Single Top Quark Physics

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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?

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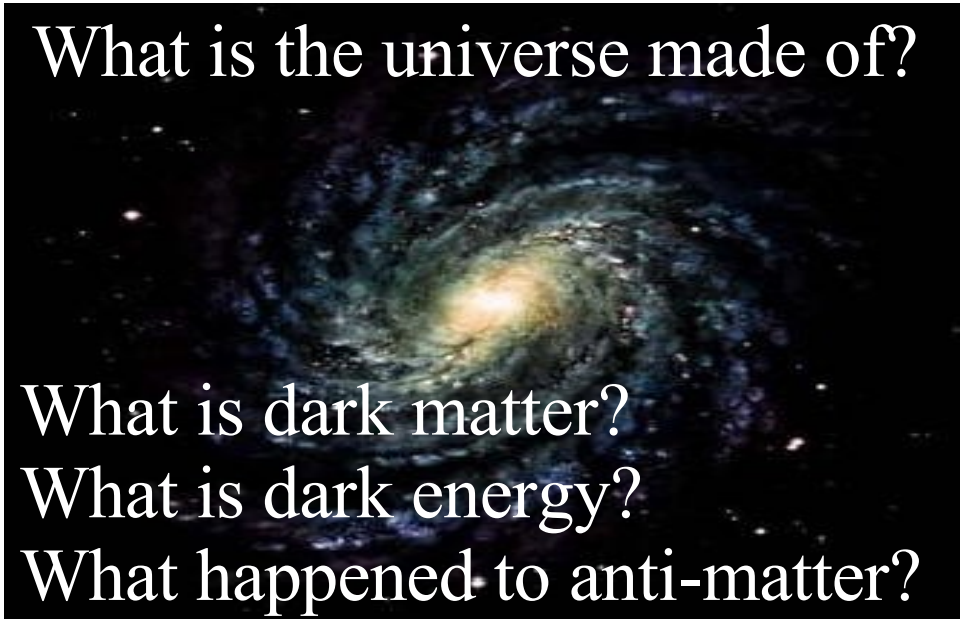
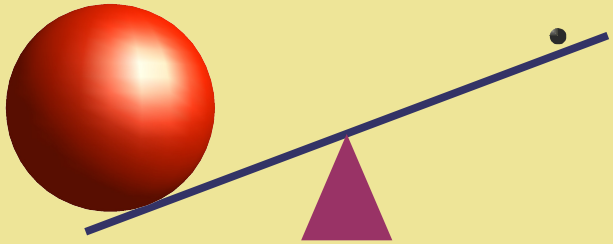
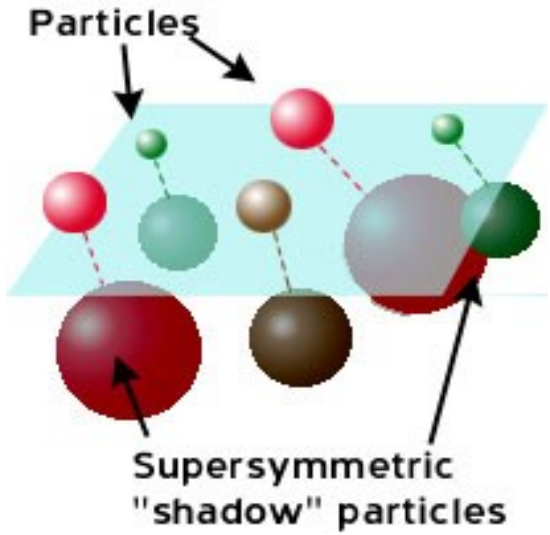
What gives mass to elementary particles?



What makes quarks so heavy and neutrinos so light?





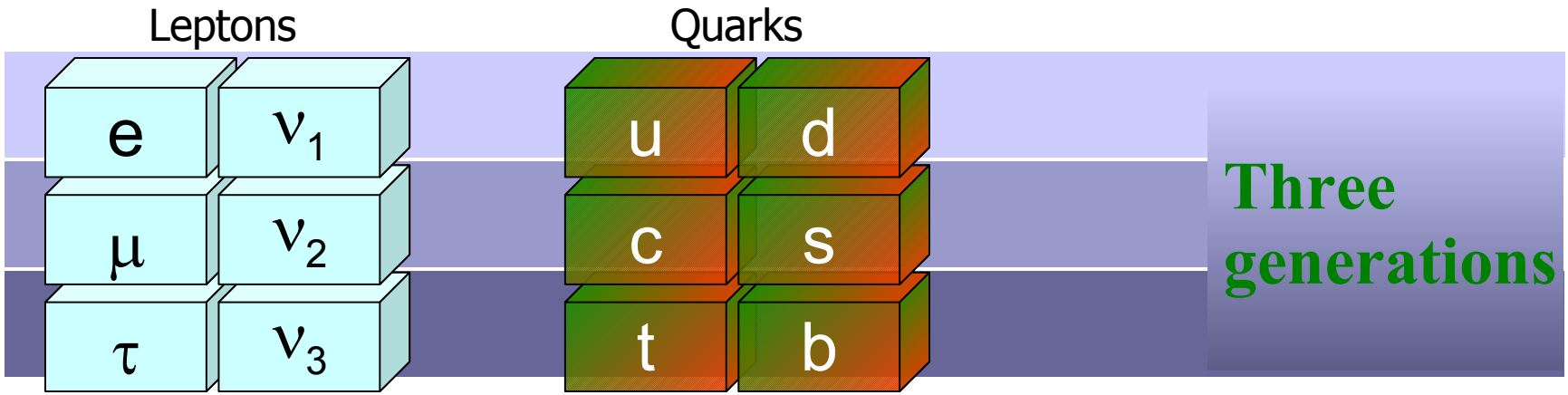
Supersymmetry? Extra spatial dimensions? ...

State of the art

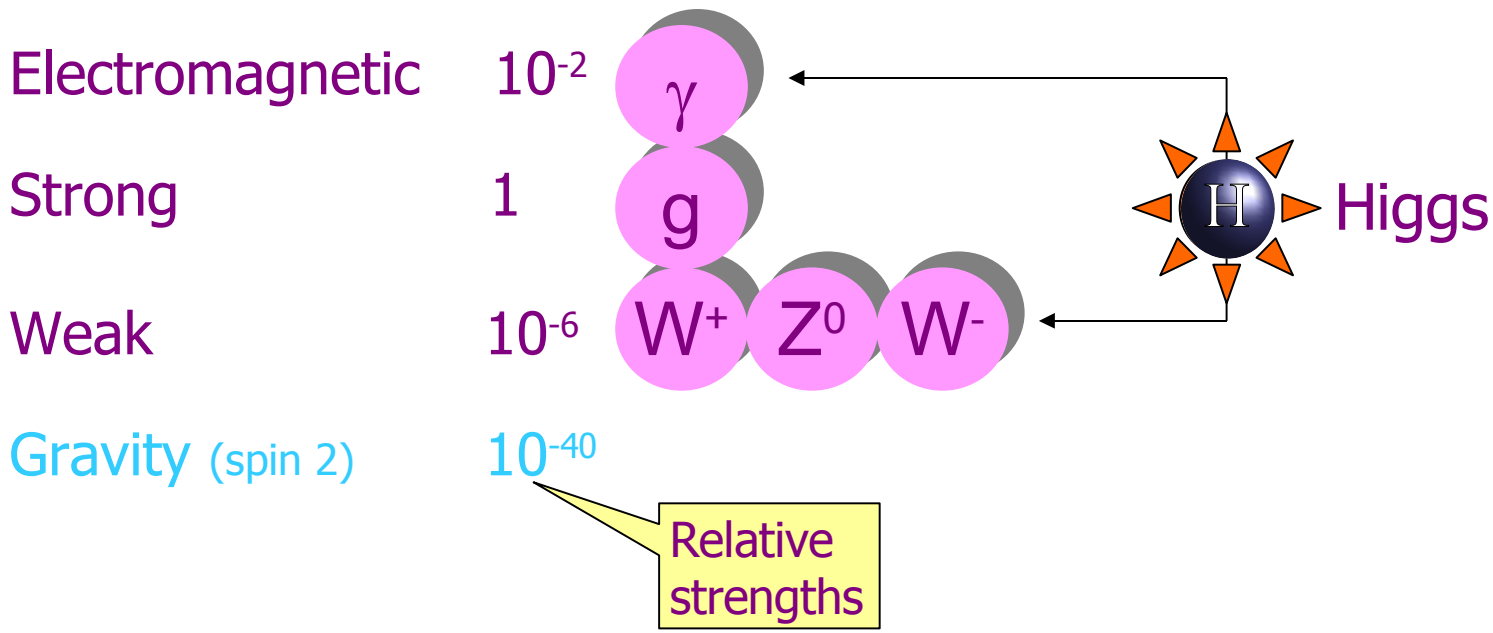
What do we know already?

Standard model of particles and forces

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



- Which interact by exchanging spin-1 vector bosons

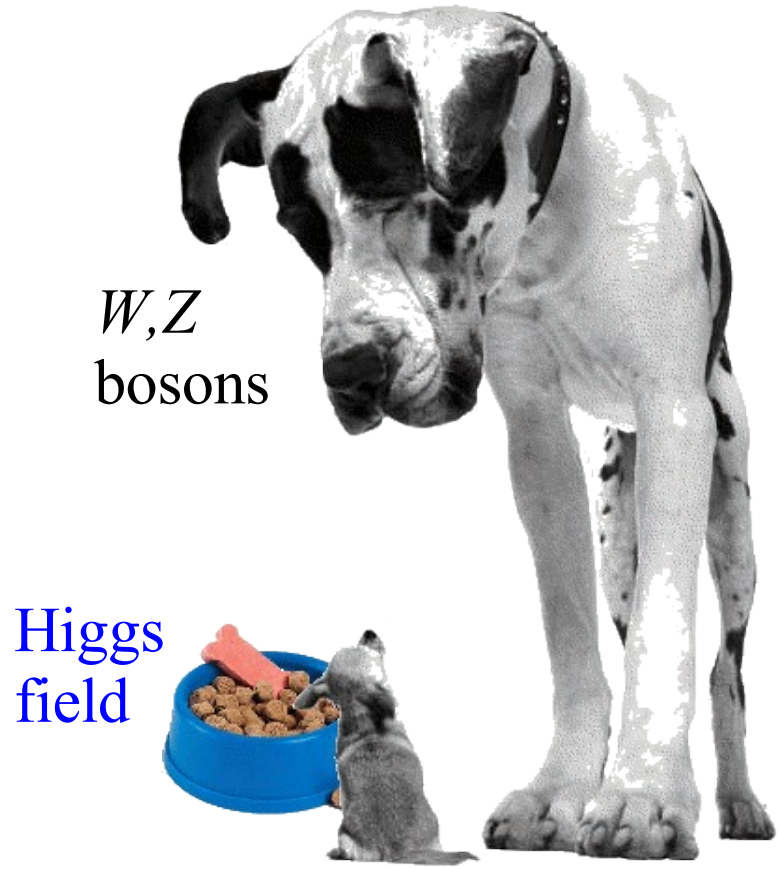


Gauge boson masses in the SM

Gauge bosons

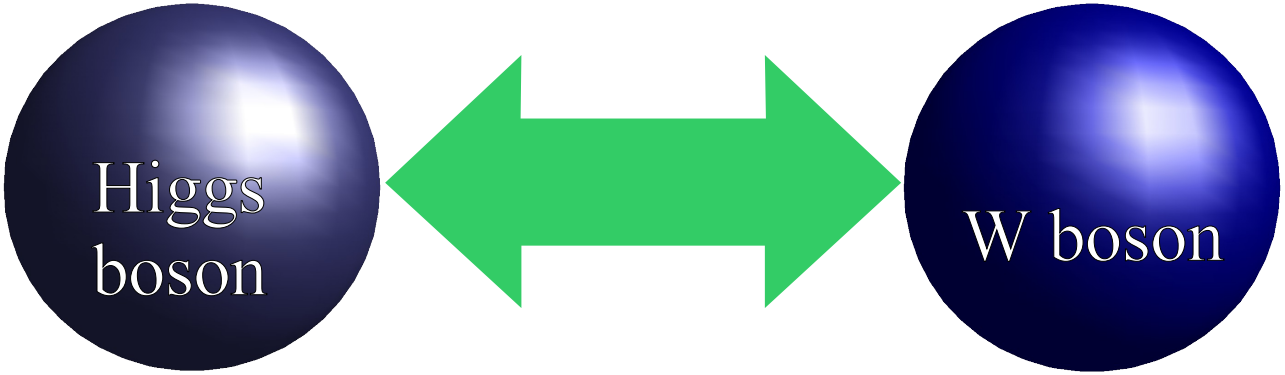
Higgs field

Electroweak symmetry breaking



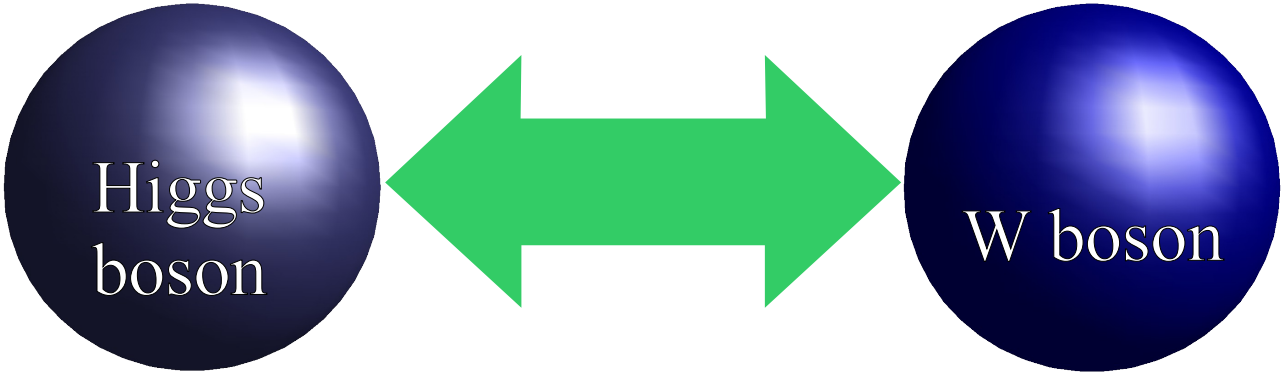
Electroweak symmetry breaking

Gauge boson coupling to Higgs field

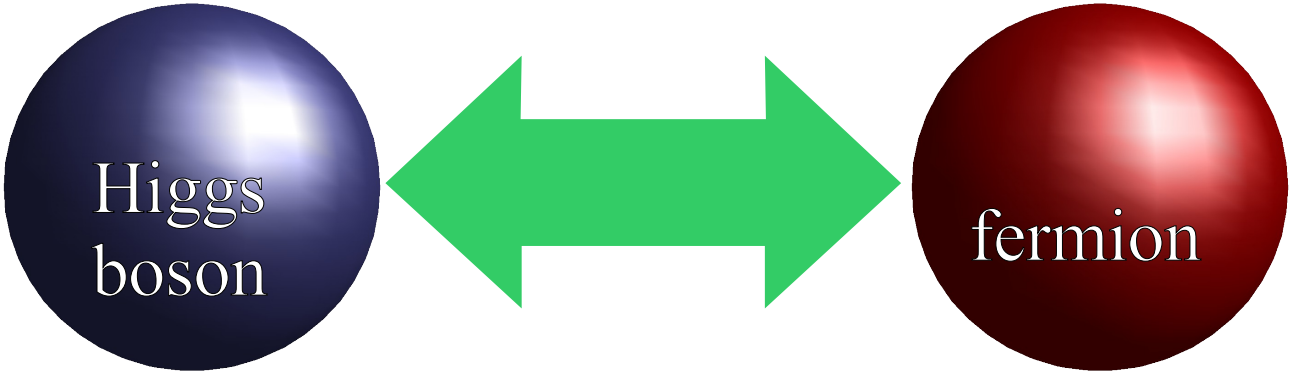


Electroweak symmetry breaking

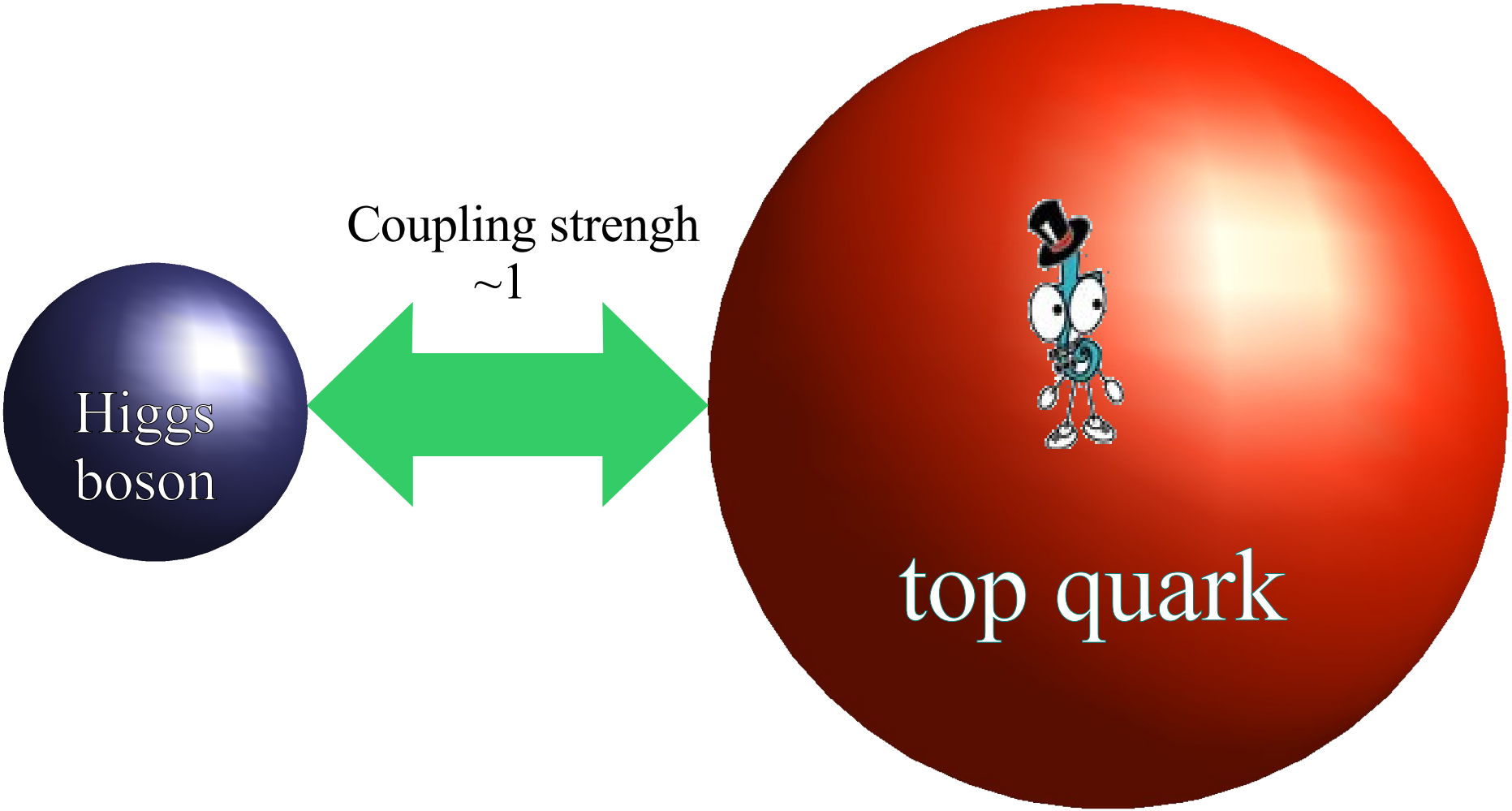
Gauge boson coupling to Higgs field



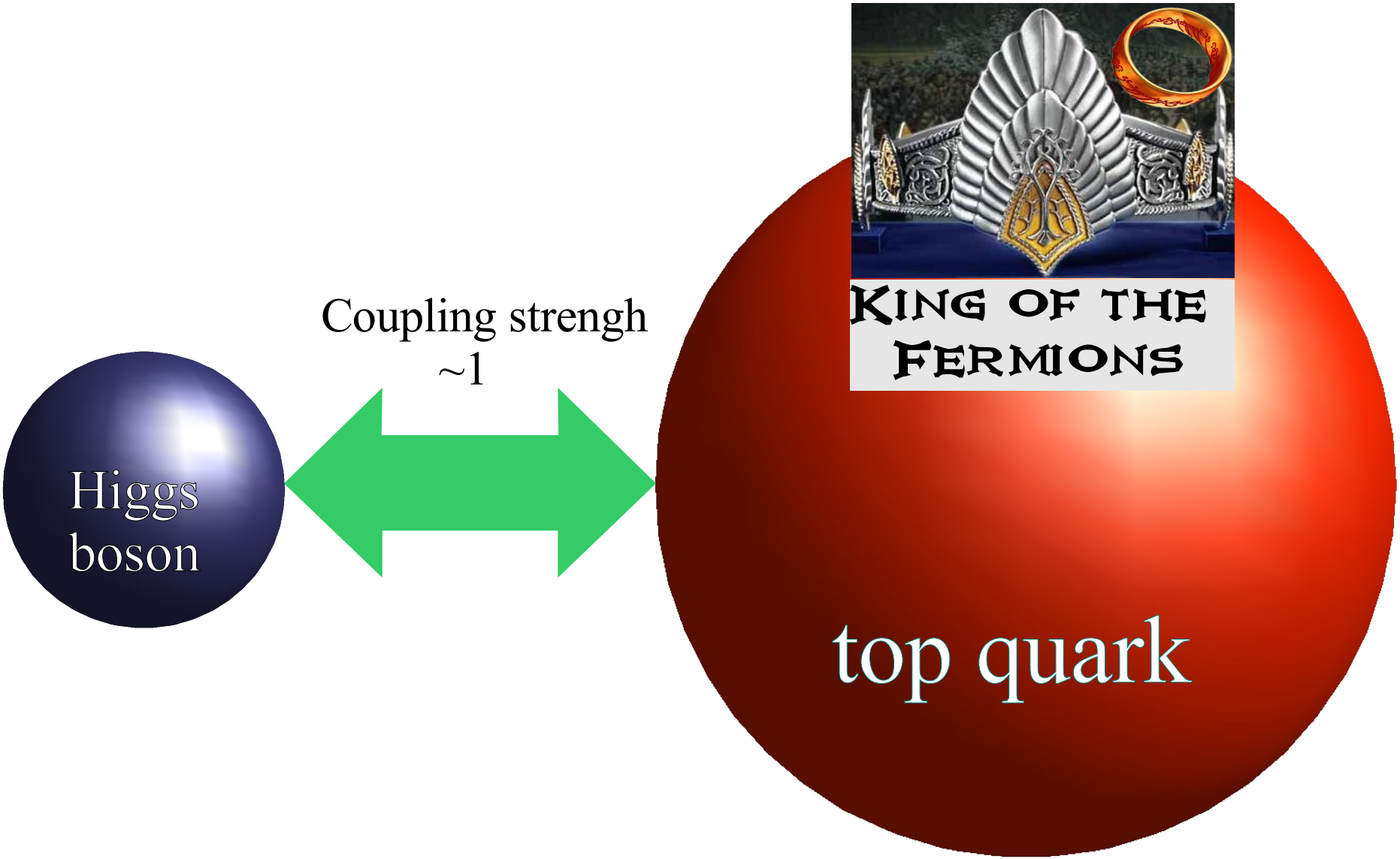
Fermions acquire mass through Higgs coupling



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
- Electroweak interactions
  - Charged current (W boson)
    - Total width
    - CKM matrix
  - Neutral current (Z boson)

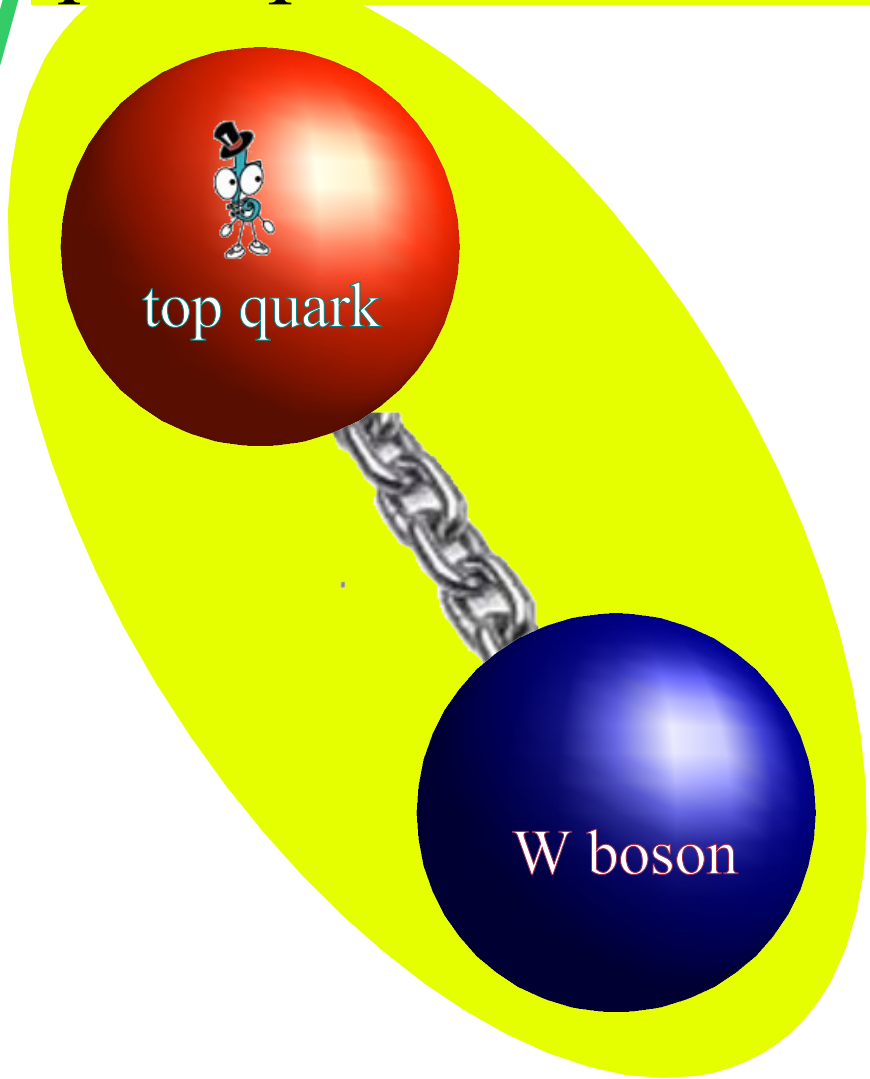
Really don't know:

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

We assume but don't actually know:

- Charge, Spin
- Electroweak interactions
  - Charged current (W boson)
    - Total width
    - CKM matrix
  - Neutral current (Z boson)

Study in single top quark production



Really don't know:

- Coupling to Higgs?
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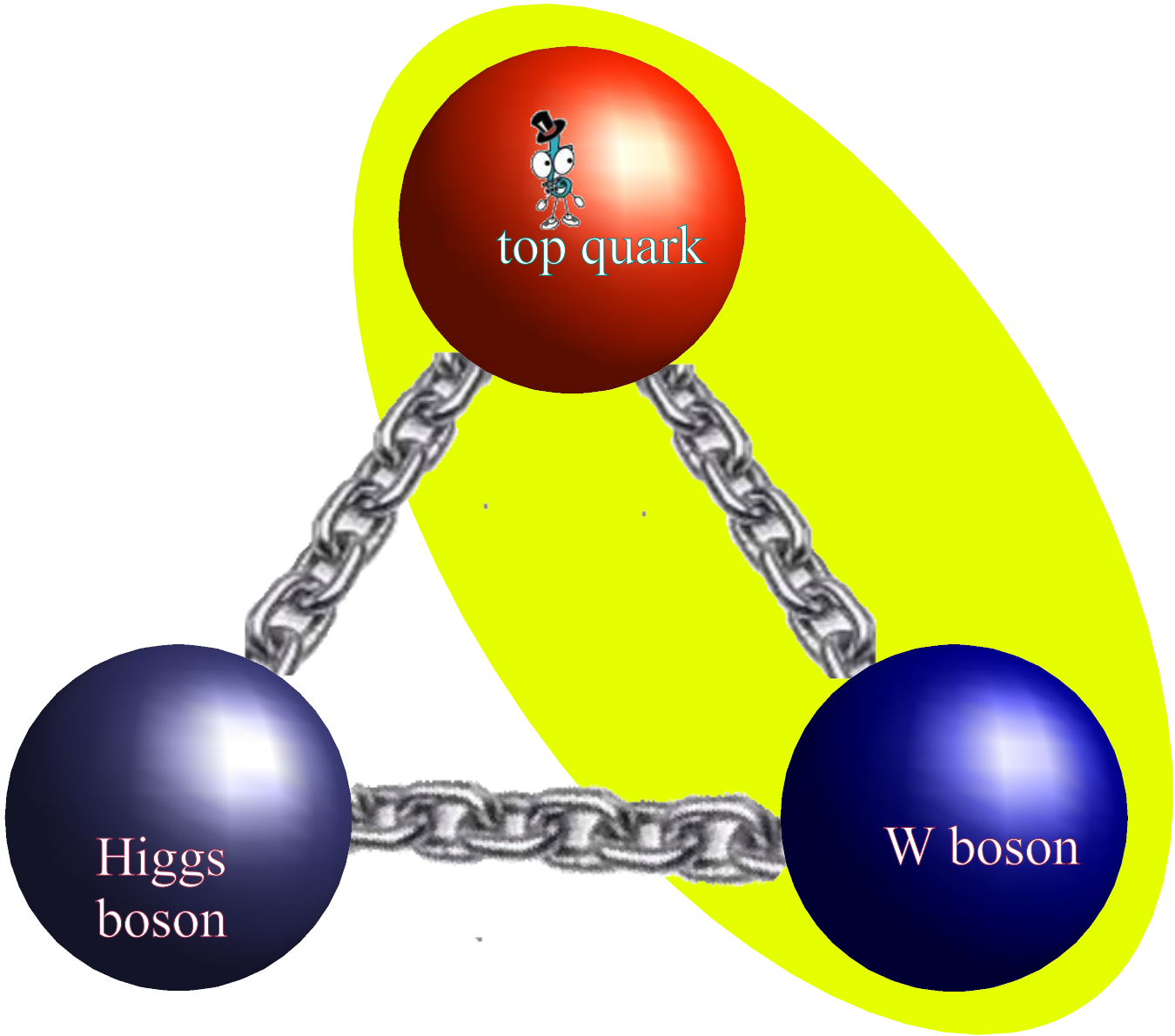
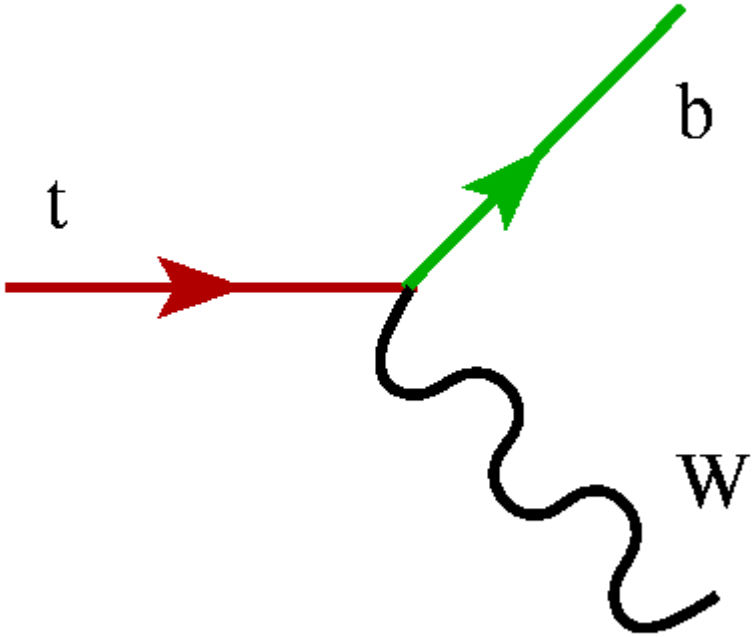
Key to electroweak symmetry breaking



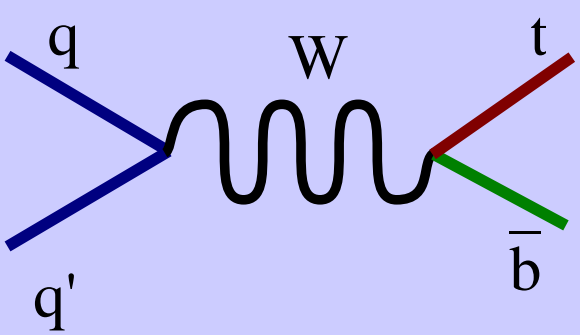
Top quark electroweak charged current interaction



top quark decay

SM single top quark production

s-channel



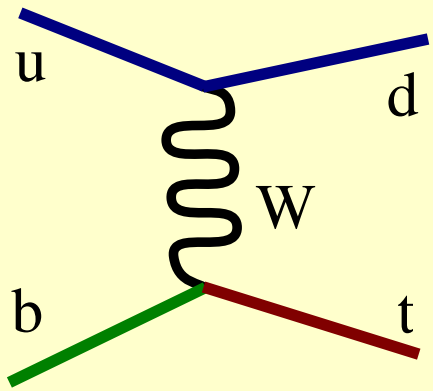
σ_{NLO}

TeV: 0.88 pb

LHC, t: 6.6 pb

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

t-channel



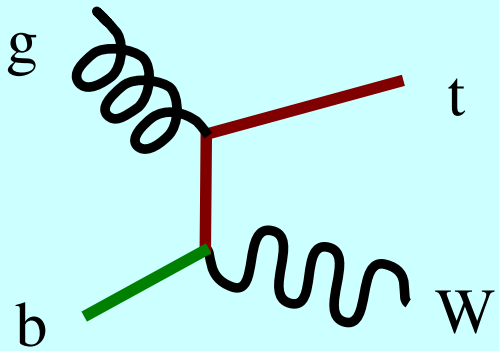
NLO

1.98pb

156 pb

91 pb

Associated production



NLO

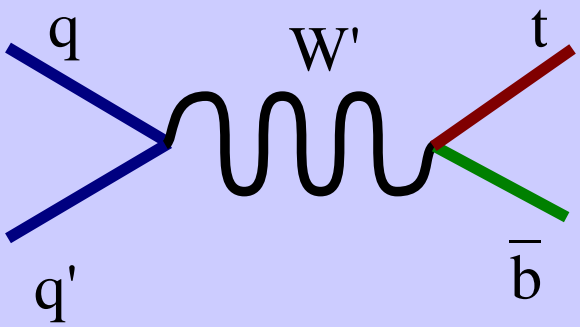
0.14 pb

34 pb

34 pb

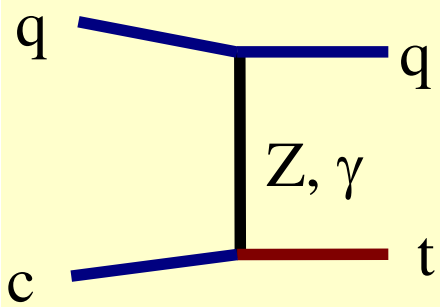
New physics

s-channel



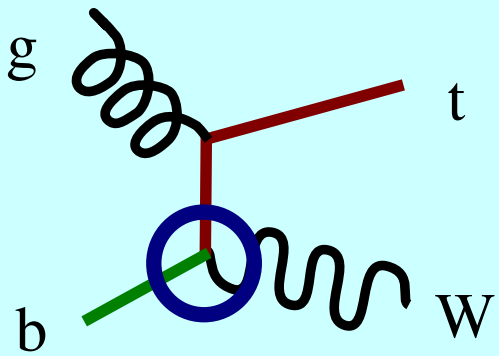
New heavy boson

t-channel



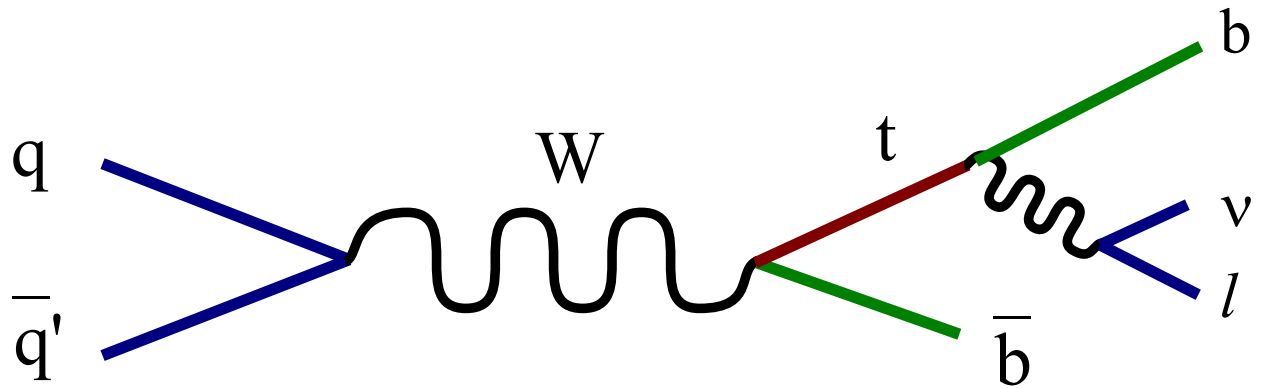
Flavor Changing Neutral Current

Associated production

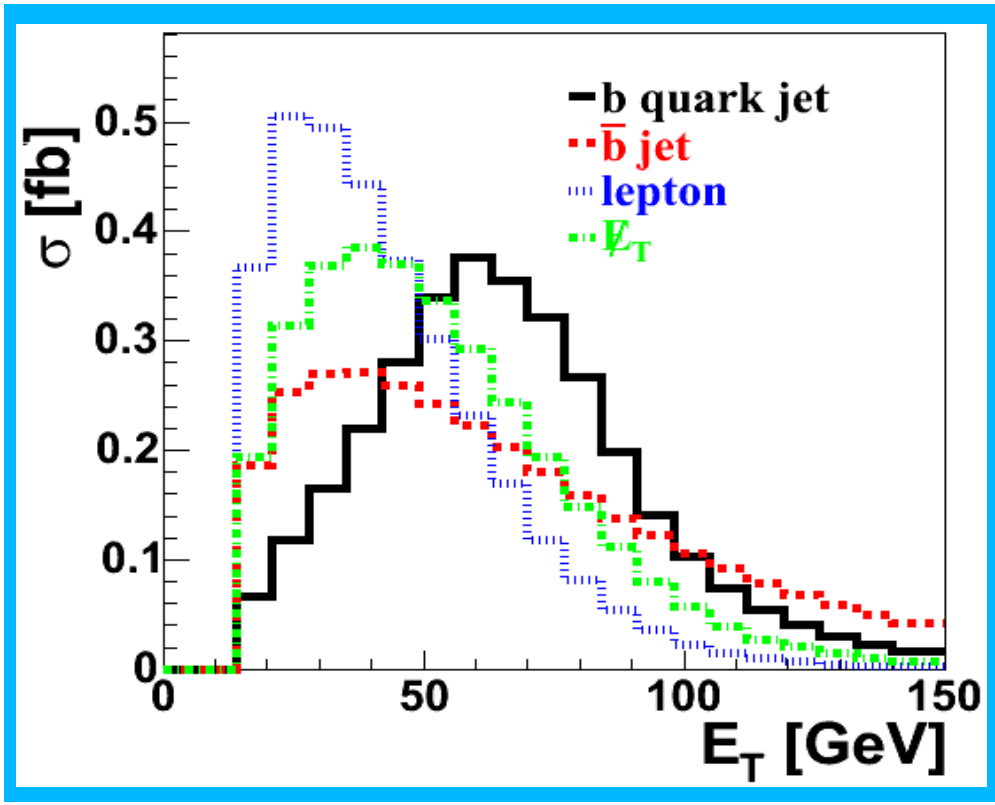


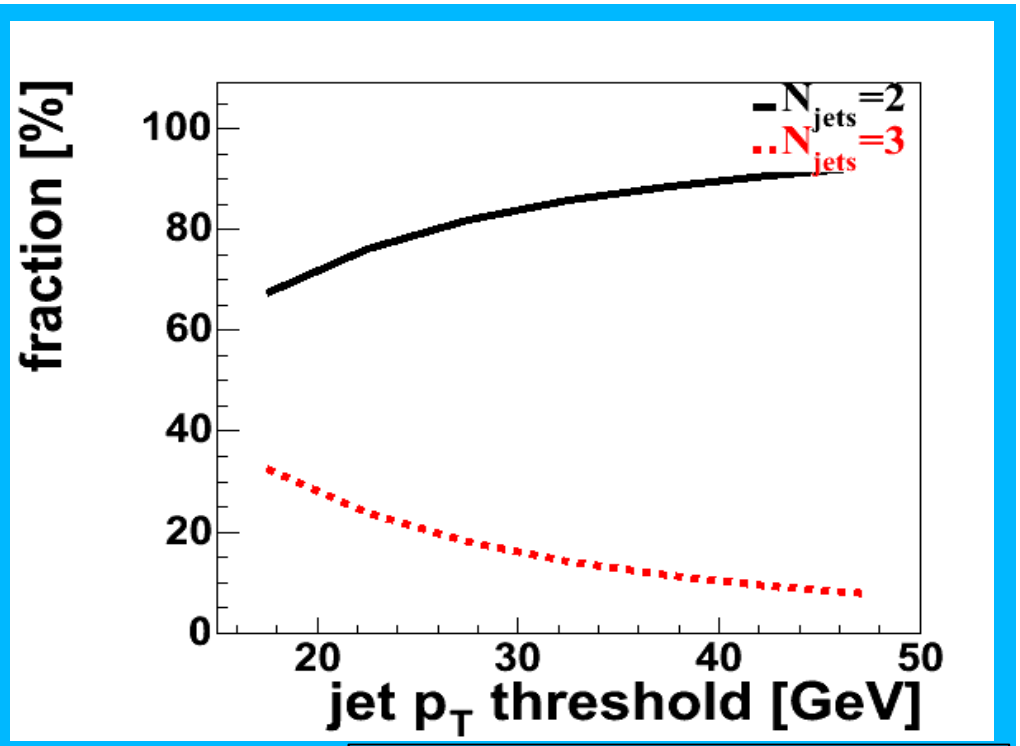
Modified Wtb coupling

Tevatron s-channel signature



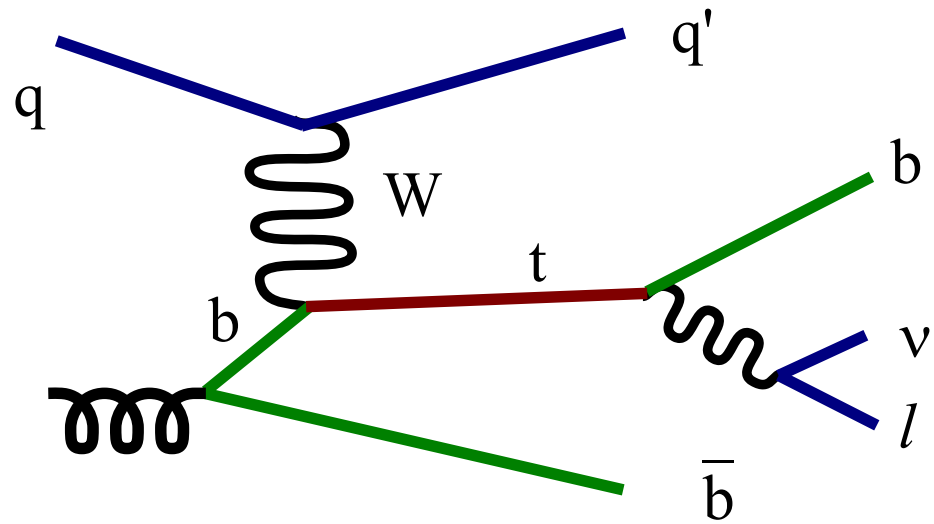
"*tb*"



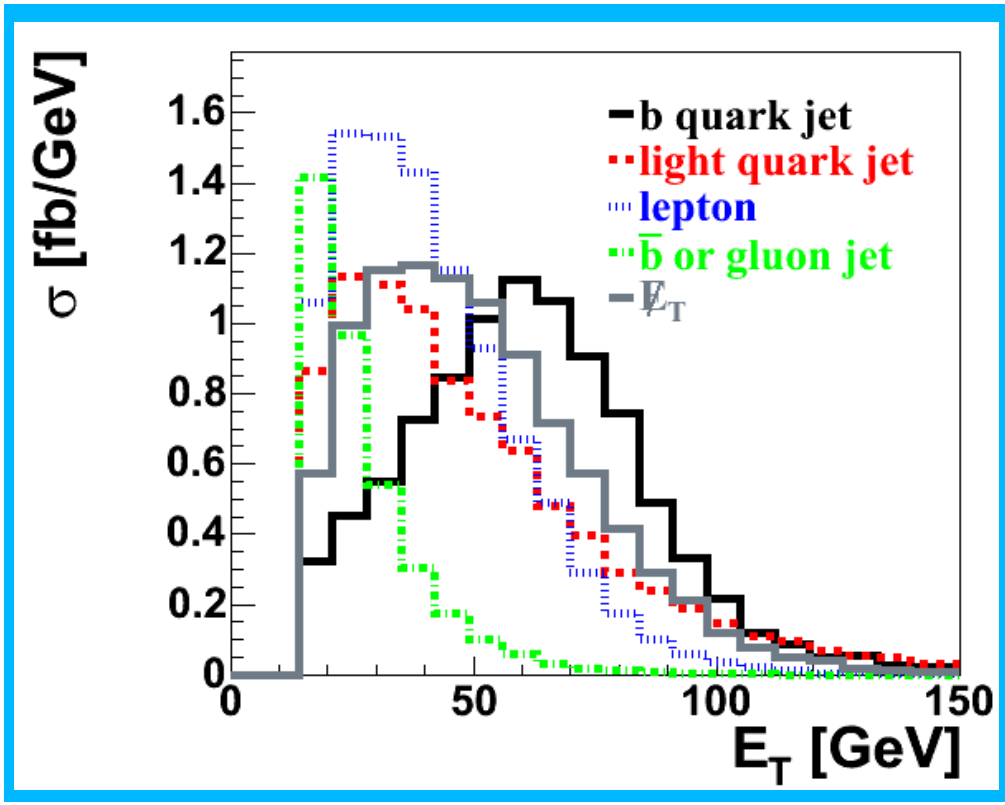


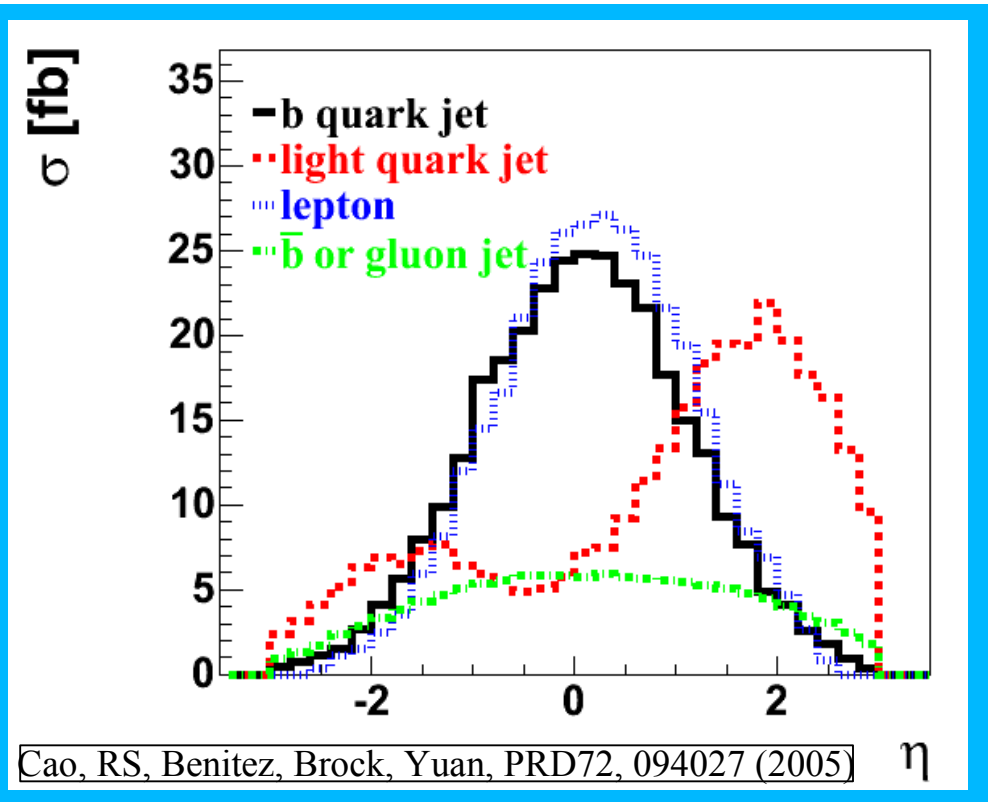
Cao, RS, Yuan PRD71, 054023 (2005)

Tevatron t-channel signature



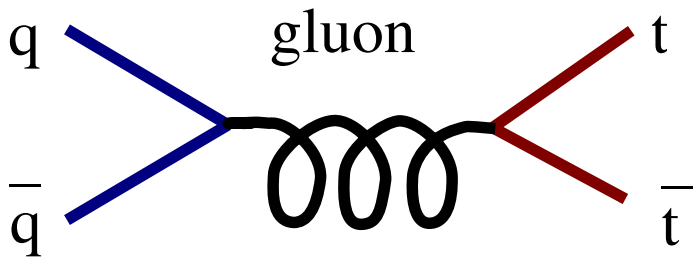
"tqb"





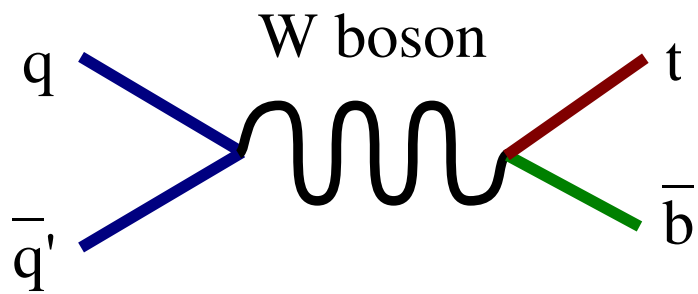
Cao, RS, Benitez, Brock, Yuan, PRD72, 094027 (2005)

Top quark pair production



$\sigma \sim 7$ pb

Single top quark production



$\sigma \sim 1$ pb (s-channel)

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

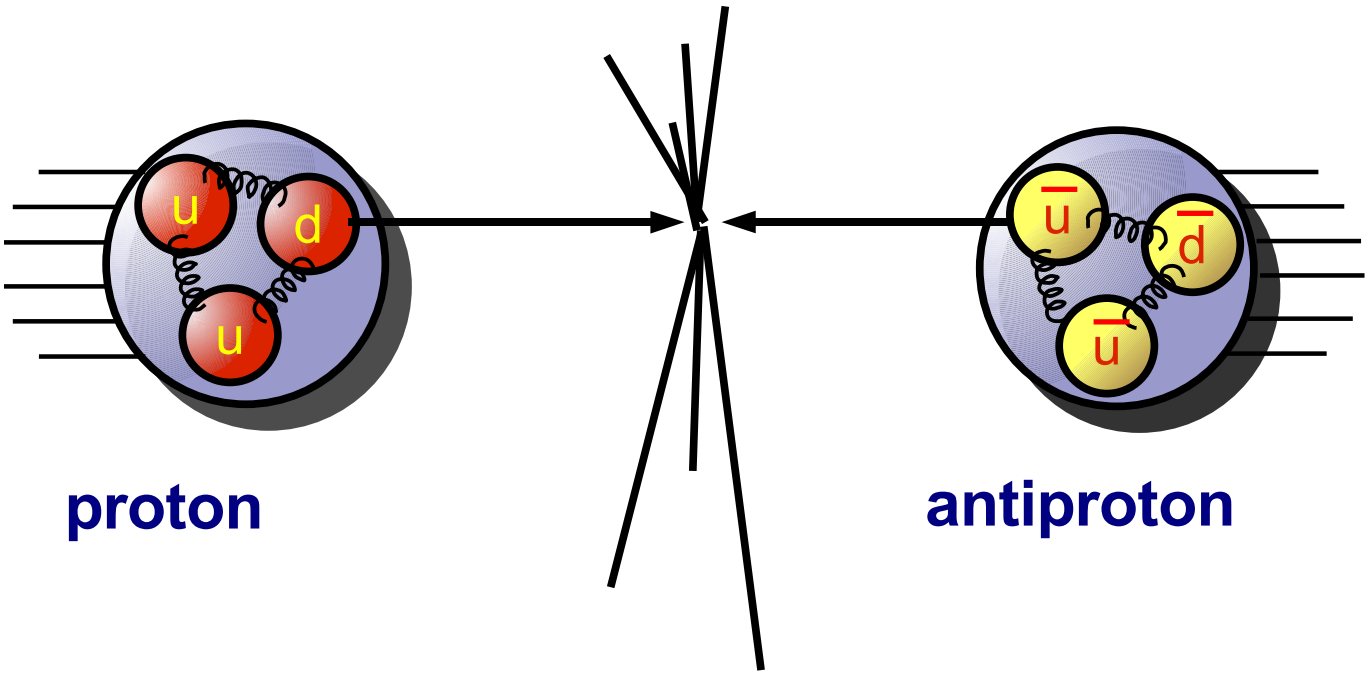
- Observe single top quark production
  - Tevatron discovery!
- Measure production cross sections
  → CKM quark mixing matrix element V_{tb}
- Look for physics beyond the standard model
  - Coupled to the heavy top quark
- Study top quark spin correlations
- Understand as background to many searches

Experimental procedure

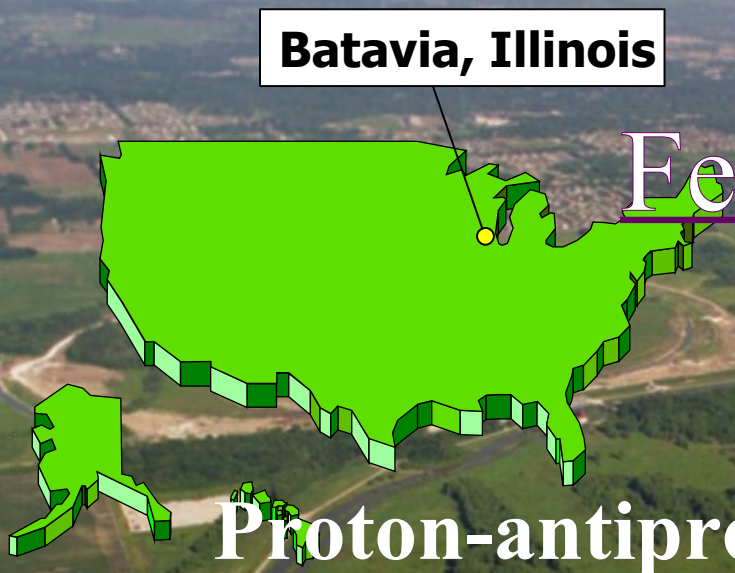
How do we find out?

The energy frontier

Probe physics at small distances
by colliding particles at high energy



Experimental setup: Fermilab Tevatron in Run II



Proton-antiproton collider

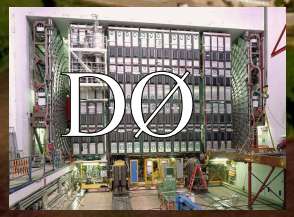
CM energy 1.96TeV

→ ***Energy frontier***

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

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

→ ***Luminosity frontier***



Experimental setup: detector configuration

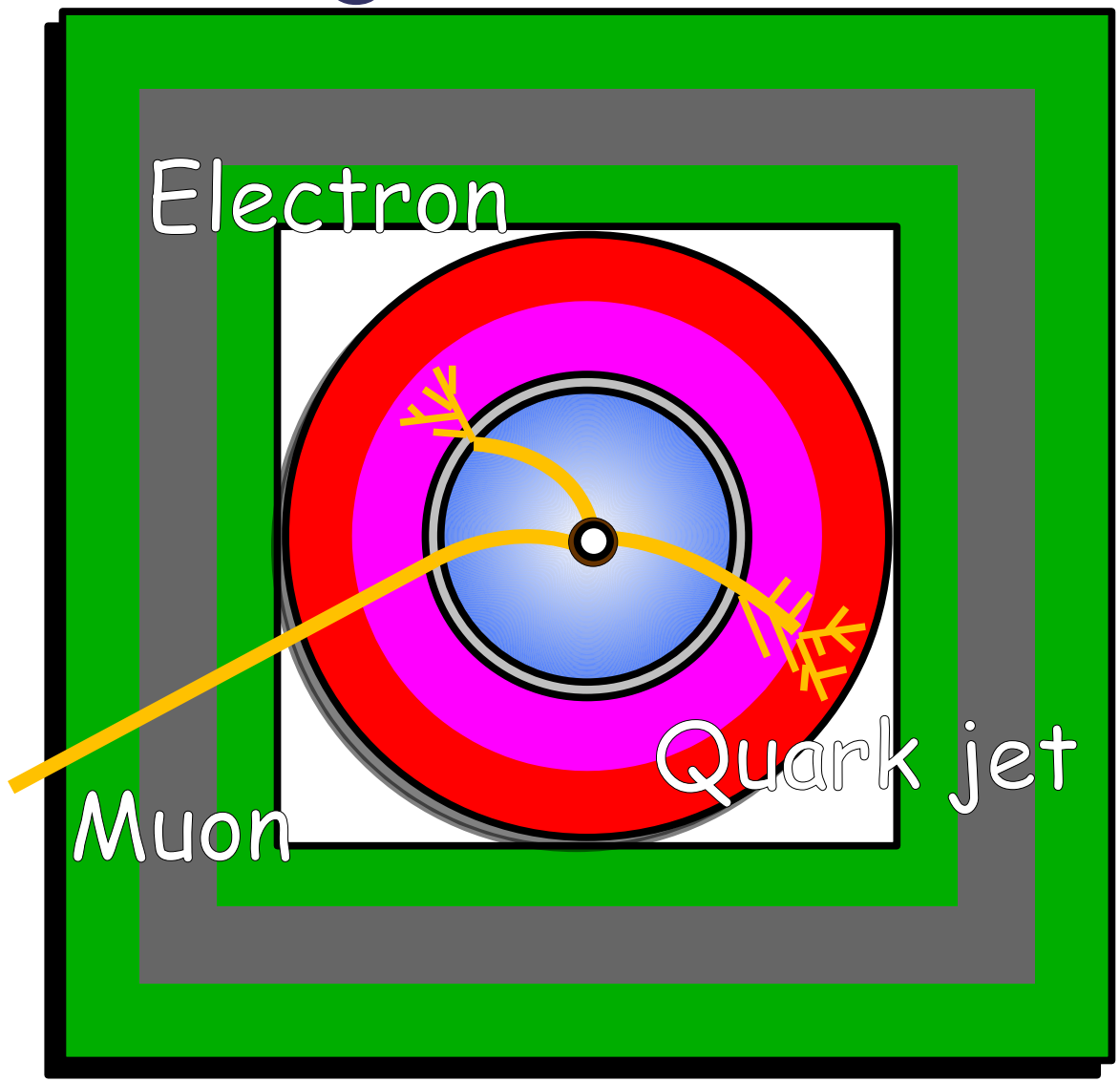
Beam pipe

Tracking detector

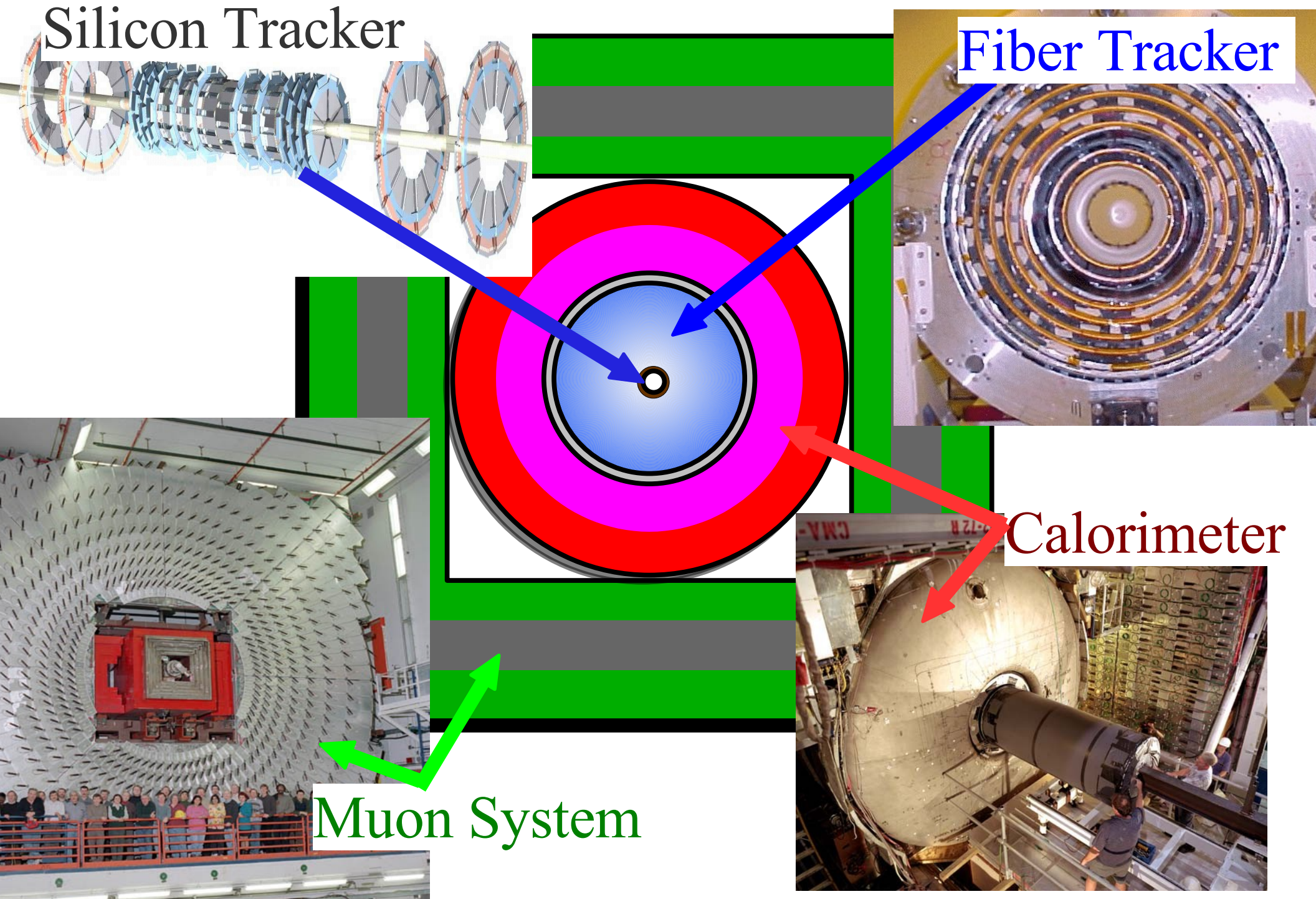
Magnet

Calorimeter:
EM and hadronic

Muon detectors
surrounding
another magnet



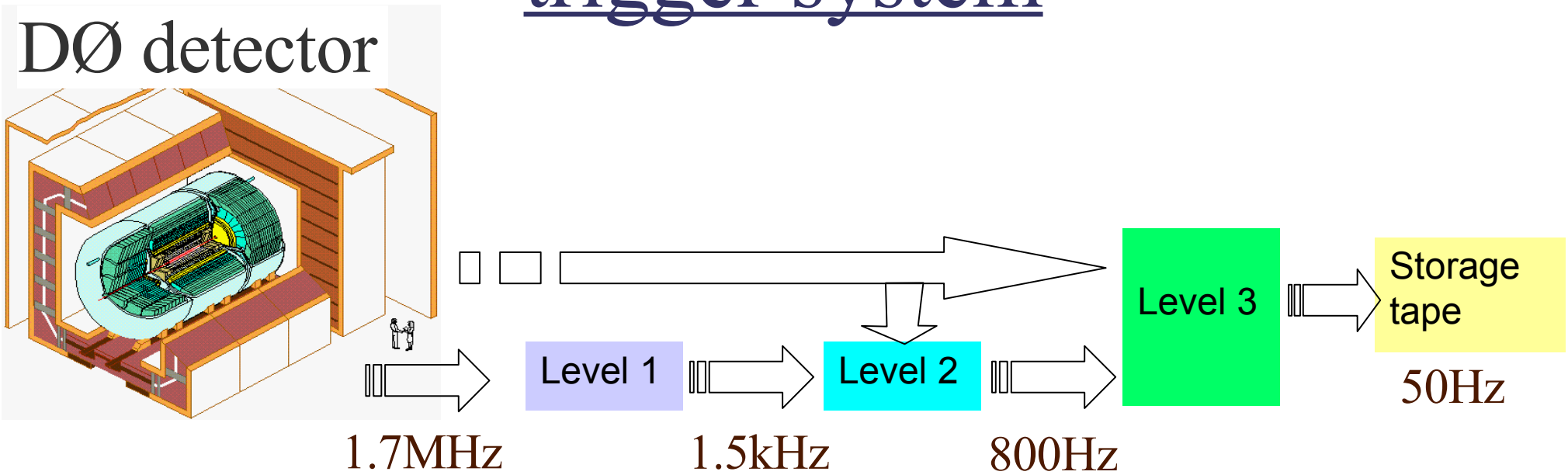
Apparatus: Run II DØ Detector



Experimenters

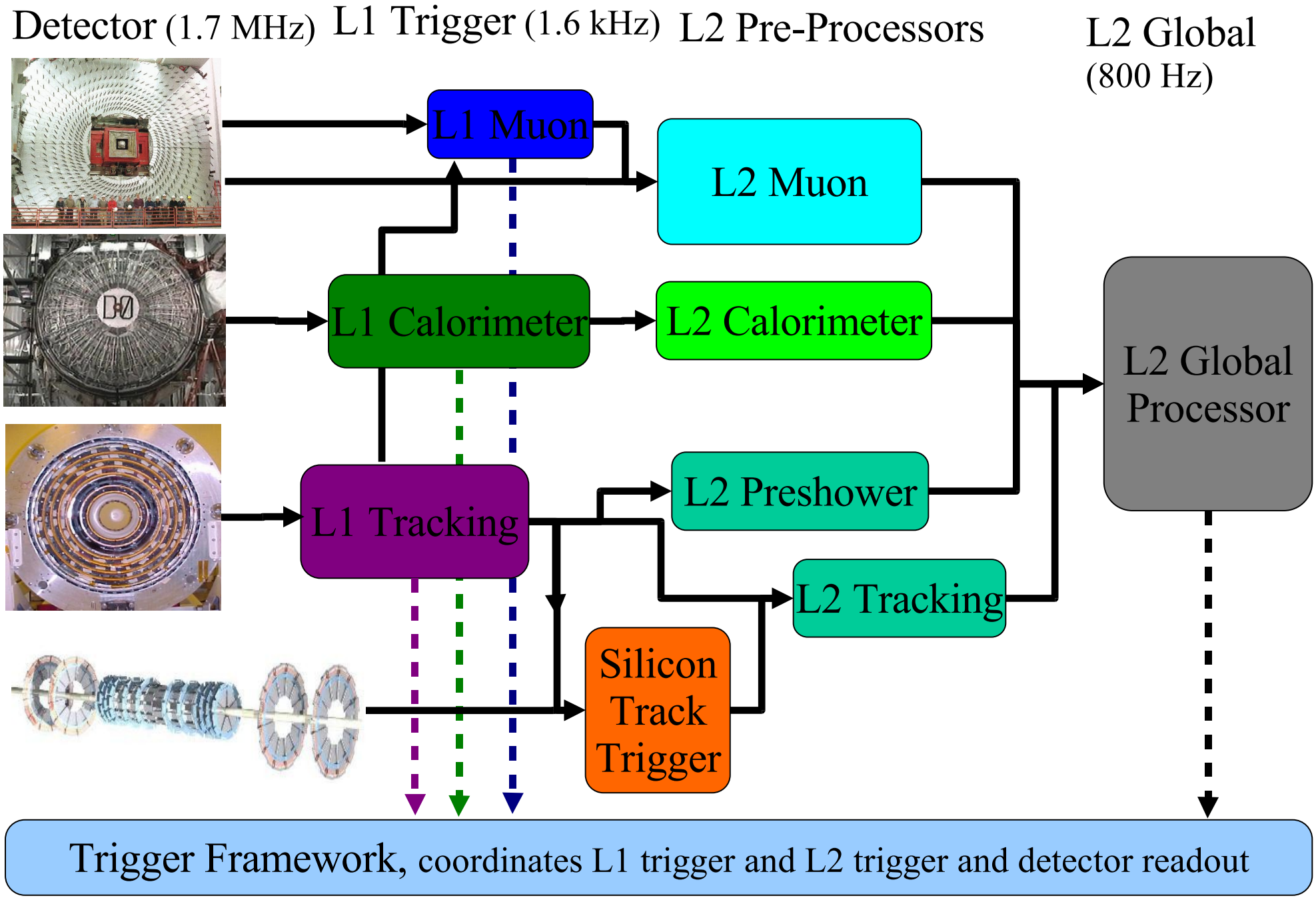
- 19 countries
- 80 institutions
- 670 physicists

Collecting interesting events: trigger system



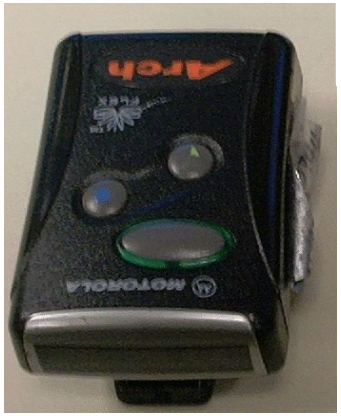
- Reduce rate of interactions (inelastic collisions) to manageable level that can be stored
- Record "interesting" events → trigger system
  - Select events containing high-energy final state objects
    - Electrons, muons, quark jets

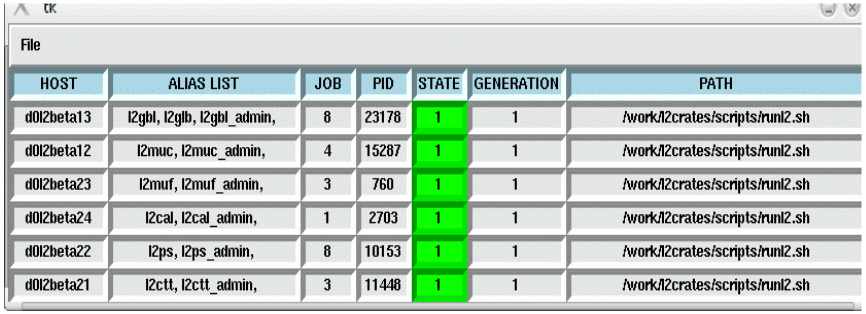
Trigger Level 1/Level 2 Dataflow



Trigger Level 2 System

- Processing on 6 CPUs
  - Commodity PCI card with custom dataflow interface
  - Intel Pentium P4 processor, running Linux
  - Centrally managed
    - Using both standard Linux tools and custom software





File

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d0l2beta24	l2cal, l2cal_admin,	1	2703	1	1	/work/l2crates/scripts/runl2.sh
d0l2beta22	l2ps, l2ps_admin,	8	10153	1	1	/work/l2crates/scripts/runl2.sh
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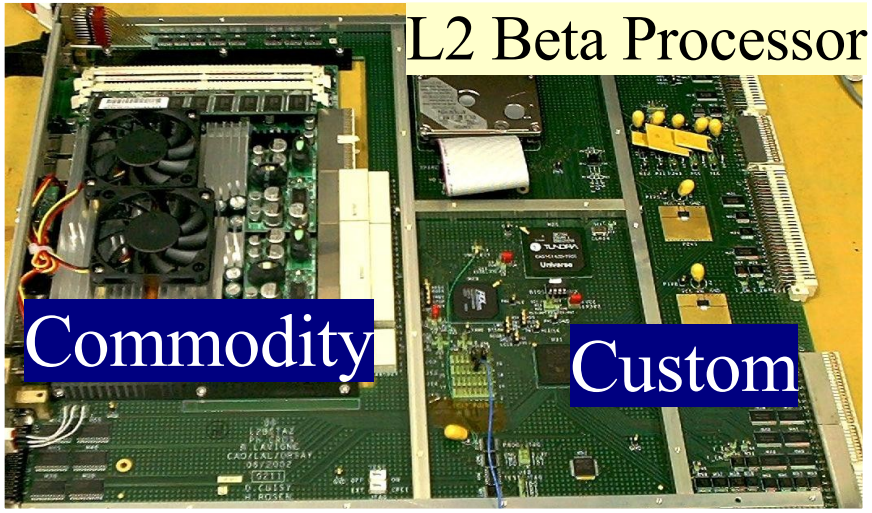
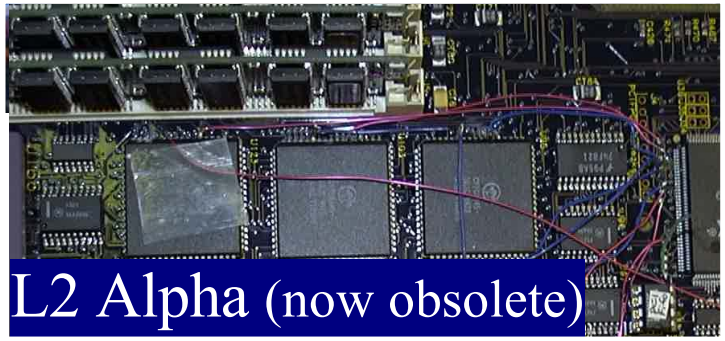
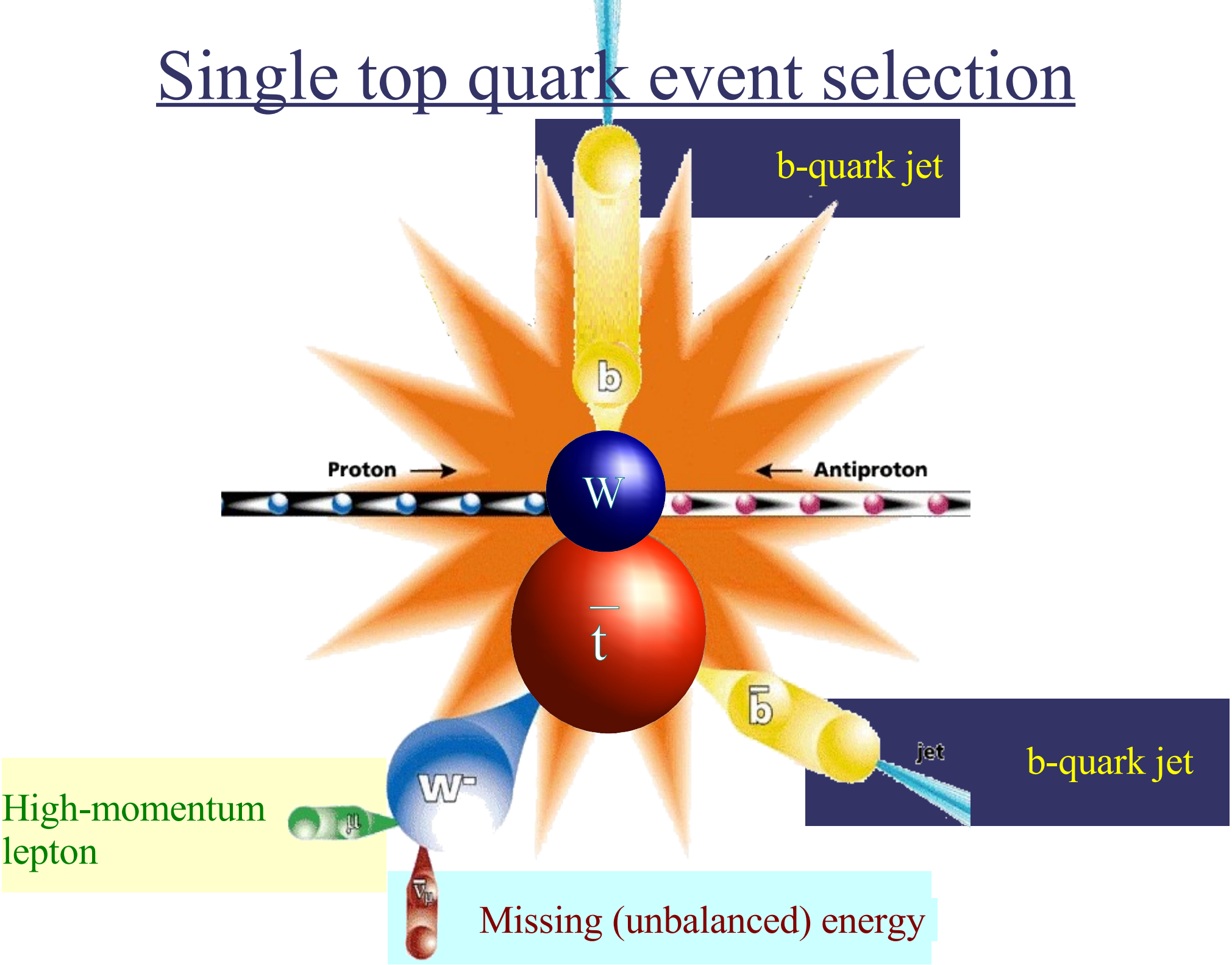




Current Results

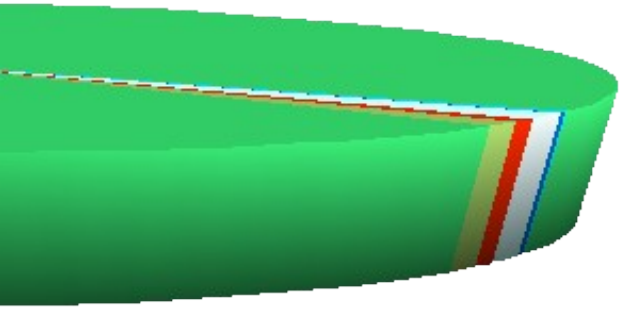
Precious data!

Single top quark event selection



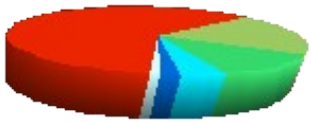
Single top quark events in data (230pb^{-1})

All:
10,000 events

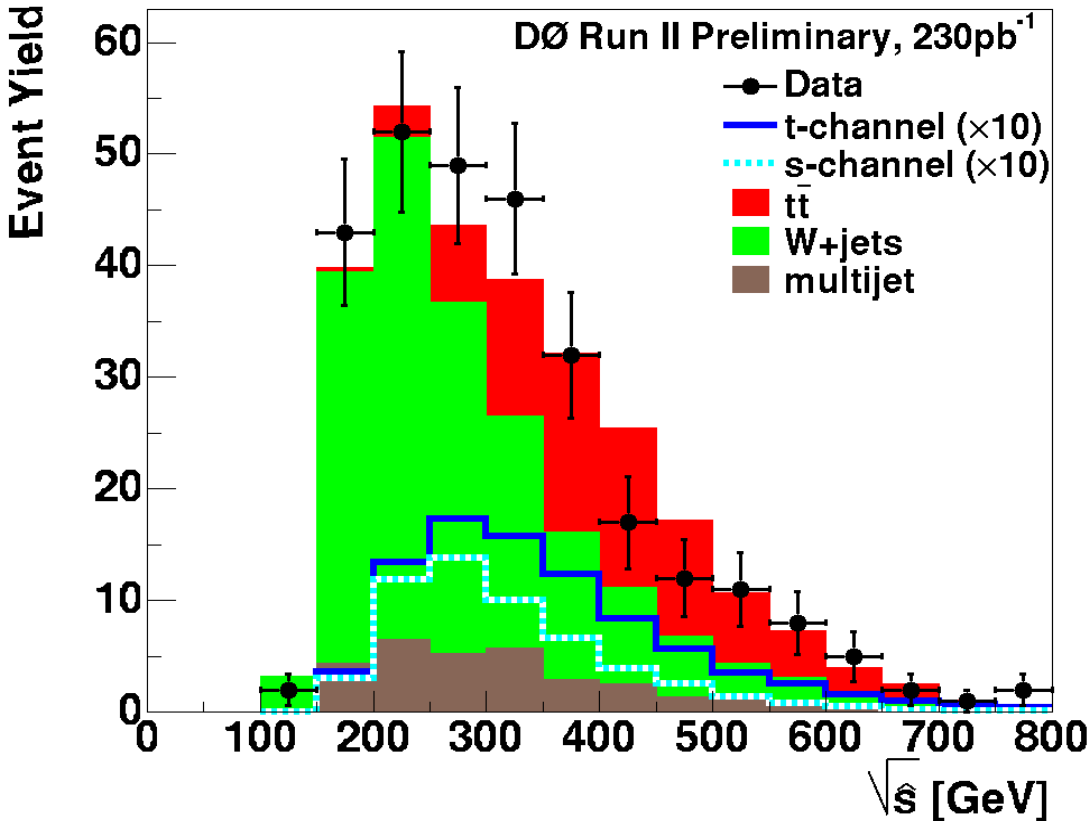


=1 b-tag:
367 events

=2 b-tags:
76 events



Top quark pairs
W+jets and
other non-top
Single top



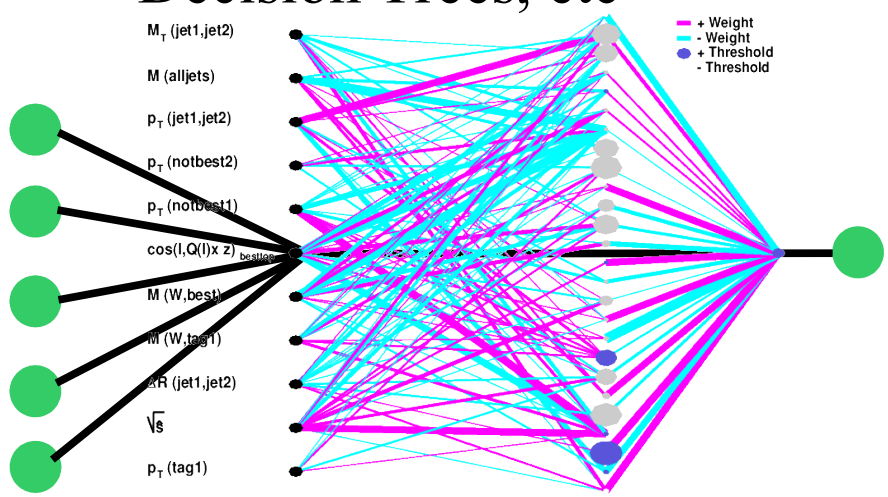
Separating Signal from Backgrounds

- Optimized event analysis

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

Neural Networks,
Decision Trees, etc

Event energy
Quark jet angle
Reconstructed top mass
Reconstructed top spin
.....

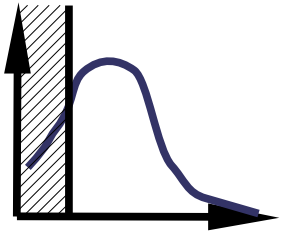


P(signal)

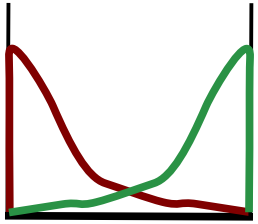
Event Analysis

- Advanced analysis techniques

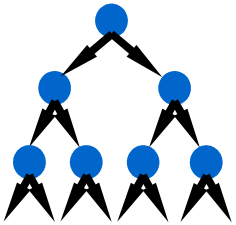
Cut-Based



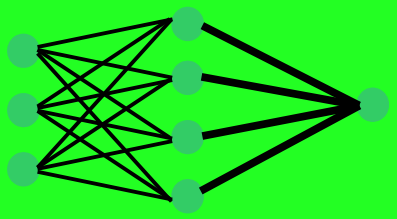
Likelihoods



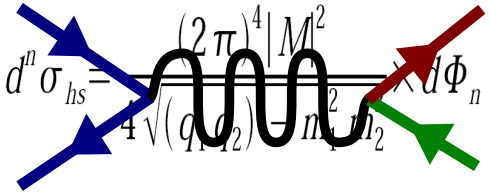
Decision Trees



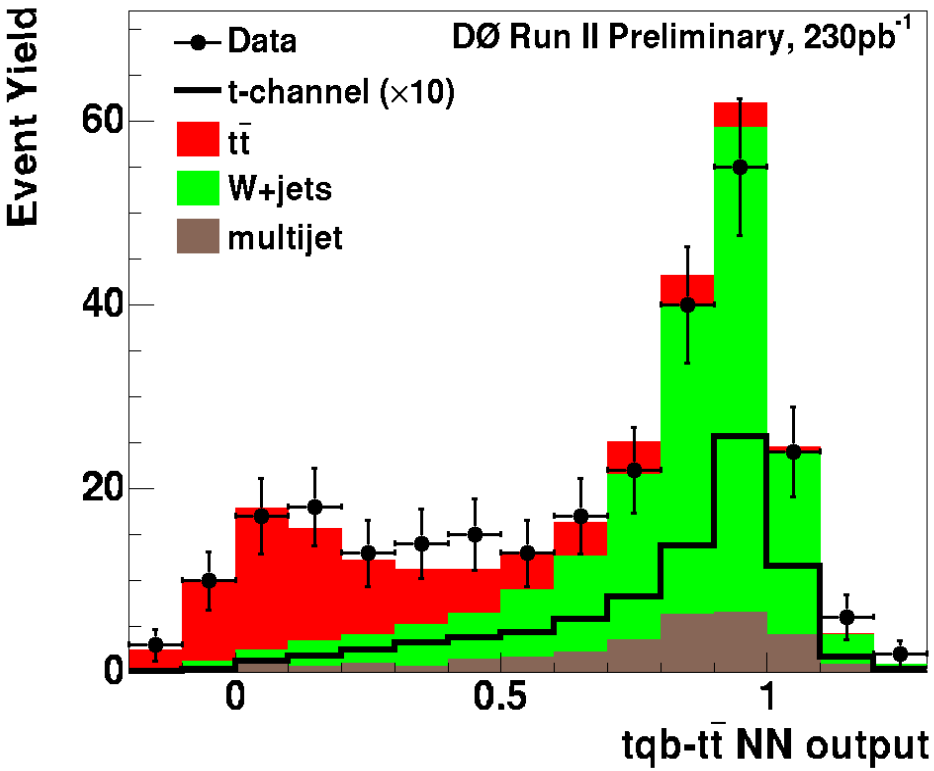
Neural Networks



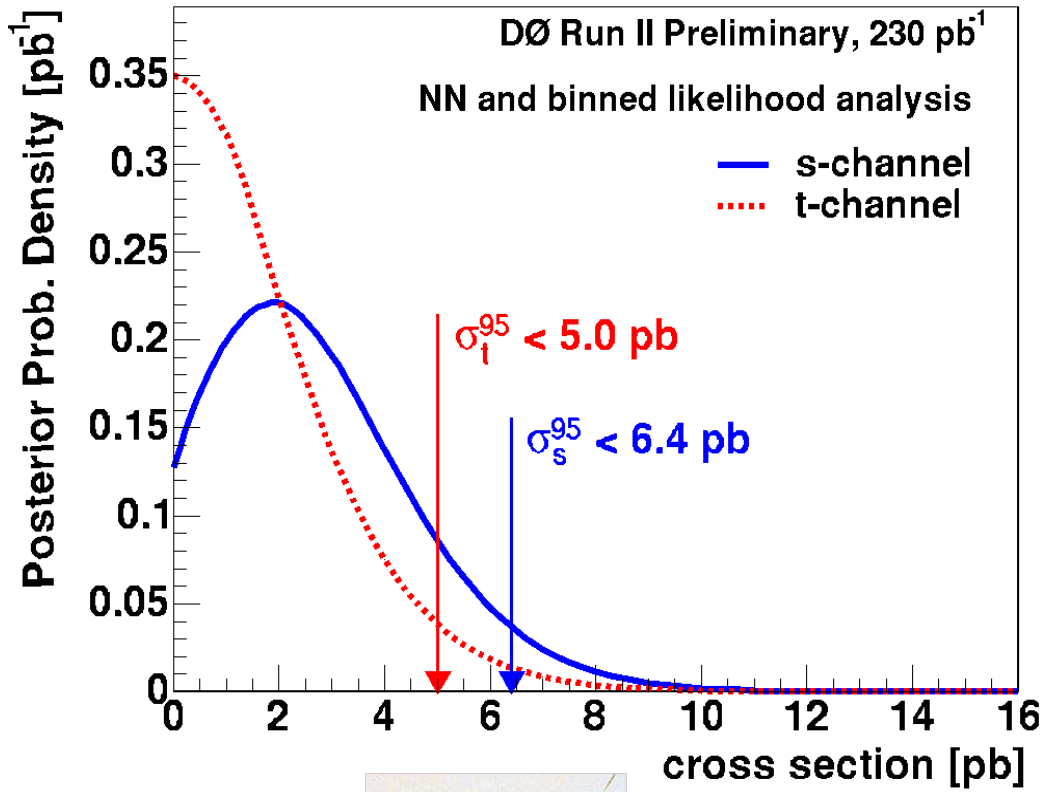
Matrix Elements



Result



- Bayesian statistical analysis
- Systematic uncertainty ~20%



Expected/Observed limit:

σ_s < 4.5 / 6.4 pb

σ_t < 5.8 / 5.0 pb

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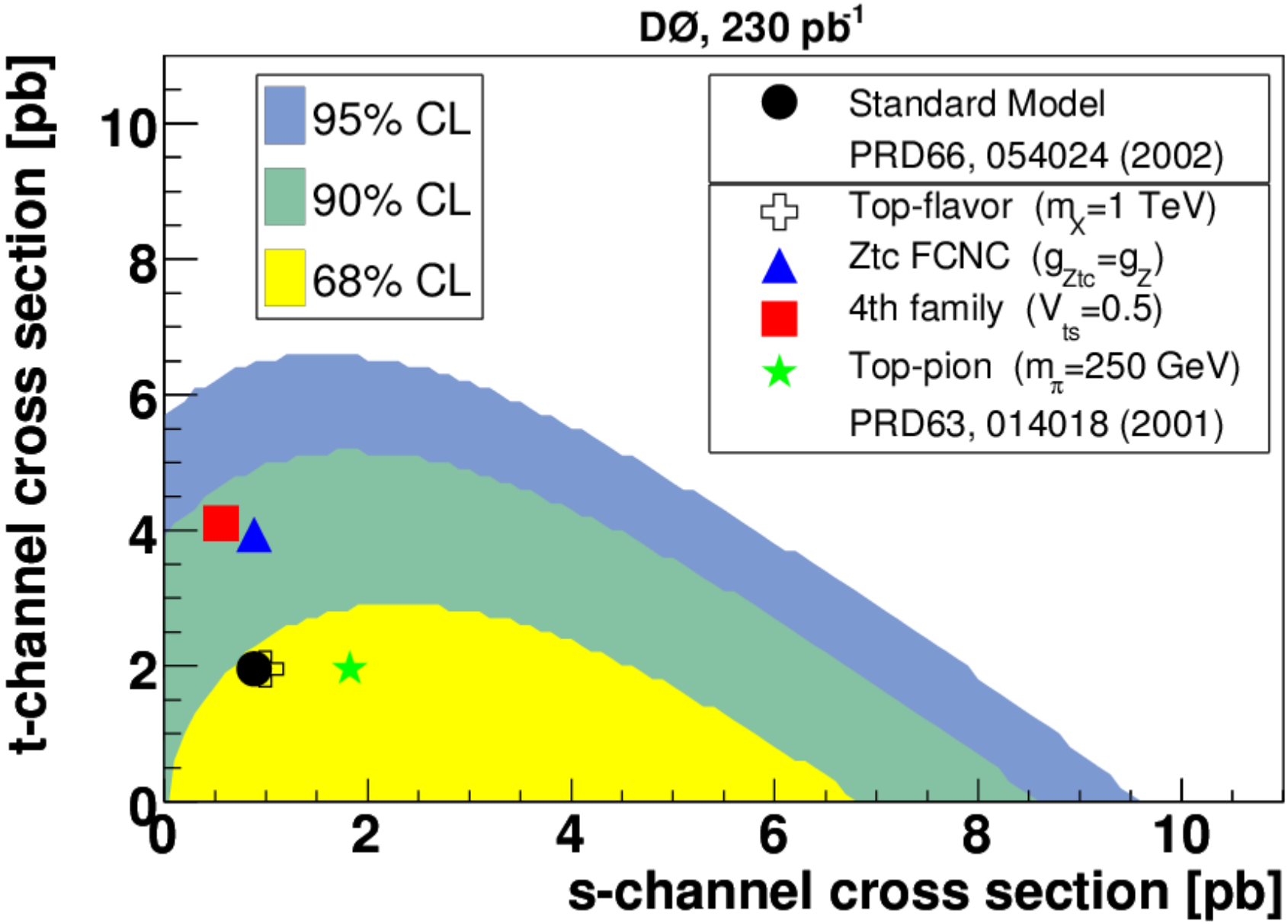
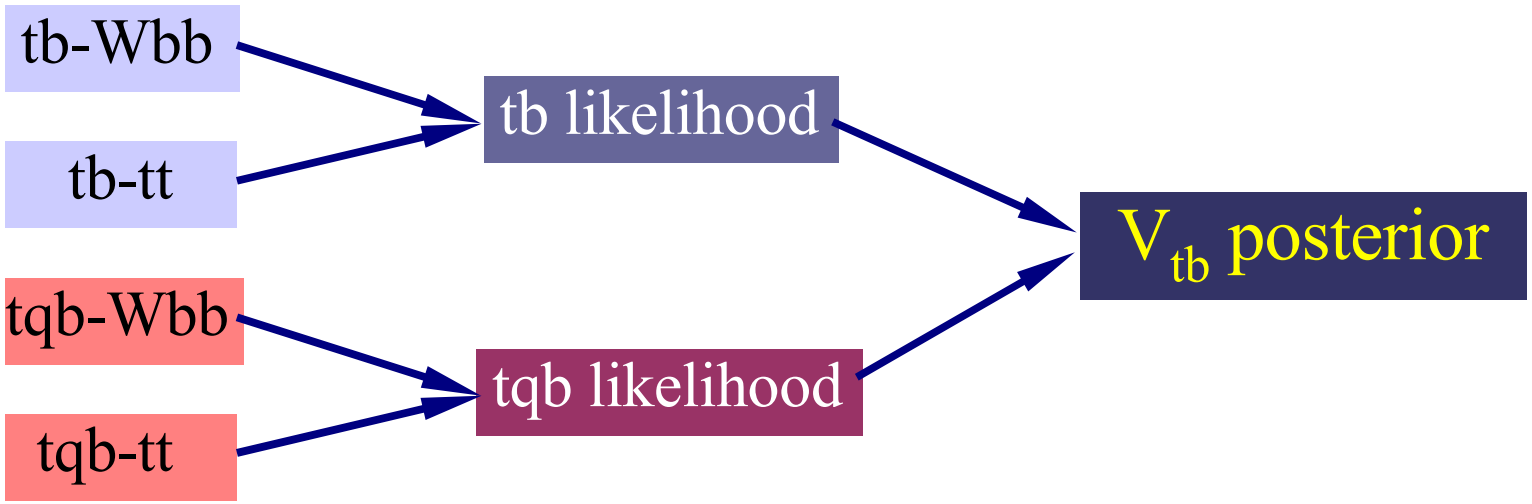
Sensitivity to non-SM Single Top



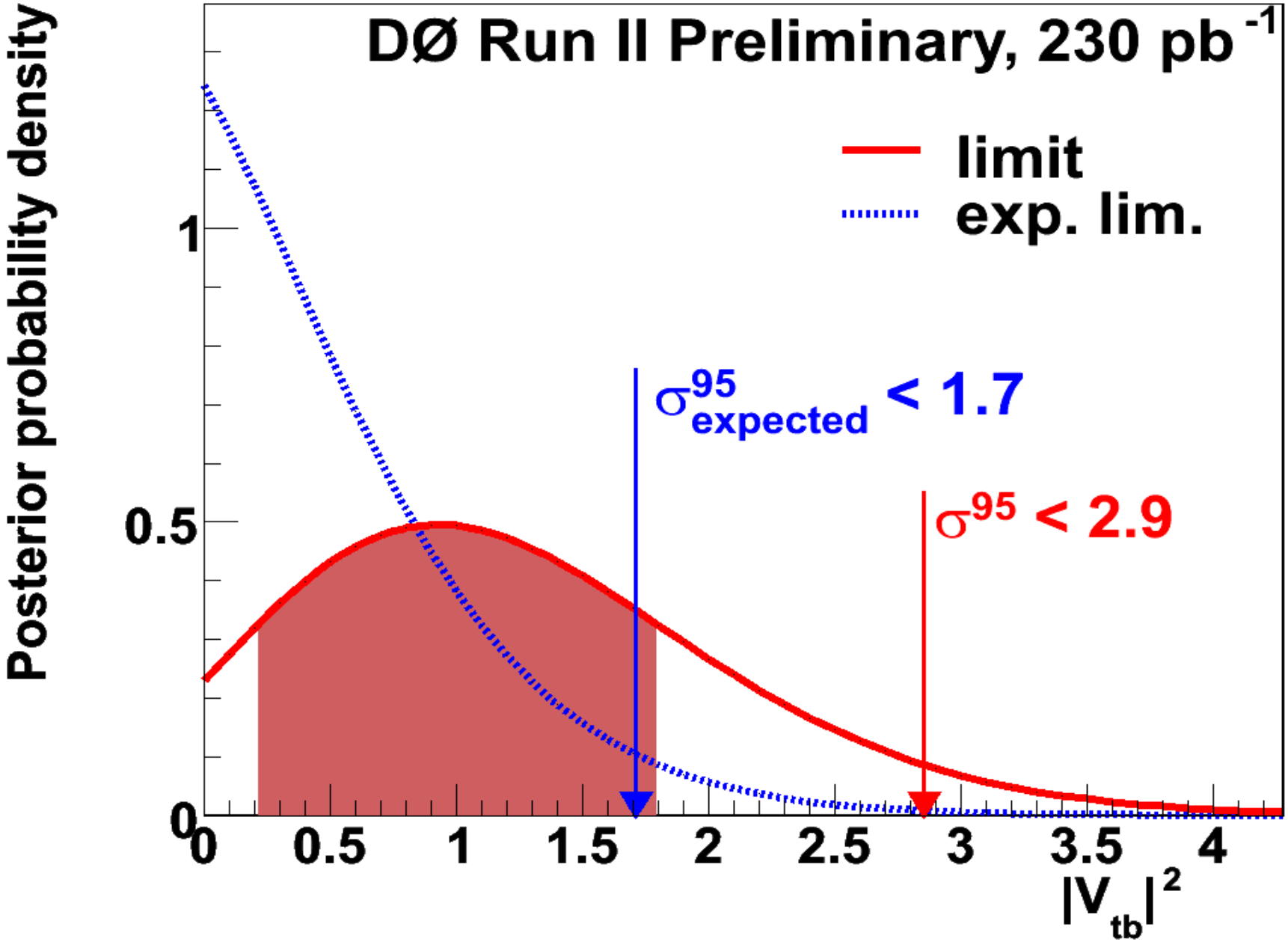
V_{tb} Coupling Limit

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



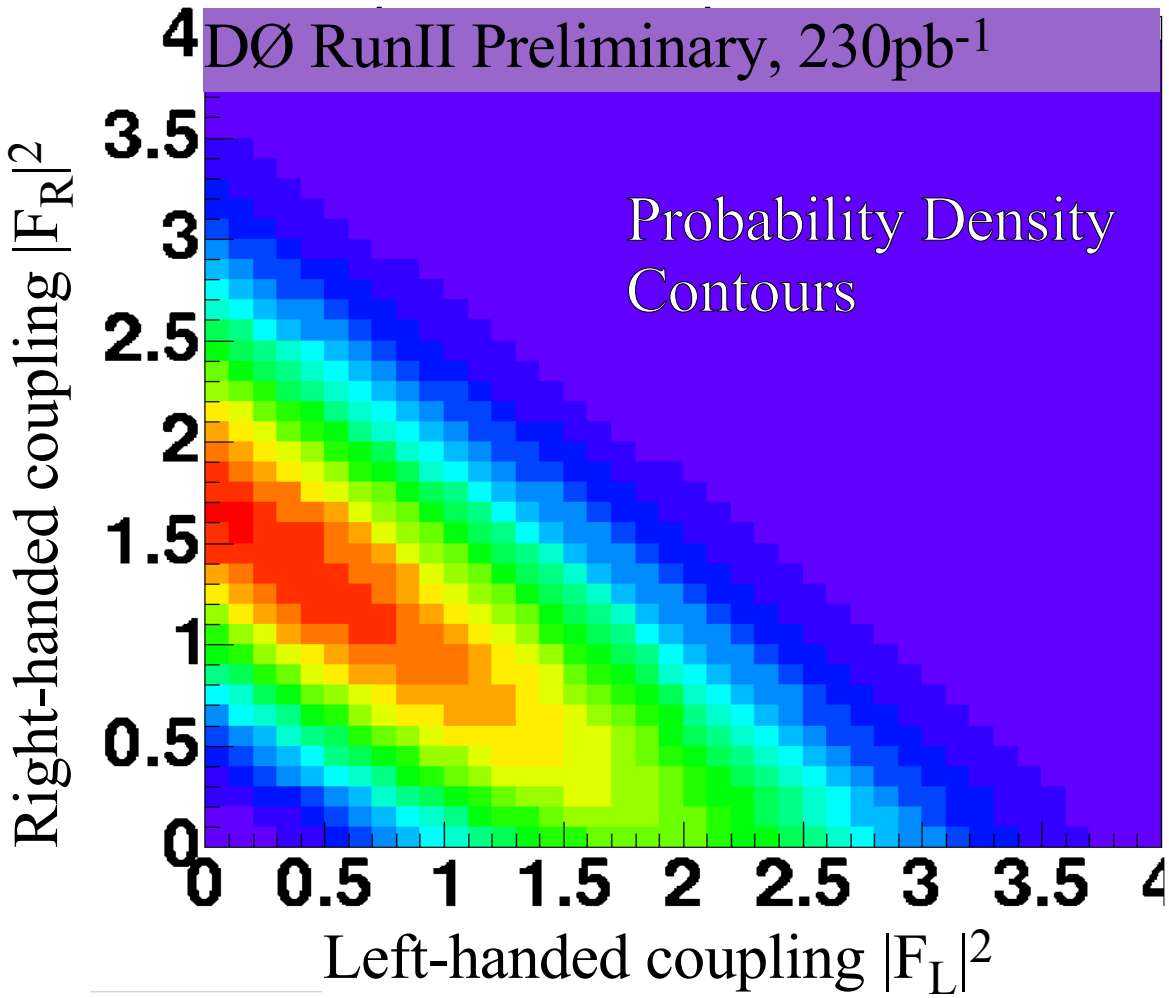
  - Need to assume SM ratio of cross sections

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

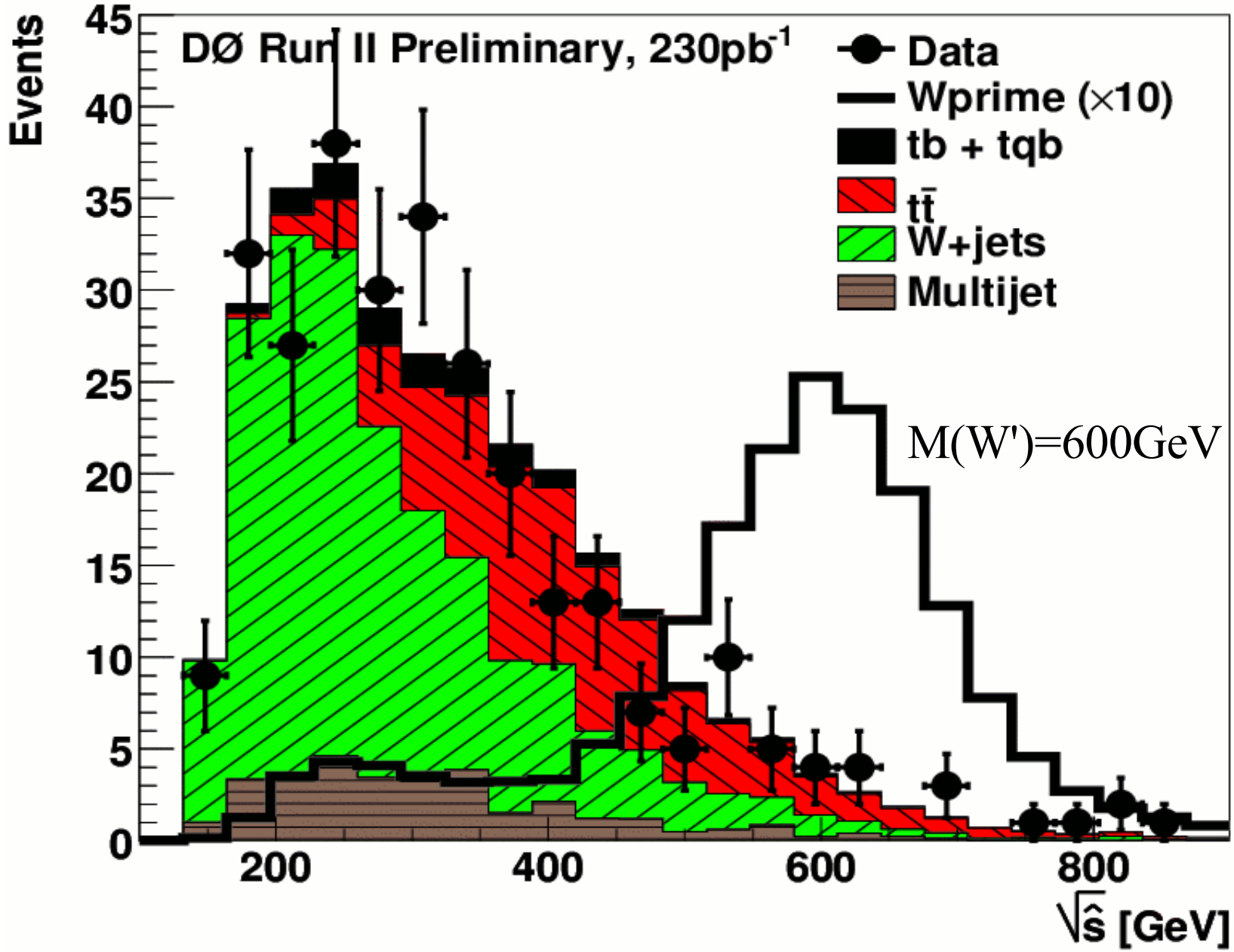


Left-handed or right-handed *W* coupling?

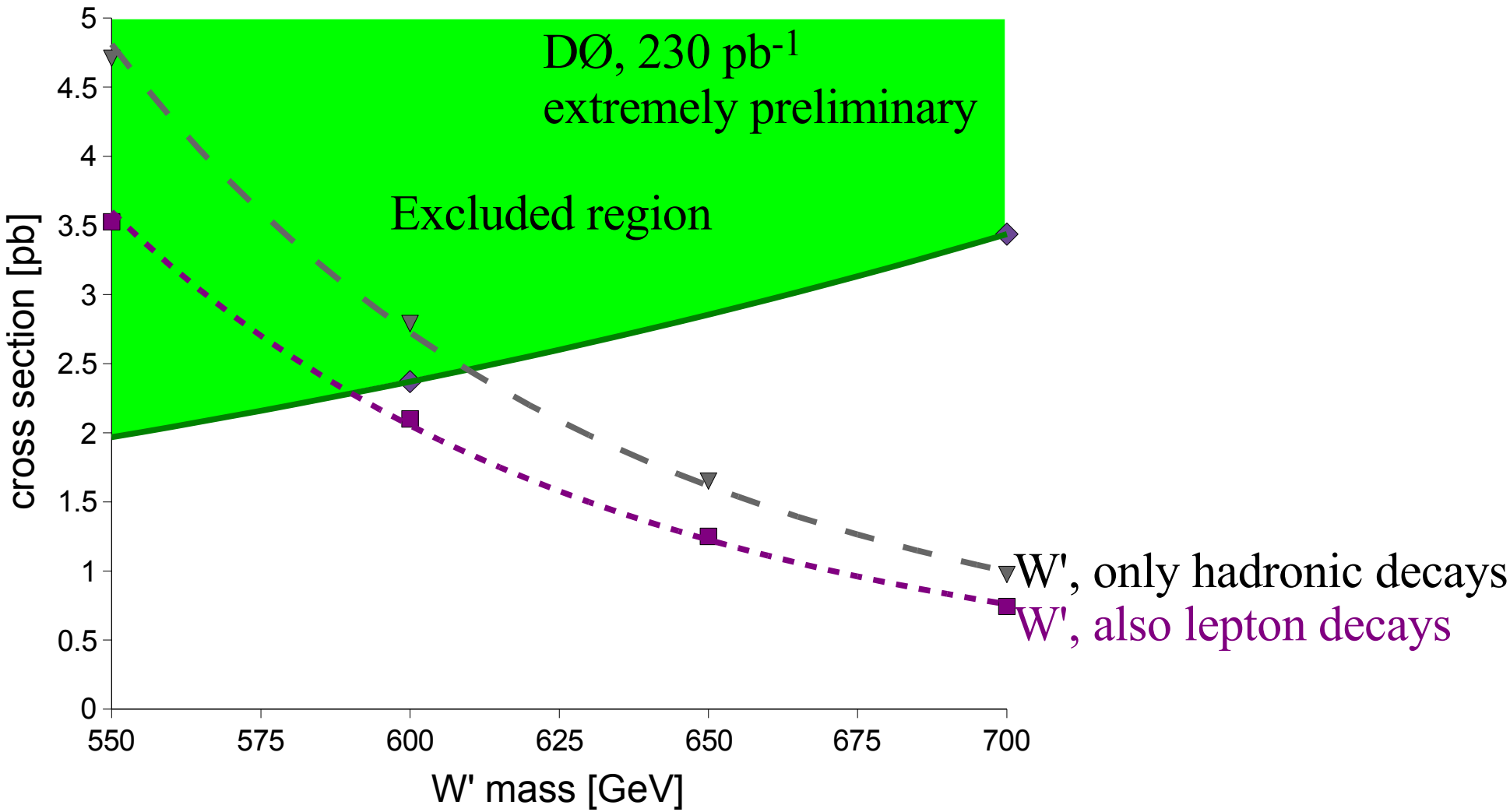
- Extremely preliminary
  - No systematic uncertainties, no full MC simulation



Extra heavy boson *W'*?

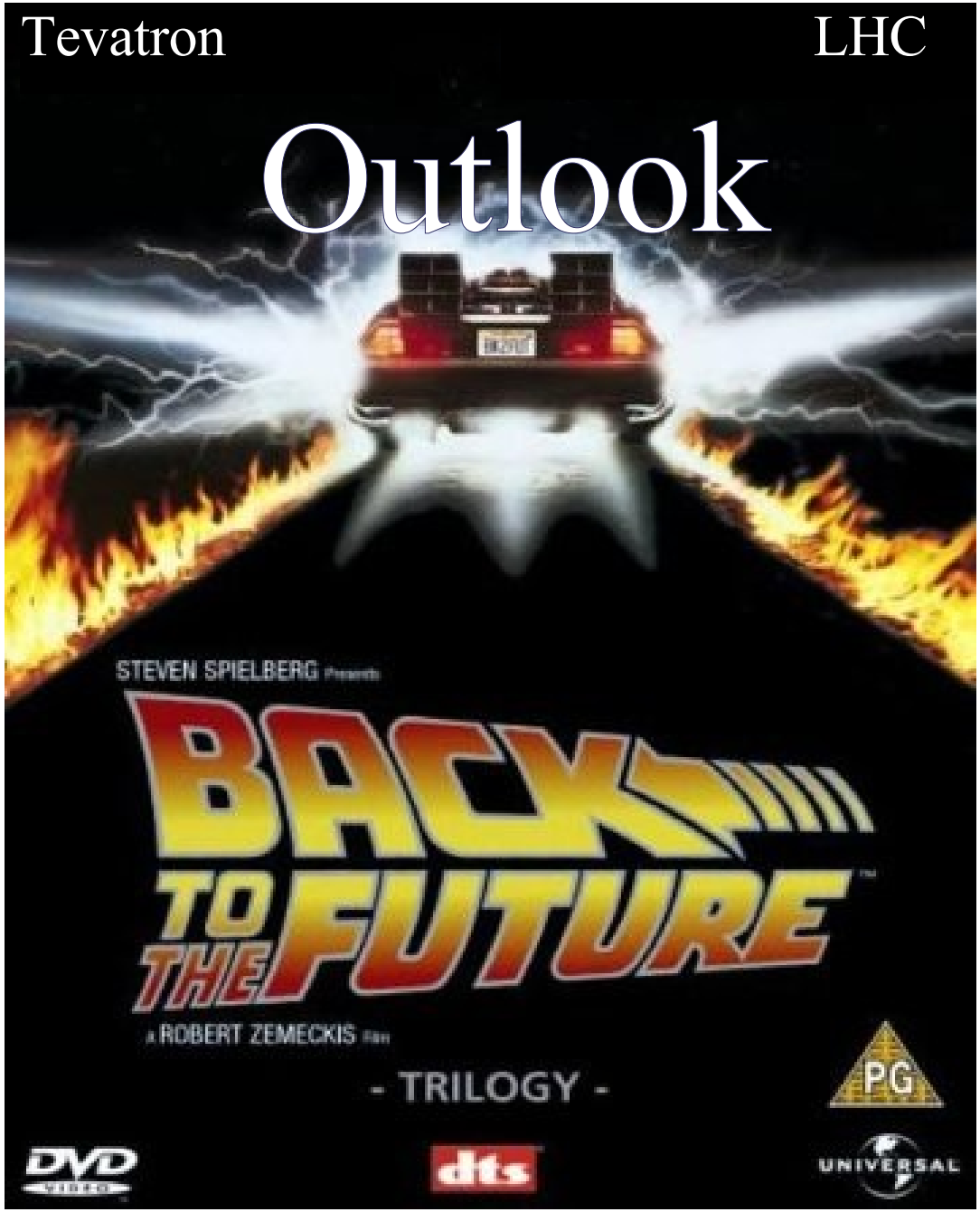


W' mass limit


DØ, 230 pb-1
extremely preliminary
Excluded region
cross section [pb]
W' mass [GeV]
W', only hadronic decays
W', also lepton decays
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
550
575
600
625
650
675
700

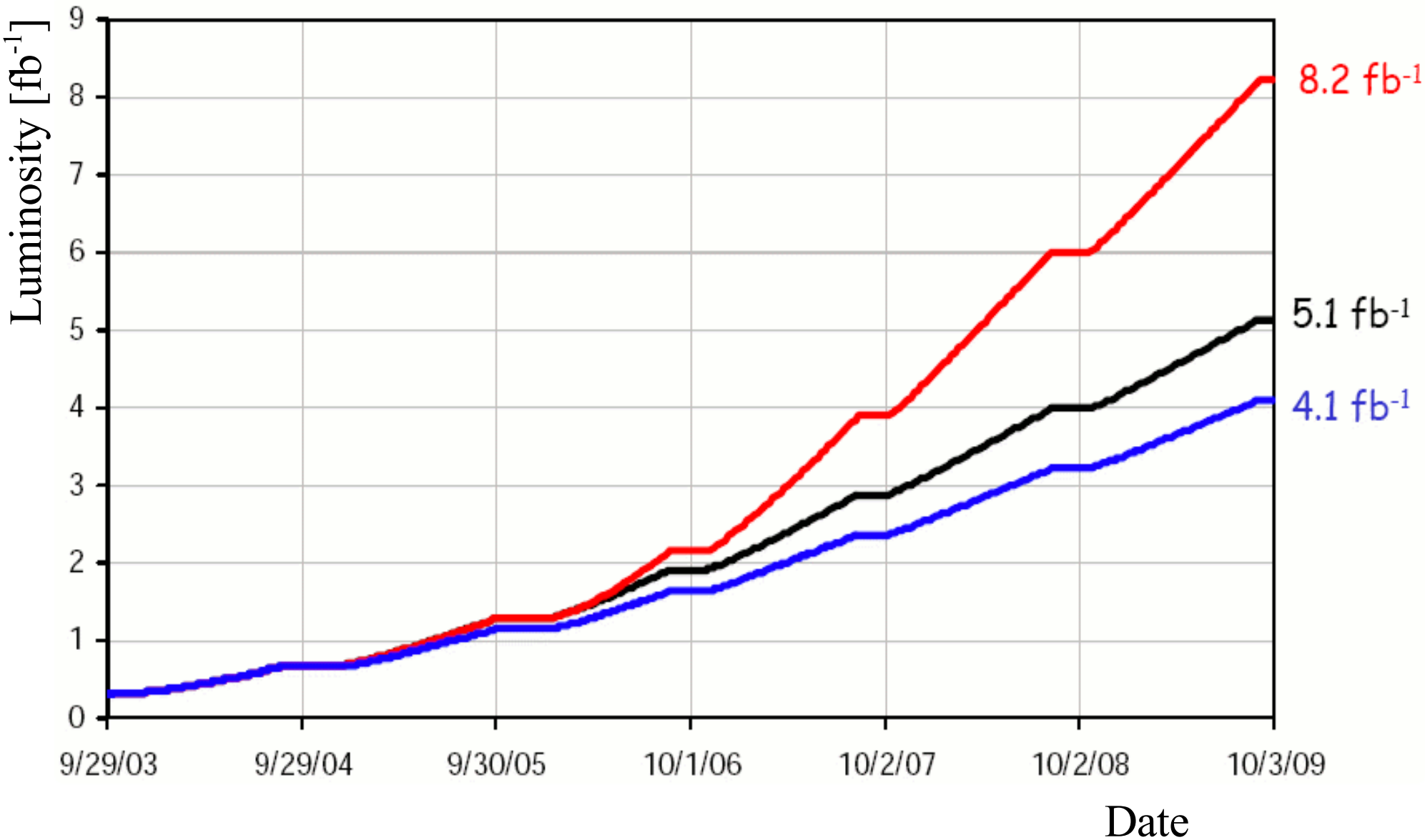
Analysis Computing

- Data storing and processing
  - And re-processing as understanding improves
  - Typically done centrally (at Fermilab)
- Monte Carlo Production
  - Every signal and background signature
  - Done centrally and on remote farms
- Final analysis computing
  - Tuning cuts, computing likelihoods, building Neural Networks, ...
  - Repeated many times
  - Done by individual users
    - Using available resources

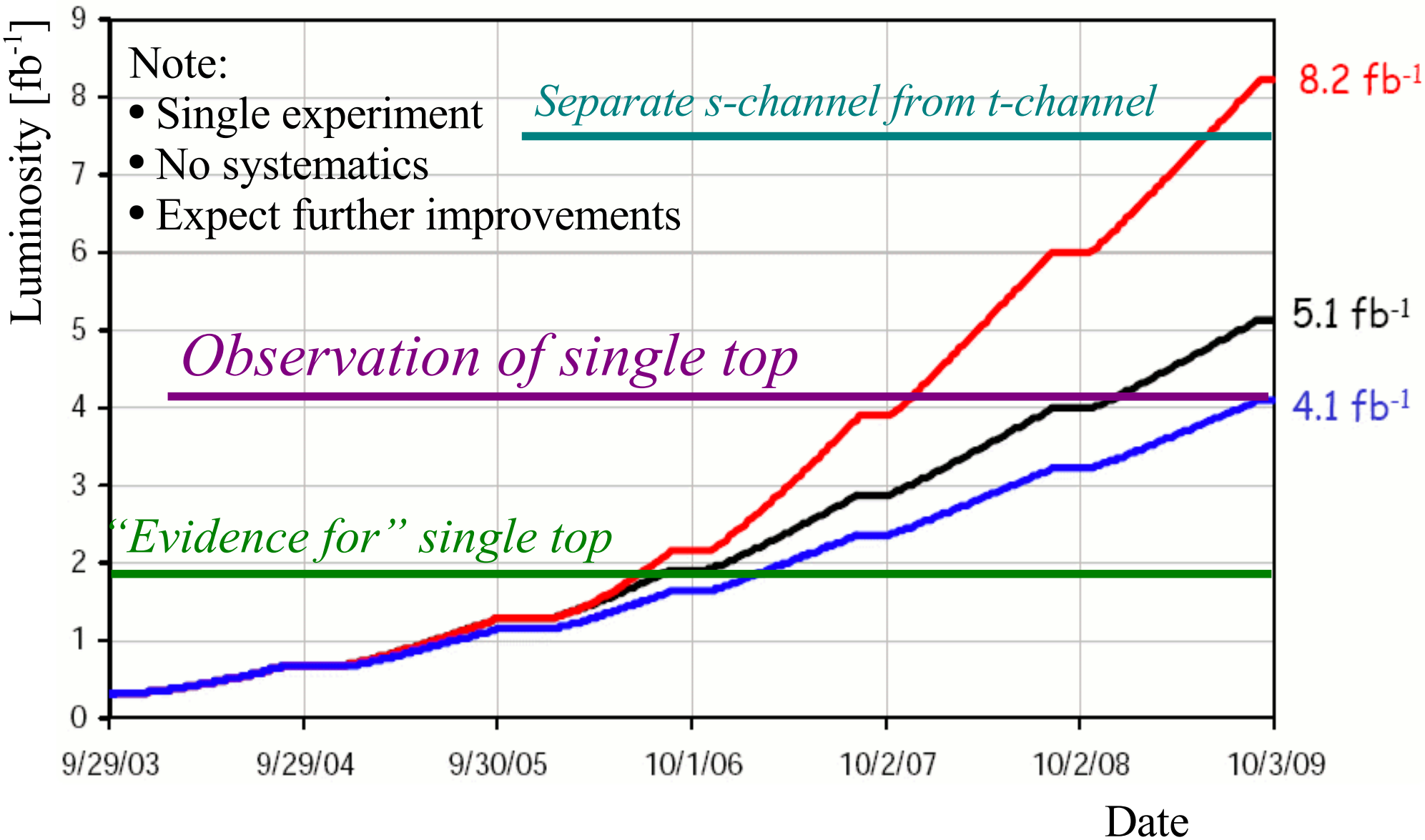


I never think of the future. It comes soon enough.
Albert Einstein

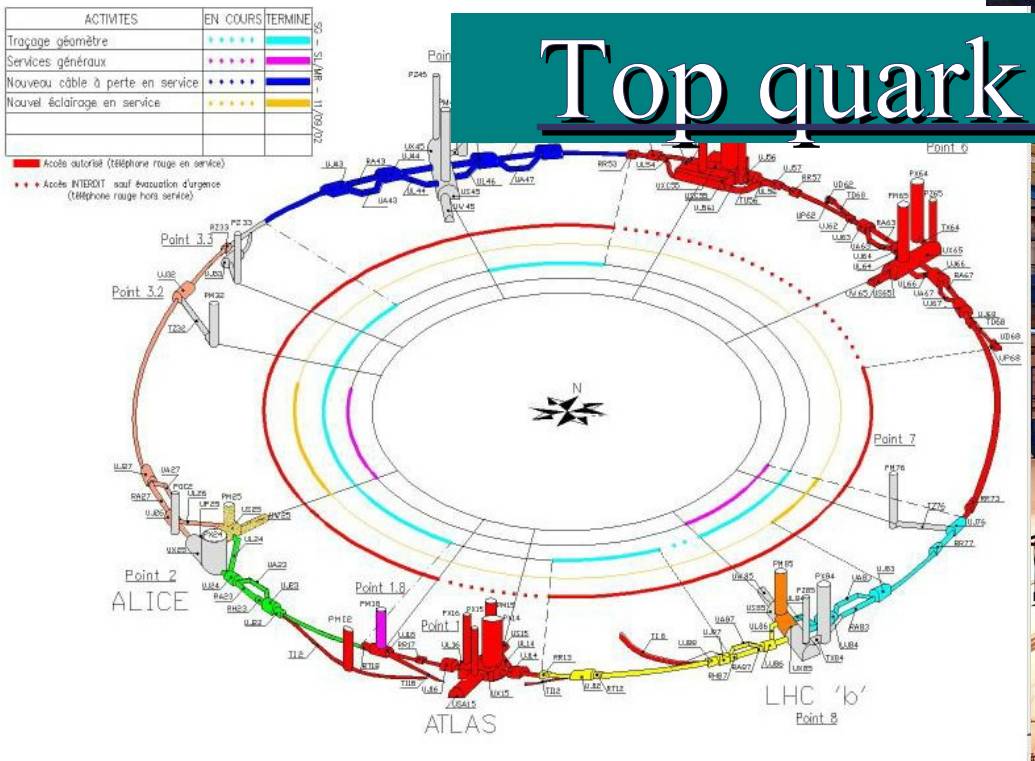
Tevatron luminosity projection

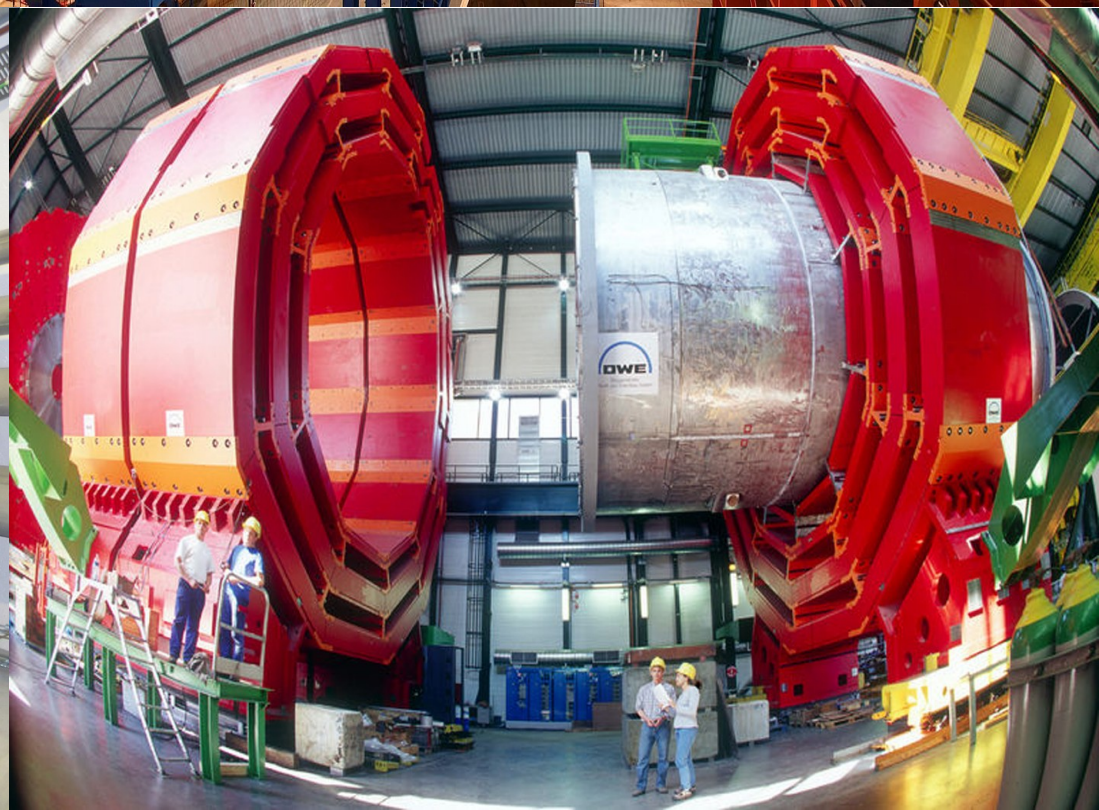


Tevatron luminosity projection

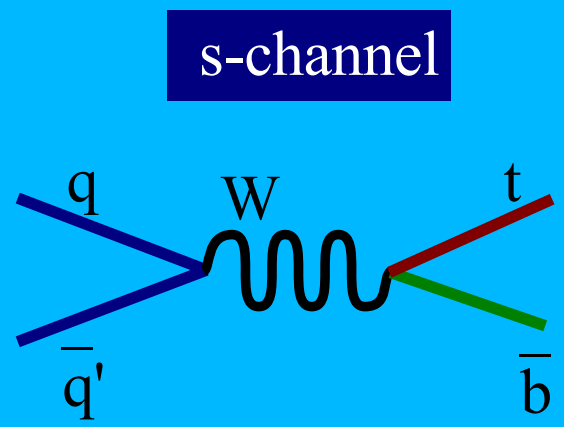


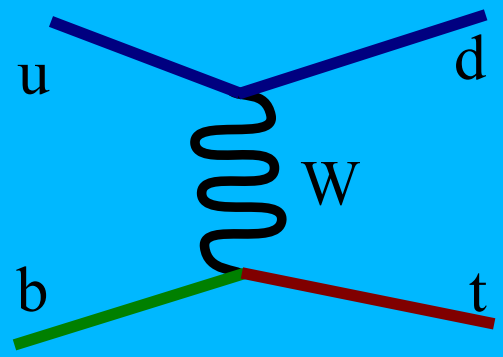
Top quark future: LHC

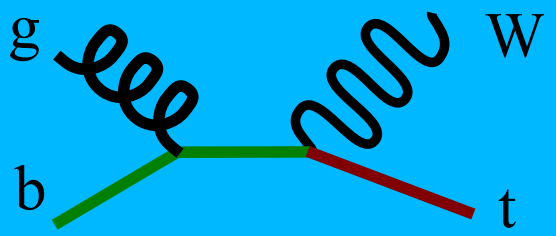




Top quark future: LHC







- 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

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