Single Top Quark Physics

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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
- Search for Single Top Quark Production
- Outlook
- Conclusions

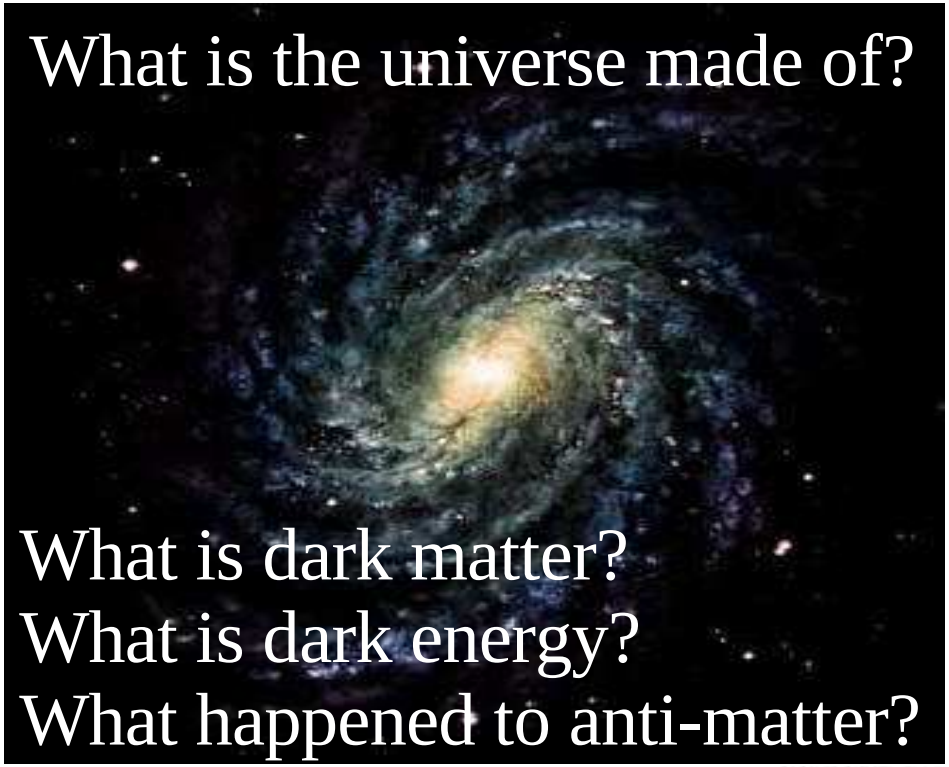
- Simplified units:
  c = 1
  - Energy, momentum, mass in GeV

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

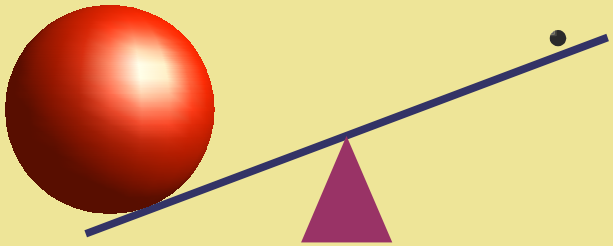
A fundamental question

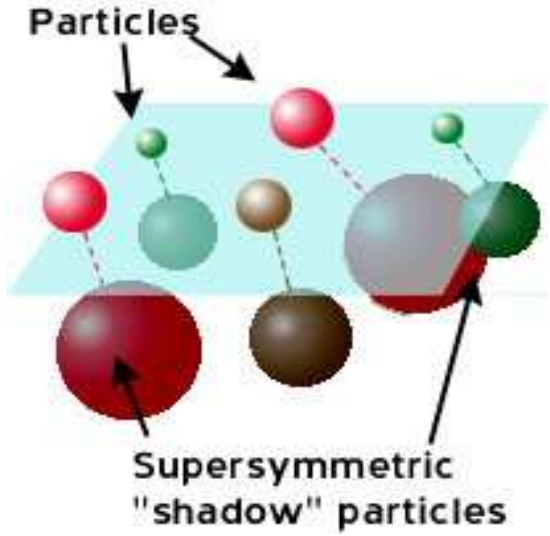
What is the origin of matter?

What is the origin of matter?



What makes quarks so heavy and neutrinos so light?





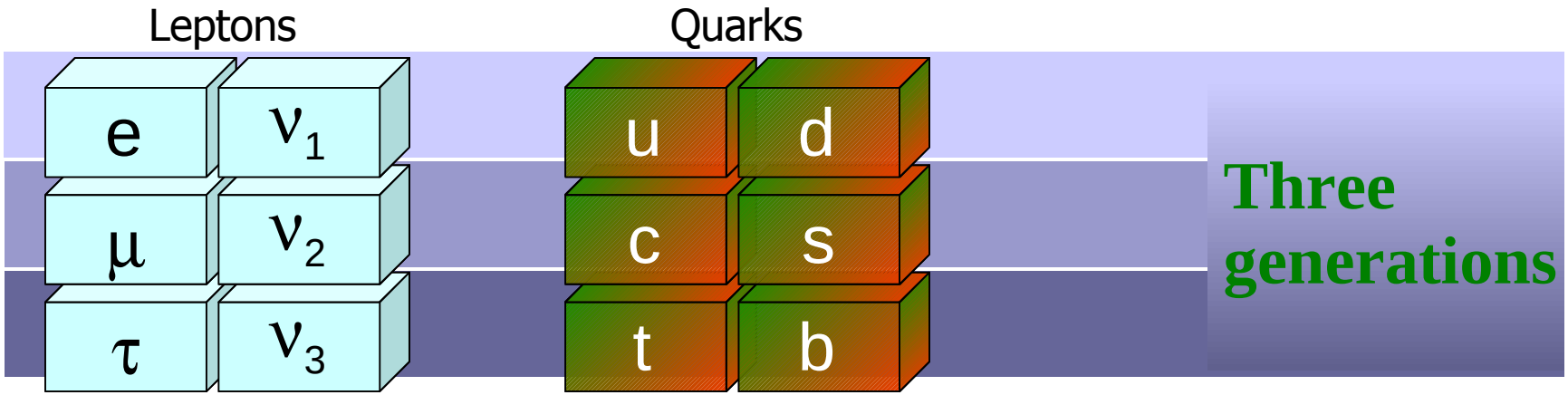
Supersymmetry? Extra spatial dimensions? ...

State of the art

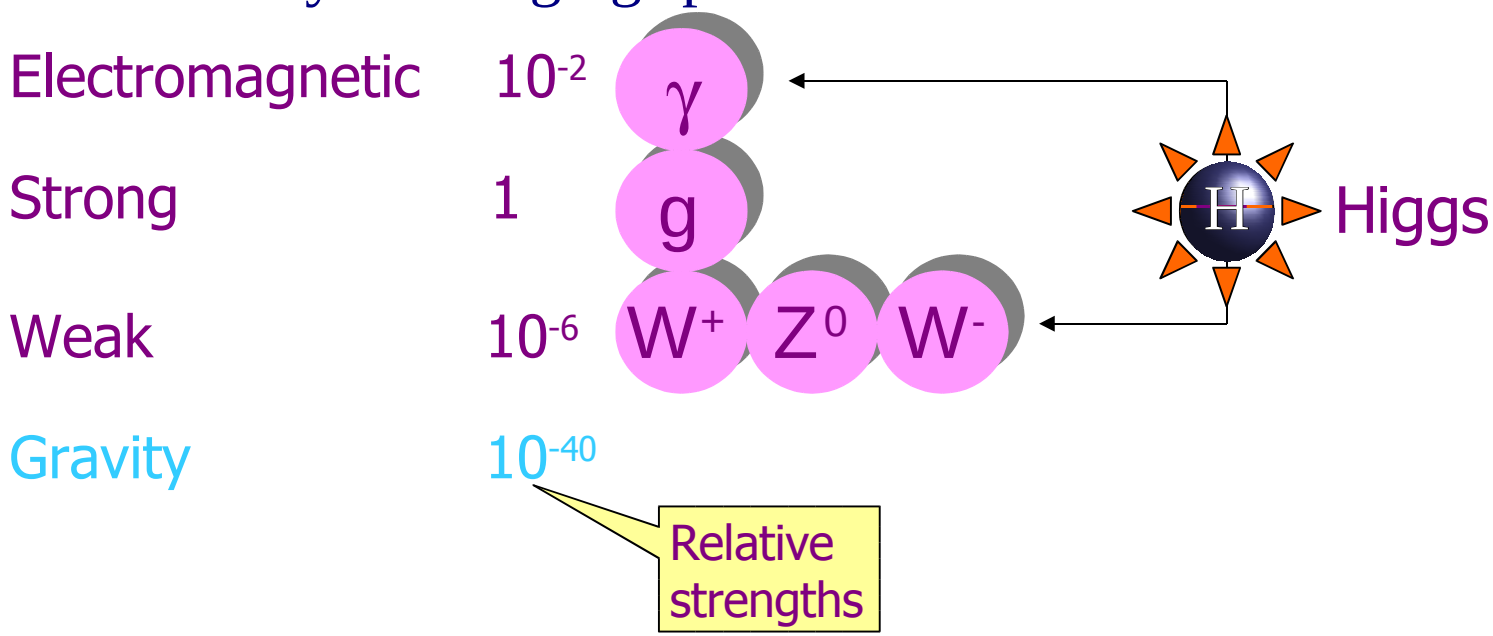
What do we know already?

Standard model of particles and forces

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

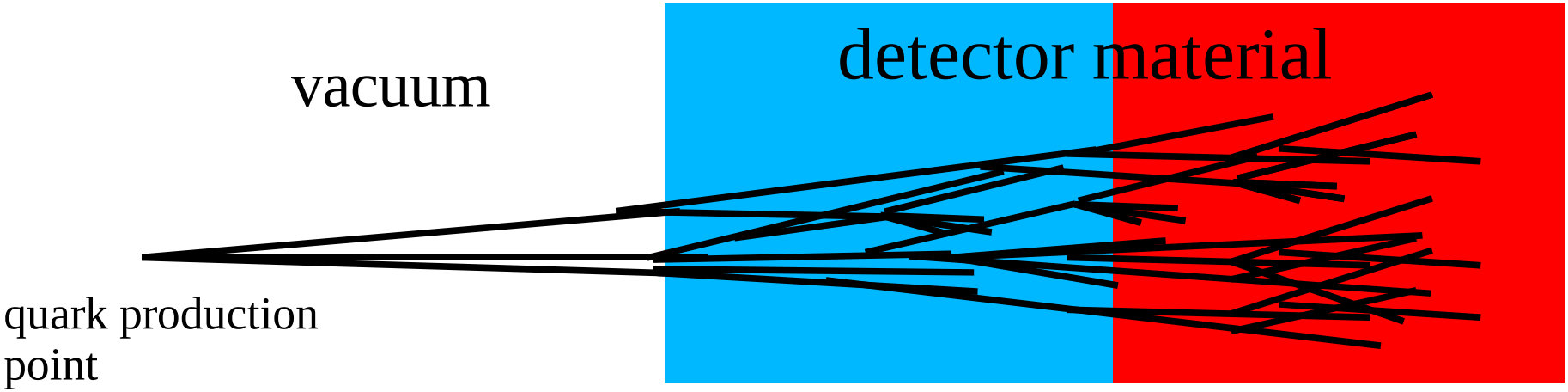


- Which interact by exchanging spin-1 vector bosons



The first two generations 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 → <u>hadronic jet</u>

Quark jet produces a hadronic shower through interactions with nuclei

Detecting quark-jets is a standard tool at the energy frontier

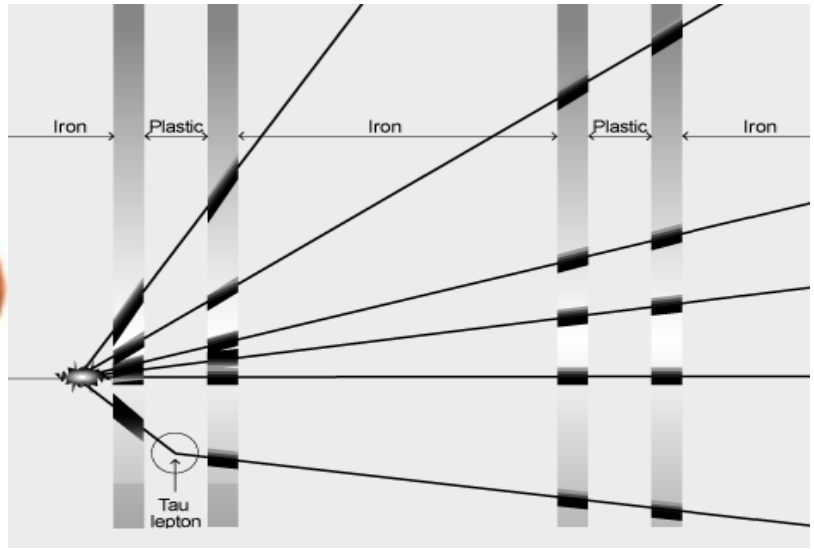
The third generation

Tau lepton

Discovered 1975 at SLAC

Tau neutrino

Discovered 2000 at Fermilab



bottom quark

Discovered 1978 at Fermilab

top quark

Discovered 1995 at Fermilab

Gauge boson masses in the SM

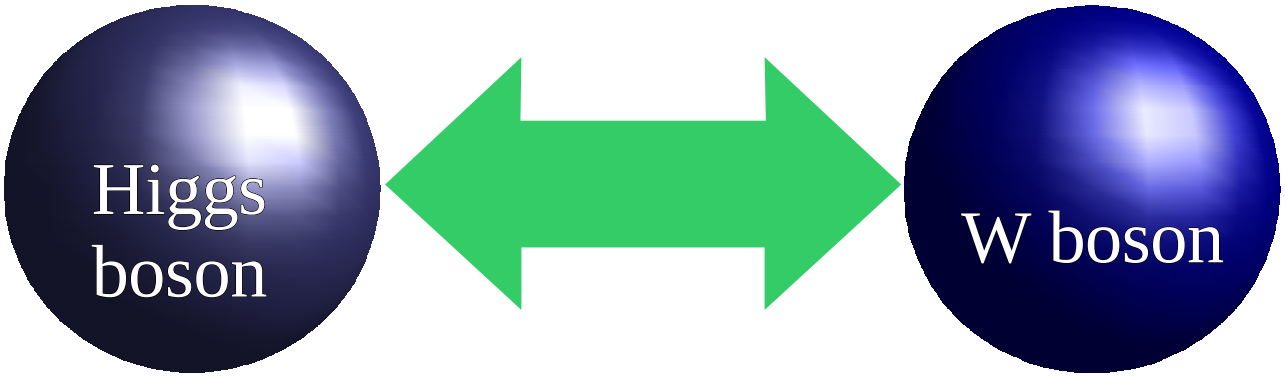
Gauge bosons

Higgs field

Electroweak symmetry breaking

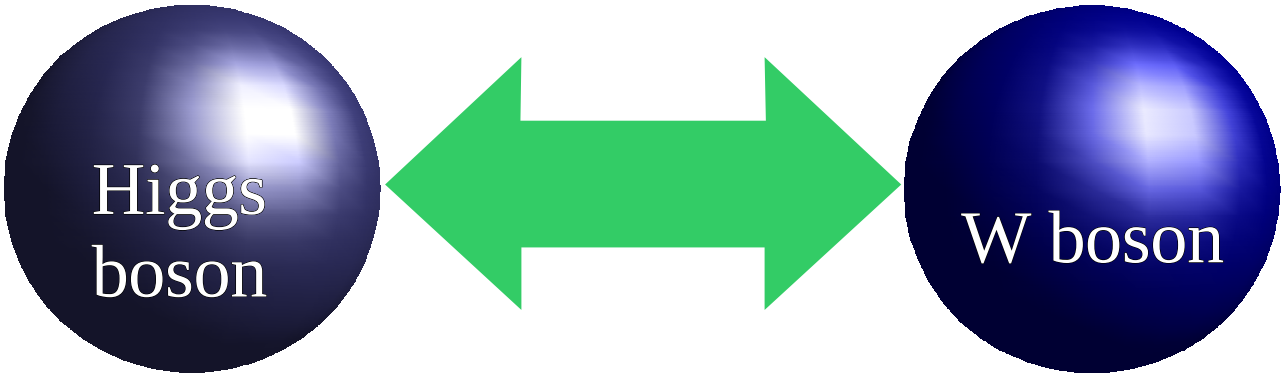
Electroweak symmetry breaking

Gauge boson coupling to Higgs field

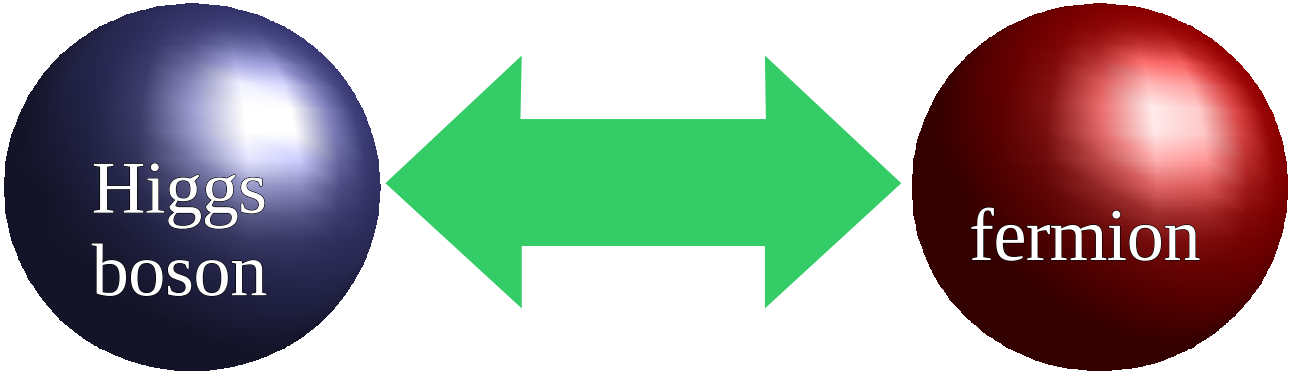


Electroweak symmetry breaking

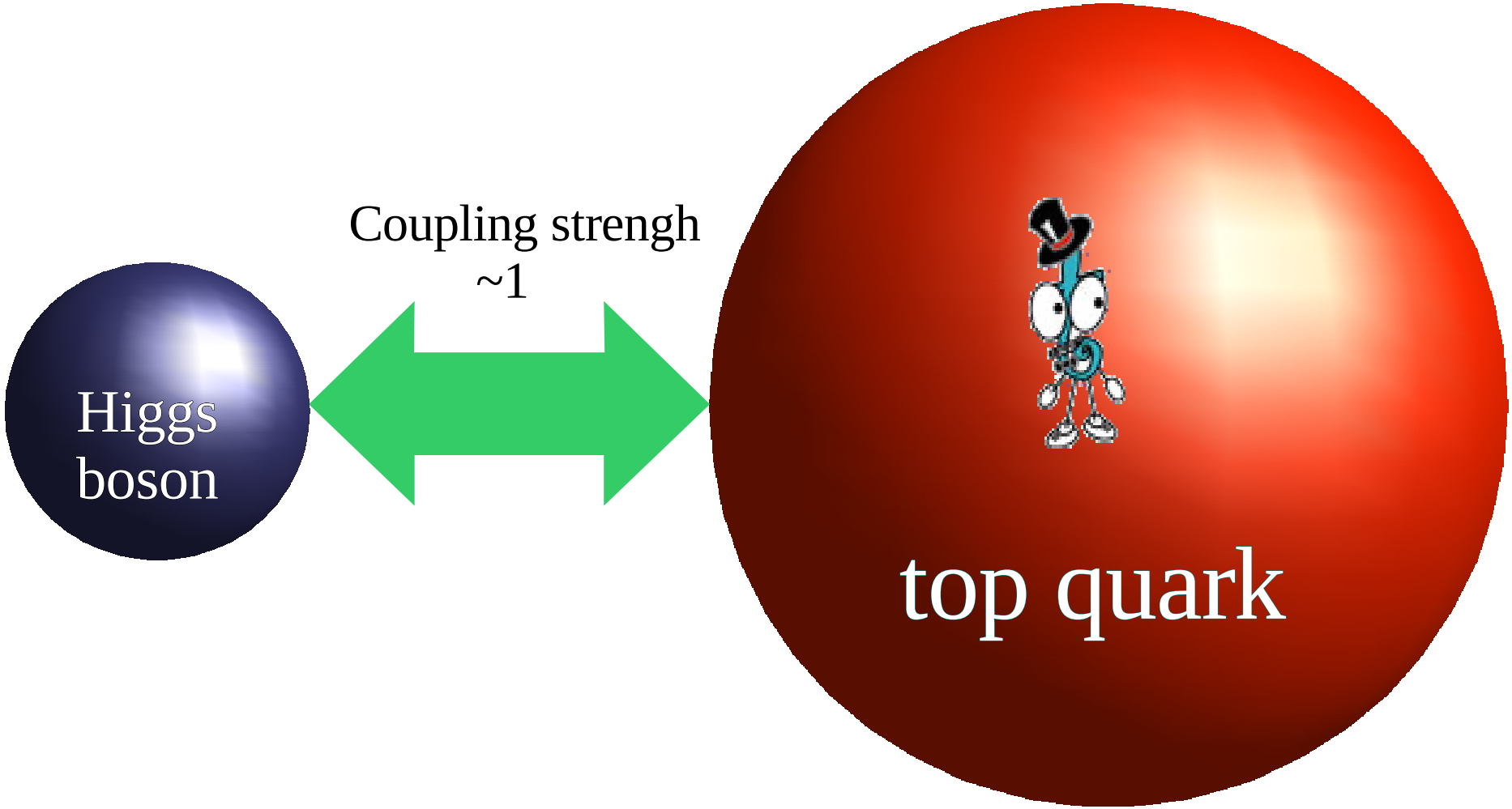
Gauge boson coupling to Higgs field



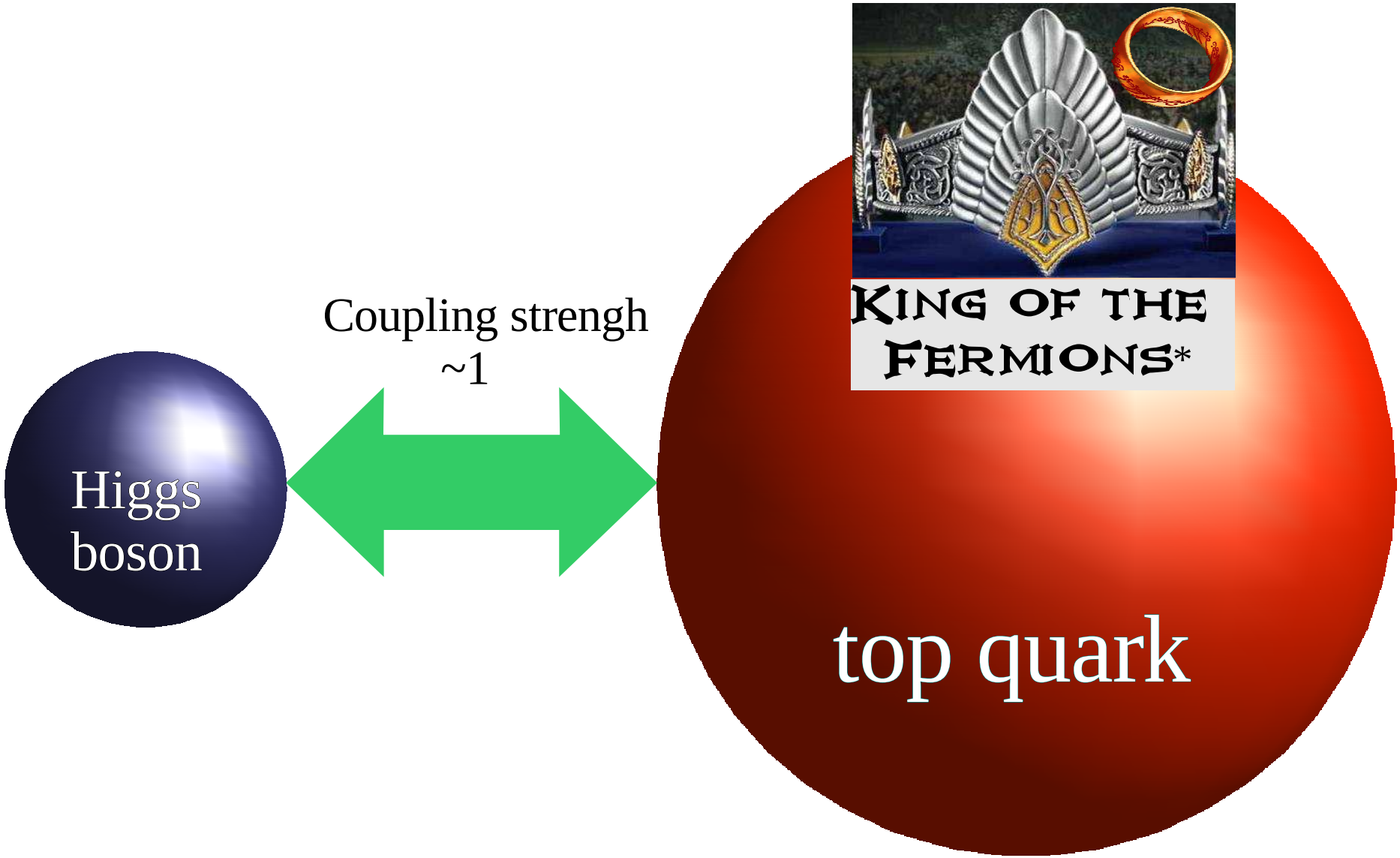
Fermions acquire mass through Higgs coupling



Top quark mass



Top quark mass



*: according to Tim Tait

PHYSICAL REVIEW LETTERS

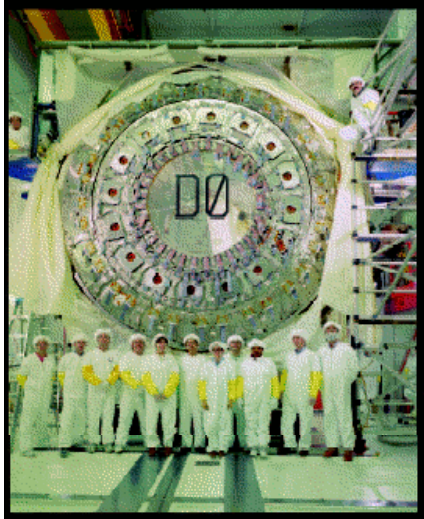
Observation of the Top Quark

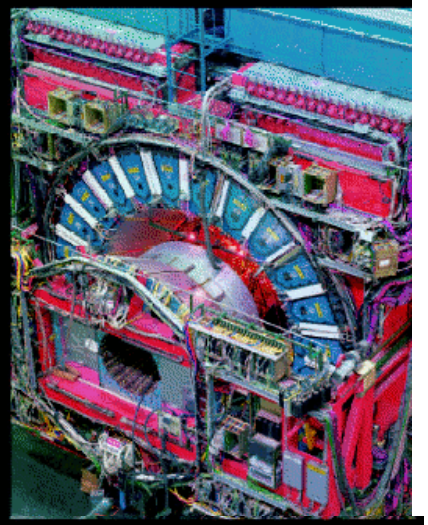
PHYSICAL REVIEW LETTERS

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





top quark

news release
fermi national accelerator laboratory

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

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NEWS MEDIA CONTACTS:
Judy Jackson, 708/840-4112 (Fermilab)
Gary Pachford, 708/252-3315 (DØ)
Jeff Sherwood, 708/586-5306 (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 unsuspected 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 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
- Electroweak interactions
  - Charged current (W boson)
    - Total width
    - CKM matrix
  - Neutral current (Z boson)

Really don't know:

- Coupling to Higgs?
- Modified weak coupling?
- SUSY? New physics?

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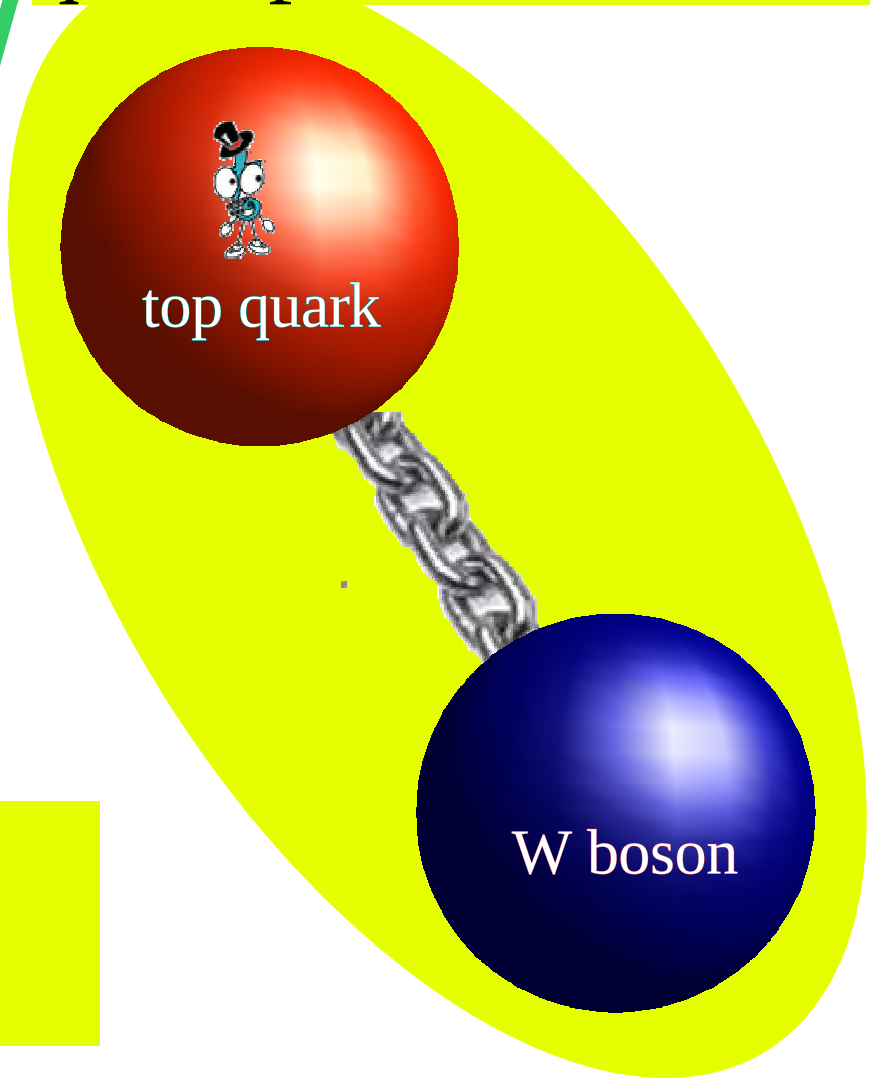
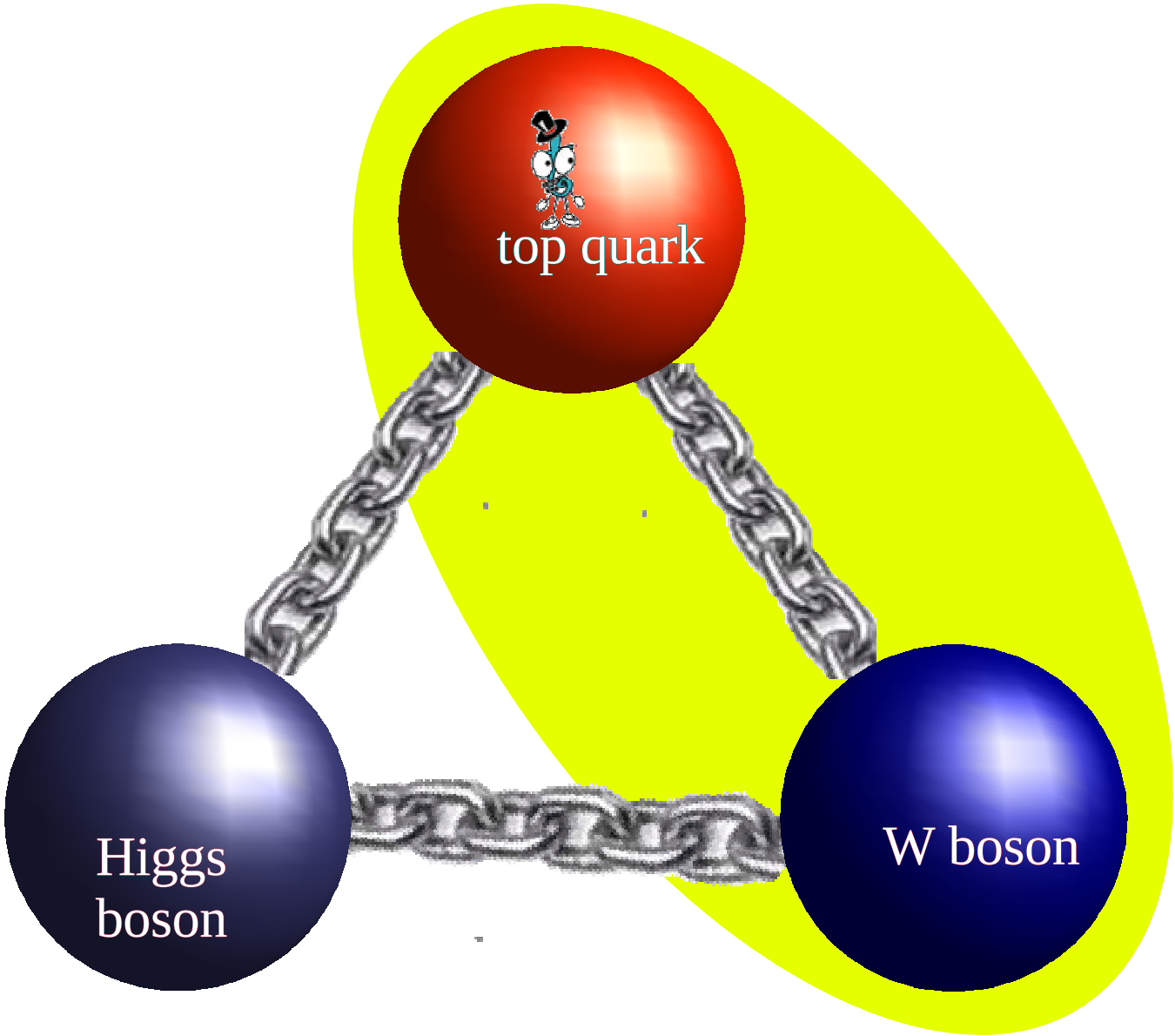
Study in single top quark production



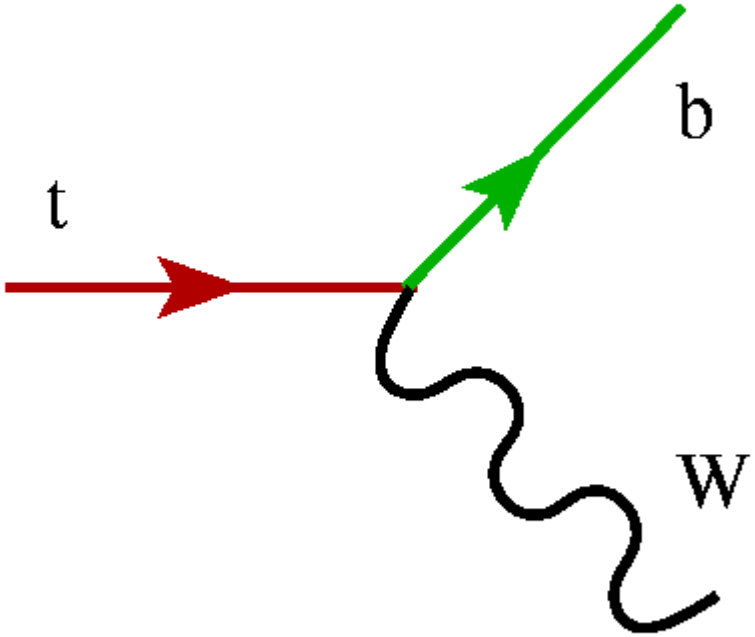
Really don't know:

- Coupling to Higgs?
- Modified weak coupling?
- SUSY? New physics?

Key to electroweak symmetry breaking



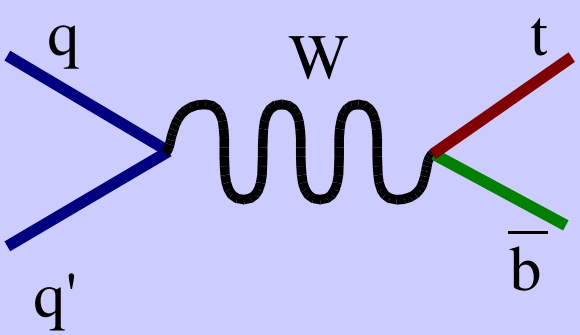
Top quark electroweak charged current interaction



top quark decay

SM single top quark production

s-channel



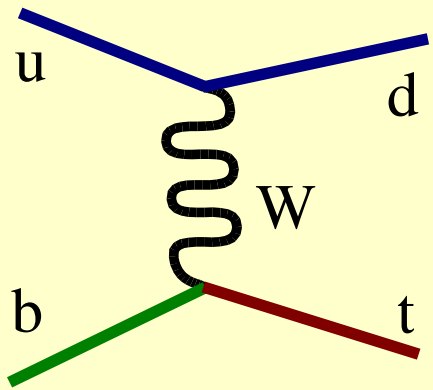
σ_{NLO}

TeV: 0.88 pb

LHC, t: 6.6 pb

LHC, $\bar{t}$: 4.1 pb

t-channel



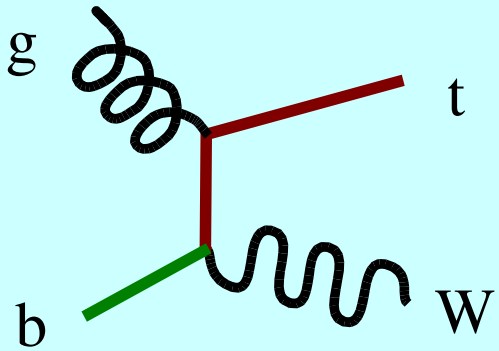
σ_{NLO}

1.98pb

156 pb

91 pb

Associated production



σ_{NLO}

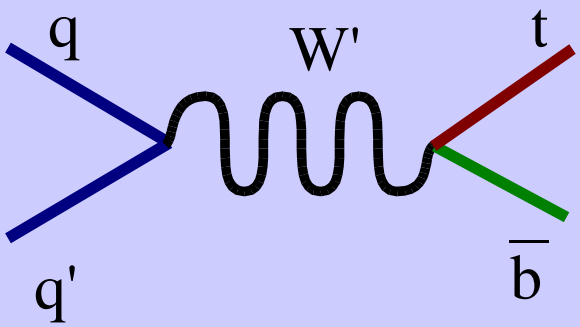
0.14 pb

34 pb

34 pb

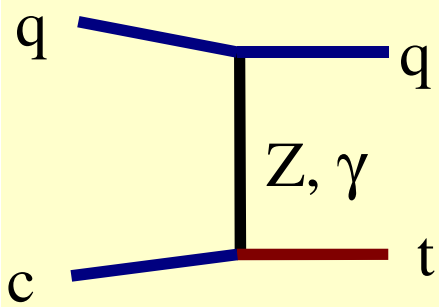
New physics

s-channel



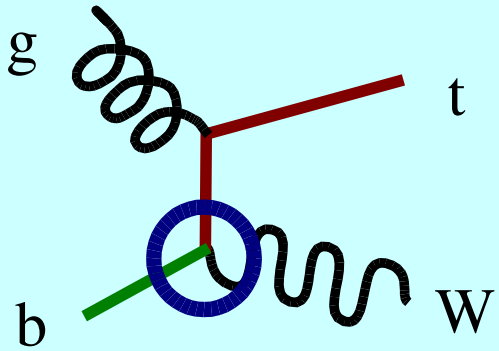
New heavy boson

t-channel



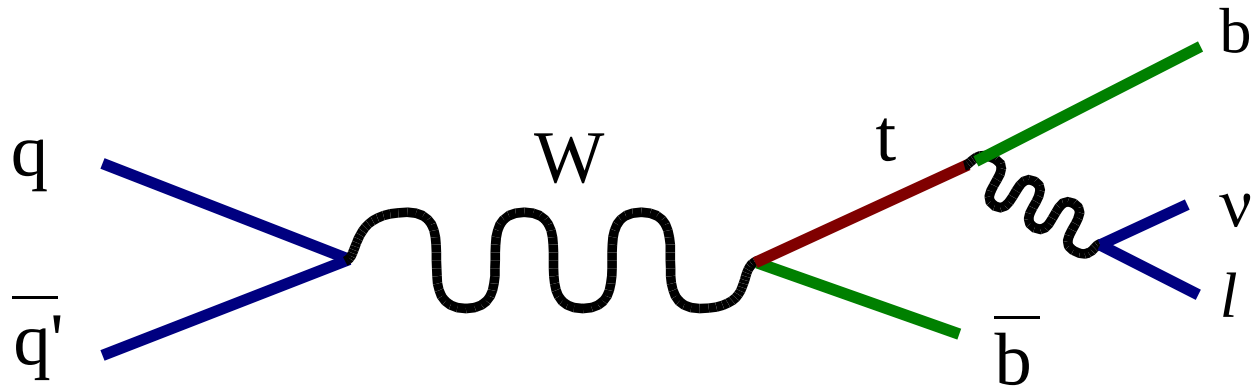
Flavor Changing Neutral Current

Associated production

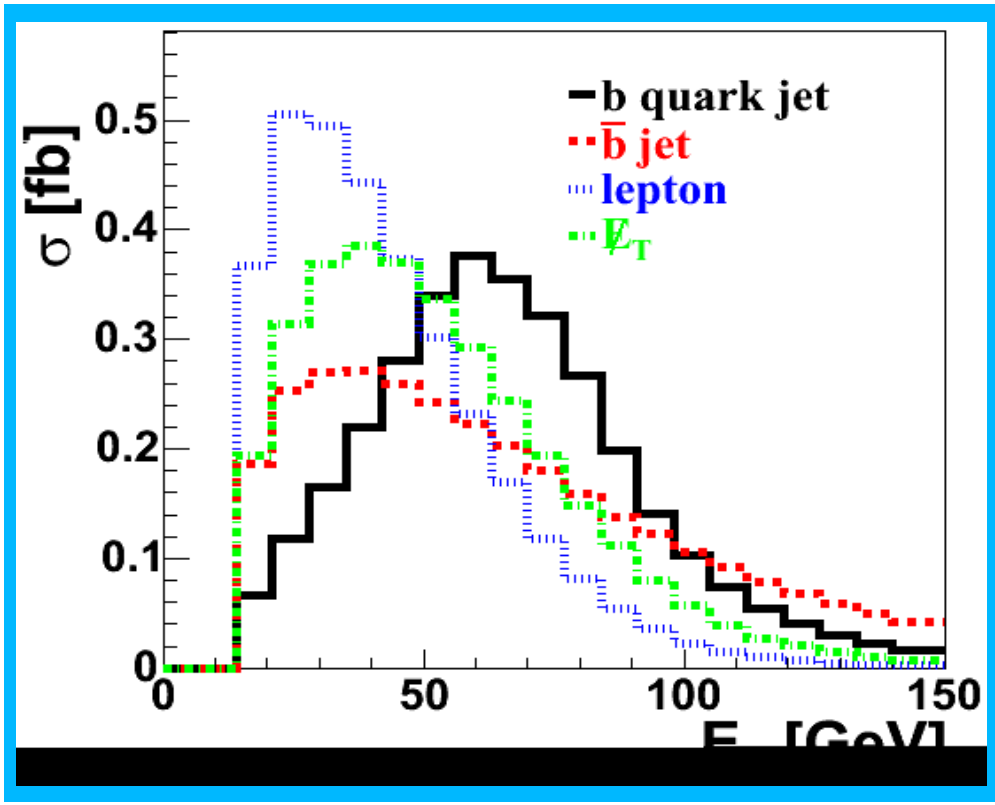


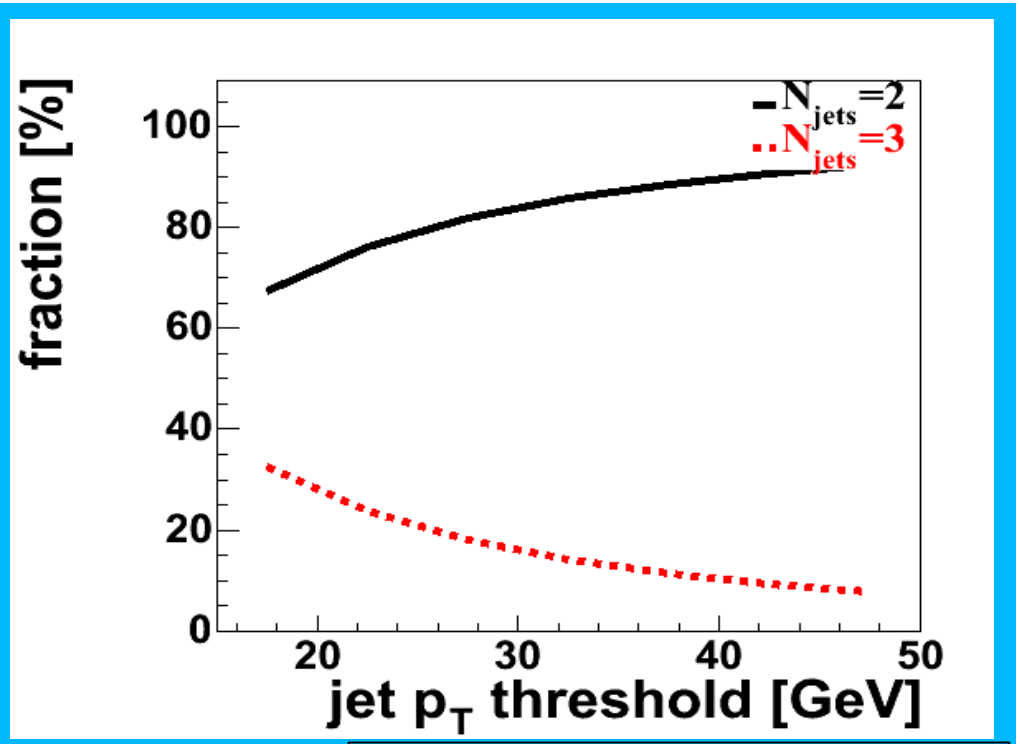
Modified Wtb coupling

Tevatron s-channel signature



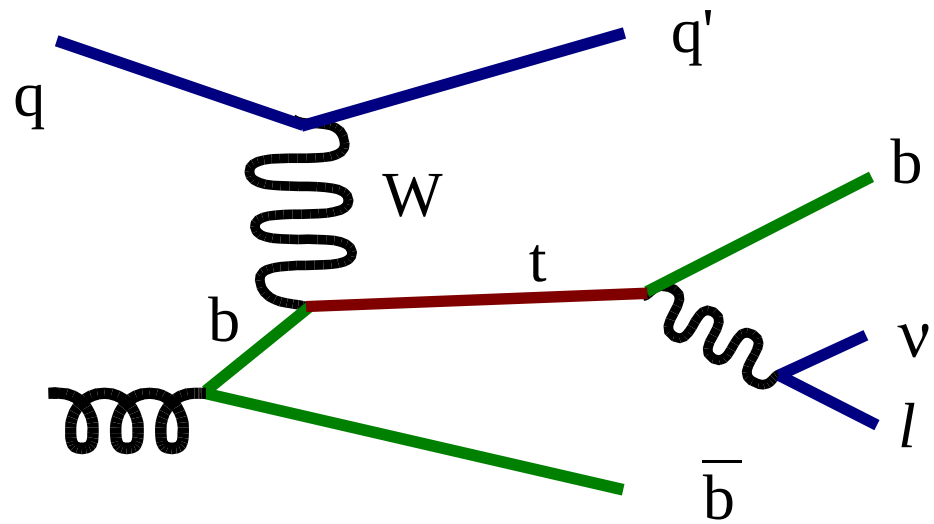
"*tb*"



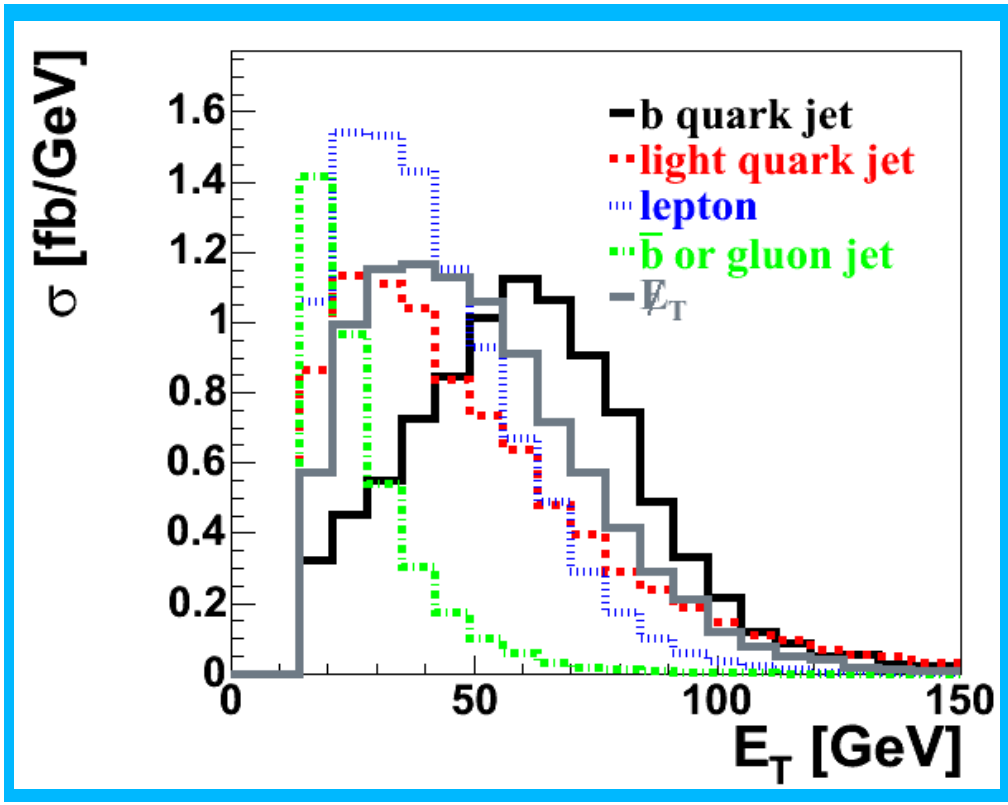


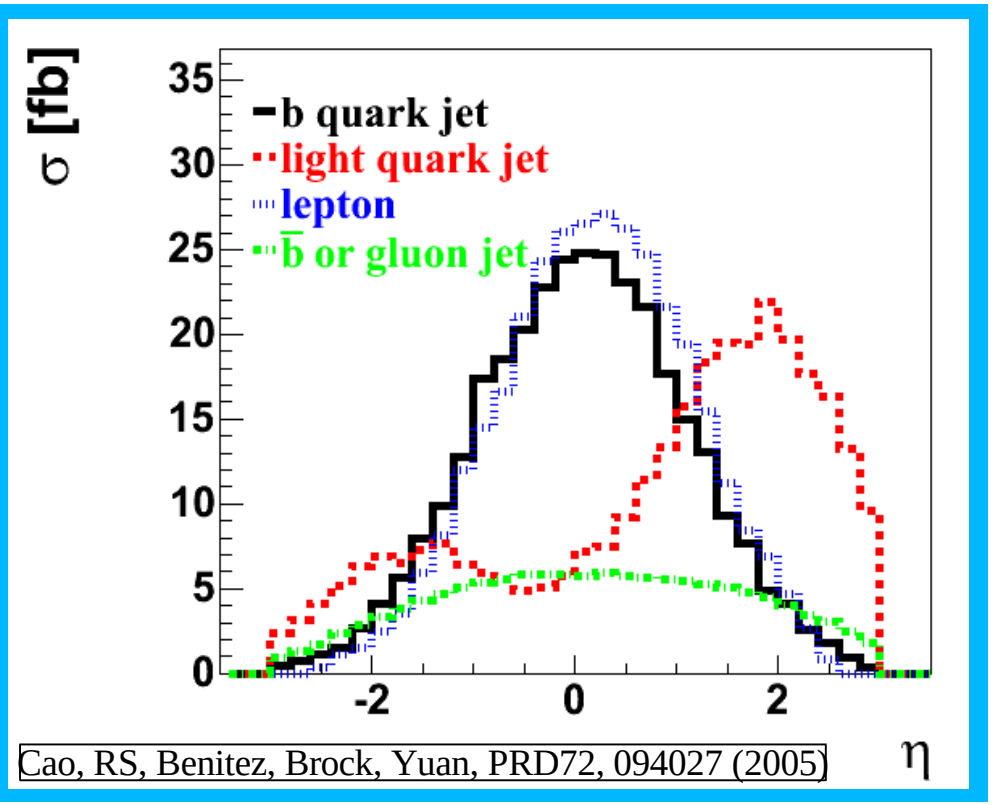
Cao, RS, Yuan PRD71, 054023 (2005)

Tevatron t-channel signature



"tqb"





Cao, RS, Benitez, Brock, Yuan, PRD72, 094027 (2005)

Tevatron single top goals

Production cross sections:	*s-channel*	*t-channel*	*s+t*
NLO calculation:	**0.88pb (±8%)**	**1.98pb (±11%)**	
Run I 95% CL limits, DØ:	< 17pb	< 22pb	
CDF:	< 18pb	< 13pb	< 14pb

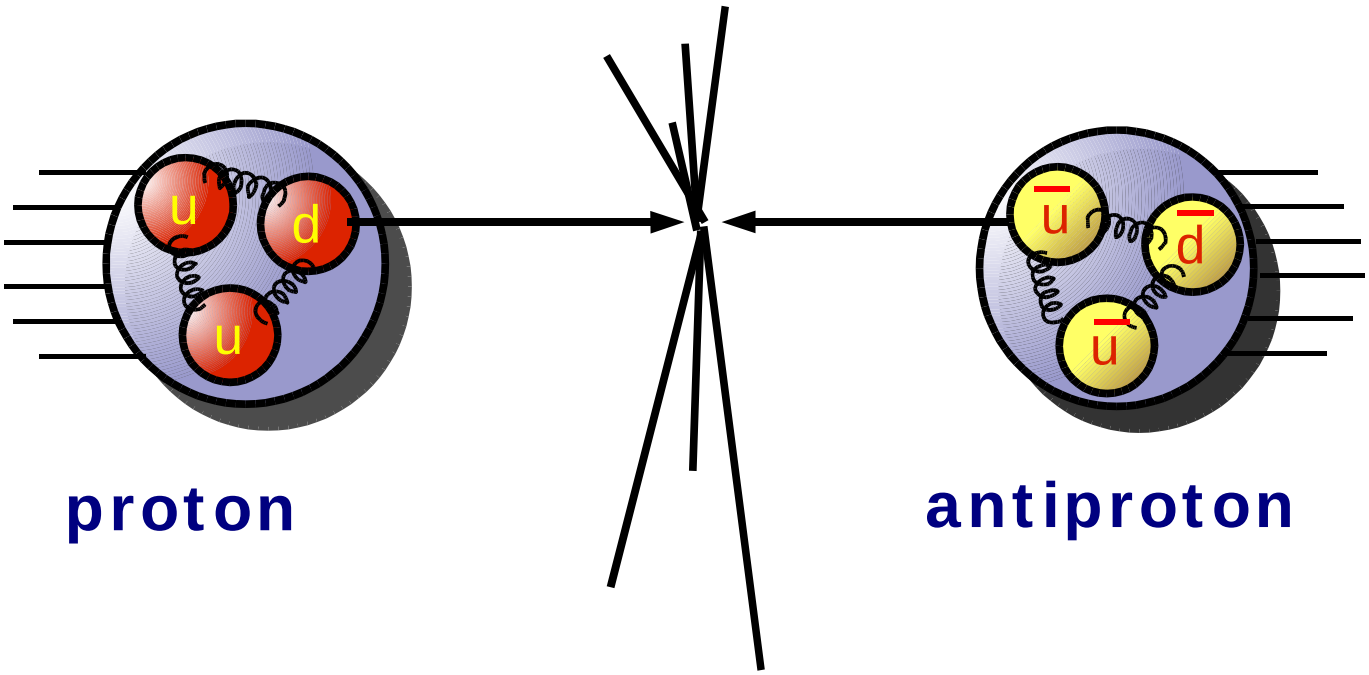
- Observe single top quark production
  - Tevatron discovery!
- Measure production cross sections
  $\rightarrow$ CKM quark mixing matrix element V_{tb}
- Look for physics beyond the standard model
  - Coupled to the heavy top quark
- Study top quark spin correlations
- Understand as background to many searches

Experimental procedure

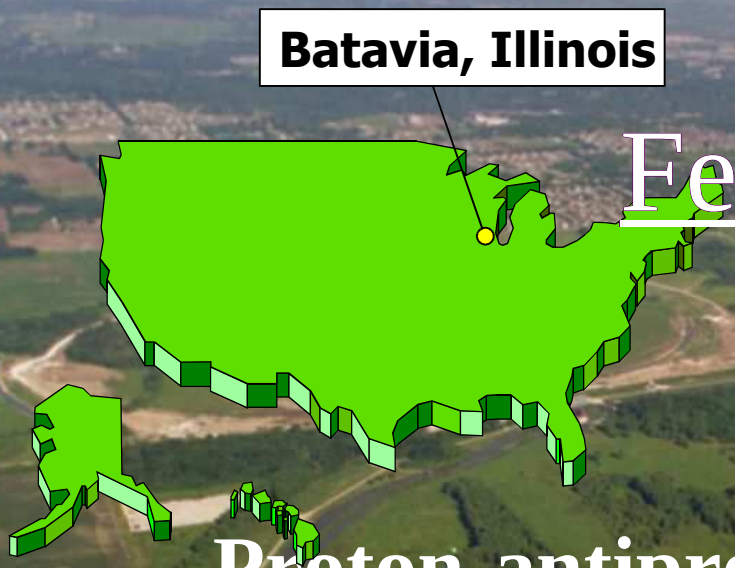
How do we find out?

The energy frontier

Probe physics at small distances
by colliding particles at high energy



Experimental setup: Fermilab Tevatron in Run II



Proton-antiproton collider

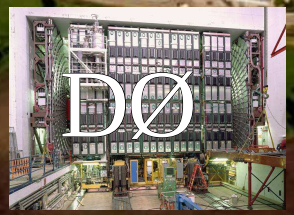
CM energy 1.96TeV

→ ***Energy frontier***

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

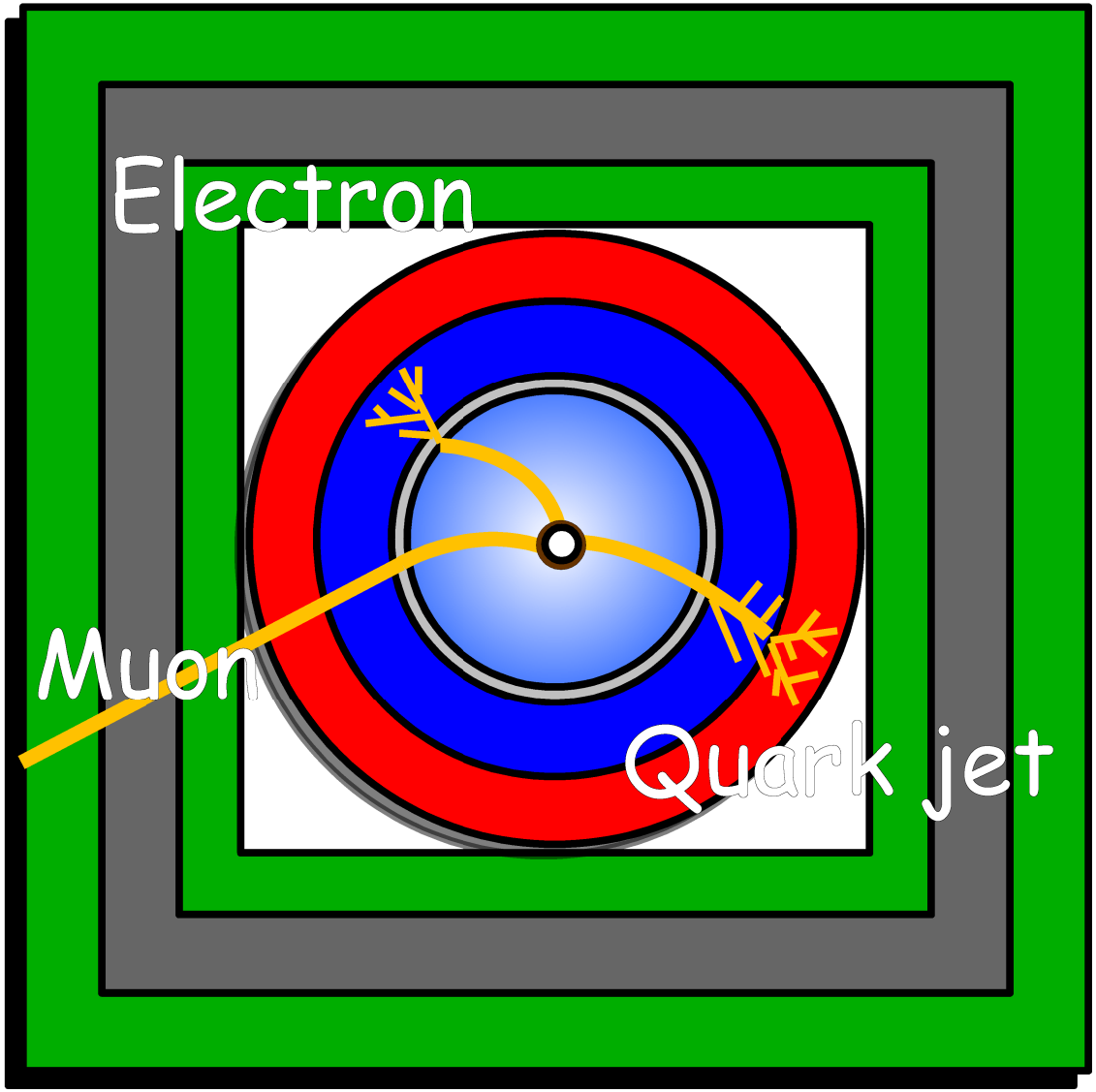
– ~3 interactions per crossing, 1.7M crossing per second

→ ***Luminosity frontier***

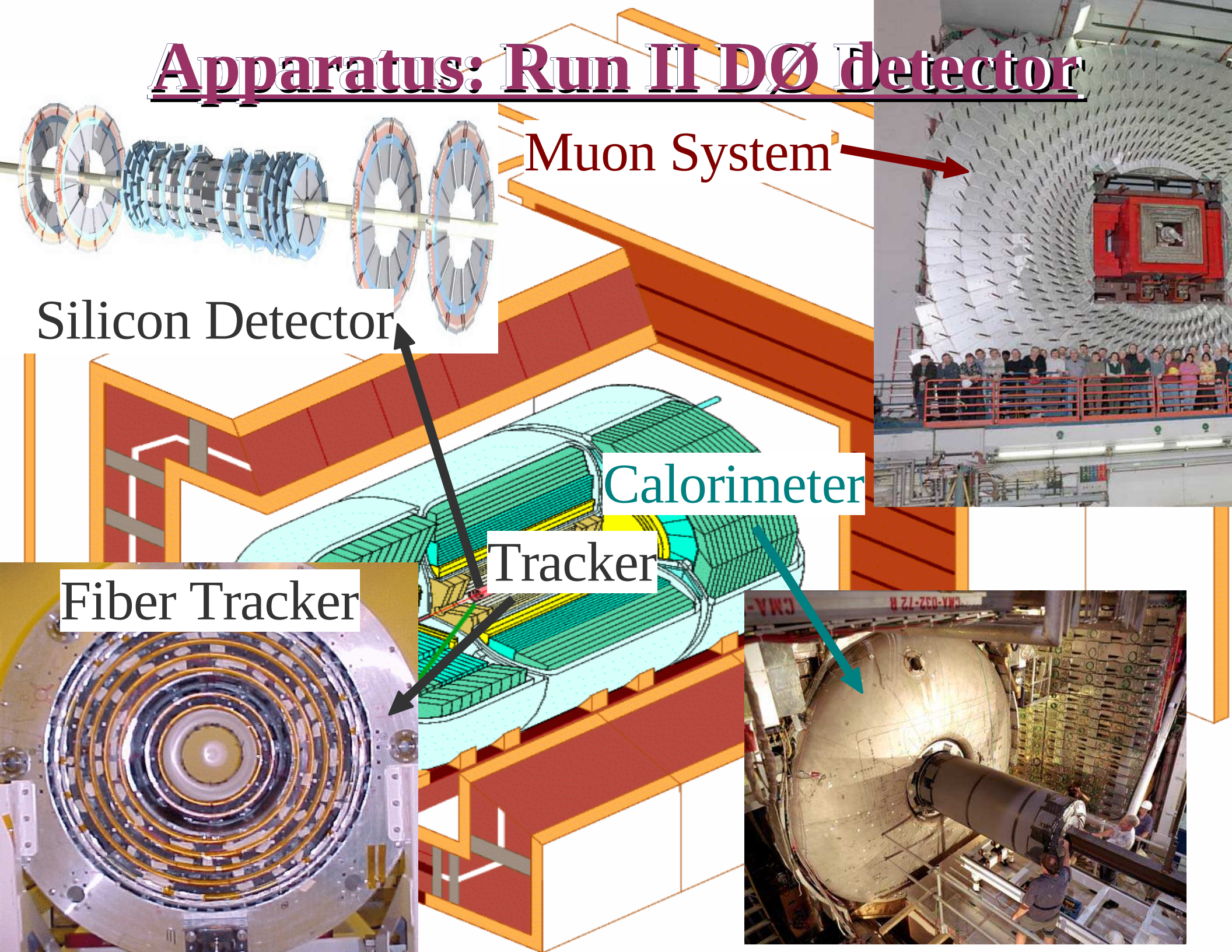


Experimental setup: detector configuration

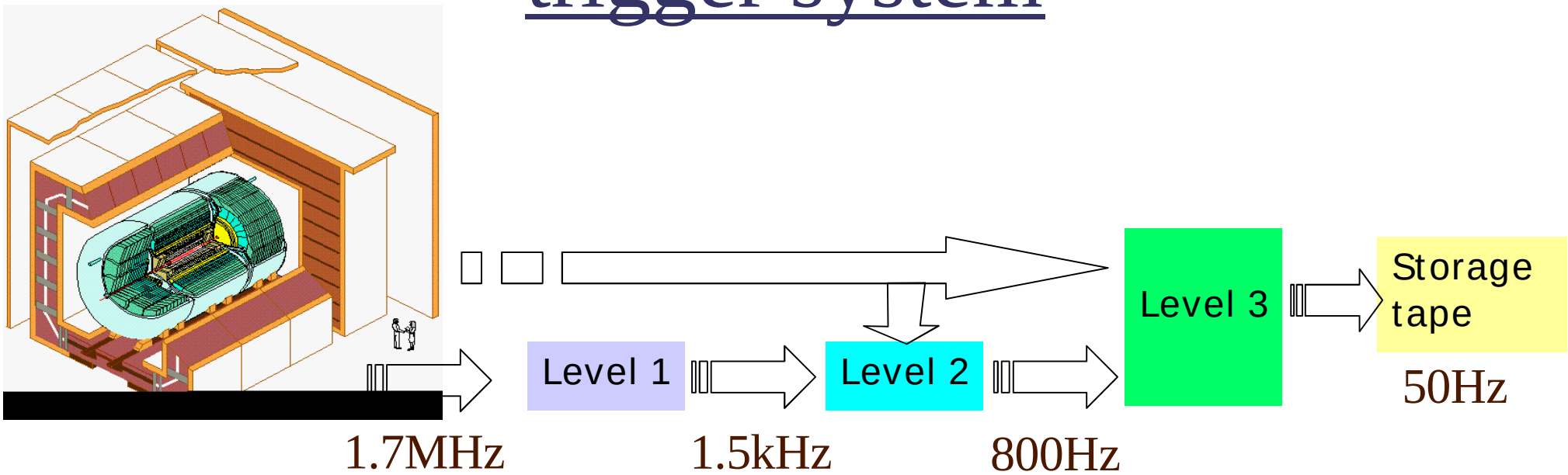
- Beam pipe
- Tracking detector
- Magnet
- EM calorimeter
- Hadronic calorimeter
- Muon detectors
- Magnet



Apparatus: Run II DØ detector



Collecting interesting events: trigger system

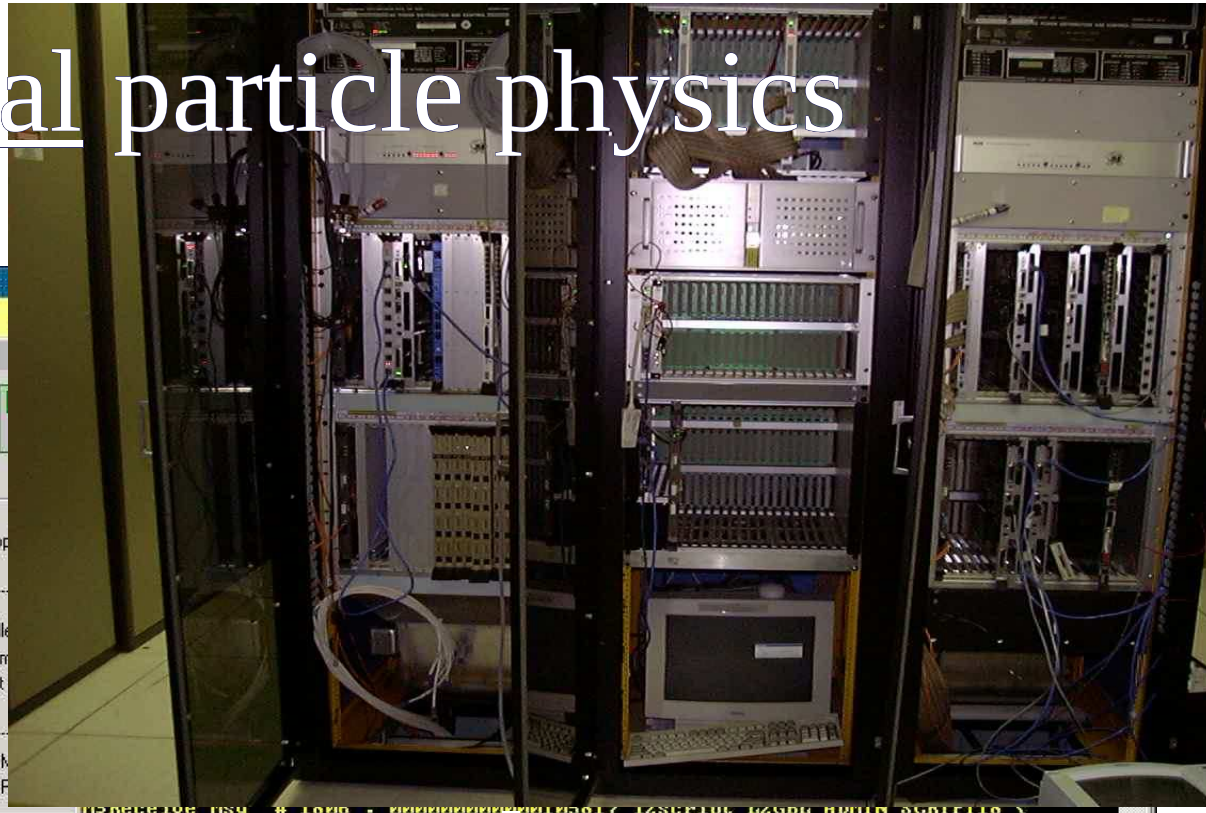


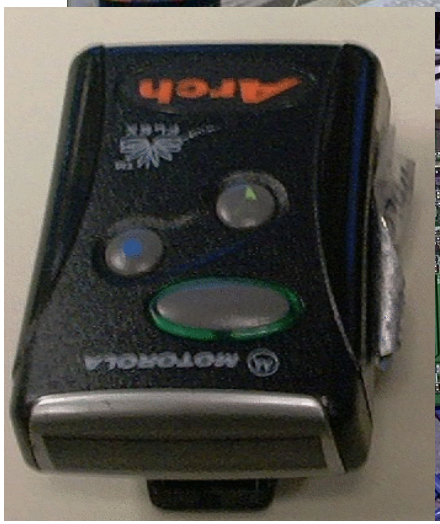
- Reduce rate of interactions (inelastic collision rate) to manageable level that can be stored
- Record "interesting" events → trigger system
  - Select events containing high-energy final state objects
    - Electrons, muons, quark jets

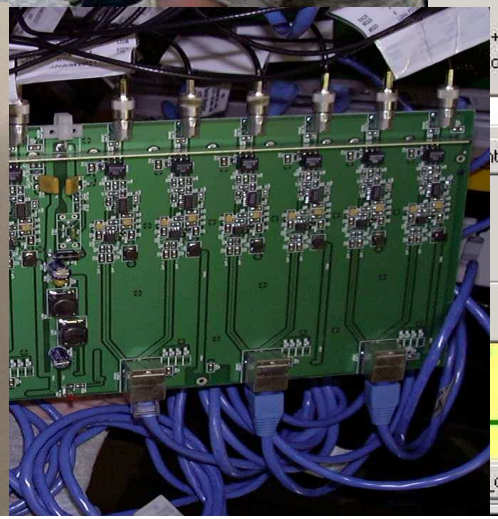
Experimenters

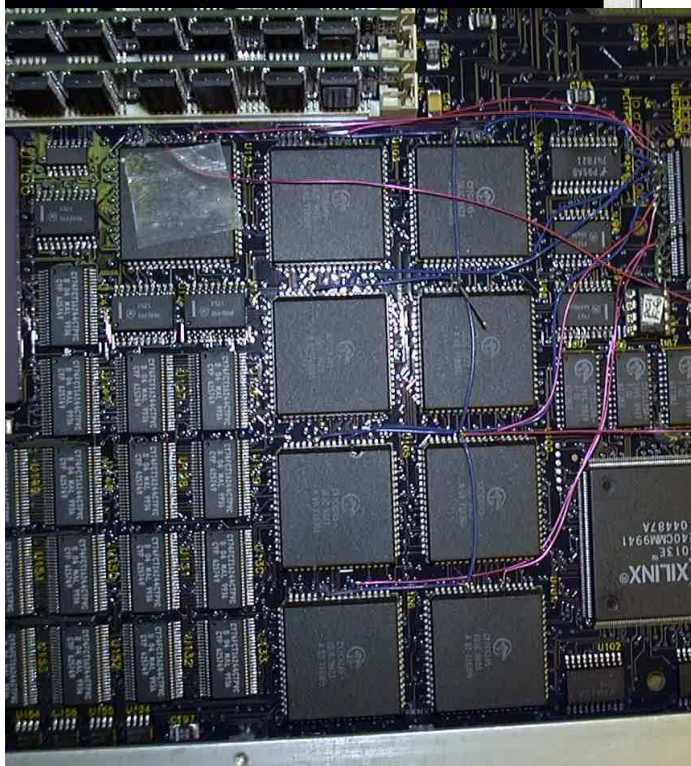
- **19 countries**
- **80 institutions**
- **670 physicists**

Experimental particle physics





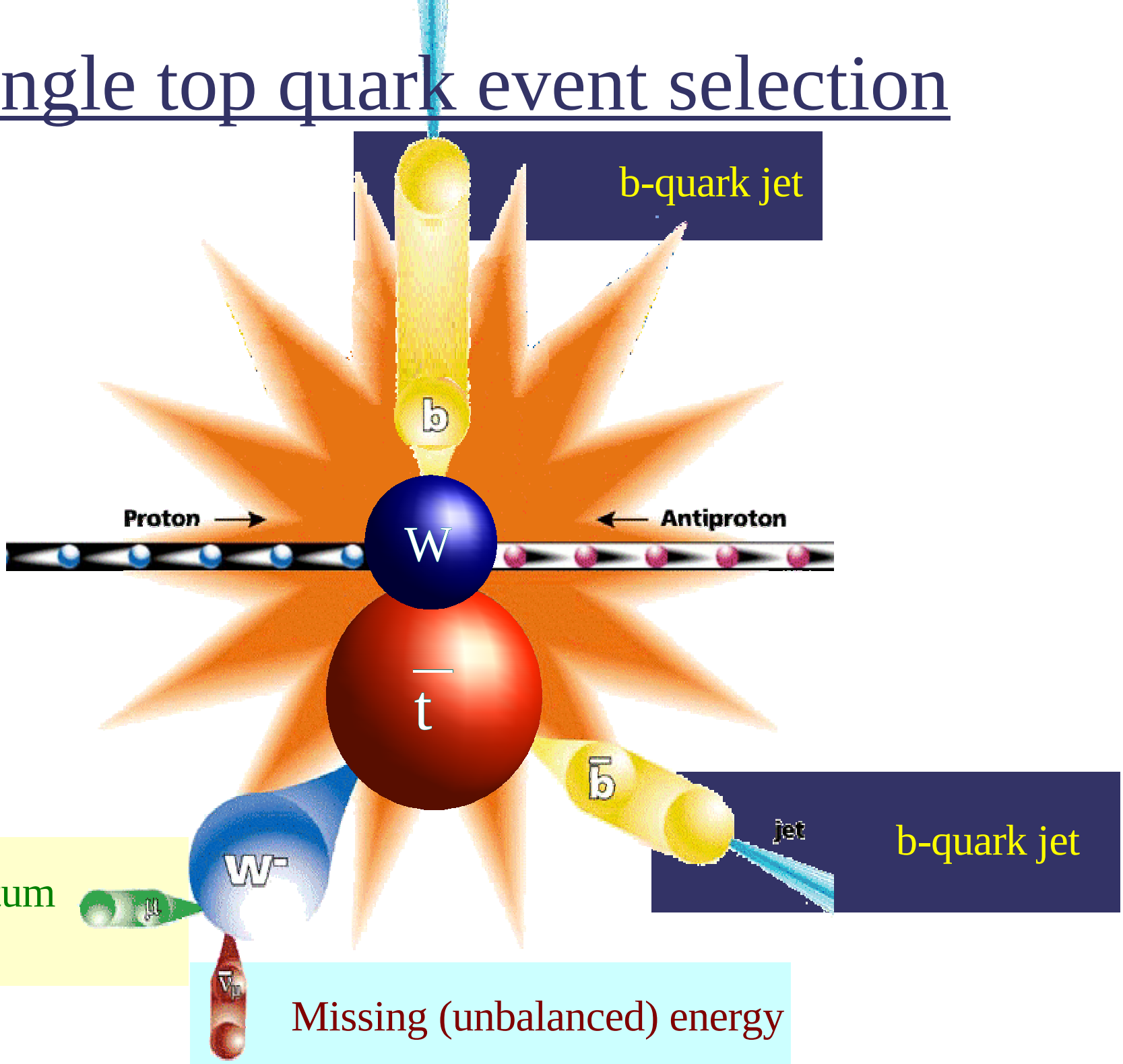




Current Results

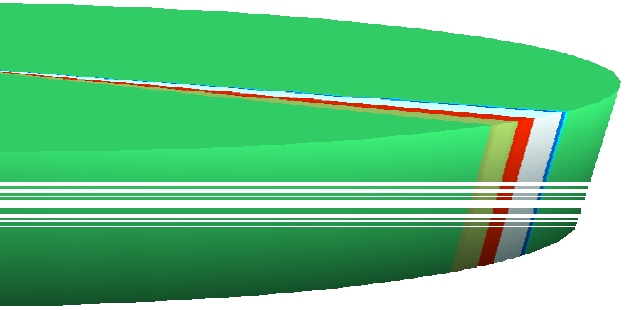
Precious data!

Single top quark event selection

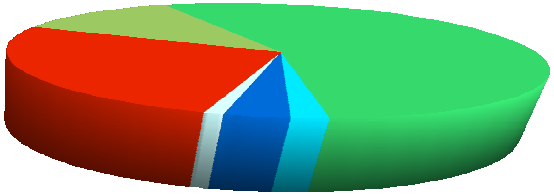


Single top quark events in data (230pb^{-1})

All:
10,000 events



=1 b-tag:
367 events

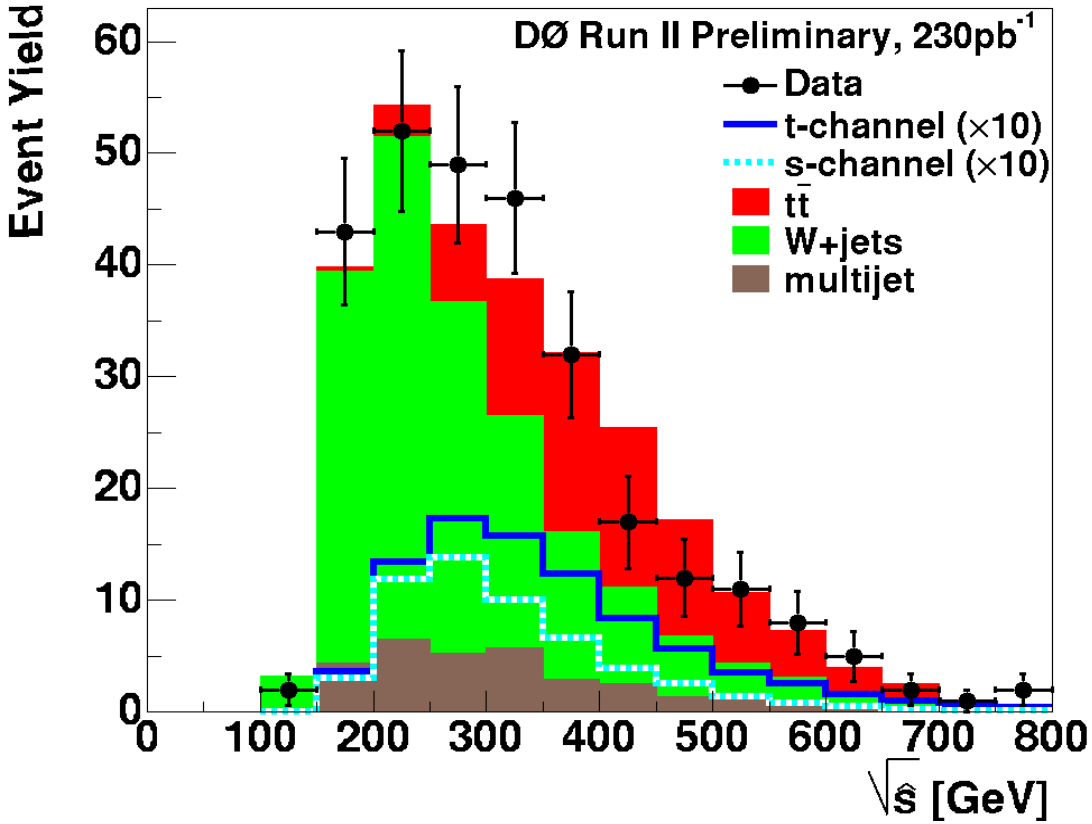


=2 b-tags:
76 events

Top quark pairs

Other Backgrounds

Single top



Separating Signal from Backgrounds

- Optimized event analysis

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

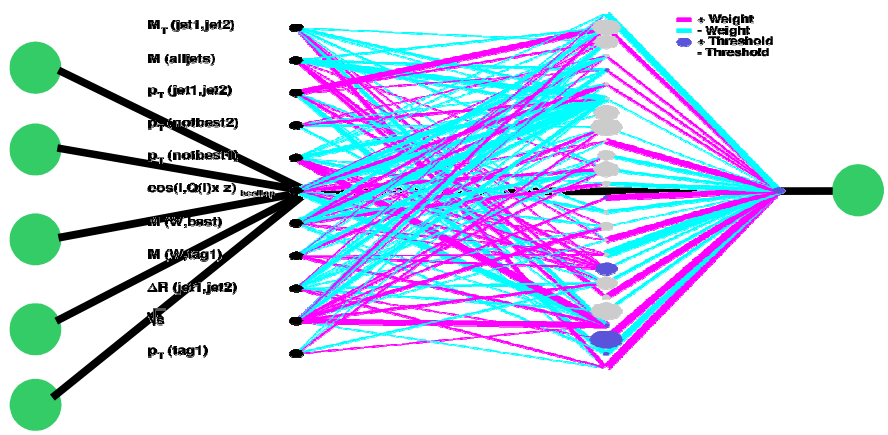
Event energy

Quark jet angle

Reconstructed top mass

Reconstructed top spin

.....

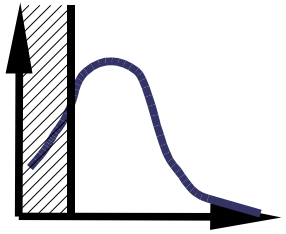


P(signal)

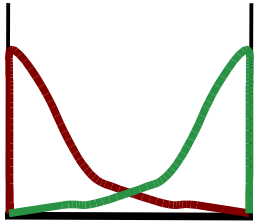
Event Analysis

- Advanced analysis techniques

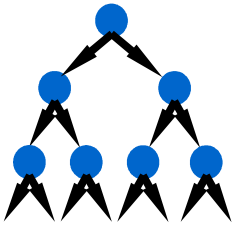
Cut-Based



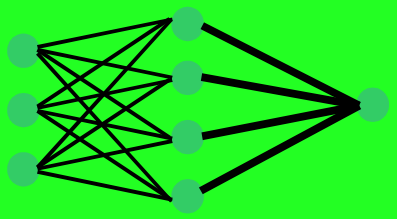
Likelihoods



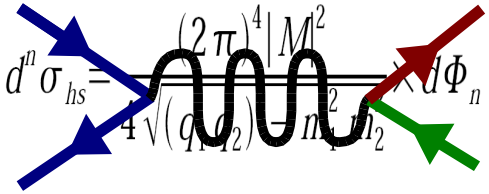
Decision Trees



Neural Networks

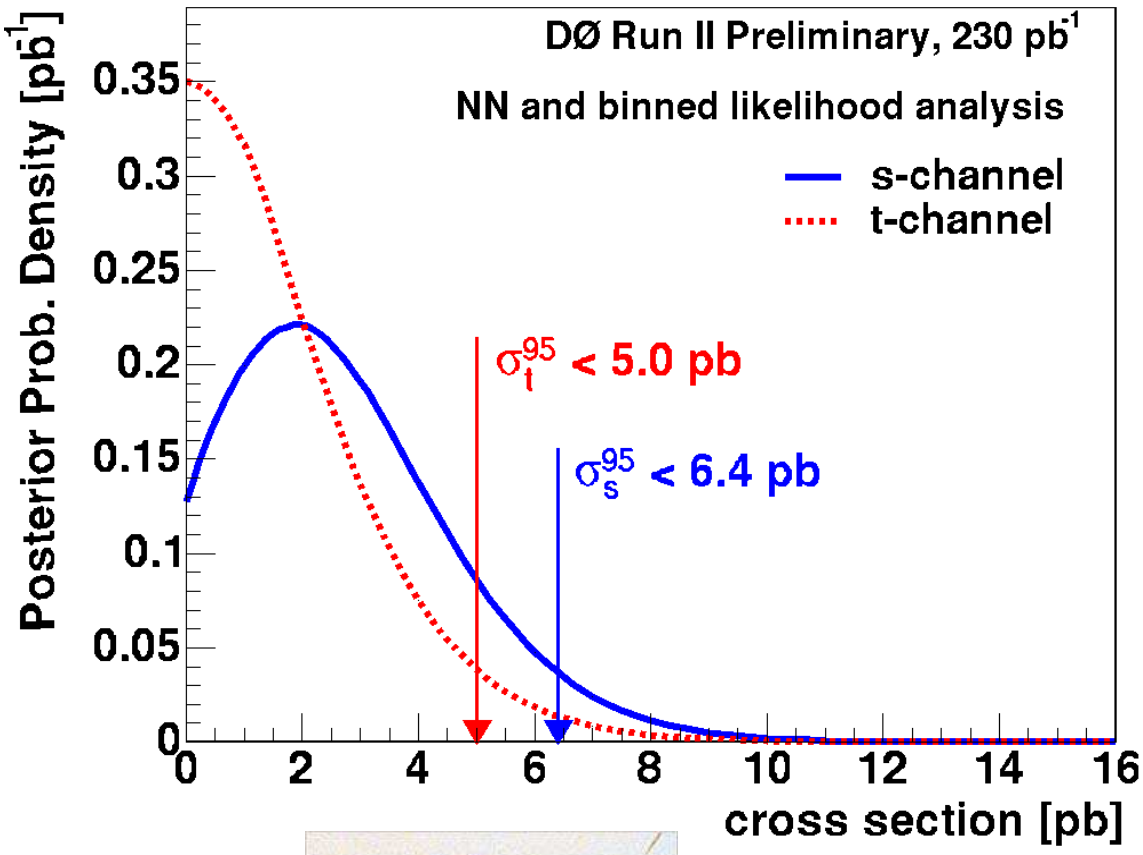


Matrix Elements



Result

- Bayesian statistical analysis
- Systematic uncertainty ~20%



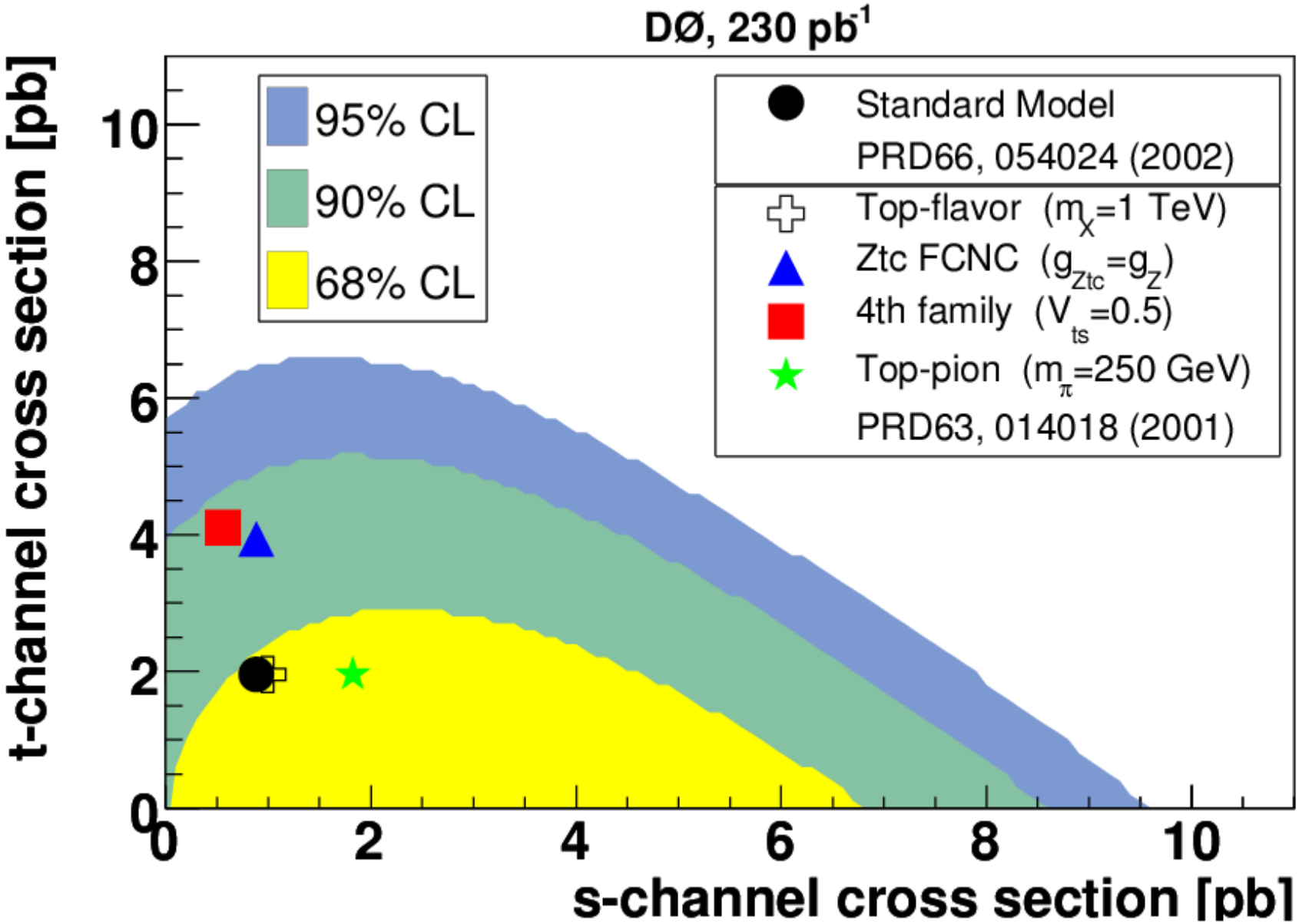
Expected/Observed limit:

σ_s < 4.5 / 6.4 pb

σ_t < 5.8 / 5.0 pb

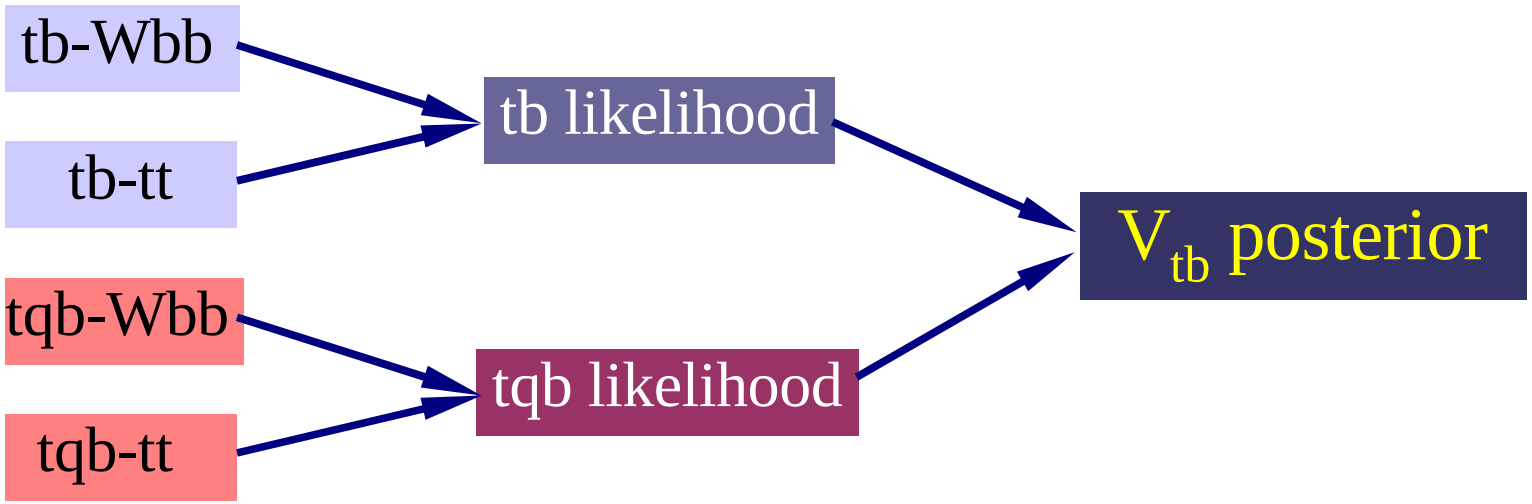
Published in PLB 622, 265 (2005)

Sensitivity to non-SM Single Top



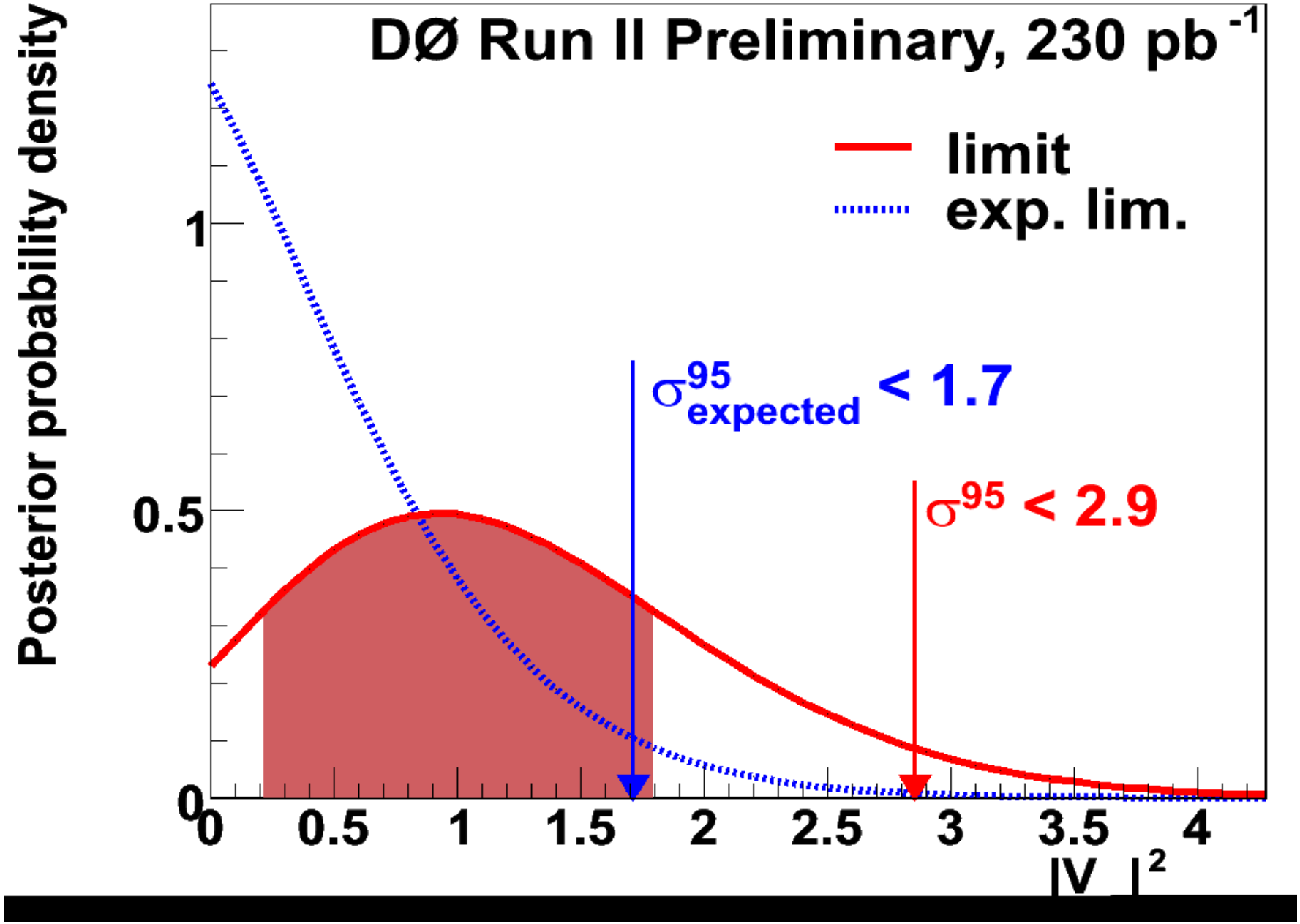
V_{tb} Coupling Limit

- Both the s-channel and t-channel cross sections are proportional to $|V_{tb}|^2$
  - Combine neural networks in a 2d likelihood function



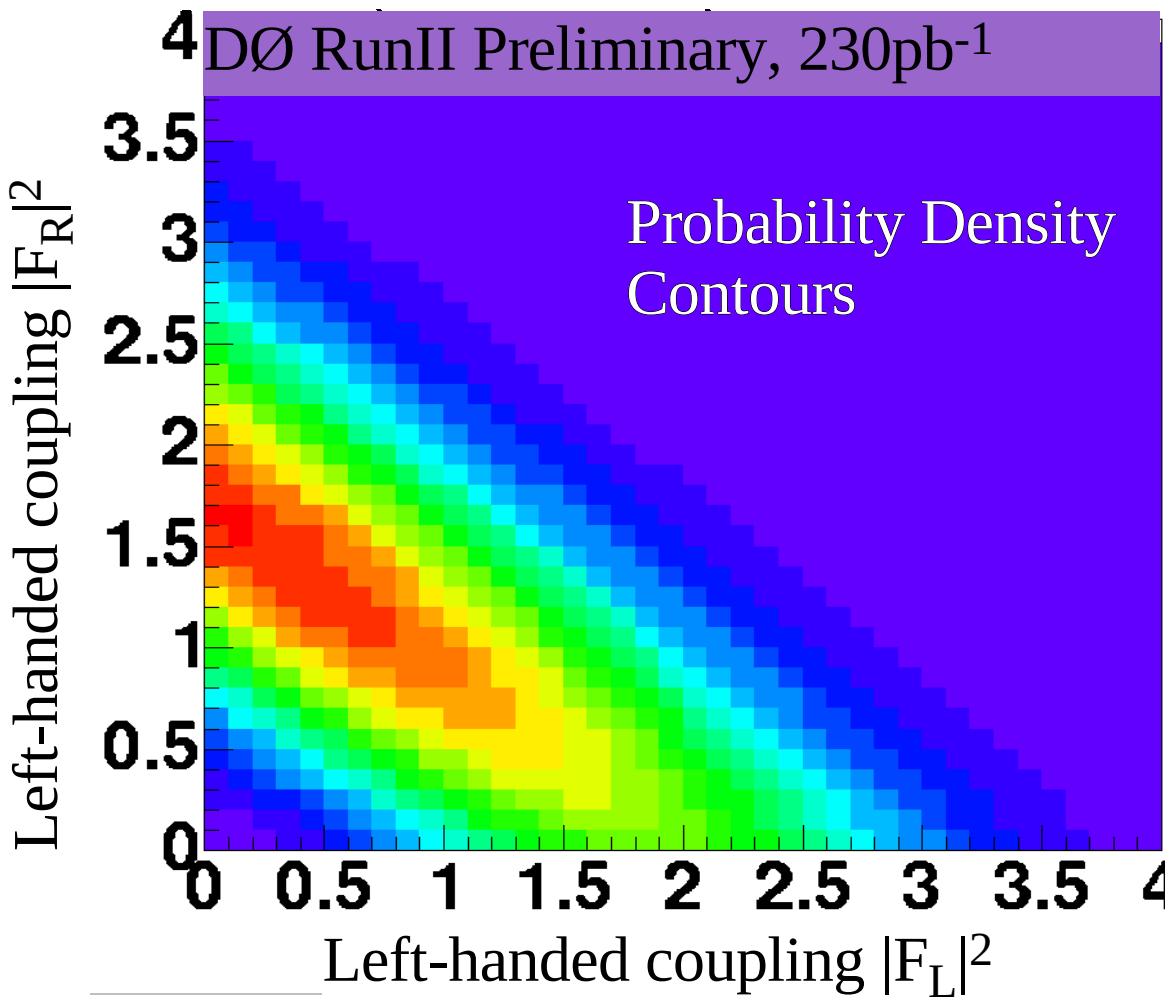
  - Need to assume SM ratio of cross sections

Probability density for $|V_{tb}|^2$

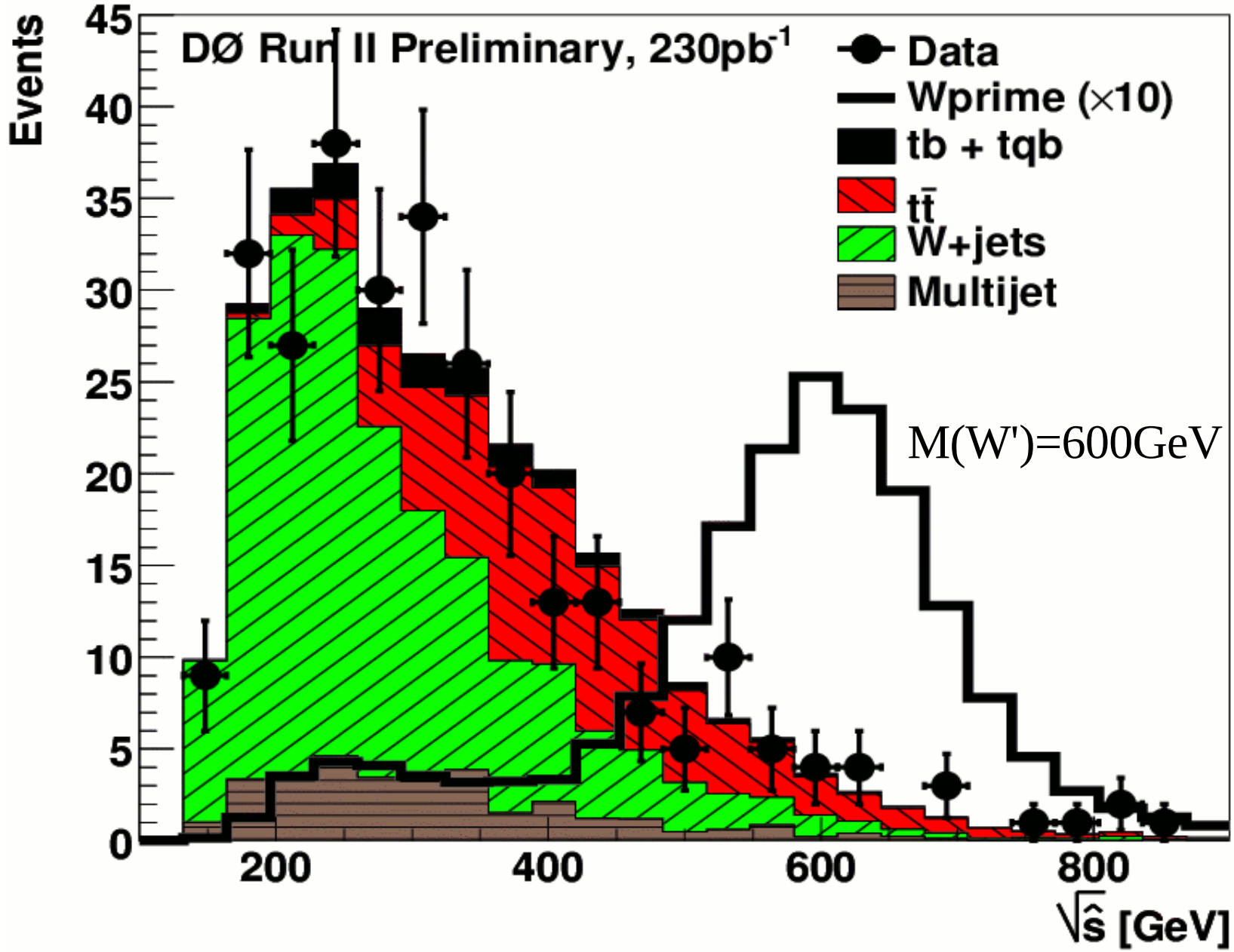


Left-handed or right-handed *W* coupling?

- Extremely preliminary
  - No systematic uncertainties, no full MC simulation



New heavy boson *W*'?

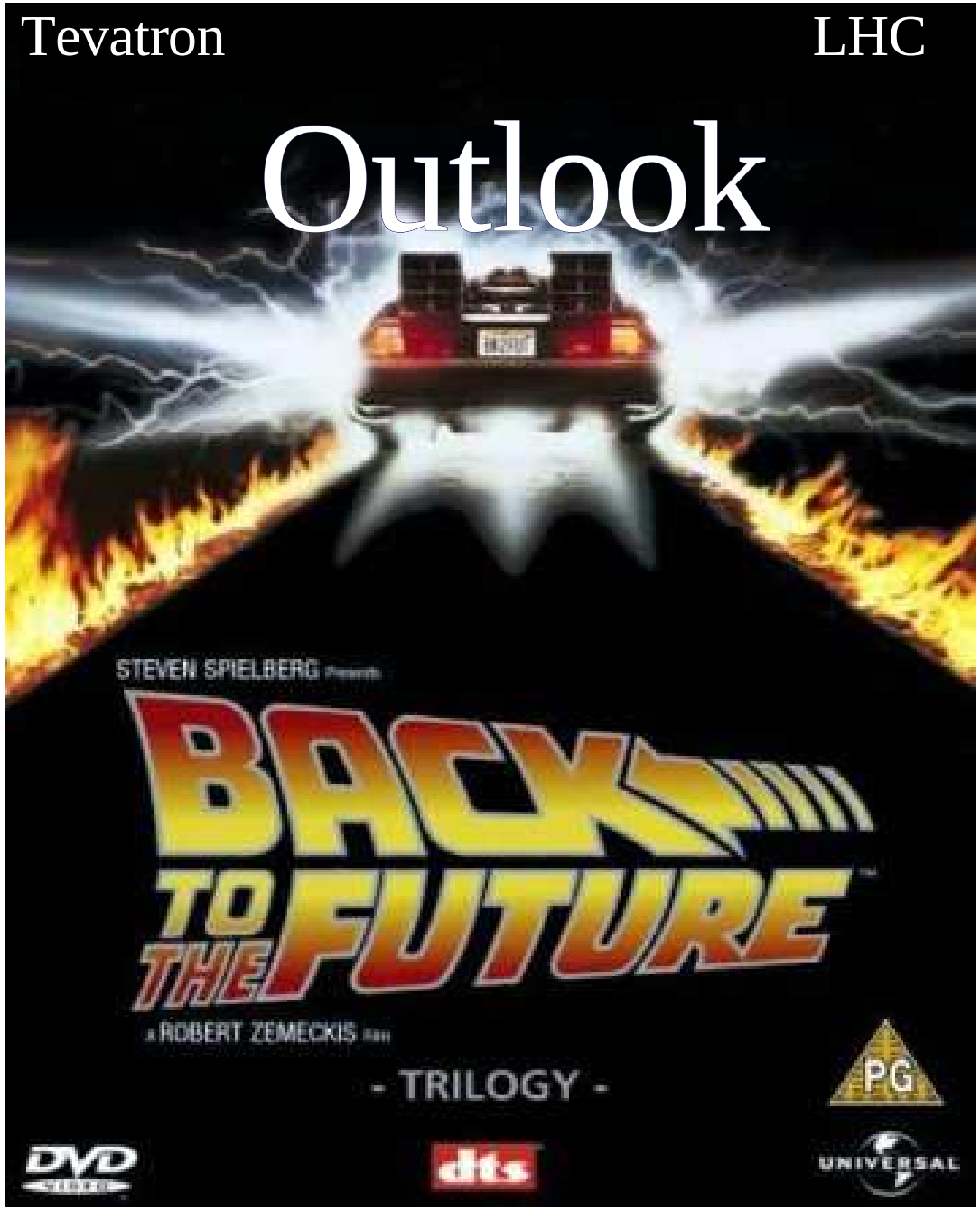


Summary

	s-channel	t-channel
NLO cross section	0.88 pb	1.98 pb

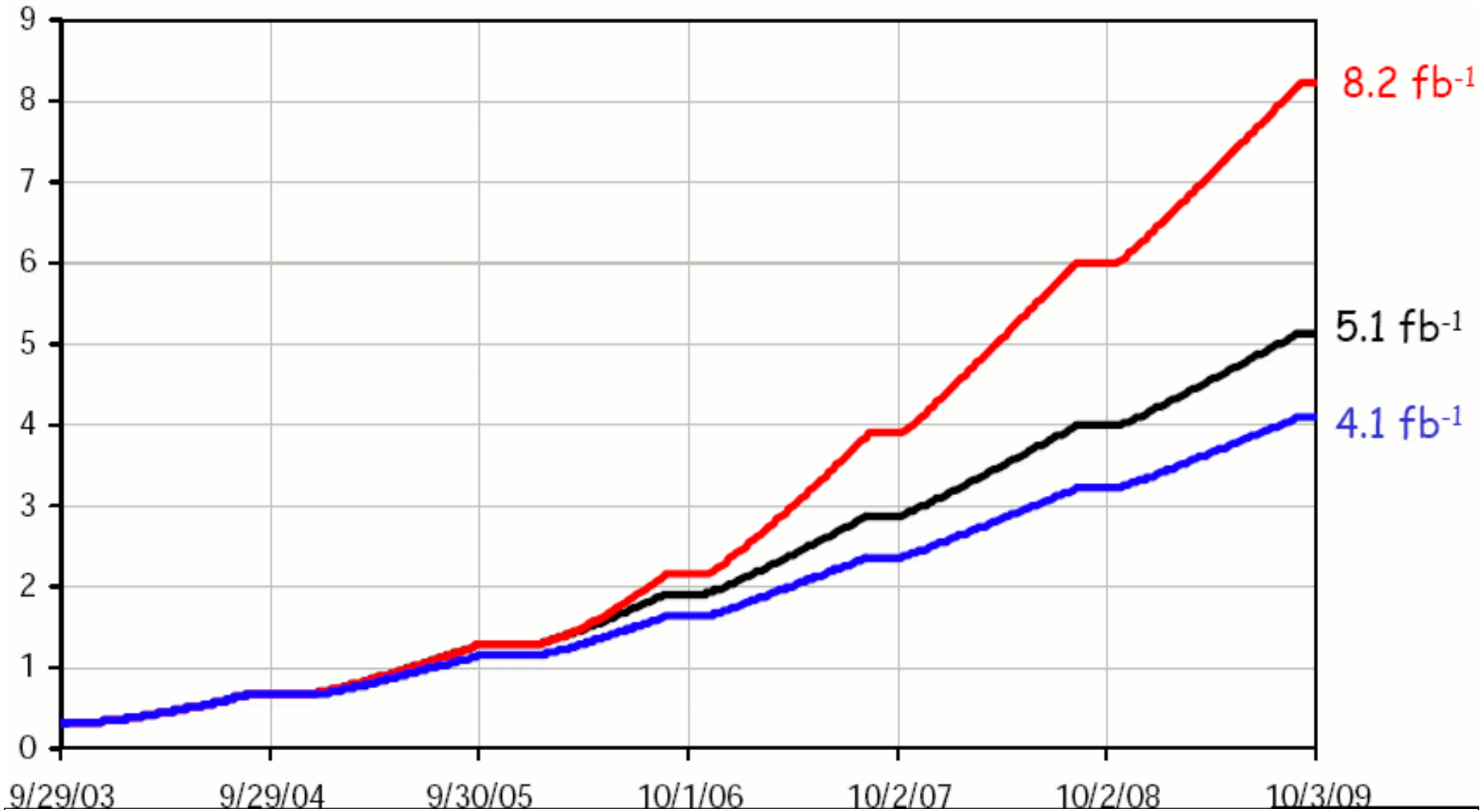
95% CL upper cross section limits [pb]

CDF ($160pb^{-1}$)	13.6	10.1
DØ NN ($230pb^{-1}$)	6.4	5.0
DØ Likelihood ($370pb^{-1}$)	5.0	4.4

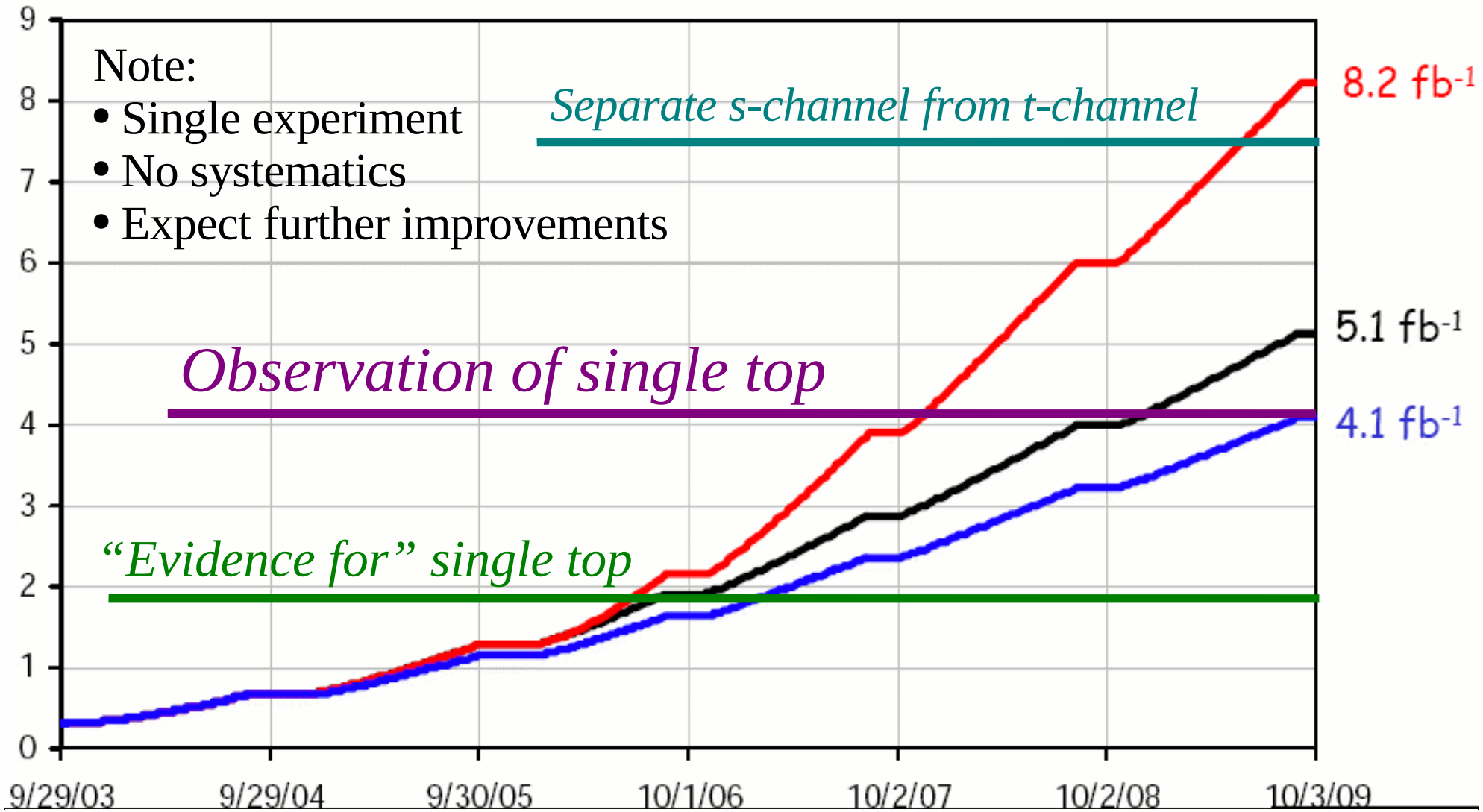


I never think of the future. It comes soon enough.
Albert Einstein

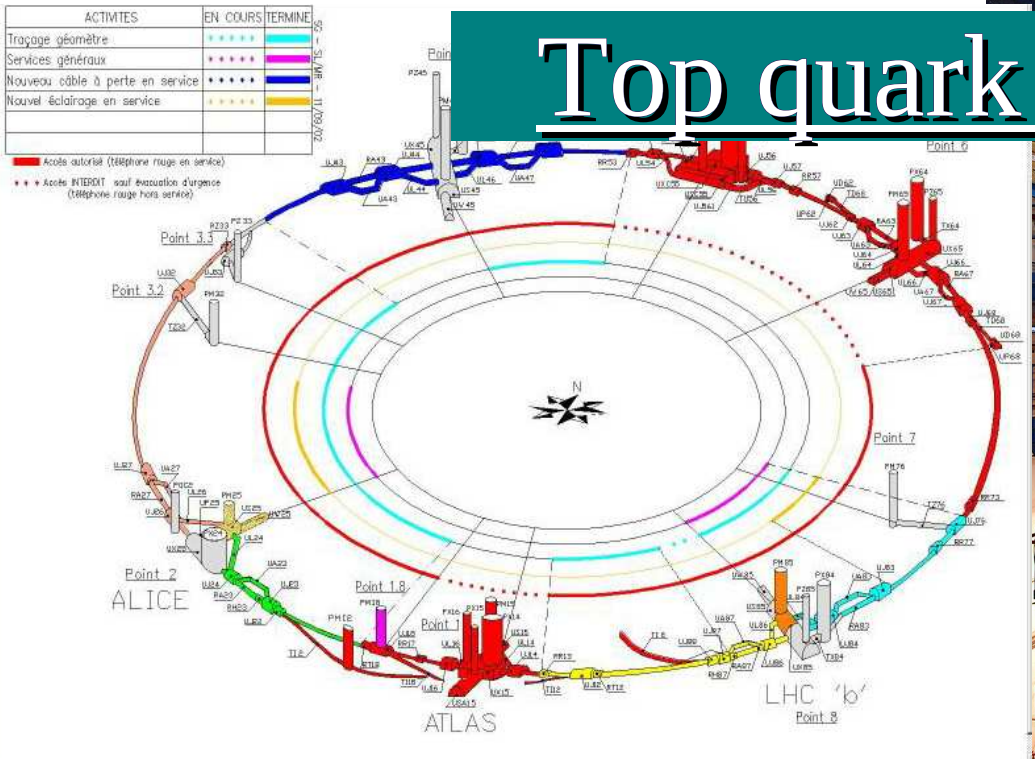
Tevatron luminosity projection

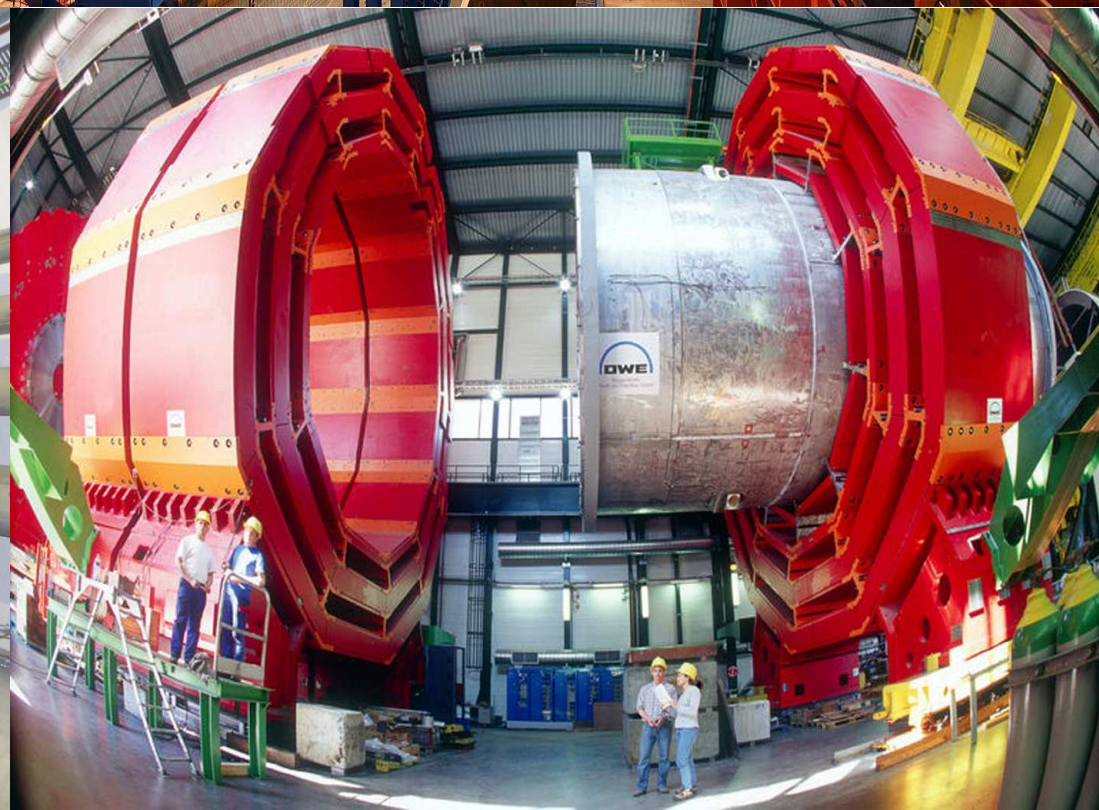


Tevatron luminosity projection

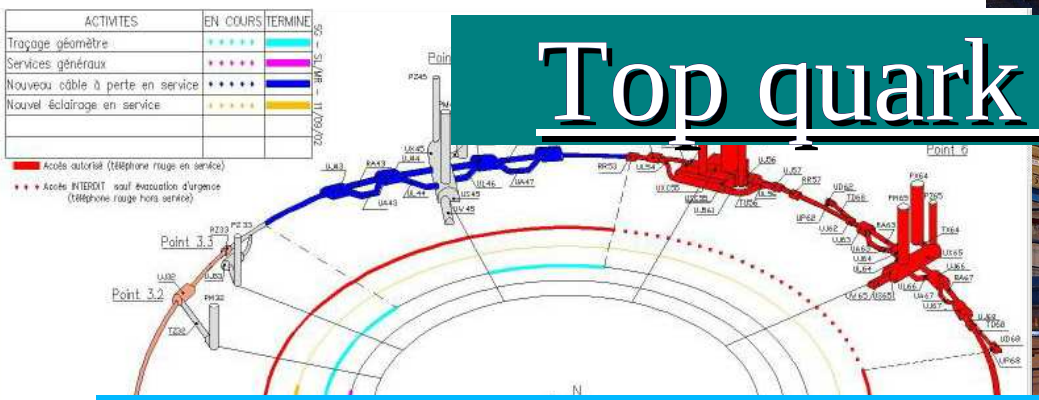


Top quark future: LHC

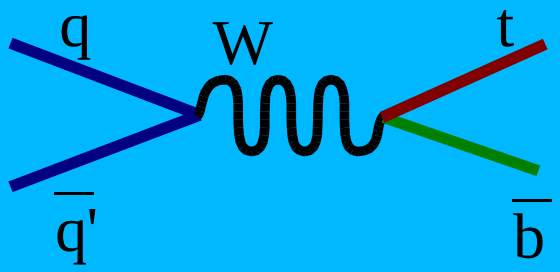




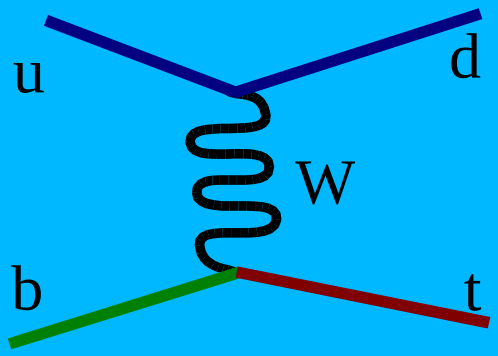
Top quark future: LHC



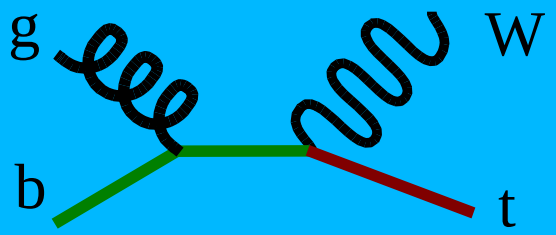
s-channel



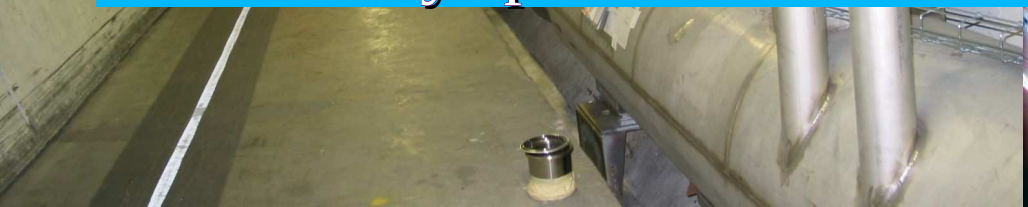
t-channel



associated production



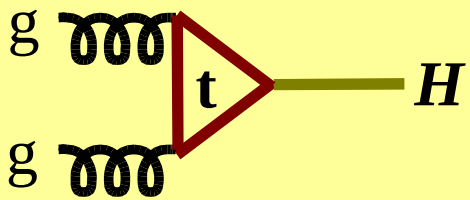
- Observe three single top production modes separately
  - t-channel: easy
  - s-channel and assoc. prod: harder
- Observe new physics *(if it can be seen)*
- Measure V_{tb} to few %
- Study spin correlations



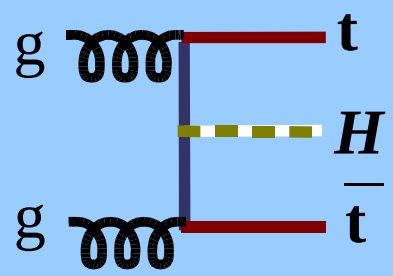
Top as the gateway to Higgs

Neutral Higgs

Dominant Higgs production mechanism at the LHC:



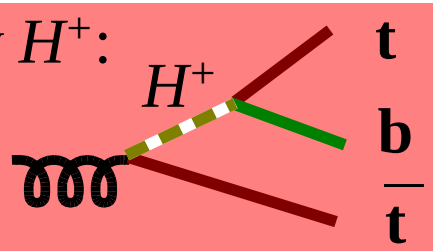
Top-Higgs Yukawa coupling measurement



Discover with ~30fb^{-1}

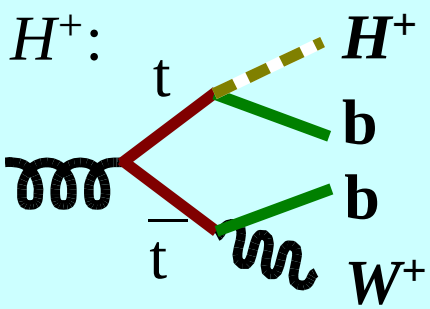
Supersymmetry: Charged Higgs

Heavy H^+:



Discovery possible with ~30fb^{-1}

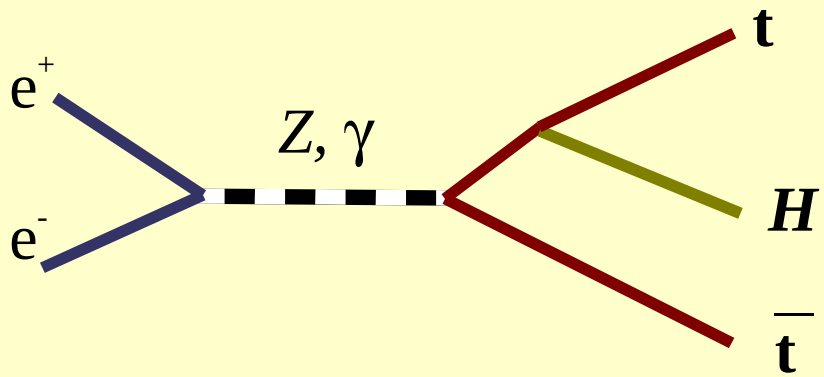
Light H^+:



Discover with ~30fb^{-1}

High precision top quark physics

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



International Linear Collider

Conclusions

- We are on a quest to reveal the origin of electroweak symmetry breaking and particle mass
- Understanding the top quark is an important step
  - In particular electroweak interaction
- The top quark is a central focus at the Tevatron
  - Run II is now producing many results
  - Single top quark search is close to SM sensitivity
- This is just the beginning
  - Analyzing ×4 dataset now
  - LHC is just around the corner

Dawn of Discoveries