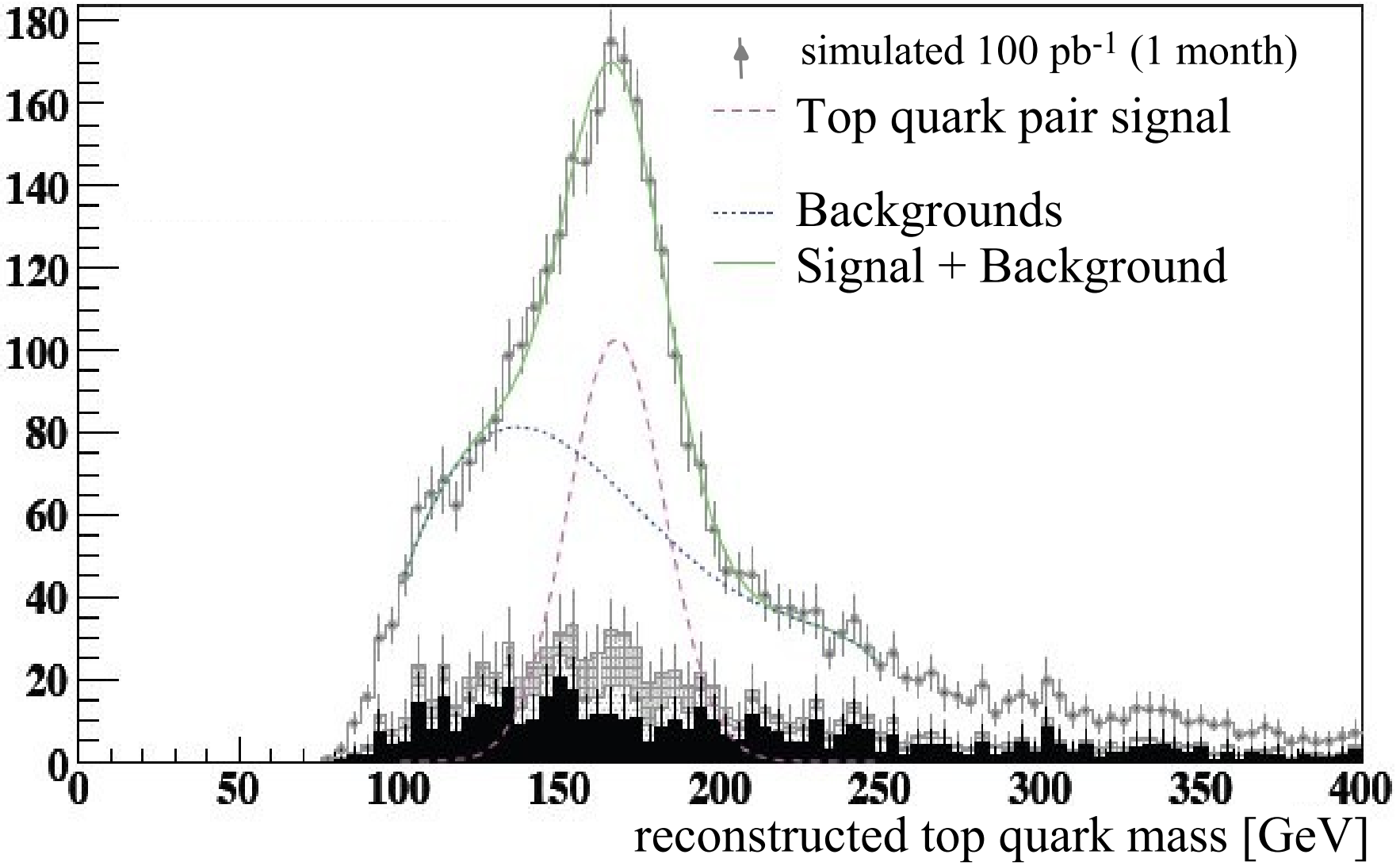
Origin of W boson and top quark mass



Something unexpected?

Top as a tool to calibrate the detector

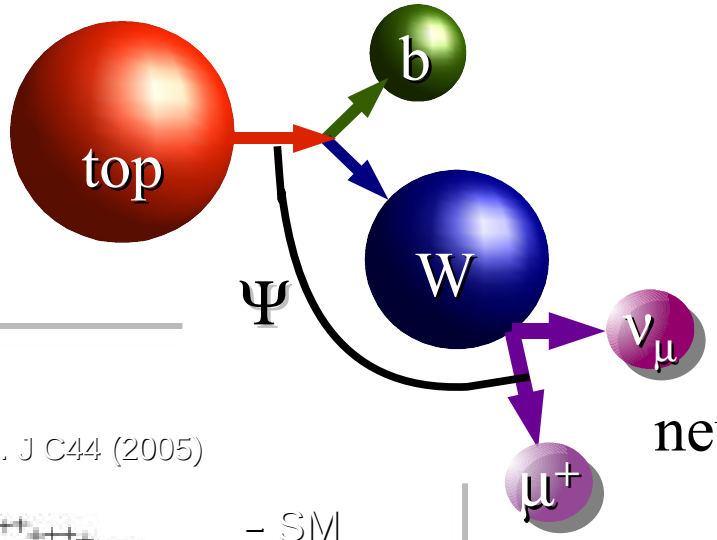
- Large sample of top quarks (10^5 events/week)
- Calibrate energy measurement, tune b-quark tagging



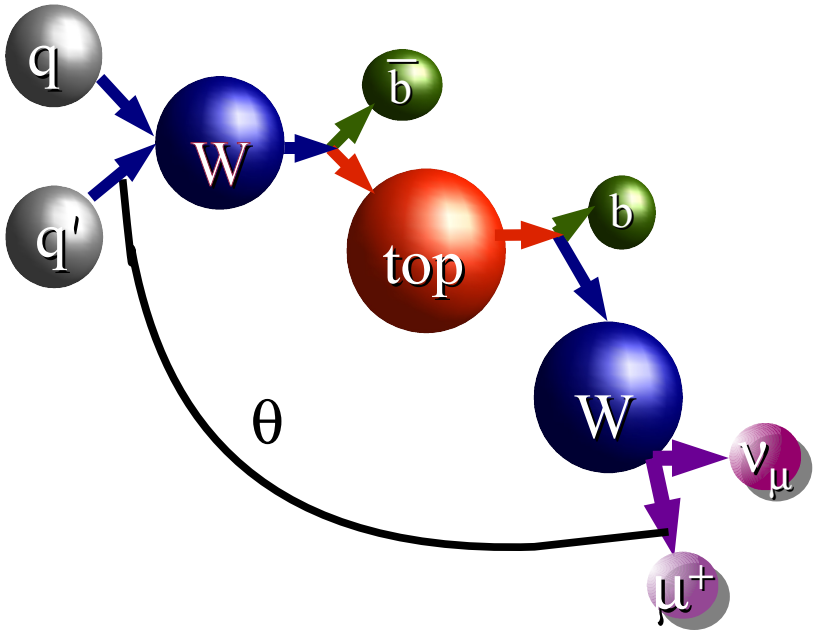
Precision top quark physics

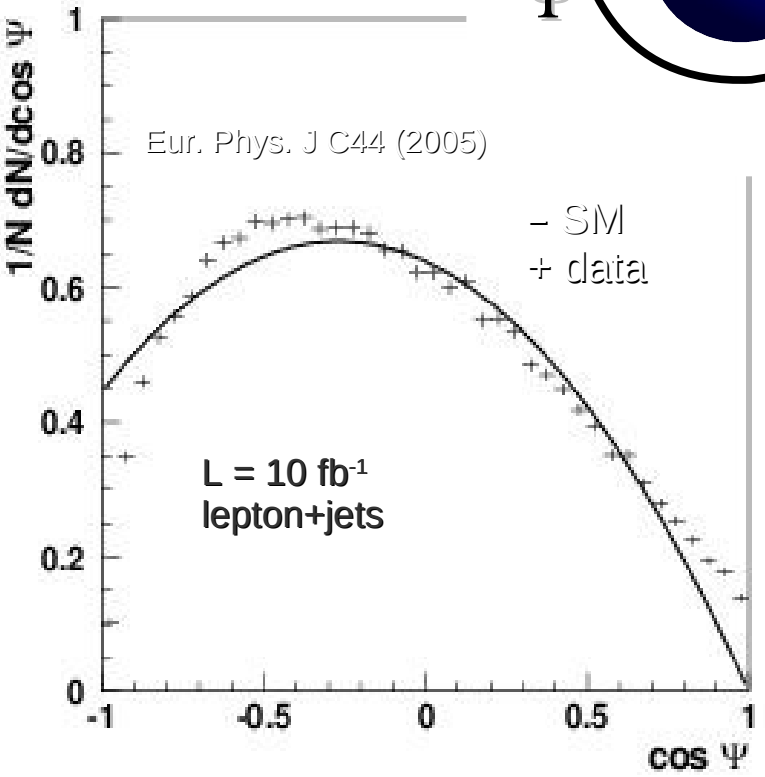
- Example: top quark polarization probes higher-order couplings
  - Especially important if Higgs is not where expected

in the top quark decay



in single top production

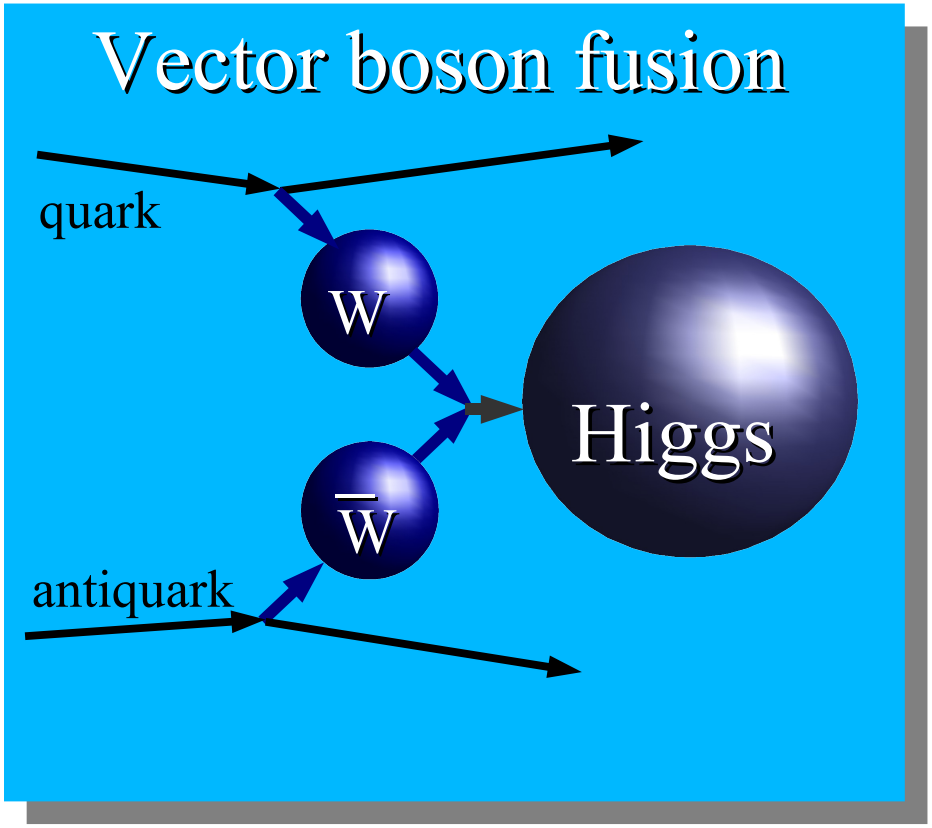


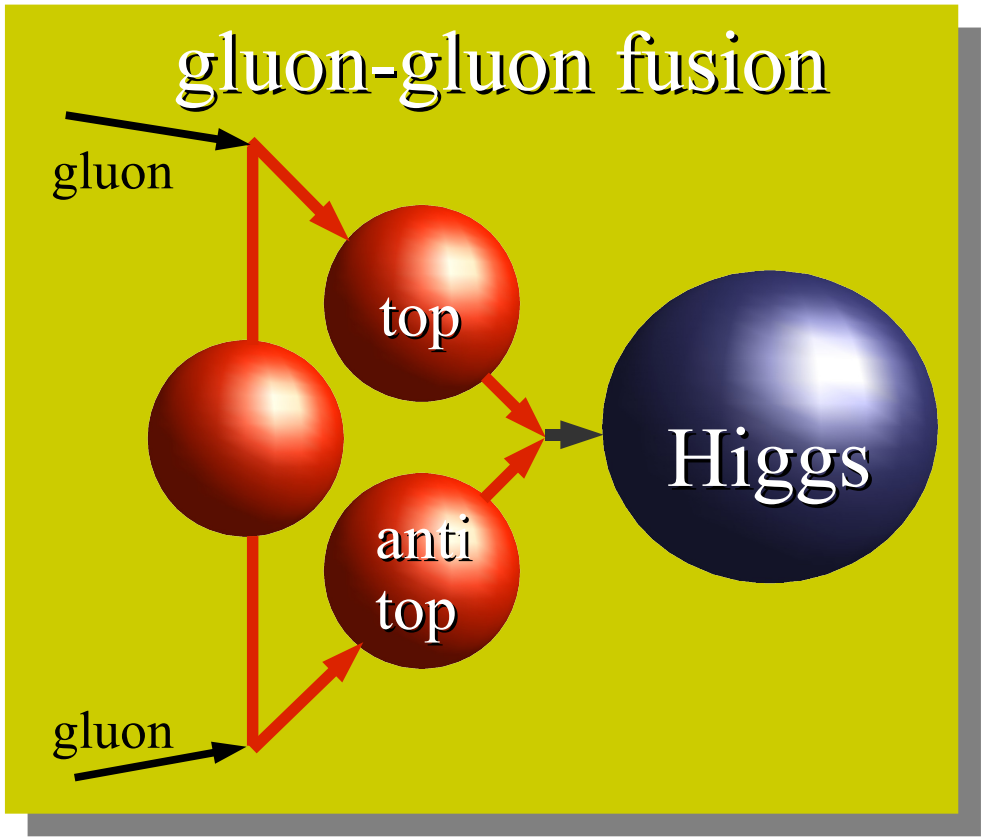


- Very sensitive to new physics by combining different channels

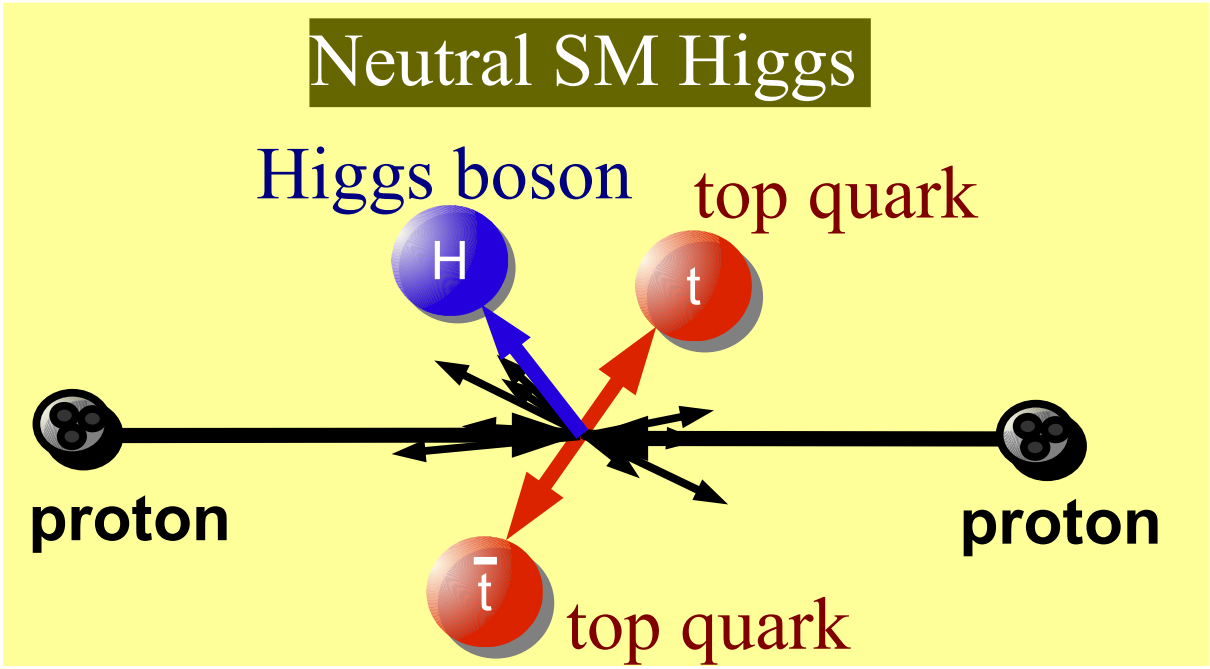
Higgs boson production at the LHC

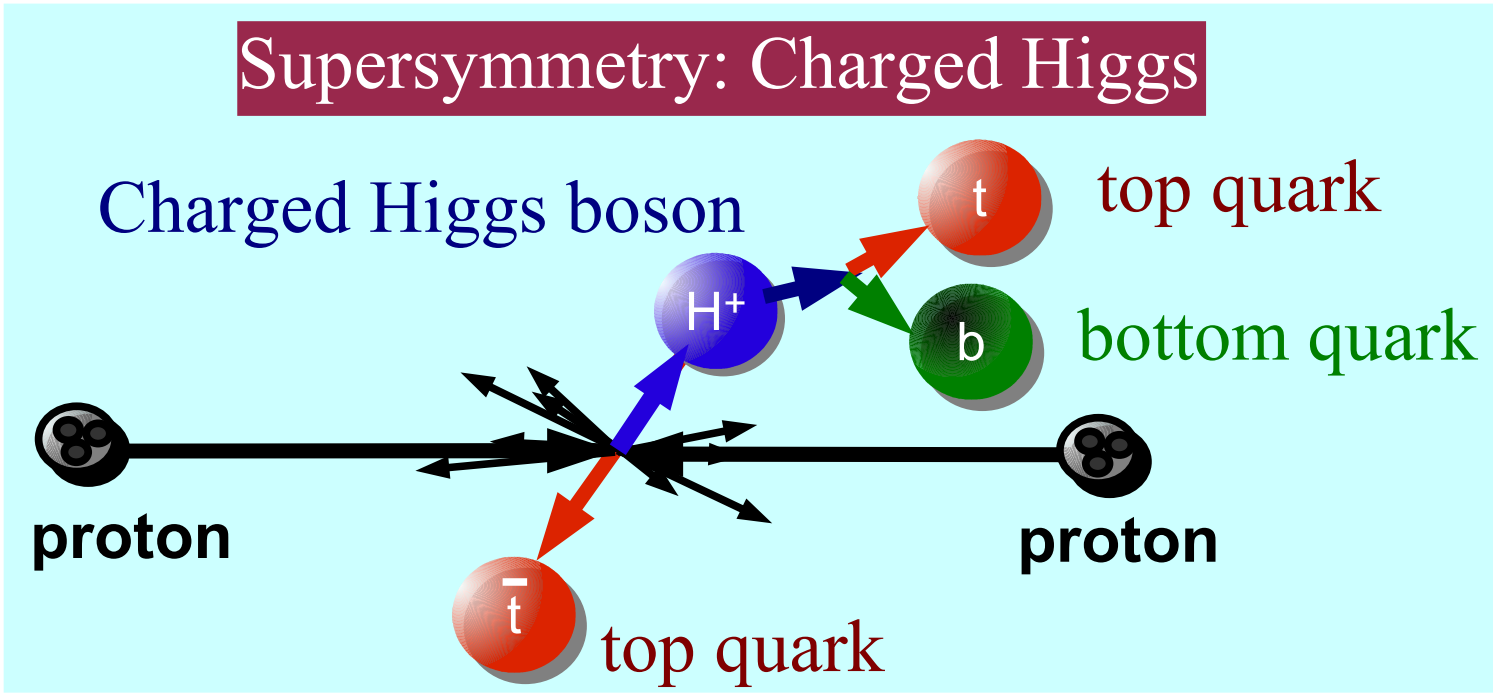
- Dominant production modes:





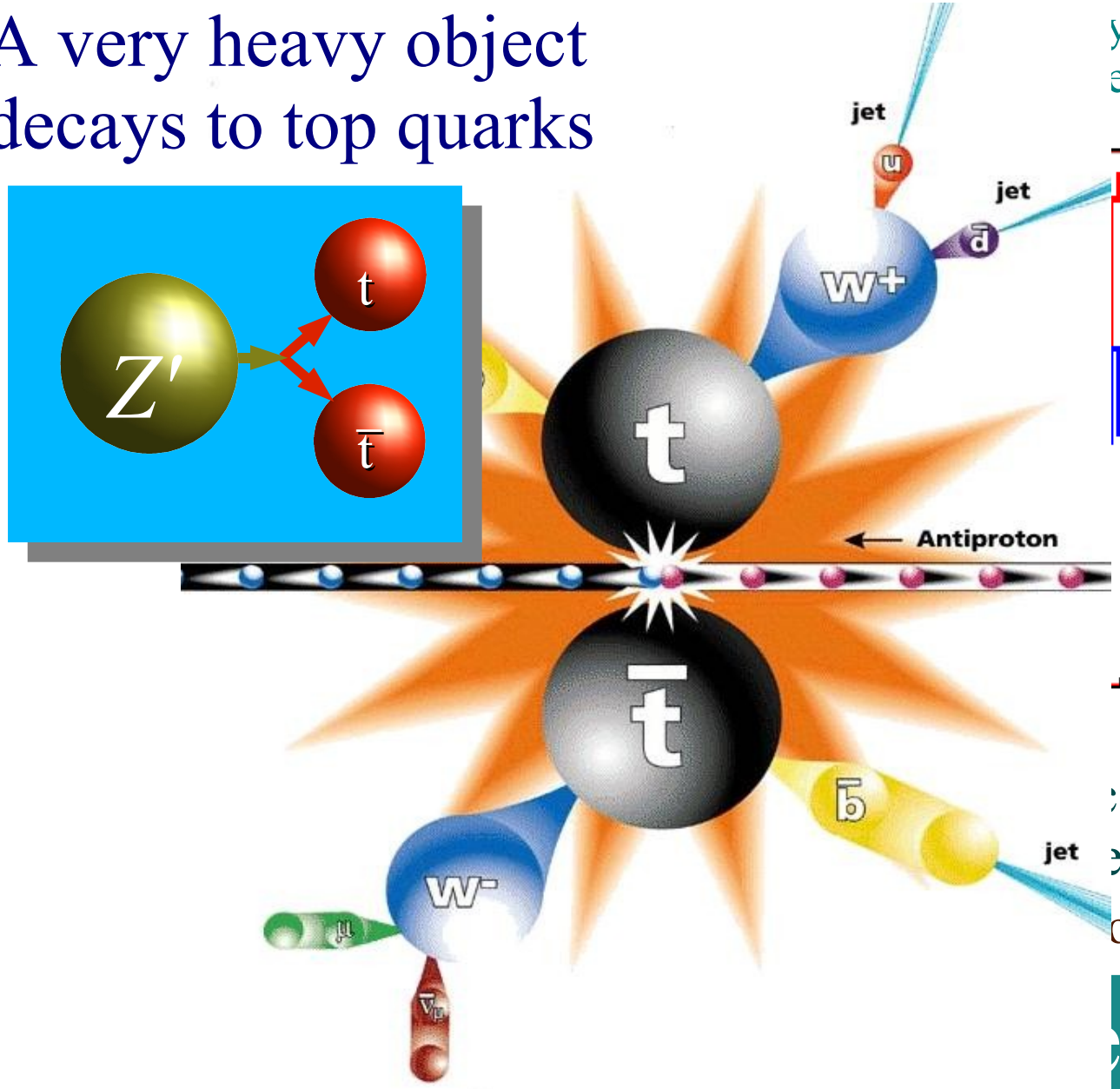
Top as the gateway to Higgs



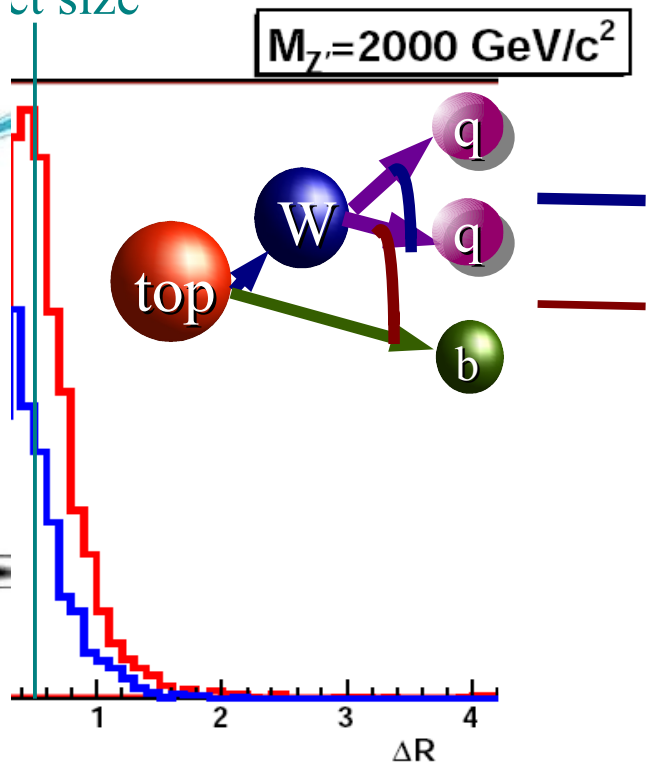


New challenges

- A very heavy object decays to top quarks



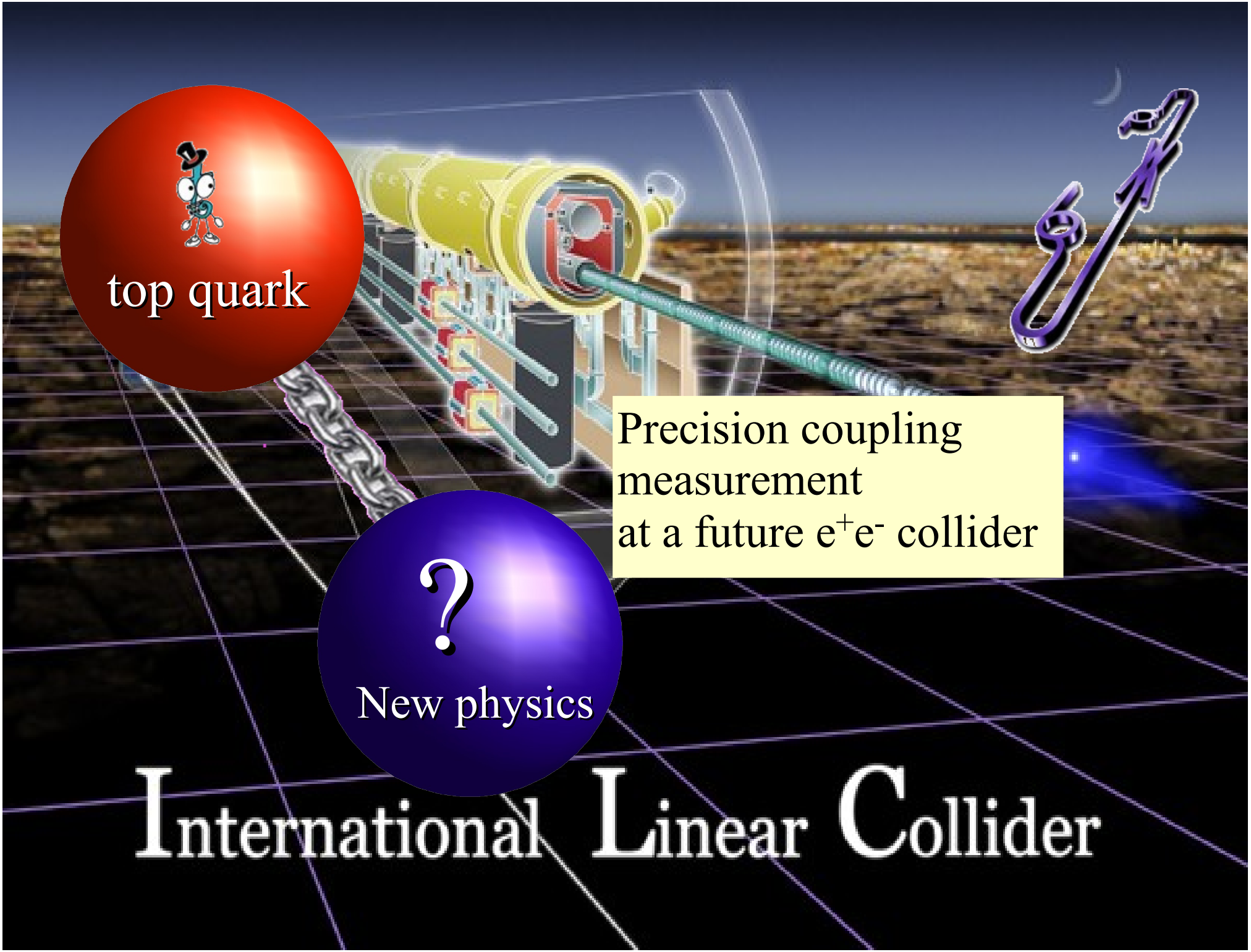
ypical quark
et size



ay products merge
et

onstruct them?

ts


top quark
?
New physics
Precision coupling
measurement
at a future e^+e^- collider
International Linear Collider

Conclusions

- We are about to find answers to two key questions:
  - Origin of the mass of the W boson?
  - Origin of fermion masses?
- The top quark is the key to understanding both
  - We are currently measuring mass, properties, couplings
- This is just the beginning
  - Tevatron will collect 5 times more data
  - LHC is just around the corner

We are close to revealing what holds the world together in its inmost folds

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, Tom Lecompte
- 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