Single Top Quark Physics

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LBL RPM seminar, 3/7/2006

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
  - The top quark
- The Energy Frontier
- Search for Single Top Quark Production
- Outlook
- Conclusions

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

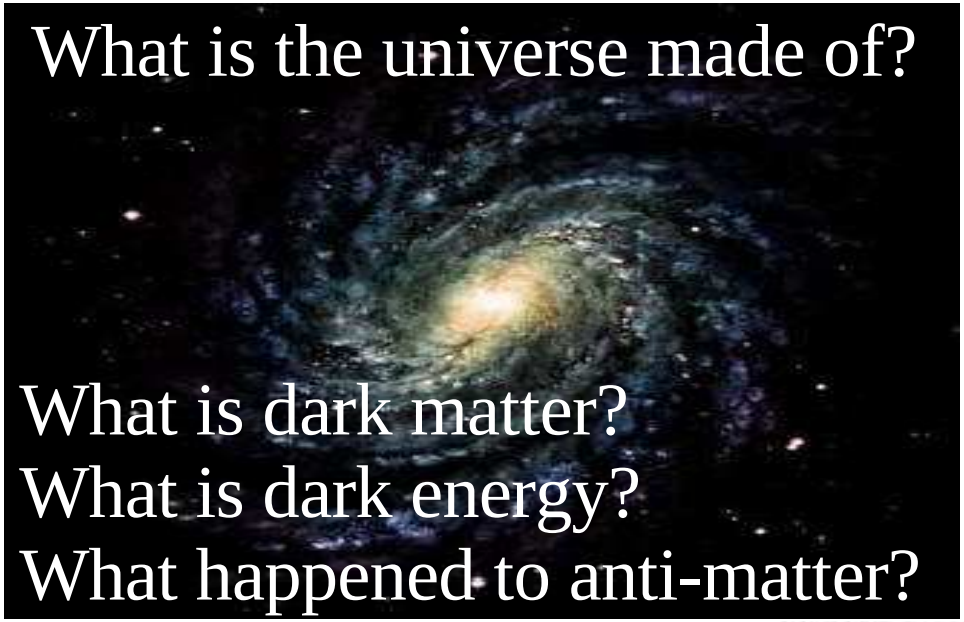
- Cross section in picobarn
  (1 barn = 10^{-24} cm^2)
  - Luminosity in $\frac{1}{\text{picobarn}}$

A fundamental question

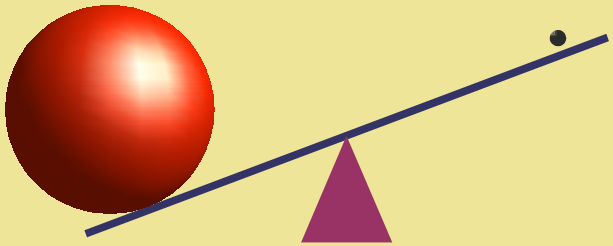
What is the origin of matter?

What is the origin of matter?

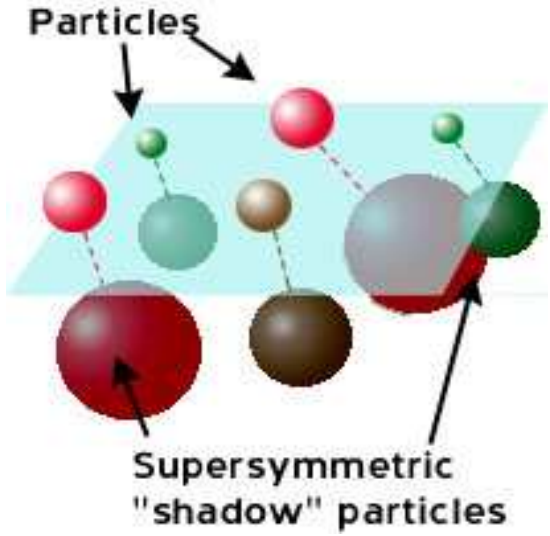
What gives mass to elementary particles?



What makes quarks so heavy and neutrinos so light?



quark neutrino



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.

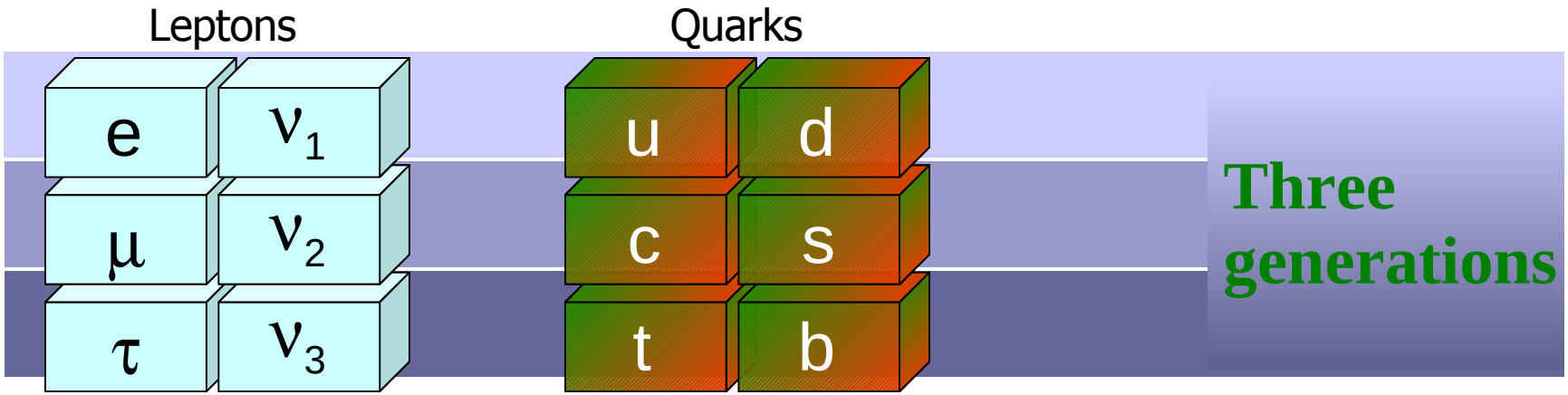
Galileo

State of the art

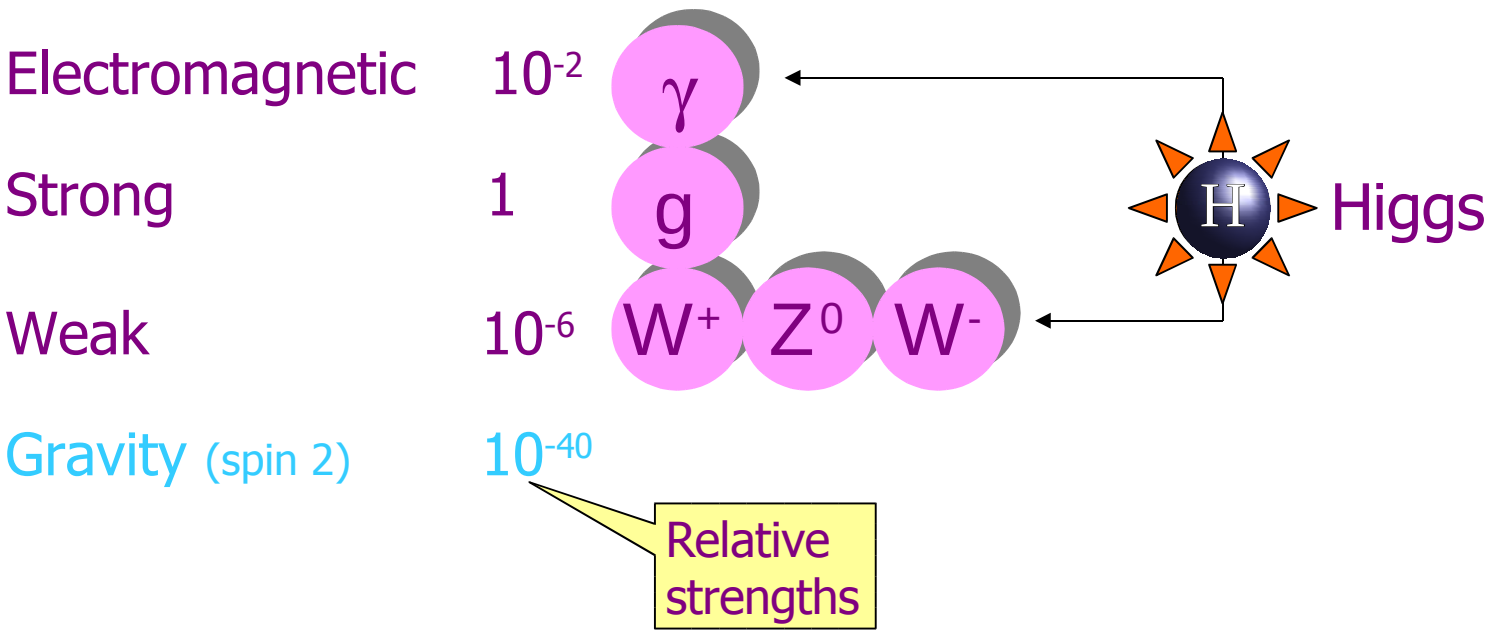
What do we know already?

Standard model of particles and forces

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

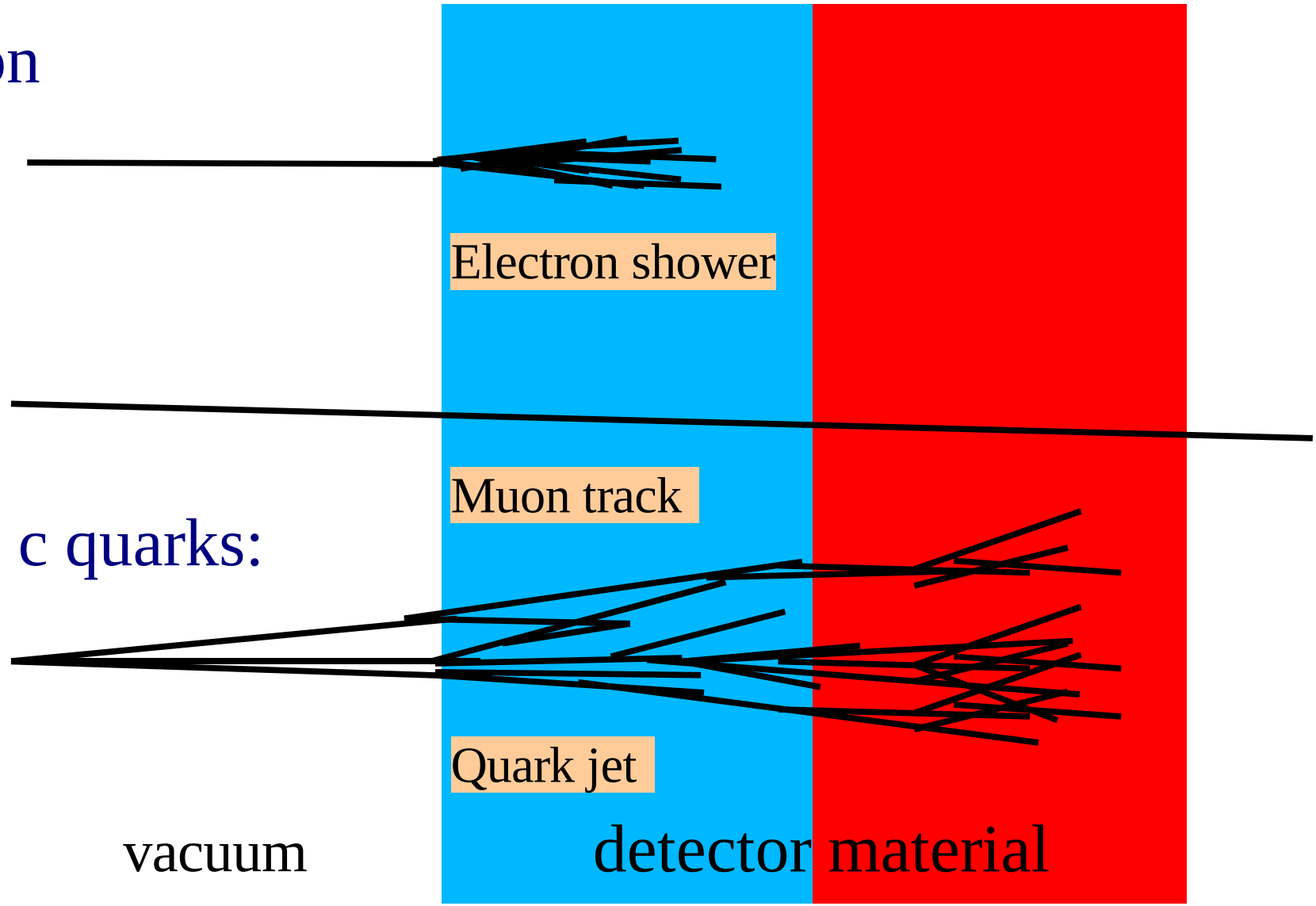


- Which interact by exchanging spin-1 vector bosons



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

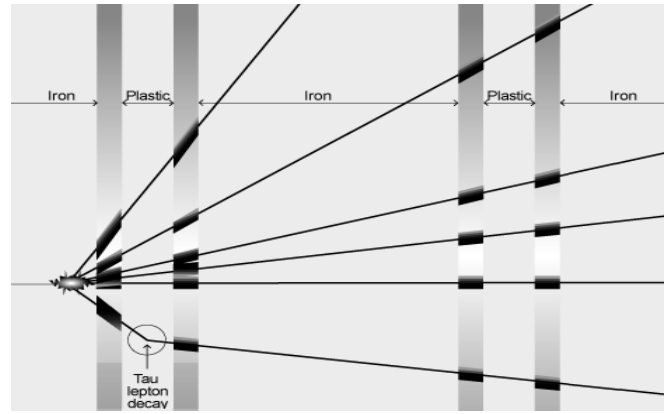
The third generation

Tau lepton

Discovered 1975 at SLAC

Tau neutrino

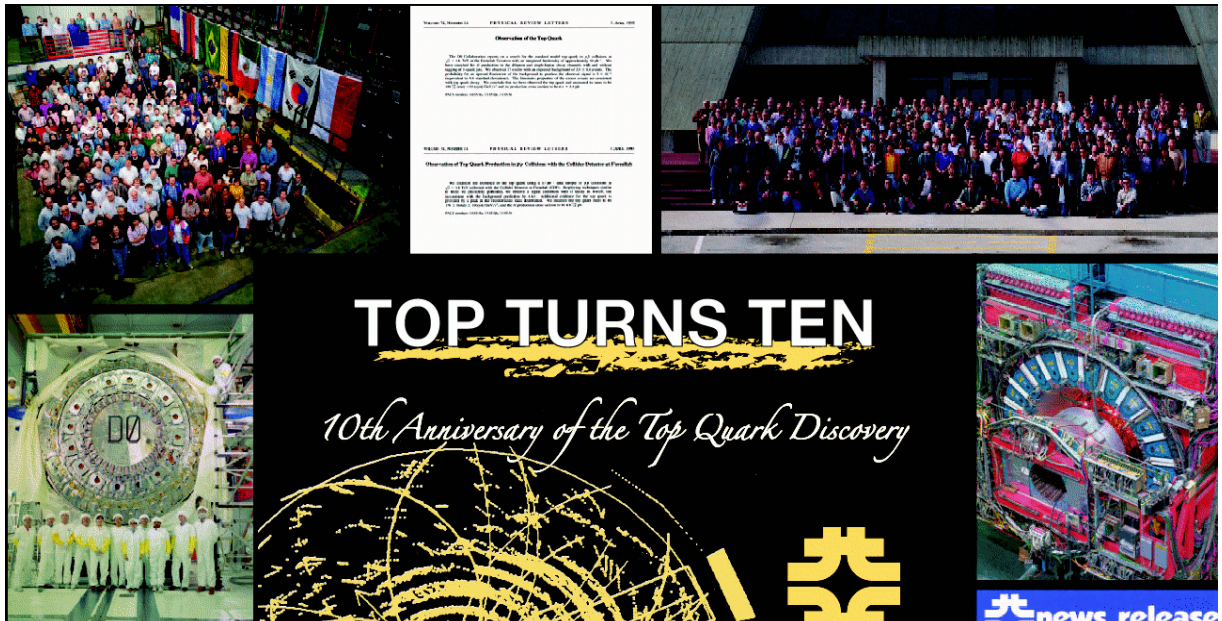
Discovered 2000 at Fermilab



bottom quark

Discovered 1978 at Fermilab

top quark

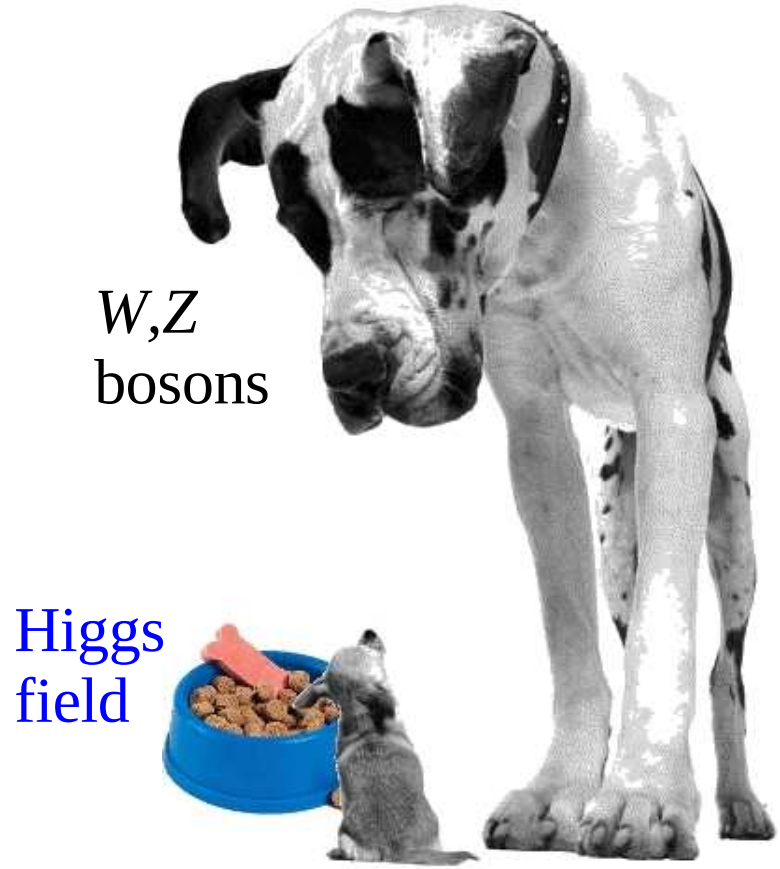


Gauge boson masses in the SM

Gauge bosons

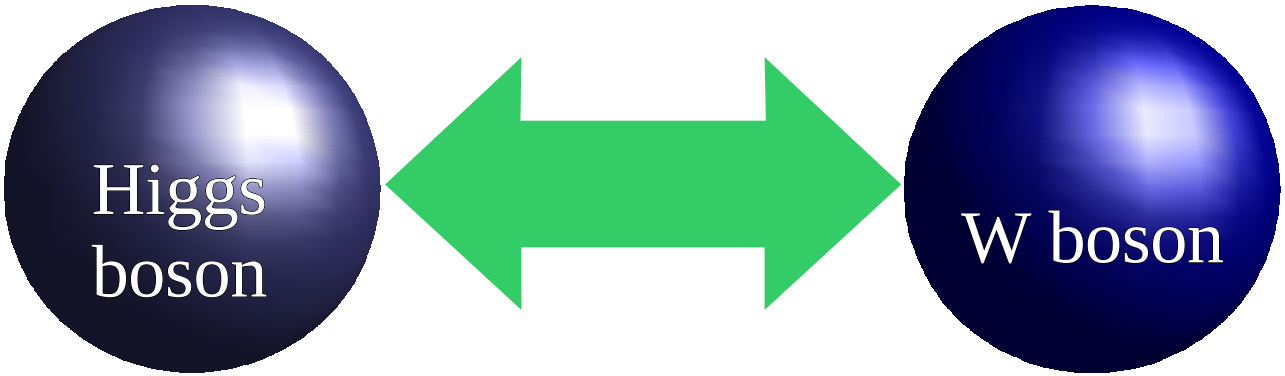
Higgs field

Electroweak symmetry breaking



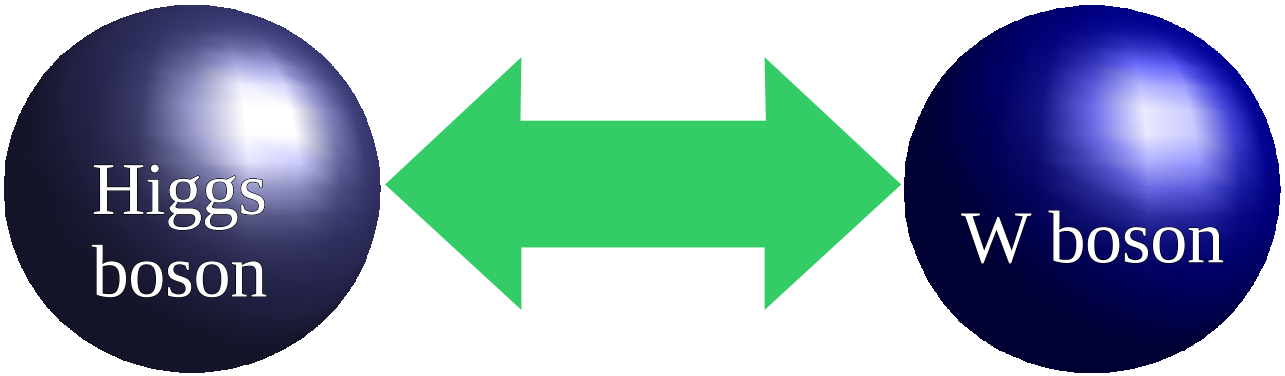
Electroweak symmetry breaking

Gauge boson coupling to Higgs field

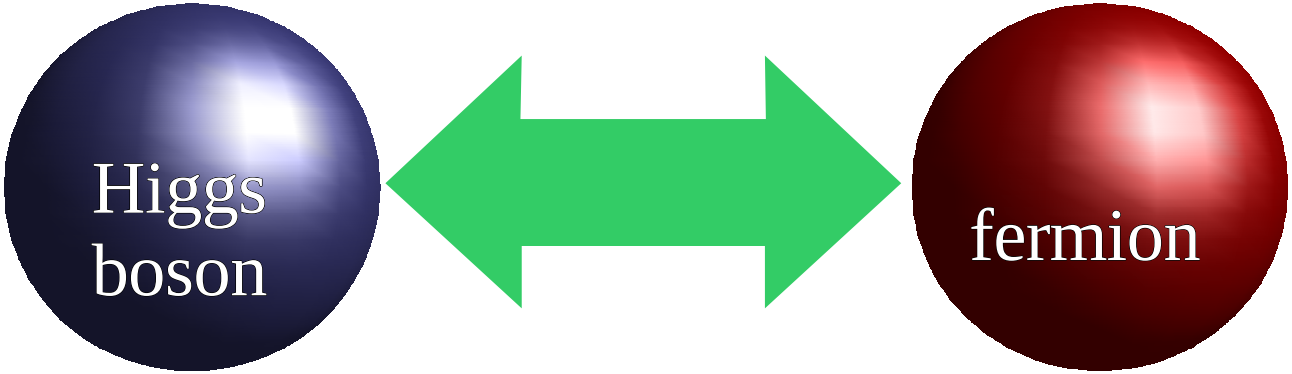


Electroweak symmetry breaking

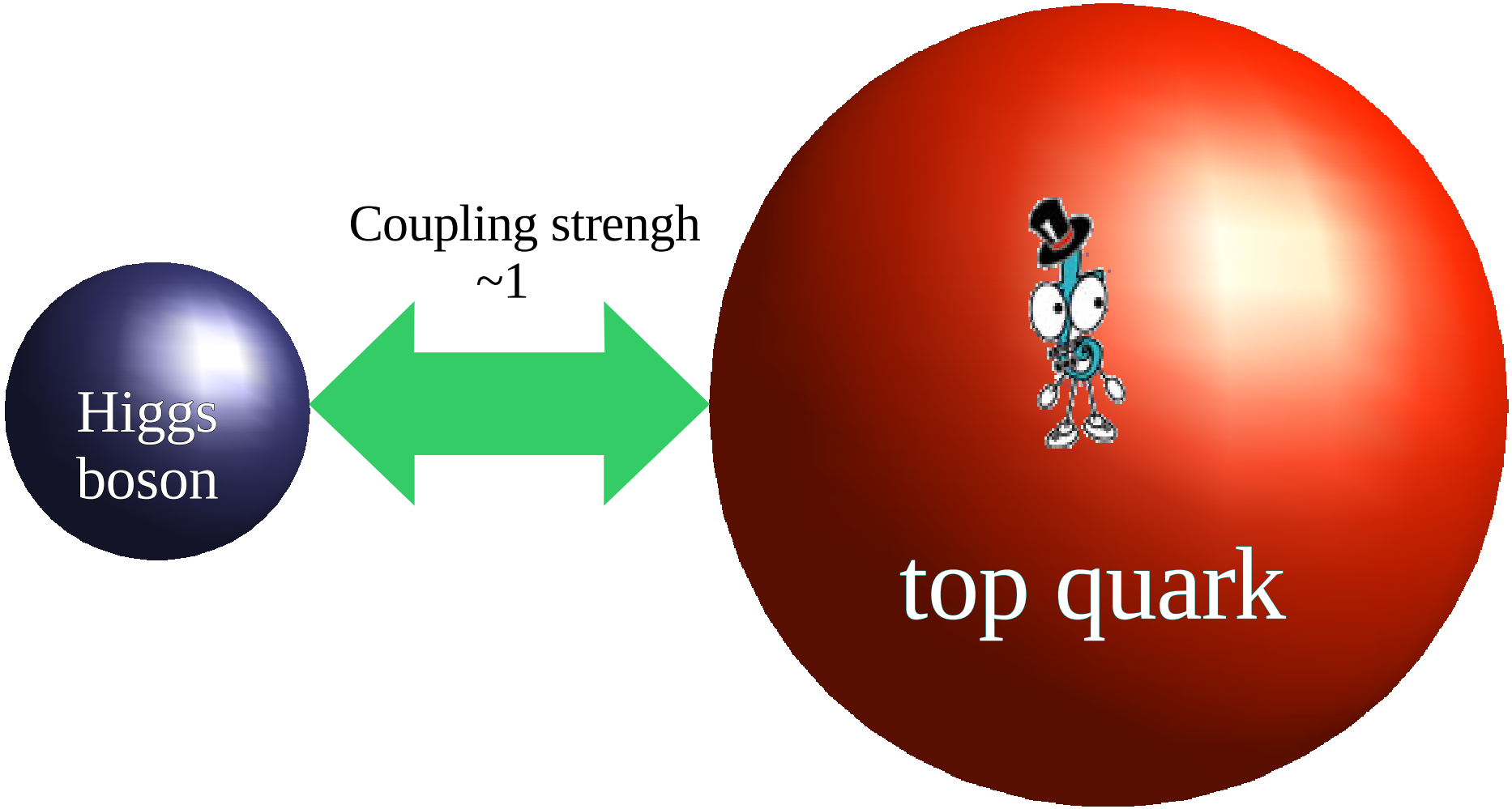
Gauge boson coupling to Higgs field



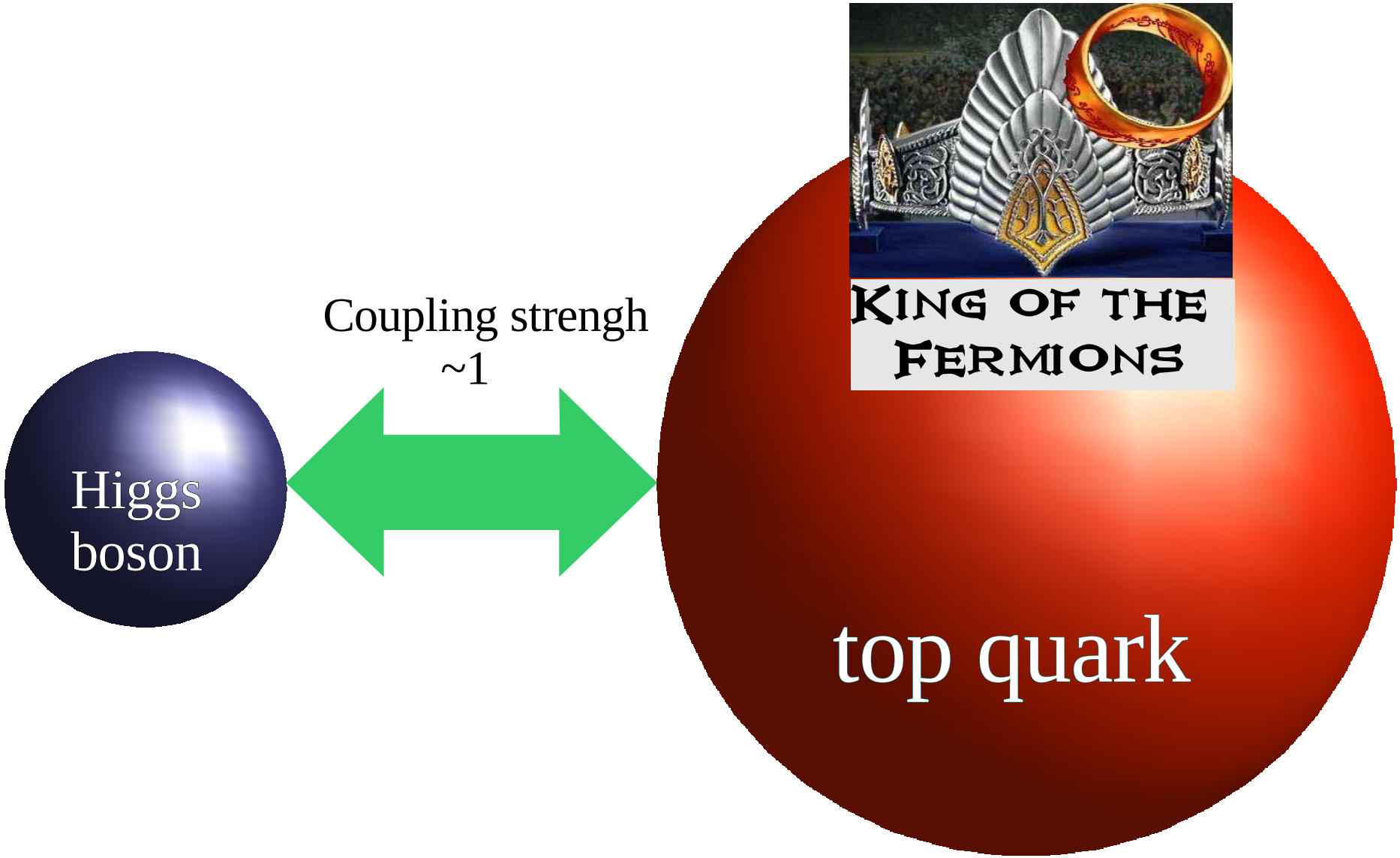
Fermions acquire mass through Higgs coupling



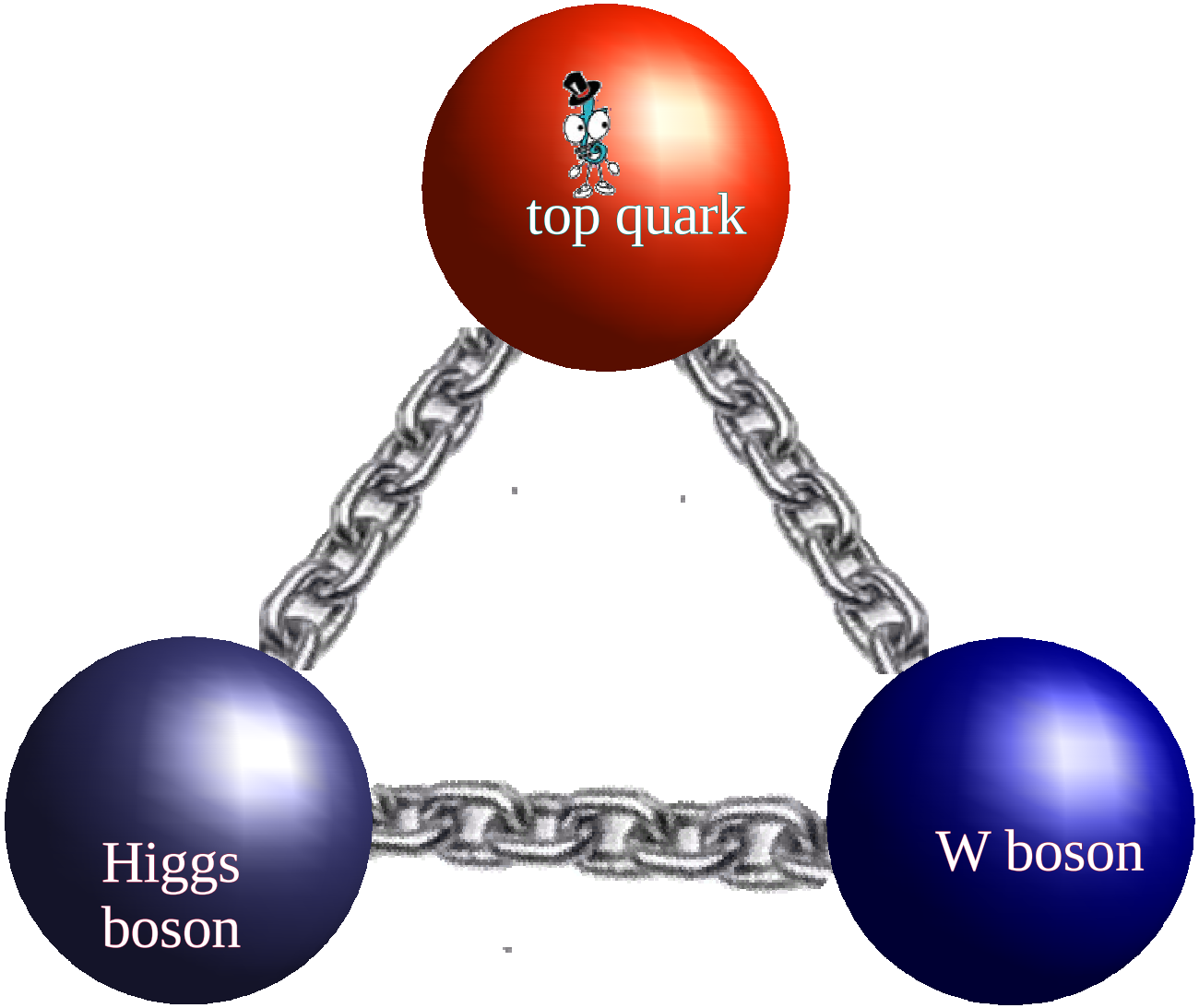
Top quark mass



Top quark mass



Key to electroweak symmetry breaking



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)

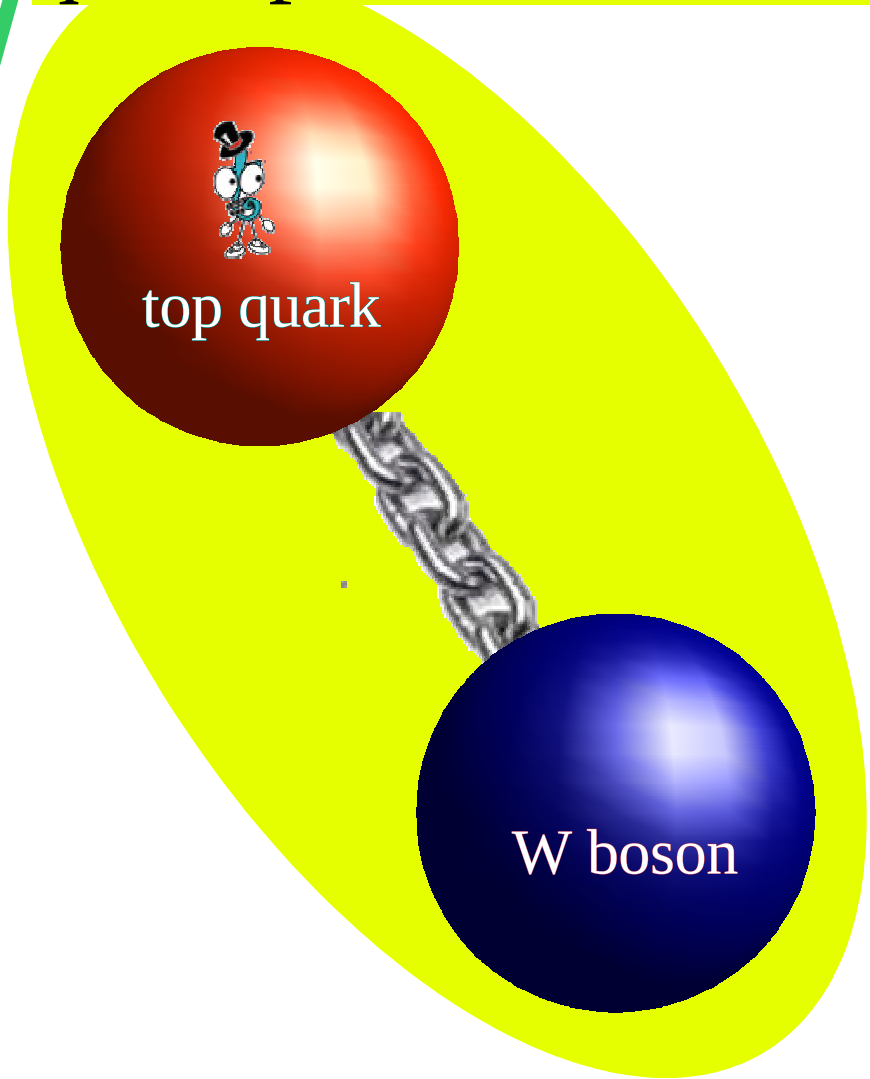
Really don't know:

- 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?
- Modified weak coupling?
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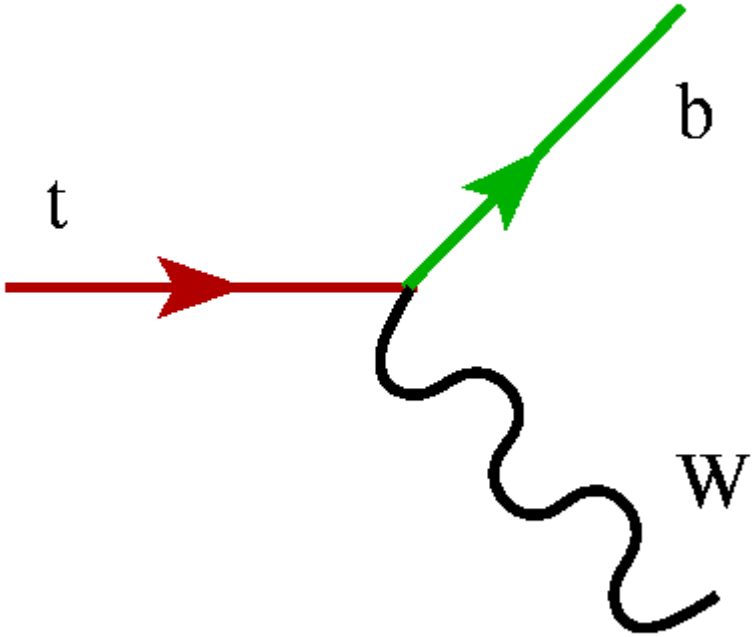
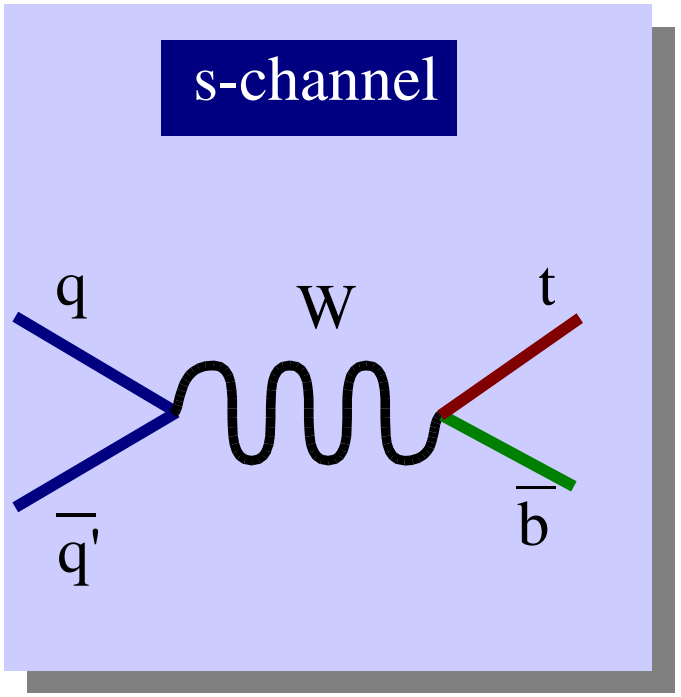
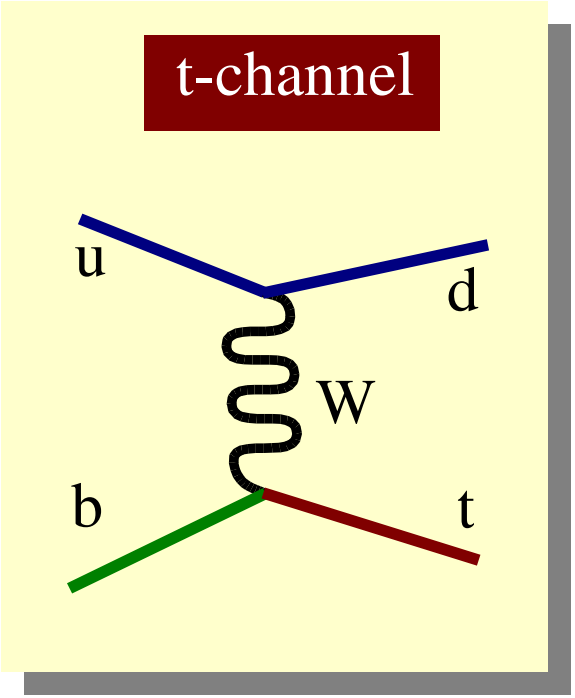
Top quark electroweak charged current interaction

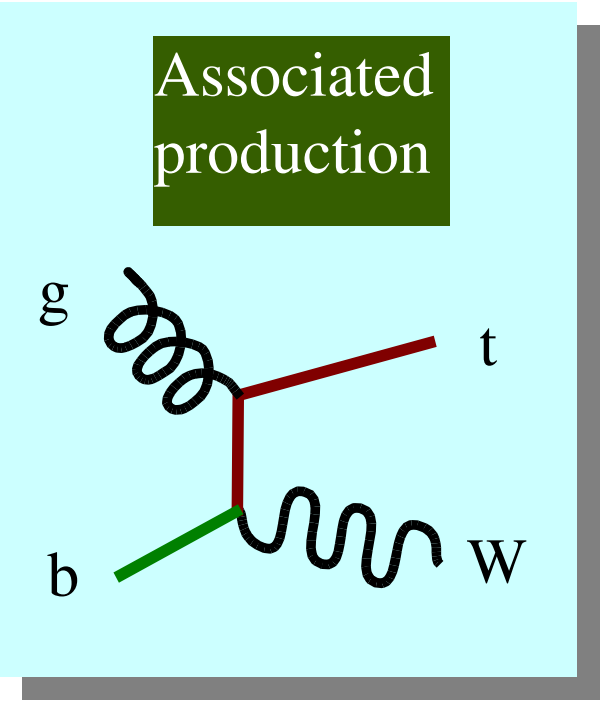


top quark decay

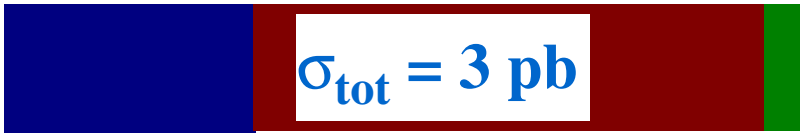
SM single top quark production







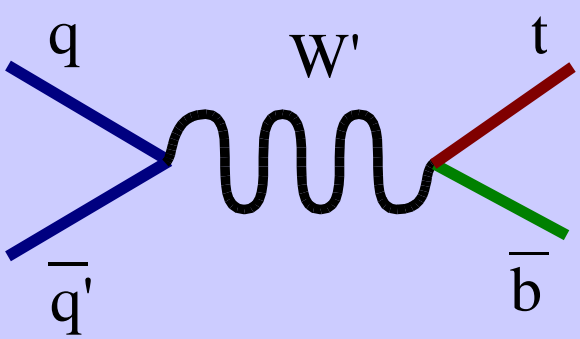
TeV:



LHC:

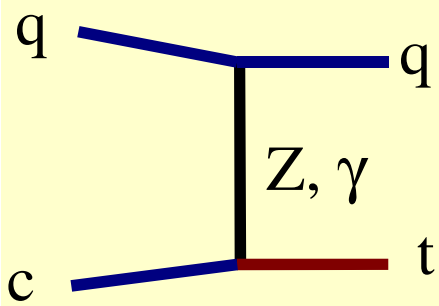
New physics

s-channel



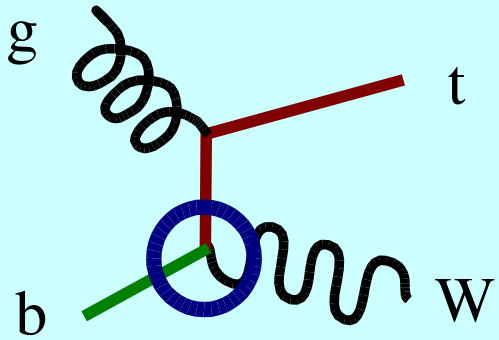
New heavy boson

t-channel

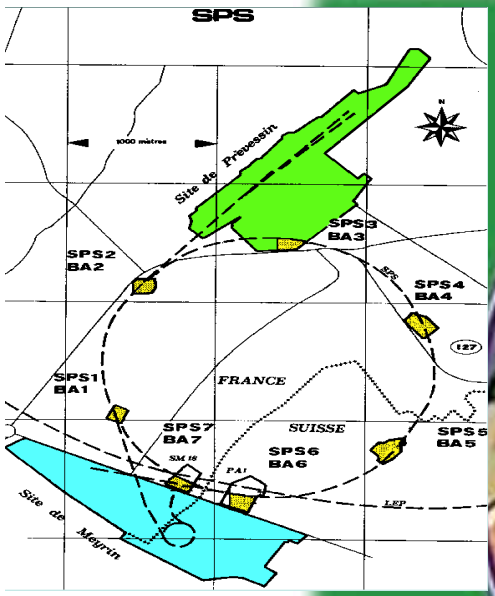


Flavor Changing Neutral Current

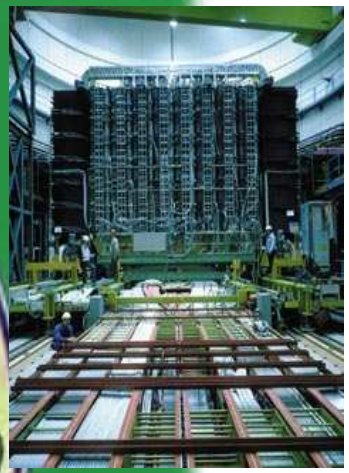
Associated production



Modified Wtb coupling


SPS
Site de Prevessin
SPS2
BA2
SPS3
BA3
SPS4
BA4
SPS1
BA1
FRANCE
SUISSE
SPS7
BA7
SPS6
BA6
SPS5
BA5
Site de Meyrin

WHERE IN THE
WORLD

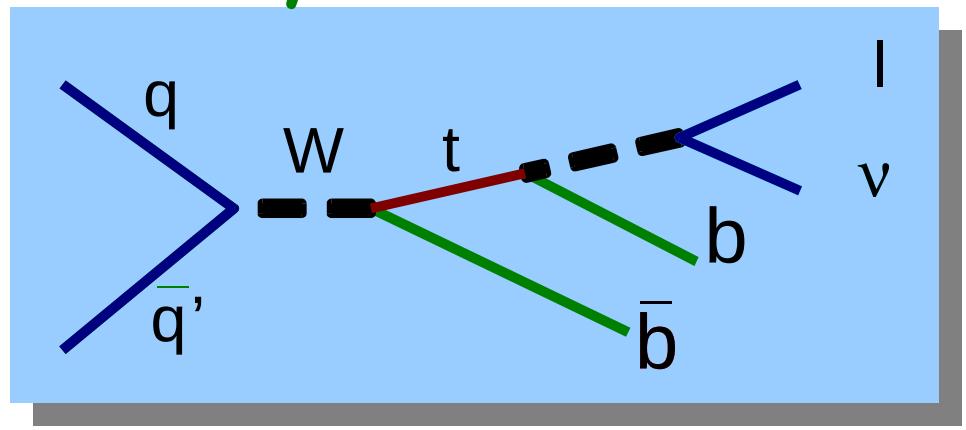


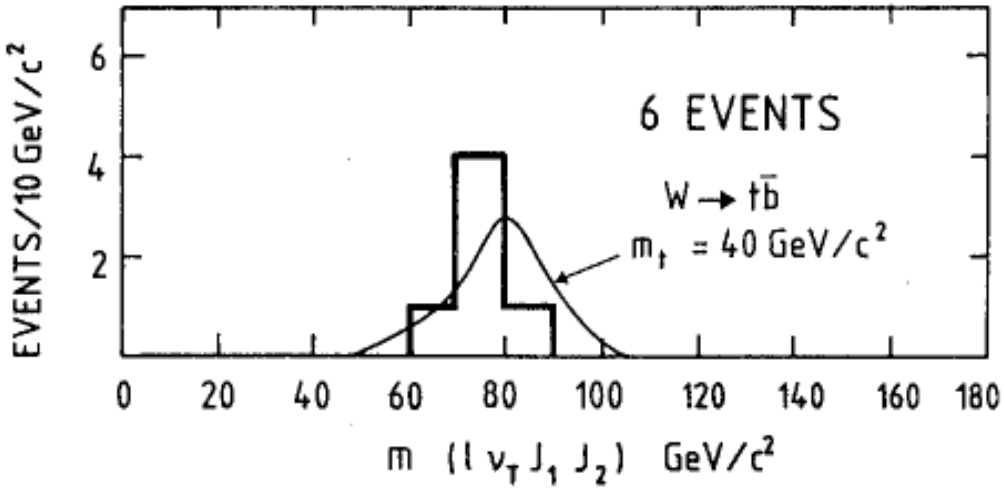
Single Top

HERA
PETRA

Top quark discovery in 1984?

- Excess of lepton+MET+2jet events at UA1 in 1984
  - Consistent with production of single top quark
    - $M_{top} \approx 40GeV$





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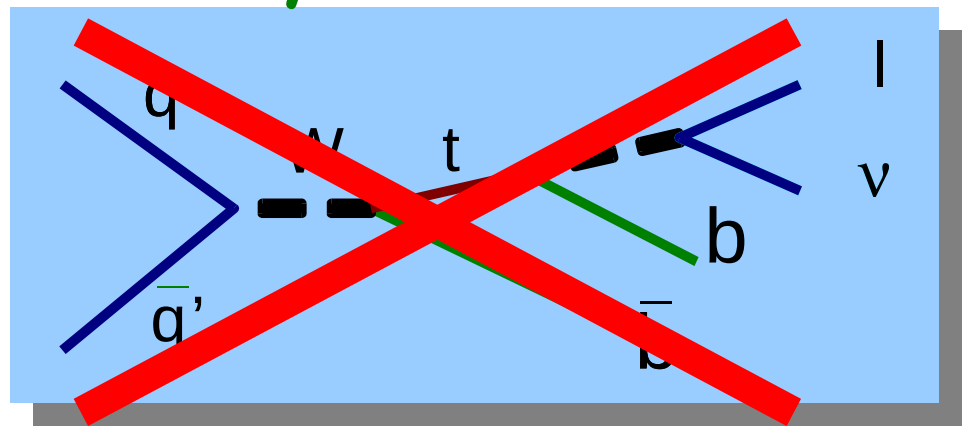
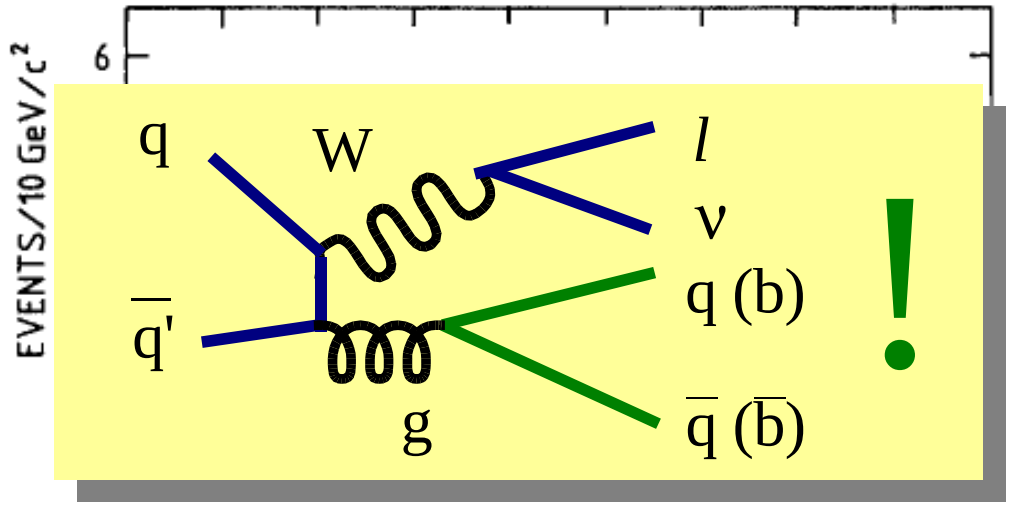
CERN comes out again on top

With the discovery of the electroweak bosons ($W^{\pm}$ and Z^0) in the bag, CERN now announces the discovery of the quark called top. What will come next?

W+jets ~~Top quark discovery~~ in 1984?

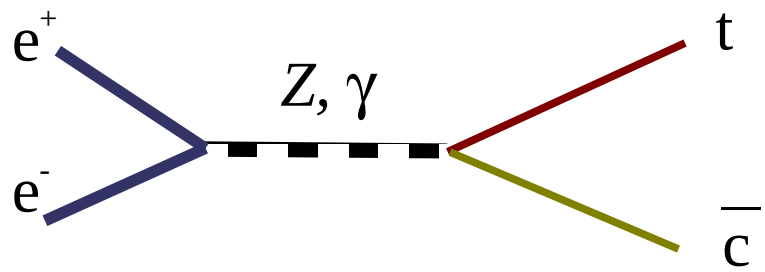
- Excess of lepton+MET+2jet events at UA1 in 1984
  - Consistent with production of single top quark
    - $M_{top} \approx 40GeV$

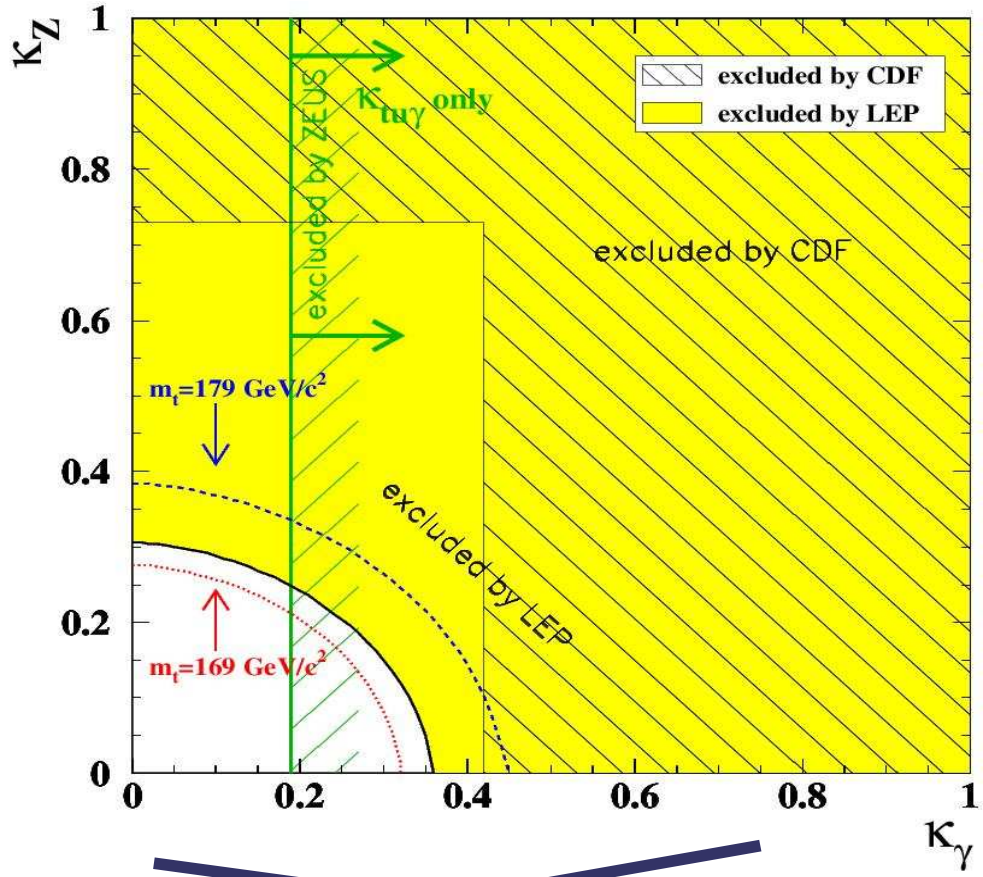




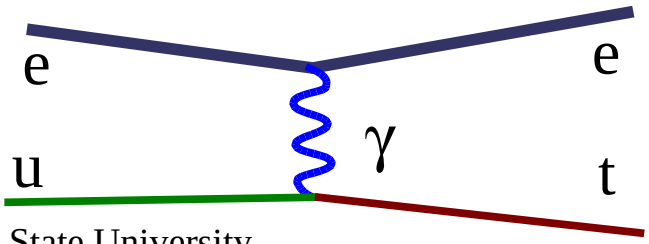
Single Top at LEP and Hera: FCNC

- LEP:
  - $e^+e^- \rightarrow tc$

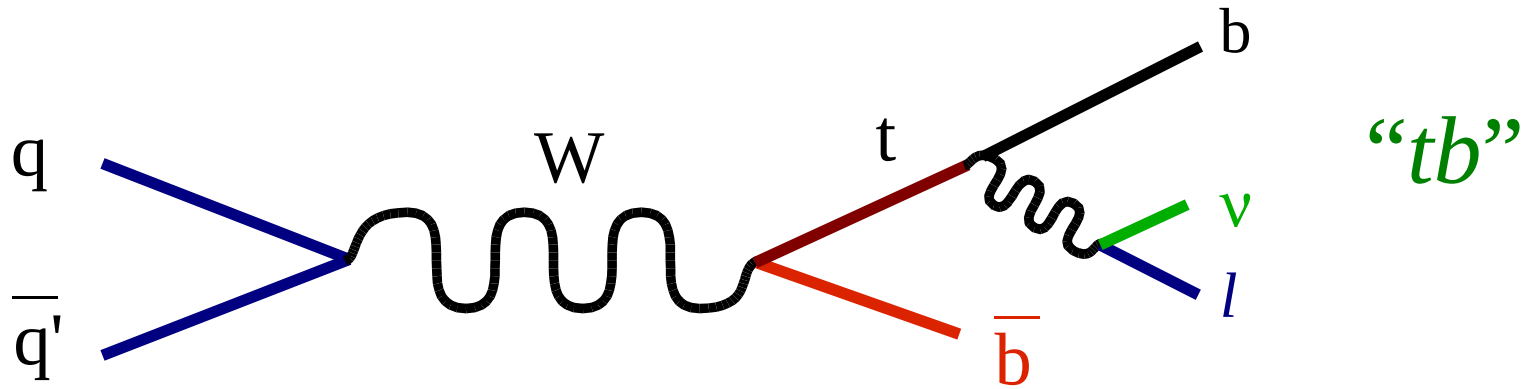


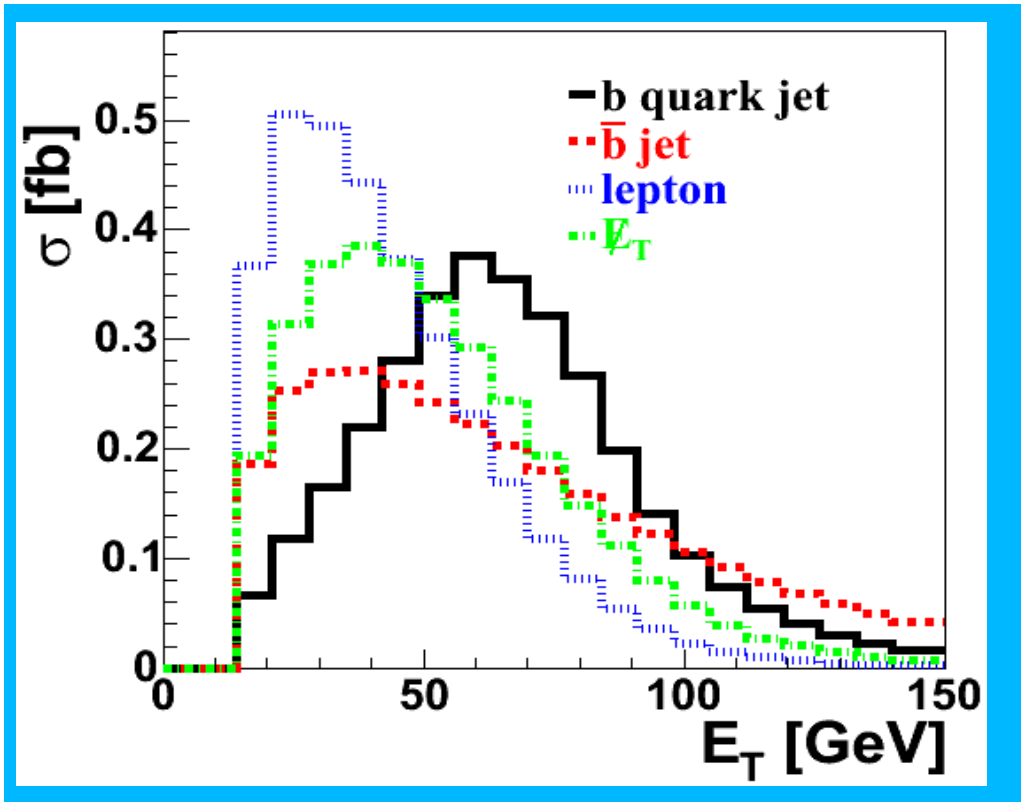


- Hera:
  - $ep \rightarrow et$



Tevatron s-channel signature





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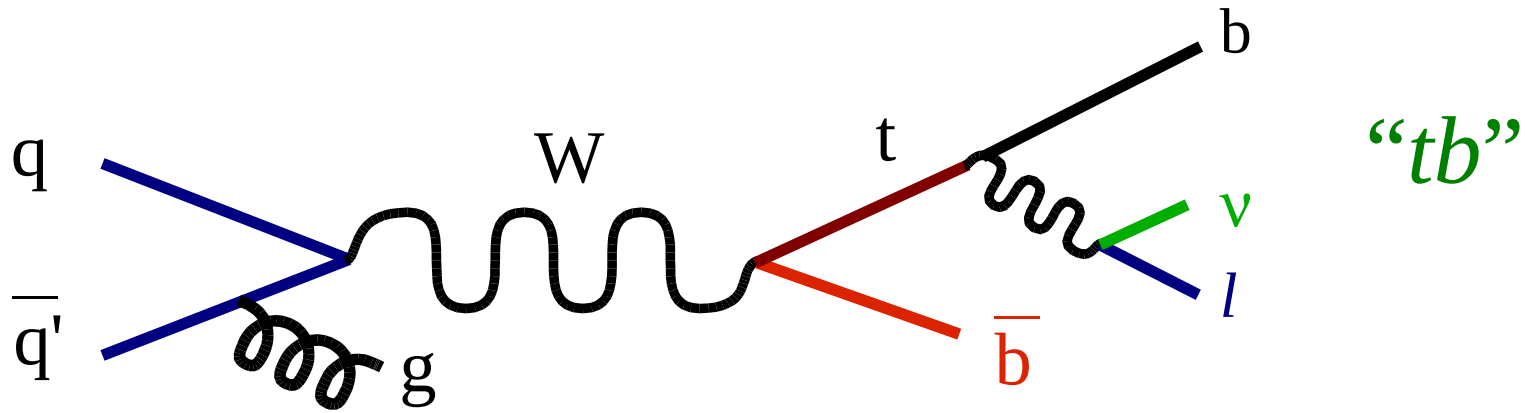
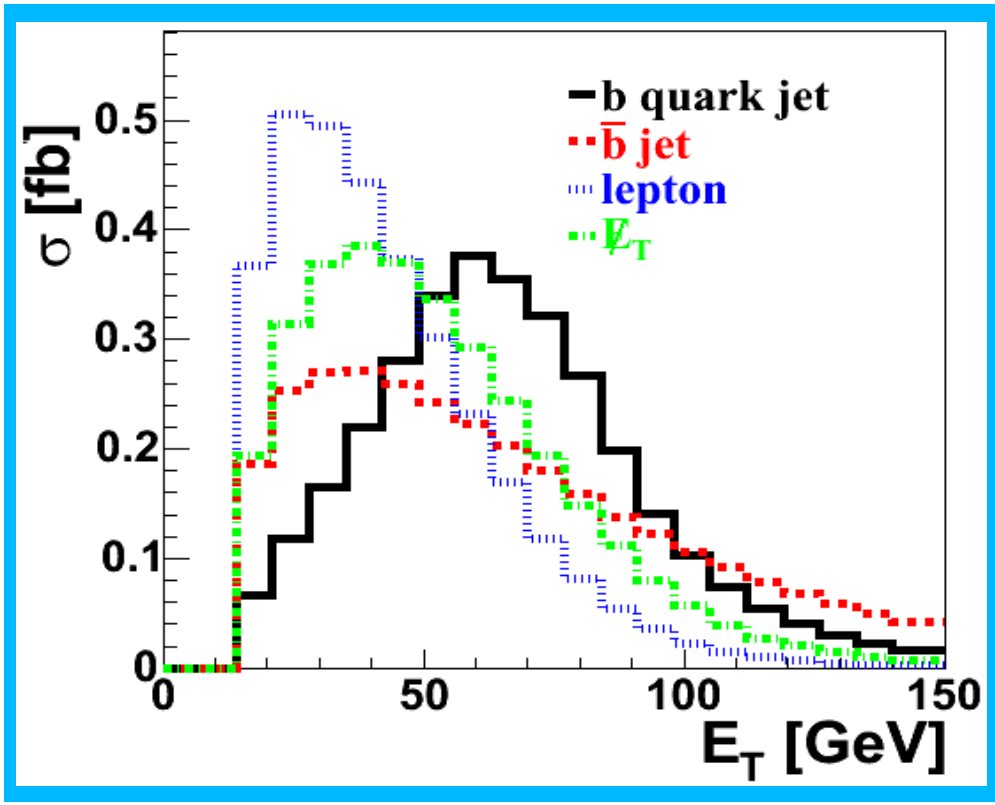
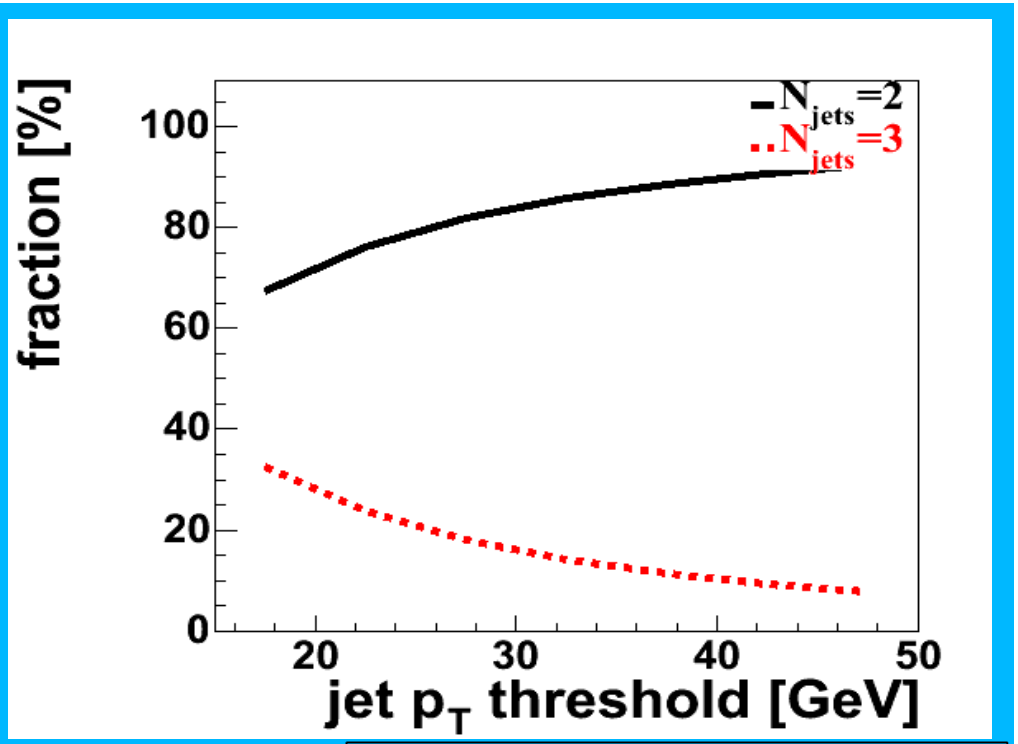
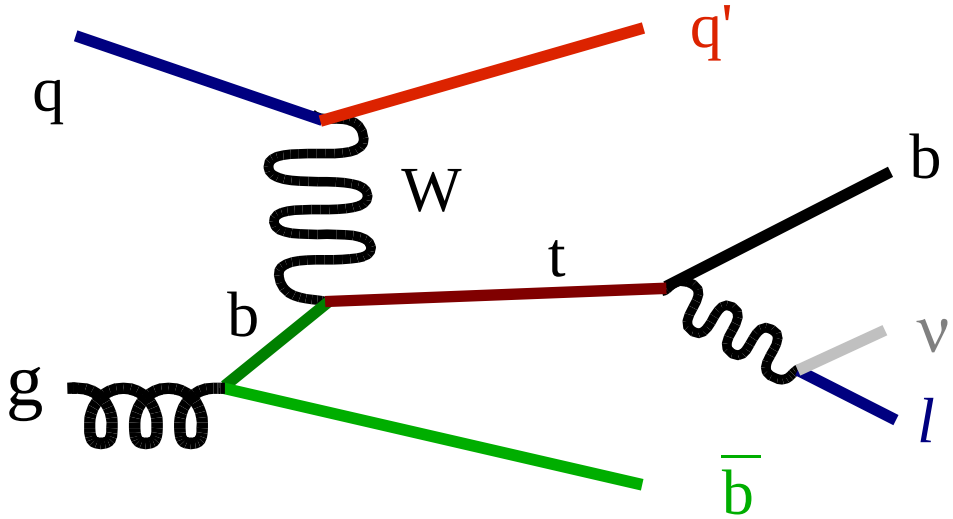




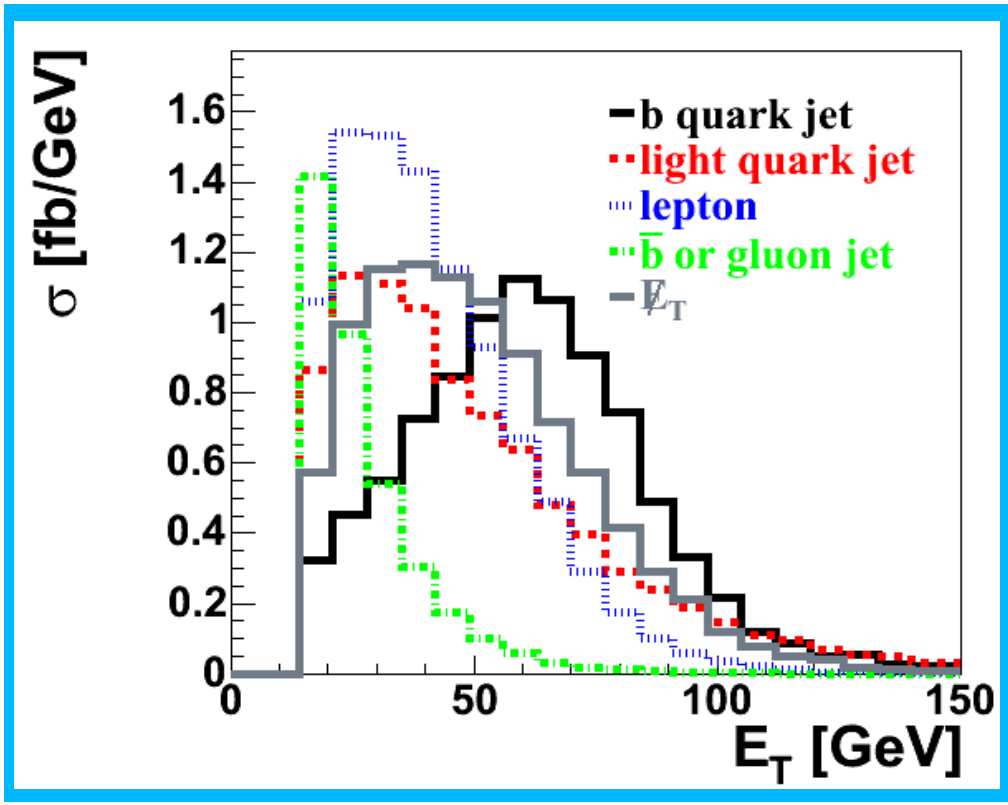


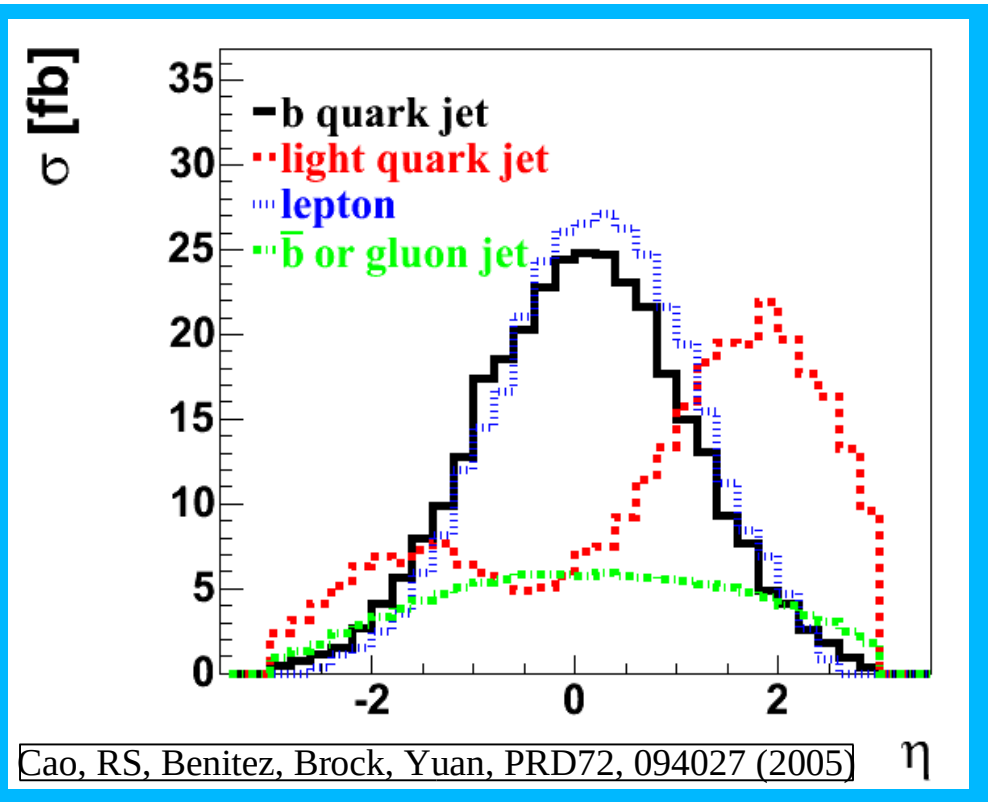
Cao, RS, Yuan PRD71, 054023 (2005)

Tevatron t-channel signature



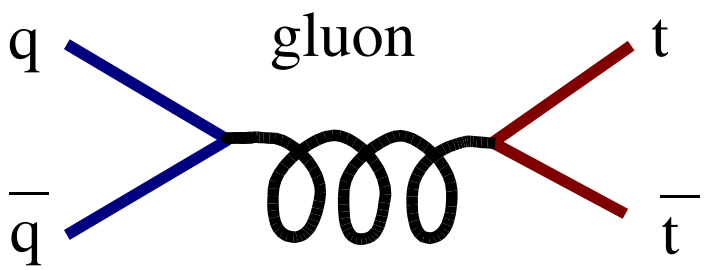
"tqb"





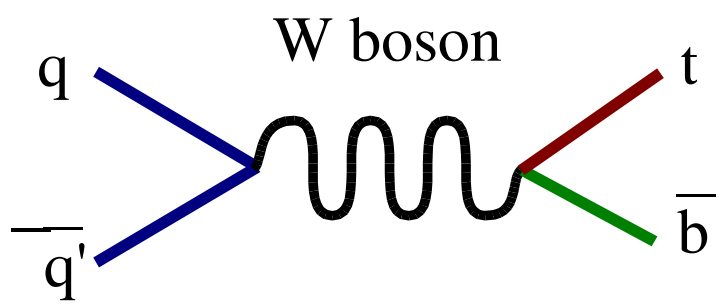
Cao, RS, Benitez, Brock, Yuan, PRD72, 094027 (2005)

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

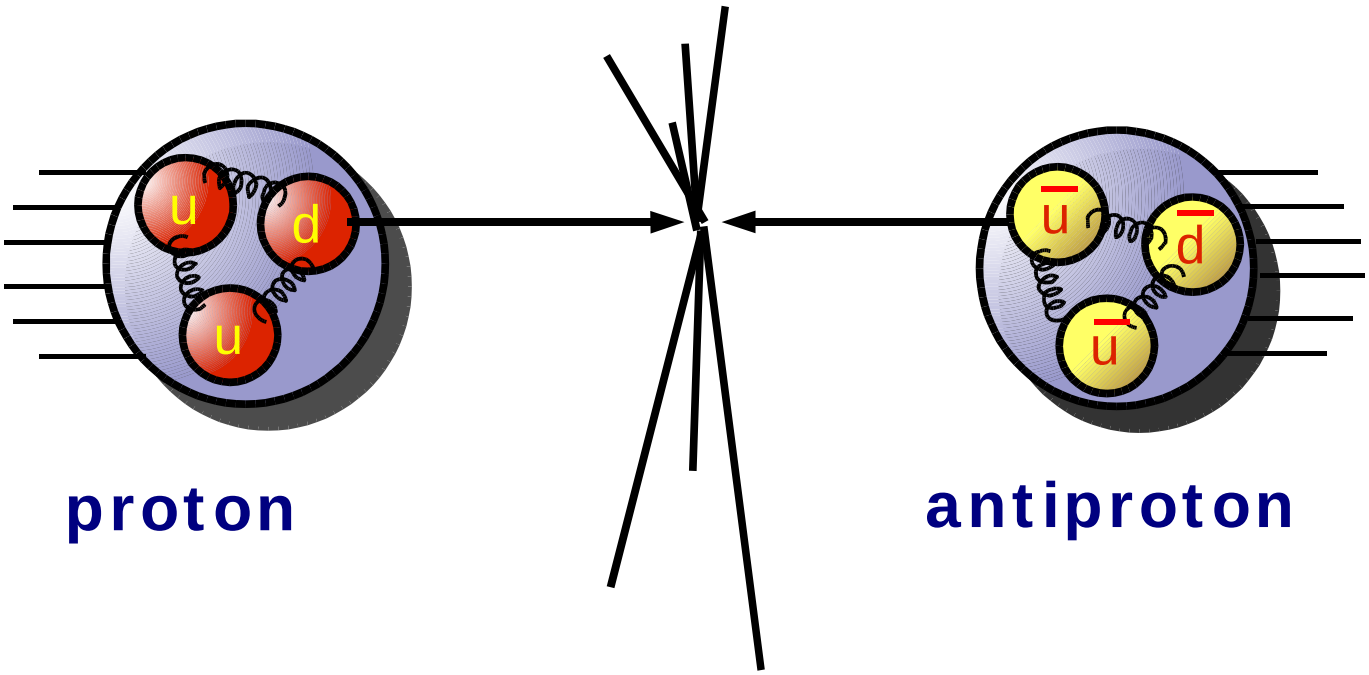
- Discover single top quark production!
- Measure production cross sections
  $\rightarrow$ CKM quark mixing matrix element V_{tb}
- Look for physics beyond the standard model
  – Coupled to the heavy top quark
- Study top quark spin correlations
- Understand as background to many searches

Experimental procedure

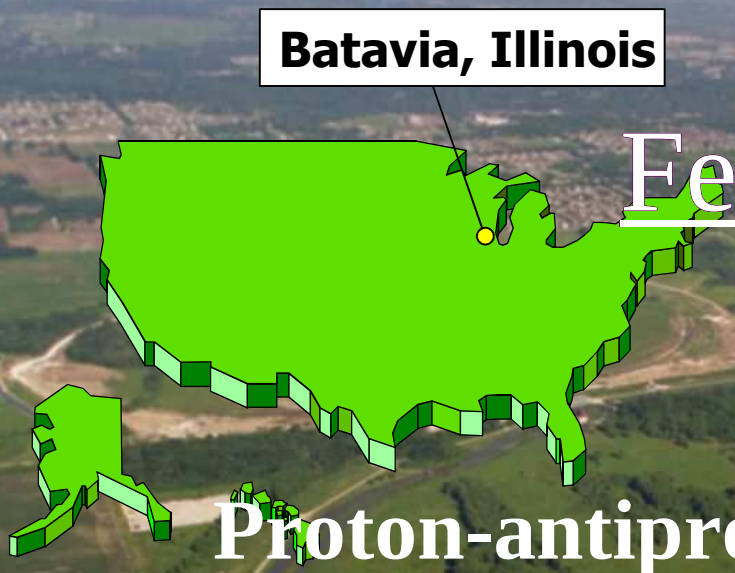
How do we find out?

The energy frontier

Probe physics at small distances
by colliding particles at high energy



Experimental setup: Fermilab Tevatron in Run II



Proton-antiproton collider

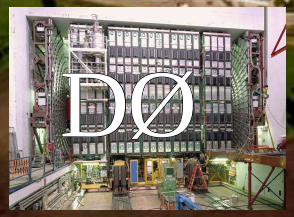
CM energy 1.96TeV

→ ***Energy frontier***

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

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

→ ***Luminosity frontier***



Experimental setup: detector configuration

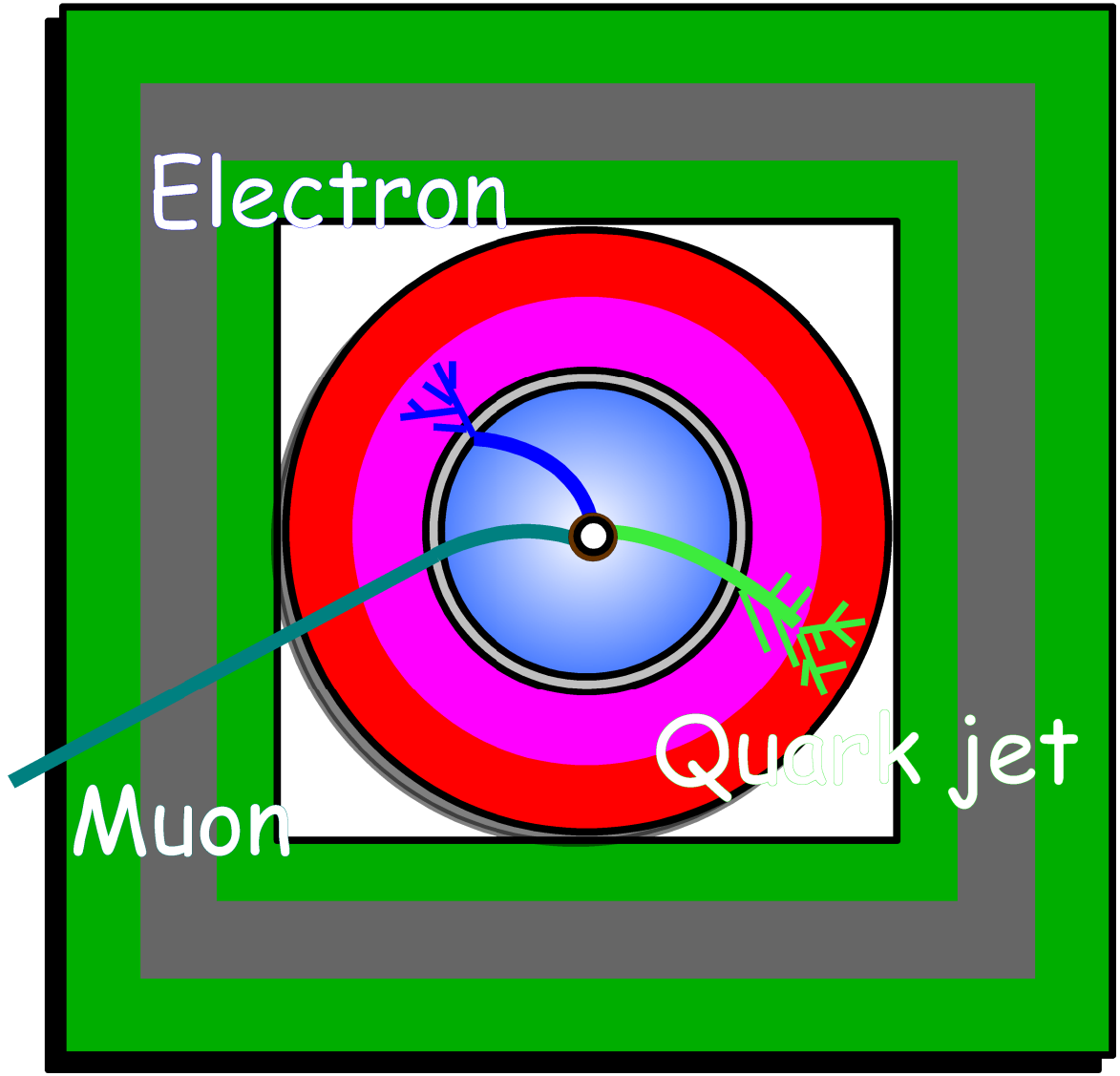
Beam pipe

Tracking detector

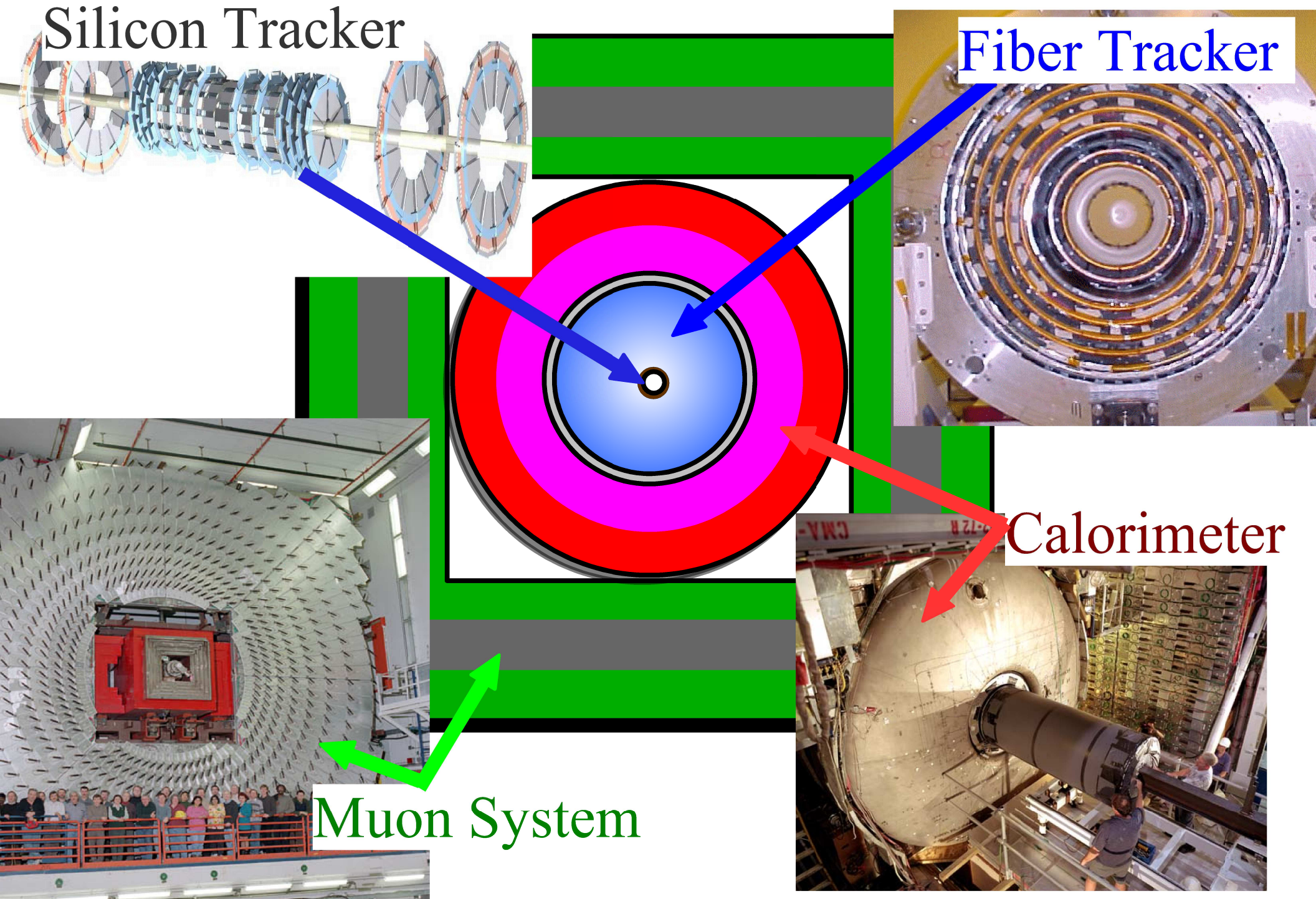
Magnet

Calorimeter:
EM and hadronic

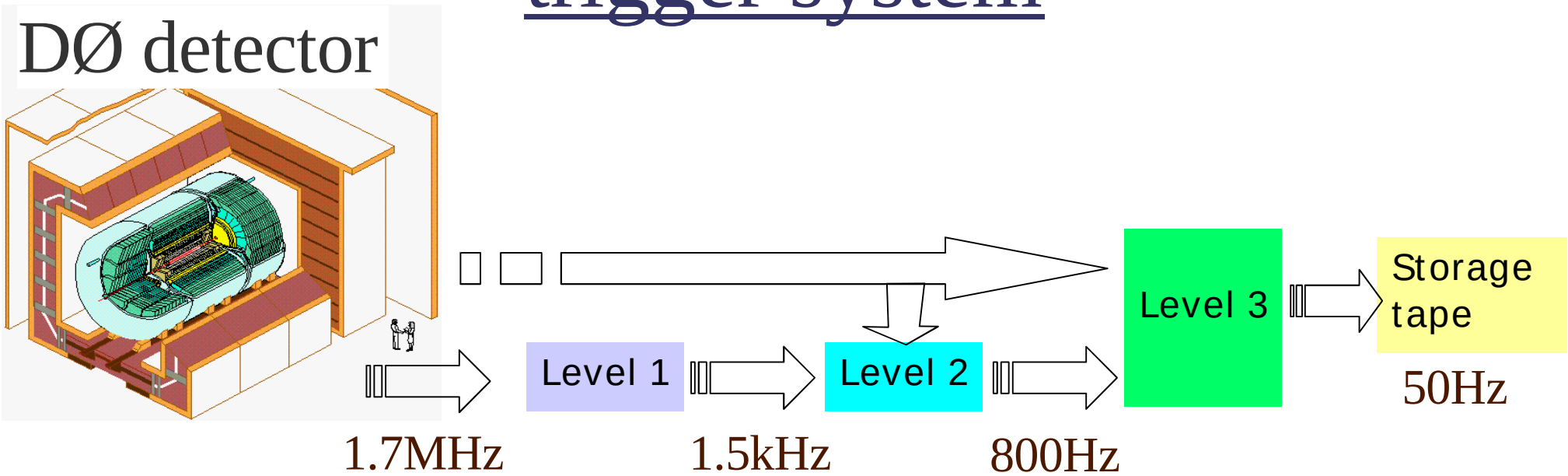
Muon detectors
surrounding
another magnet



Apparatus: Run II DØ Detector



Collecting interesting events: trigger system

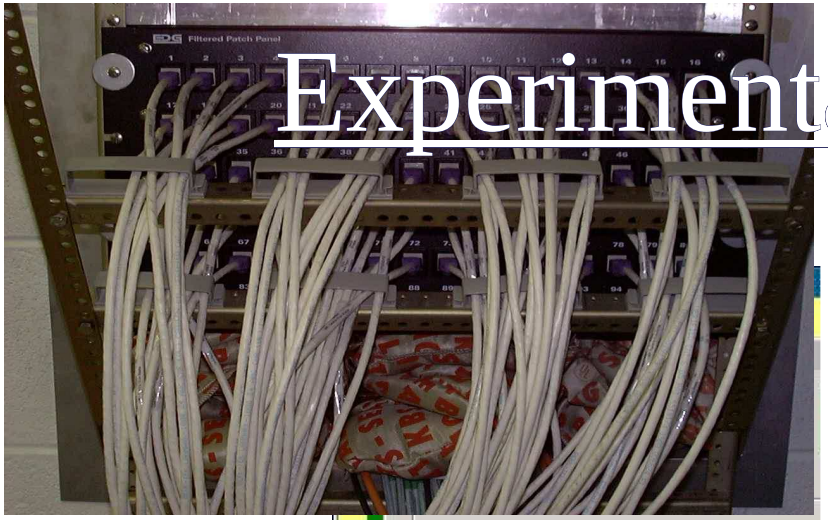


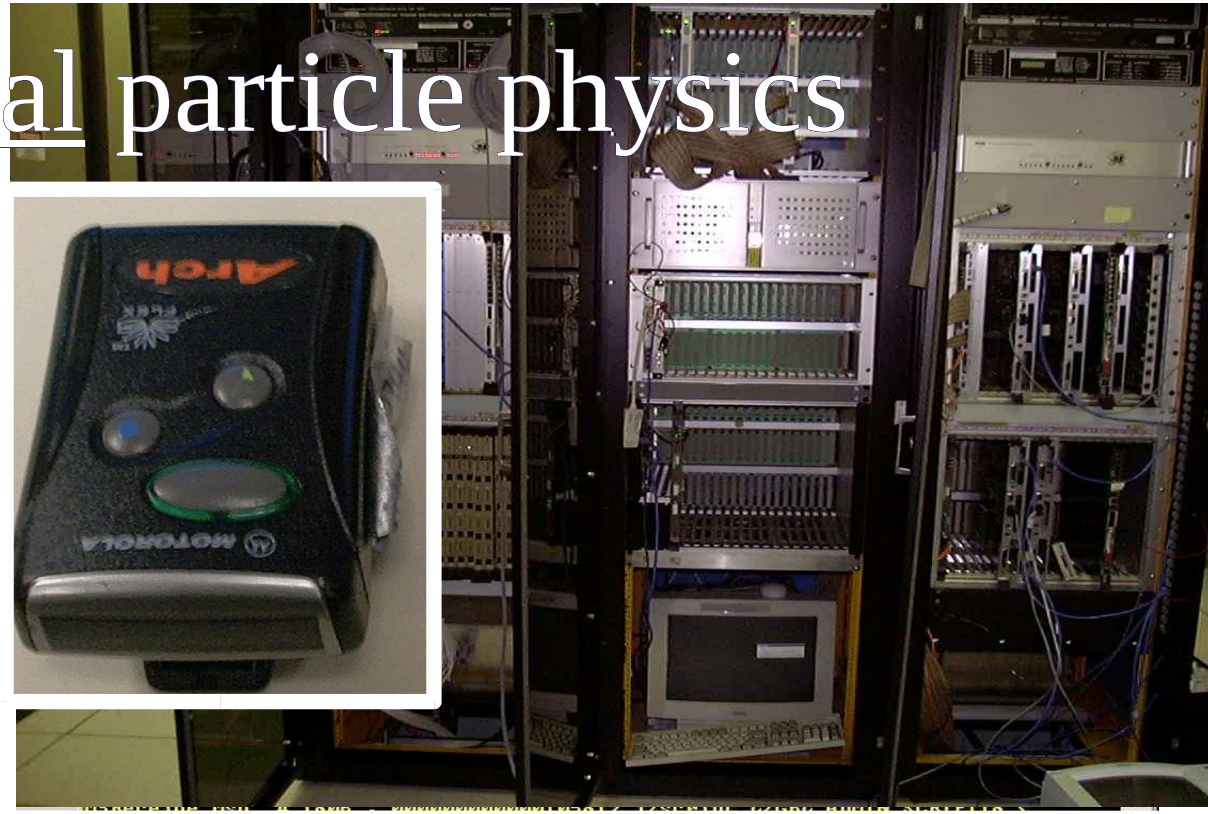
- Reduce rate of interactions (inelastic collisions) to manageable level that can be stored
- Record "interesting" events → trigger system
  - Select events containing high-energy final state objects
    - Electrons, muons, quark jets

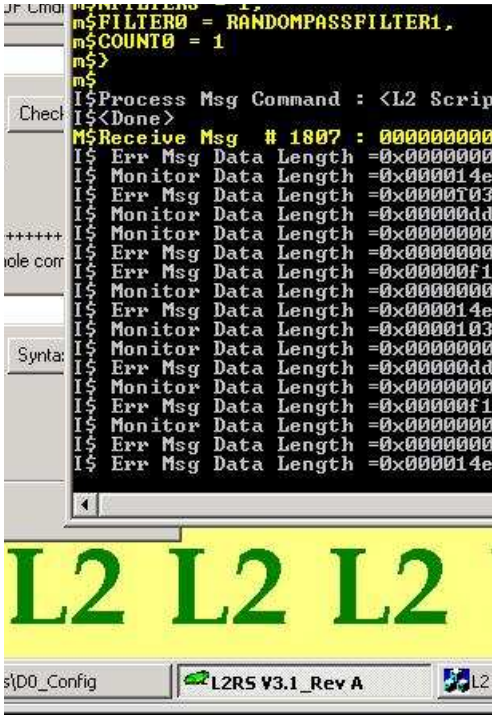
Experimenters

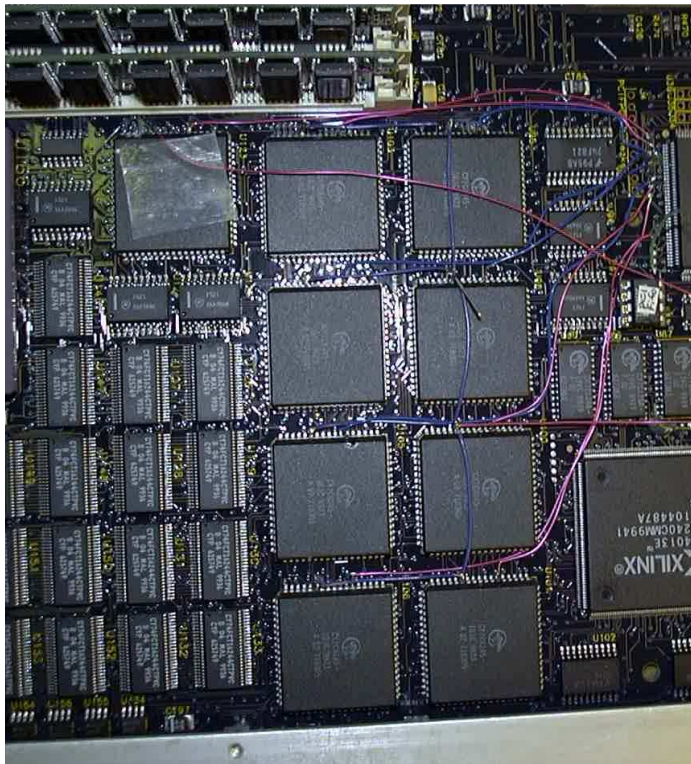
- **19 countries**
- **80 institutions**
- **670 physicists**

Experimental particle physics





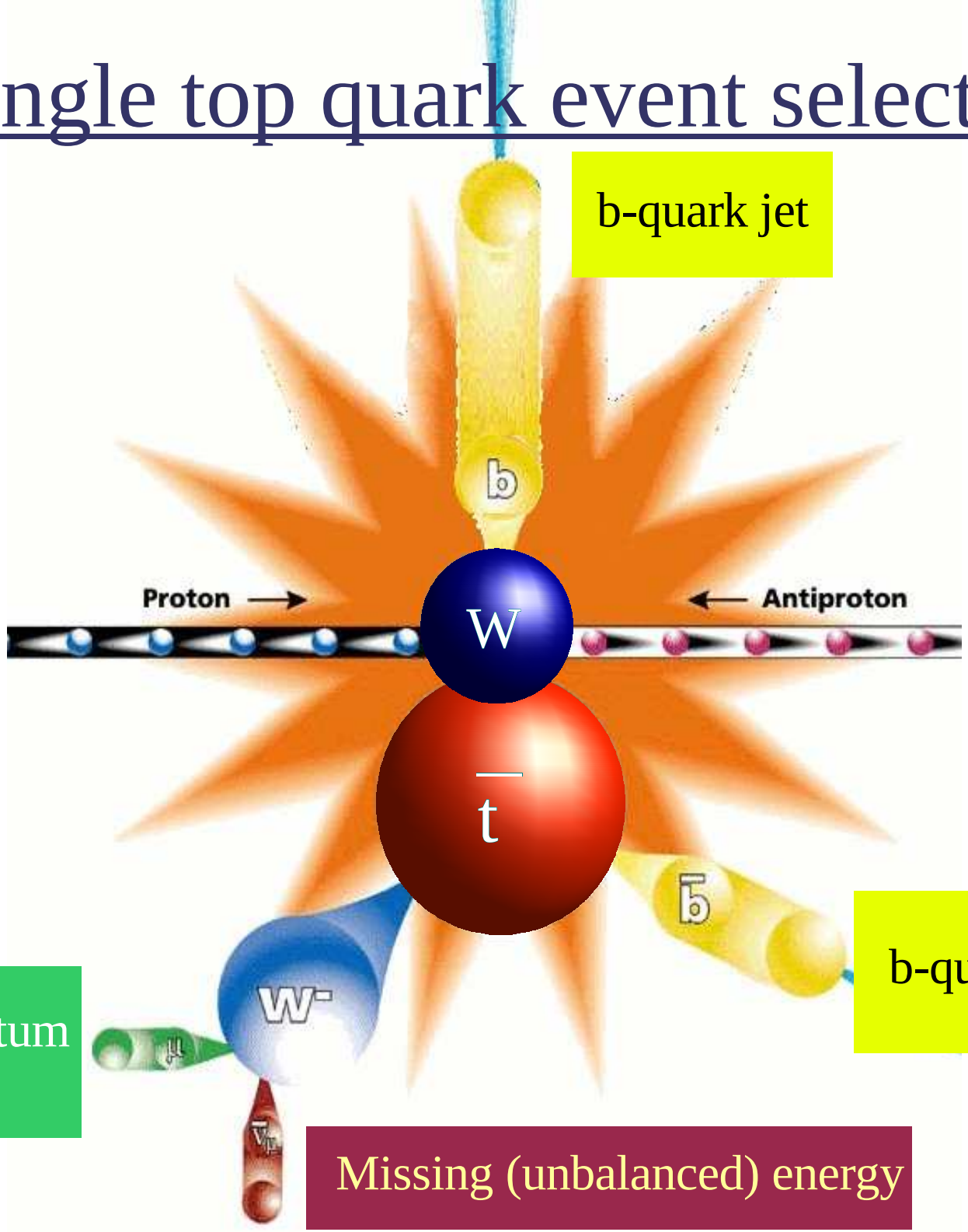




Current Results

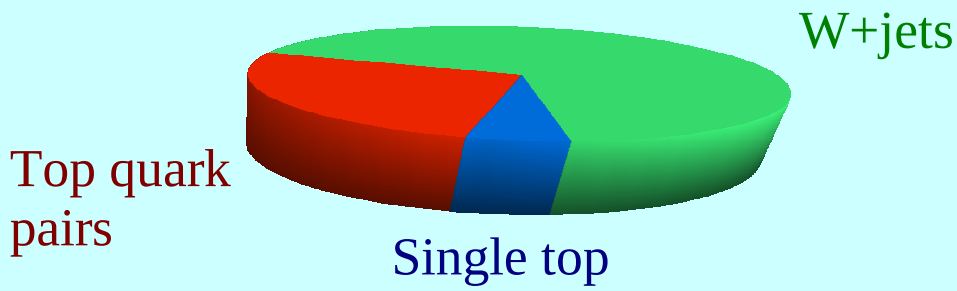
Precious data!

Single top quark event selection

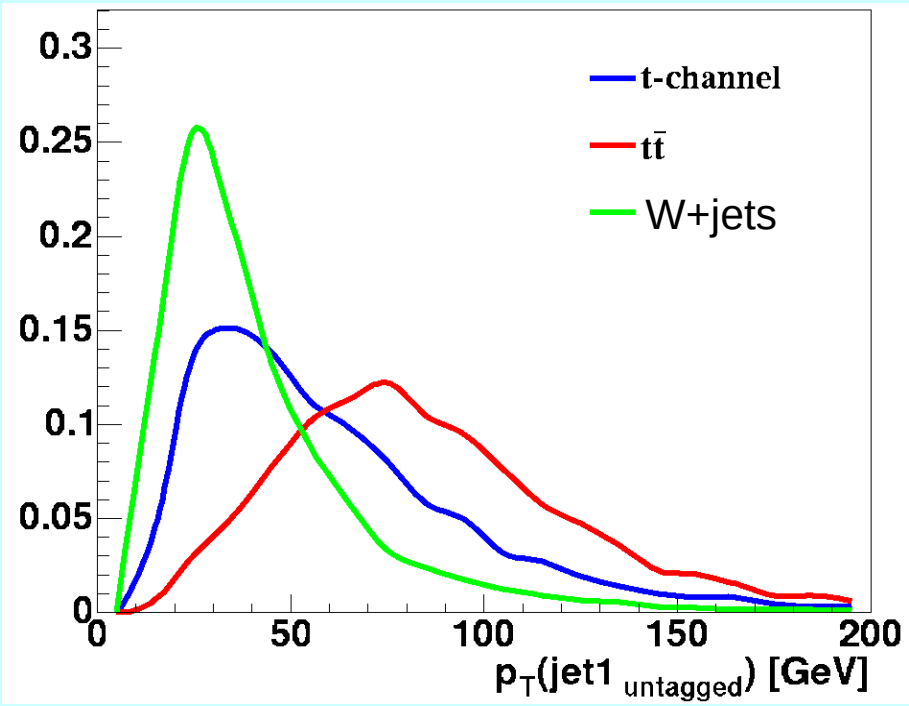


Single top quark search

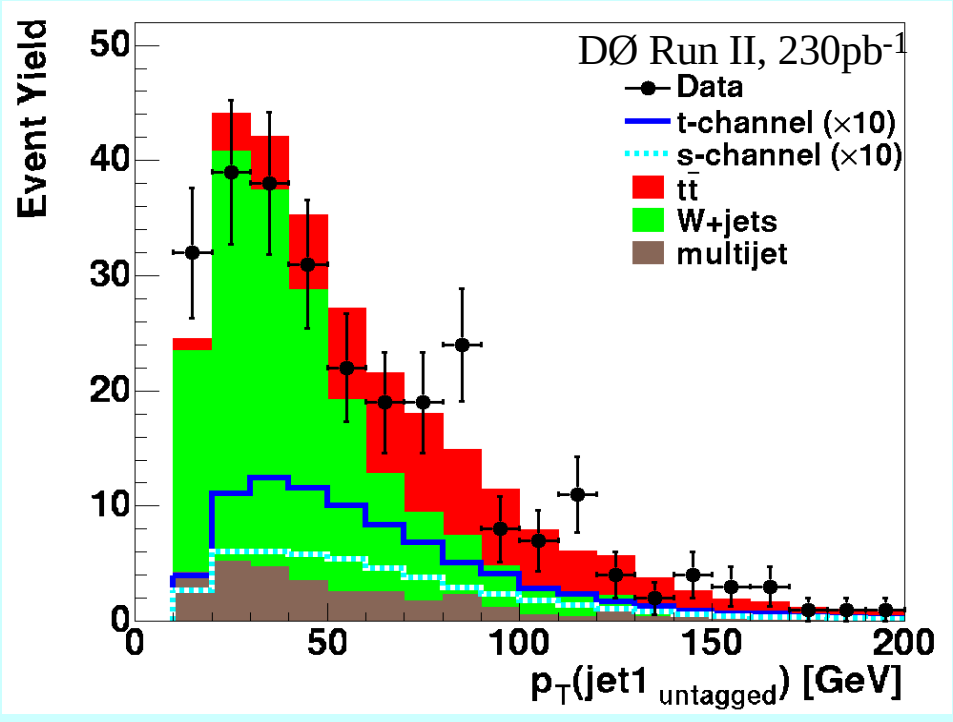
Event Sample Composition (~ 1 ev pb)



Kinematic distributions



Data-background comparison

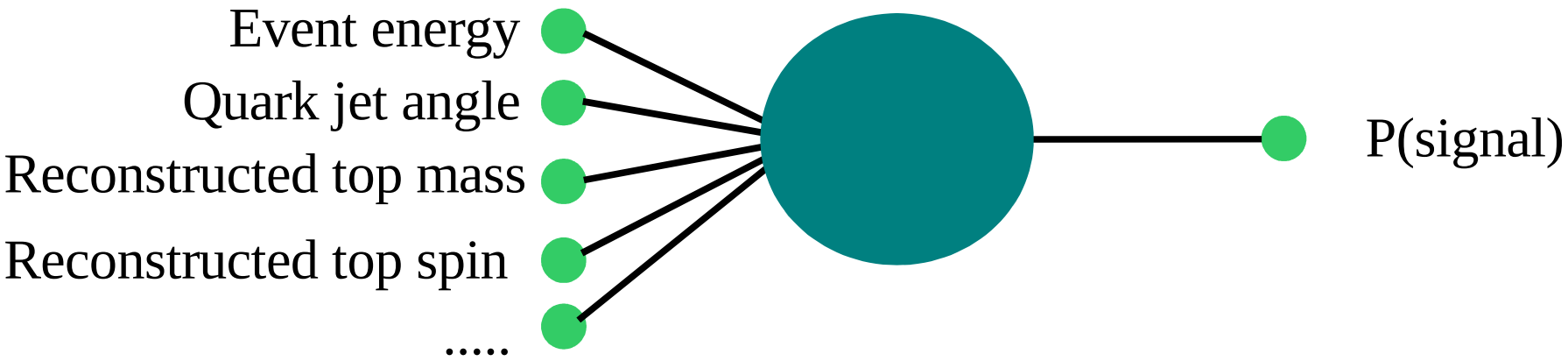


Optimized Event Analysis

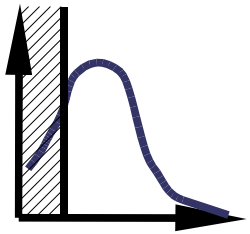
Input:
discriminating variables

Method:
multivariate analysis

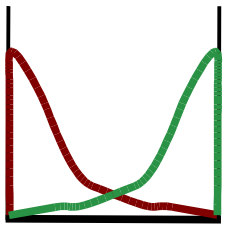
Output:
signal probability



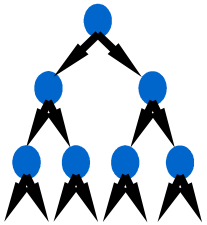
Cut-Based



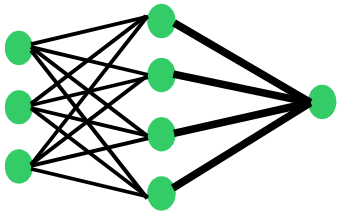
Likelihoods



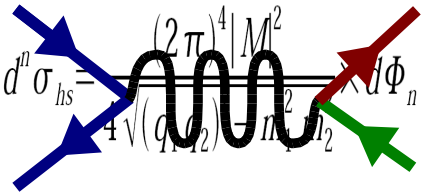
Decision Trees



Neural Networks

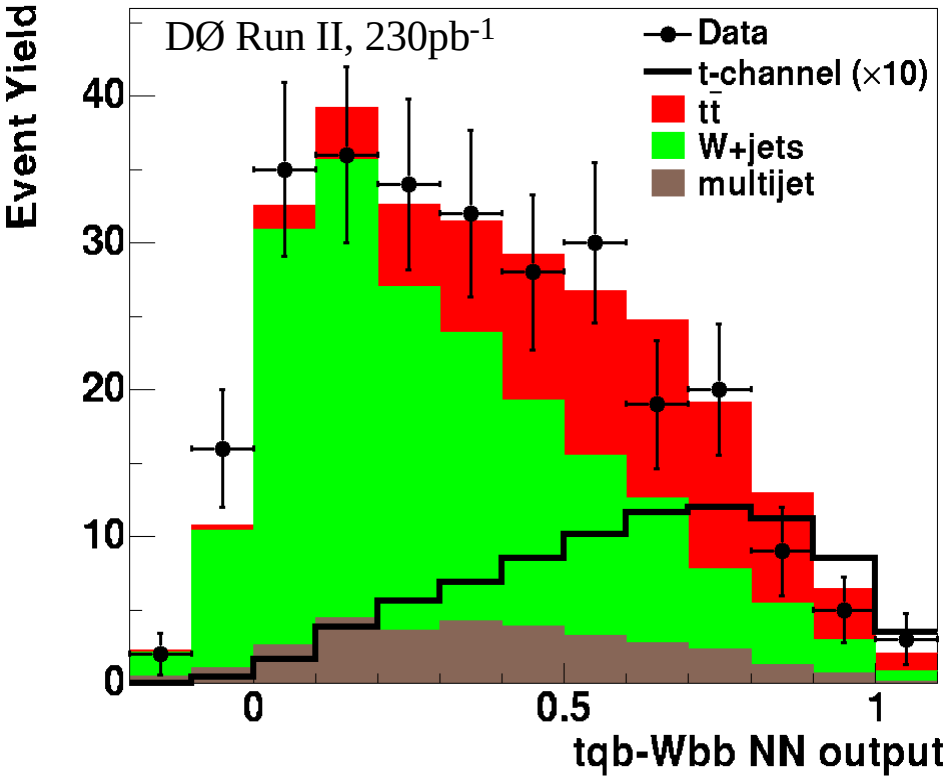


Matrix Elements

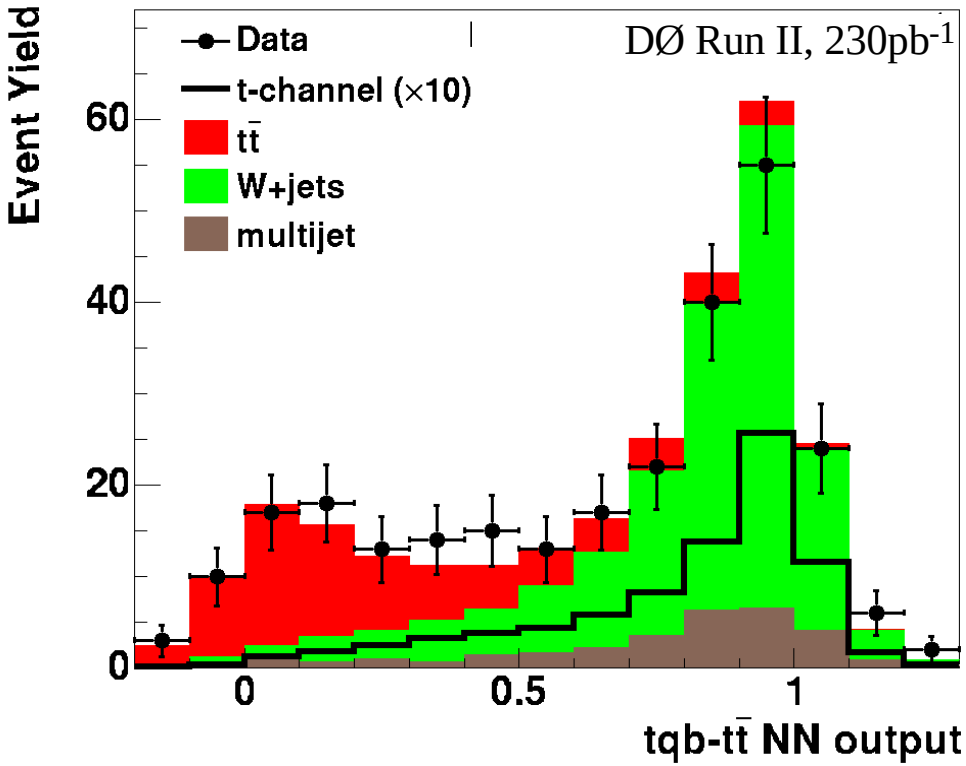


NN result

W+jets filter

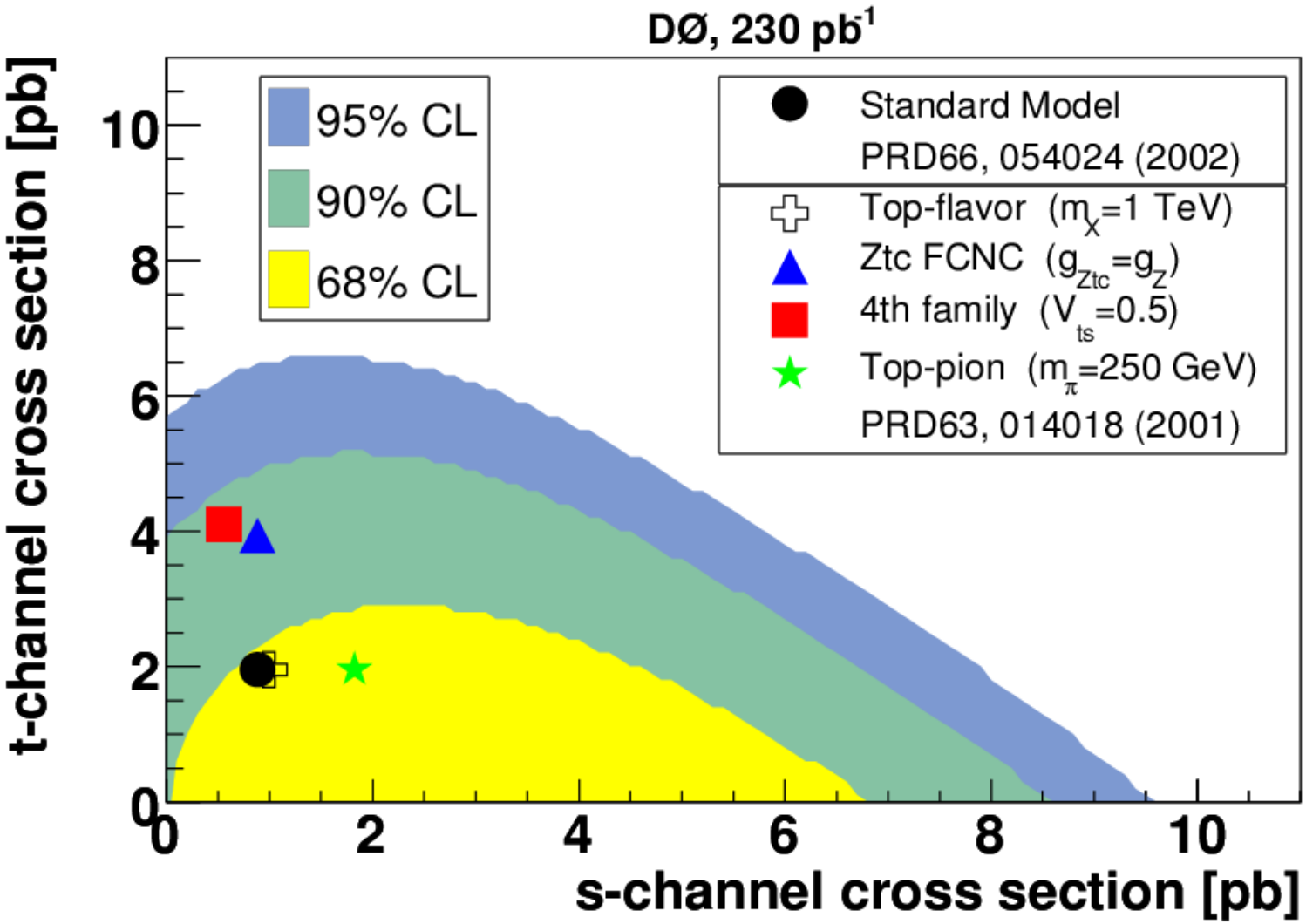


$t\bar{t}$ filter



- Bayesian statistical analysis
- Systematic uncertainty ~20%

Single top cross section limit



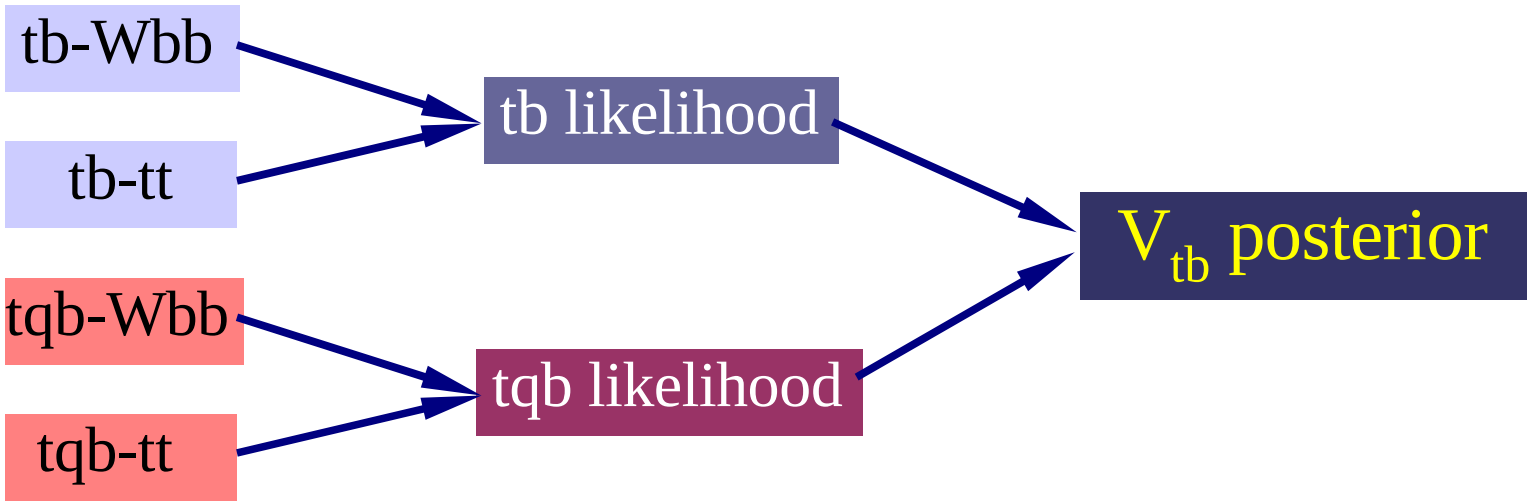
95% CL cross section limit:

$\sigma_t < 5.0$ pb $\sigma_s < 6.4$ pb

Published in PLB 622, 265 (2005)

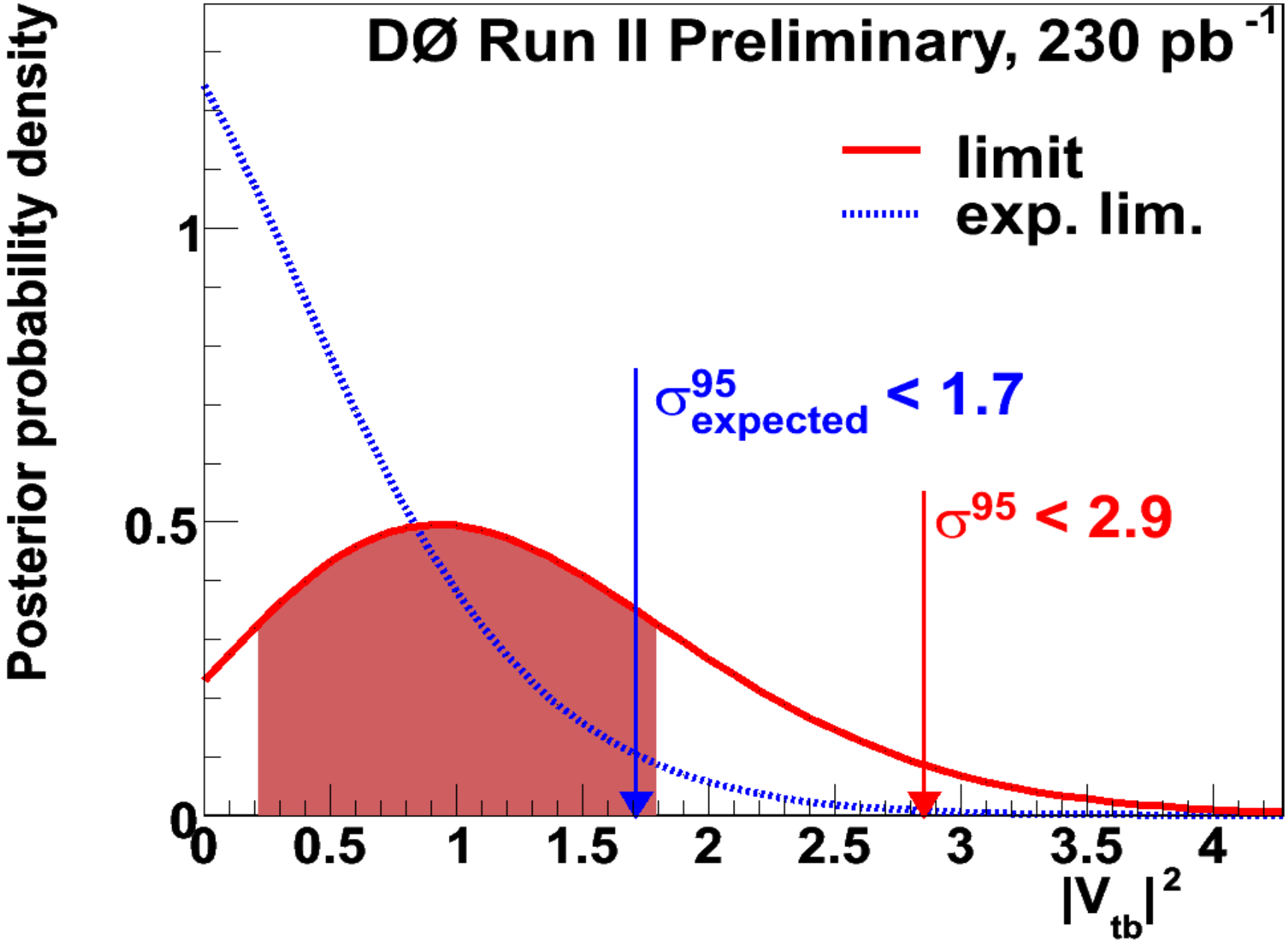
V_{tb} Coupling Limit

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



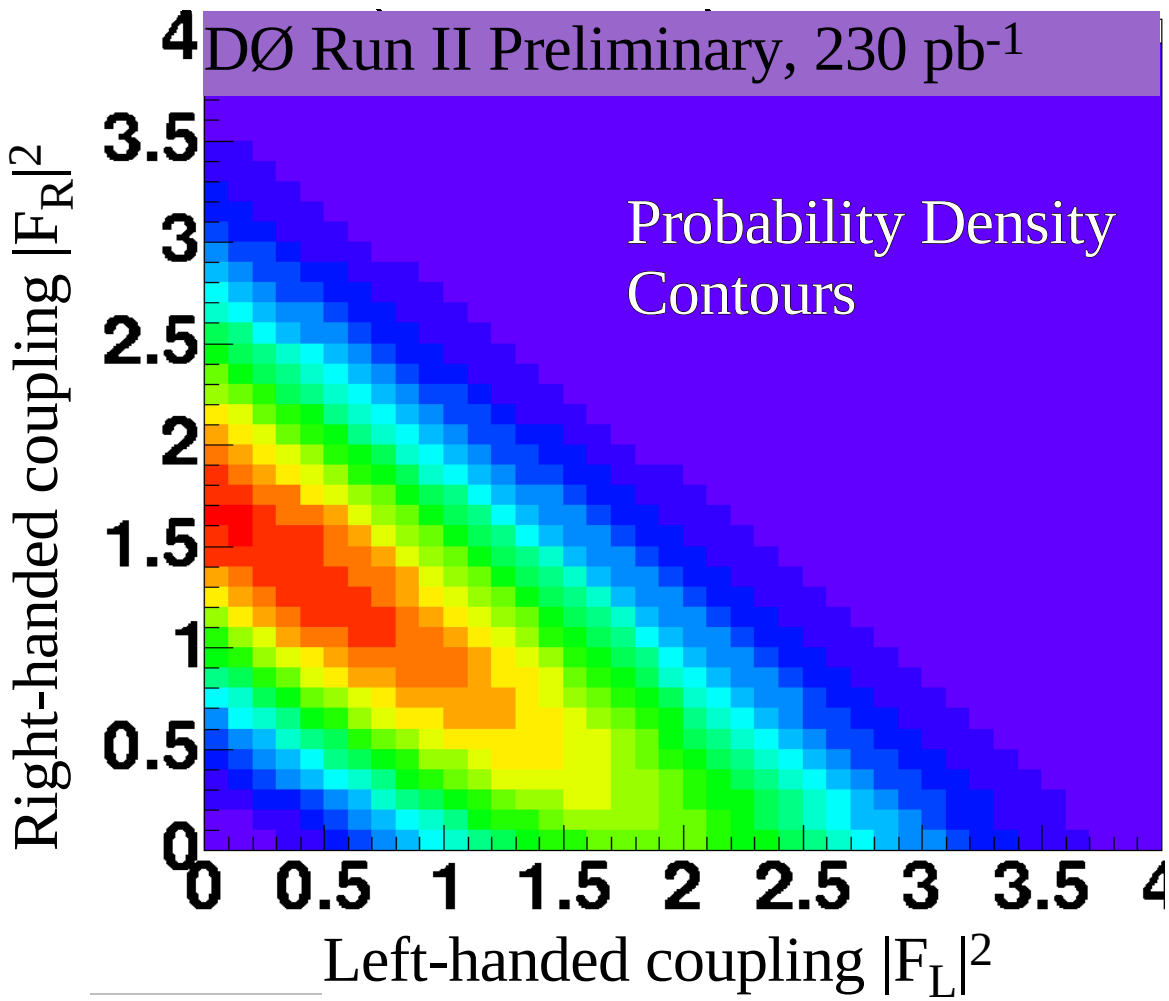
  - Need to assume SM ratio of cross sections

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

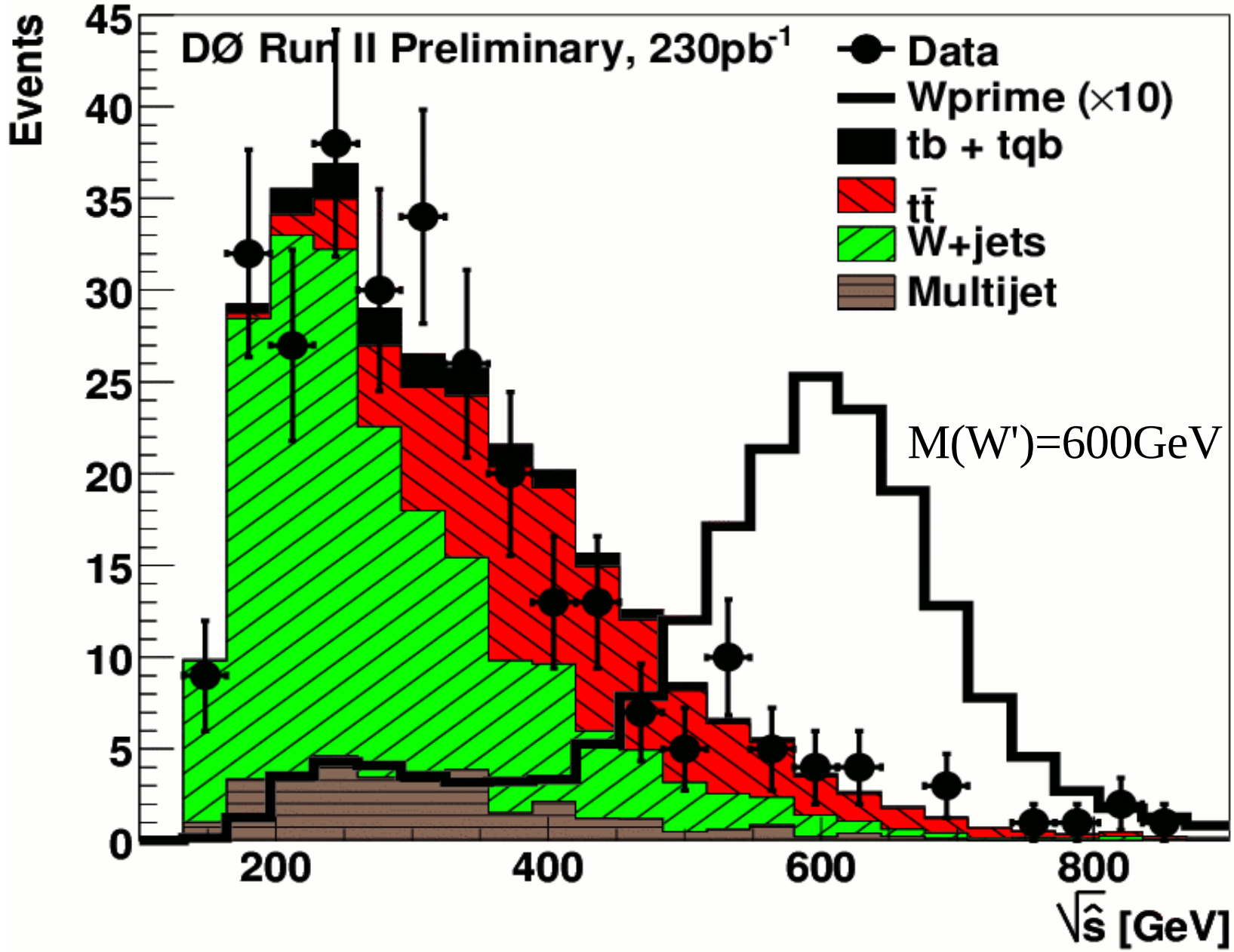


Left-handed or right-handed *W* coupling?

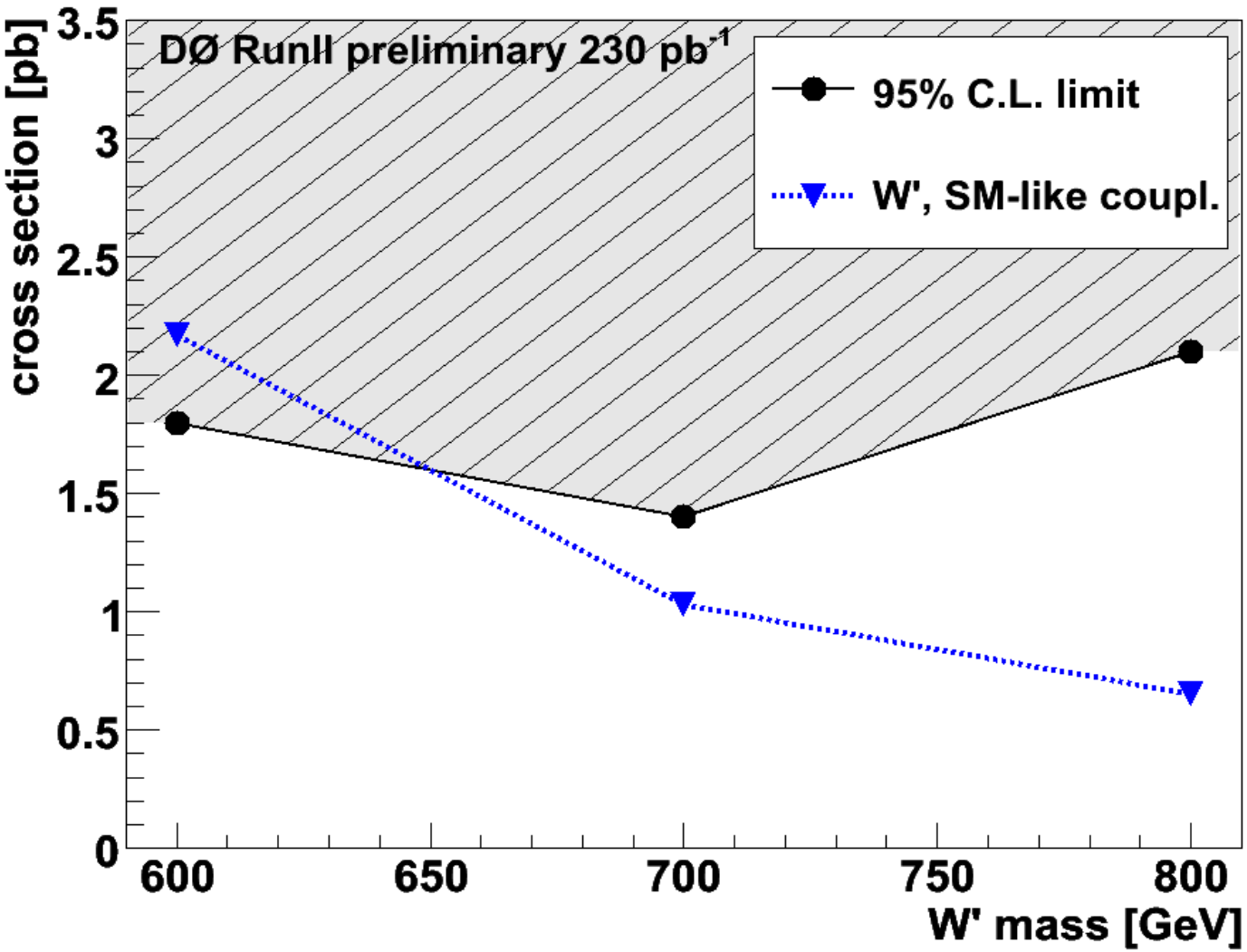
- Extremely preliminary
  - No systematic uncertainties



New heavy boson *W*'?

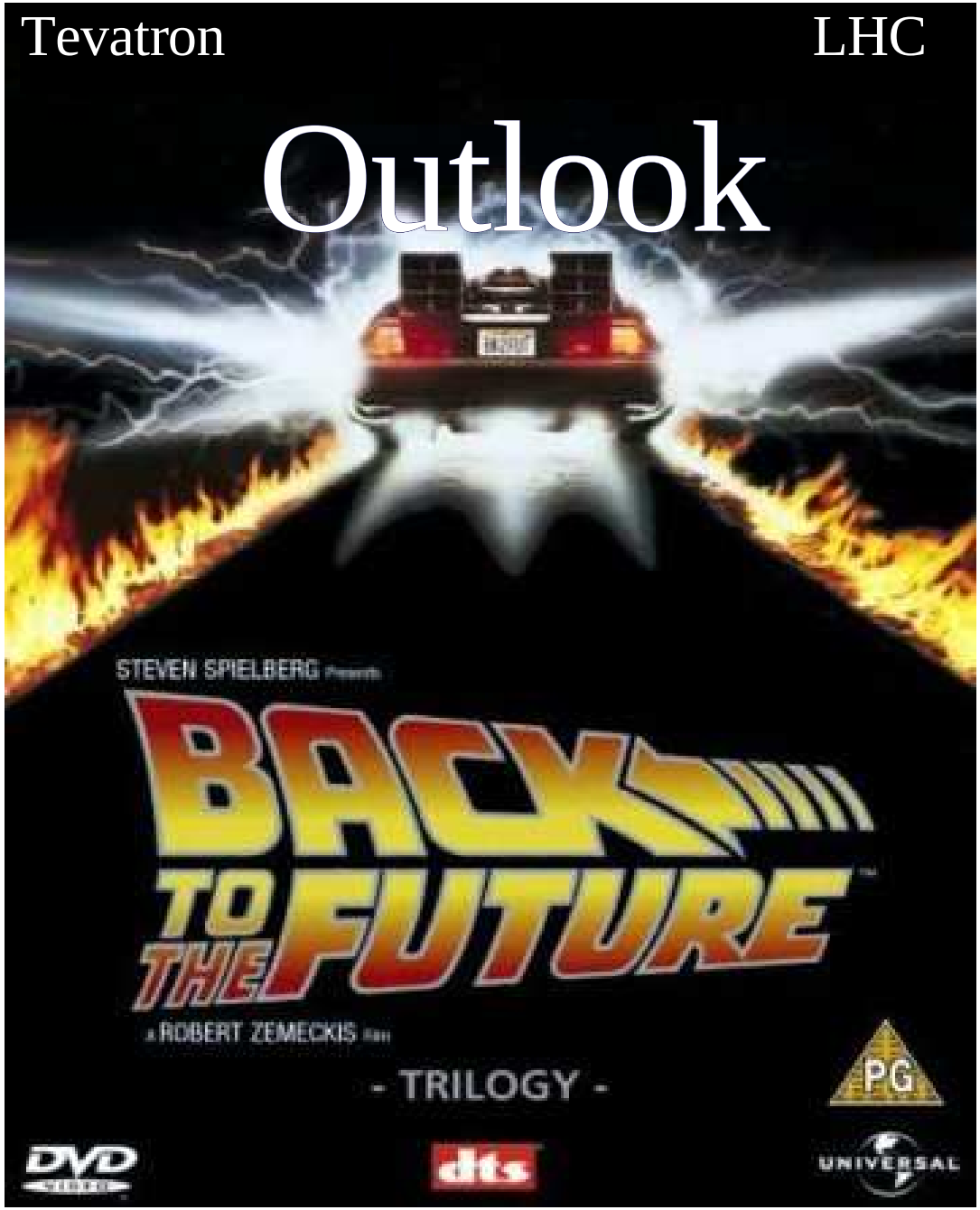


Result


DØ RunII preliminary 230 pb^{-1}
95% C.L. limit
W', SM-like coupl.
cross section [pb]
3.5
3
2.5
2
1.5
1
0.5
0
600
650
700
750
800
W' mass [GeV]

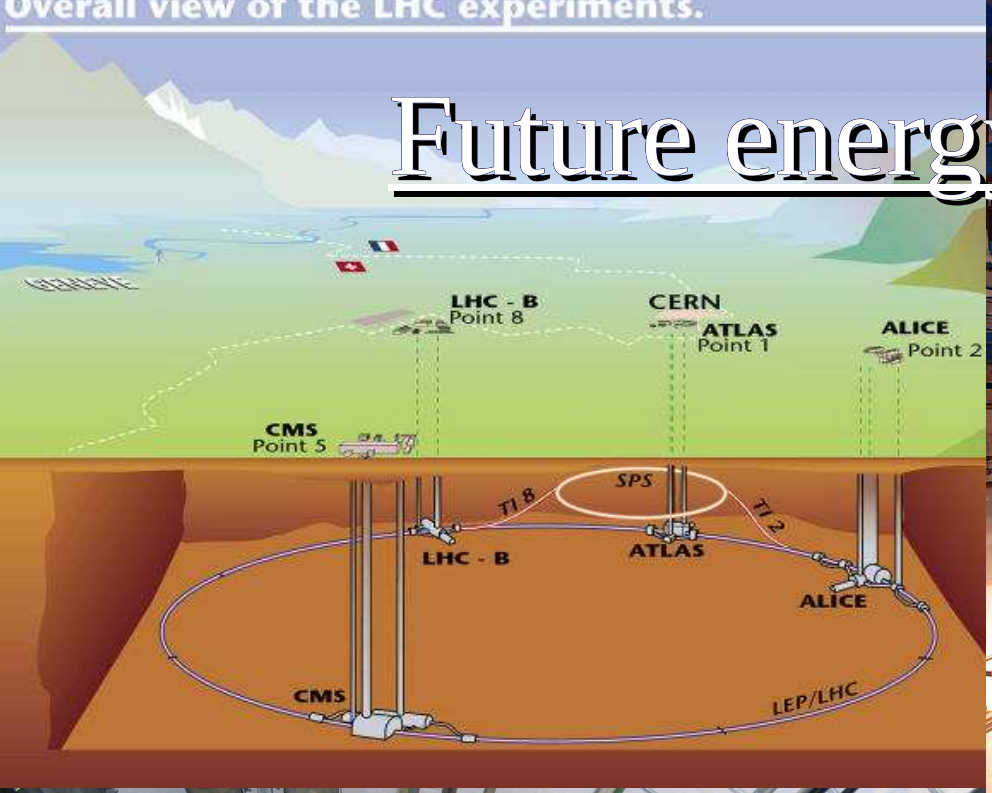
Tevatron LHC

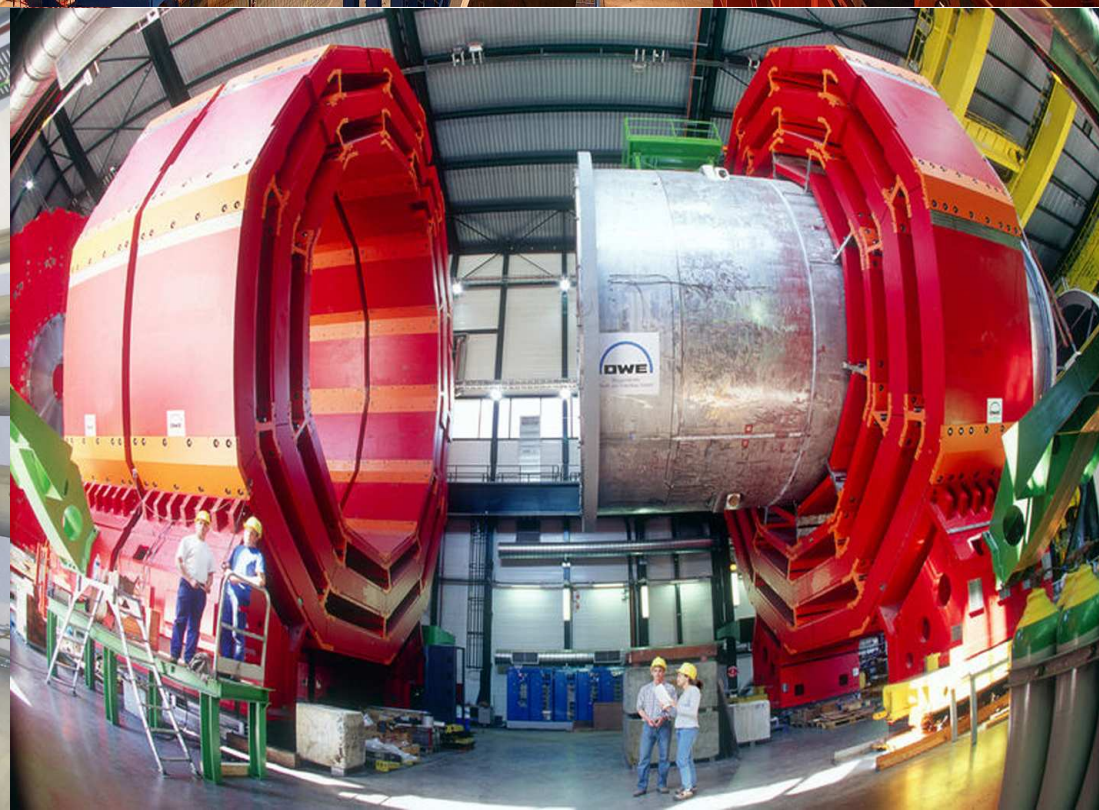
Outlook



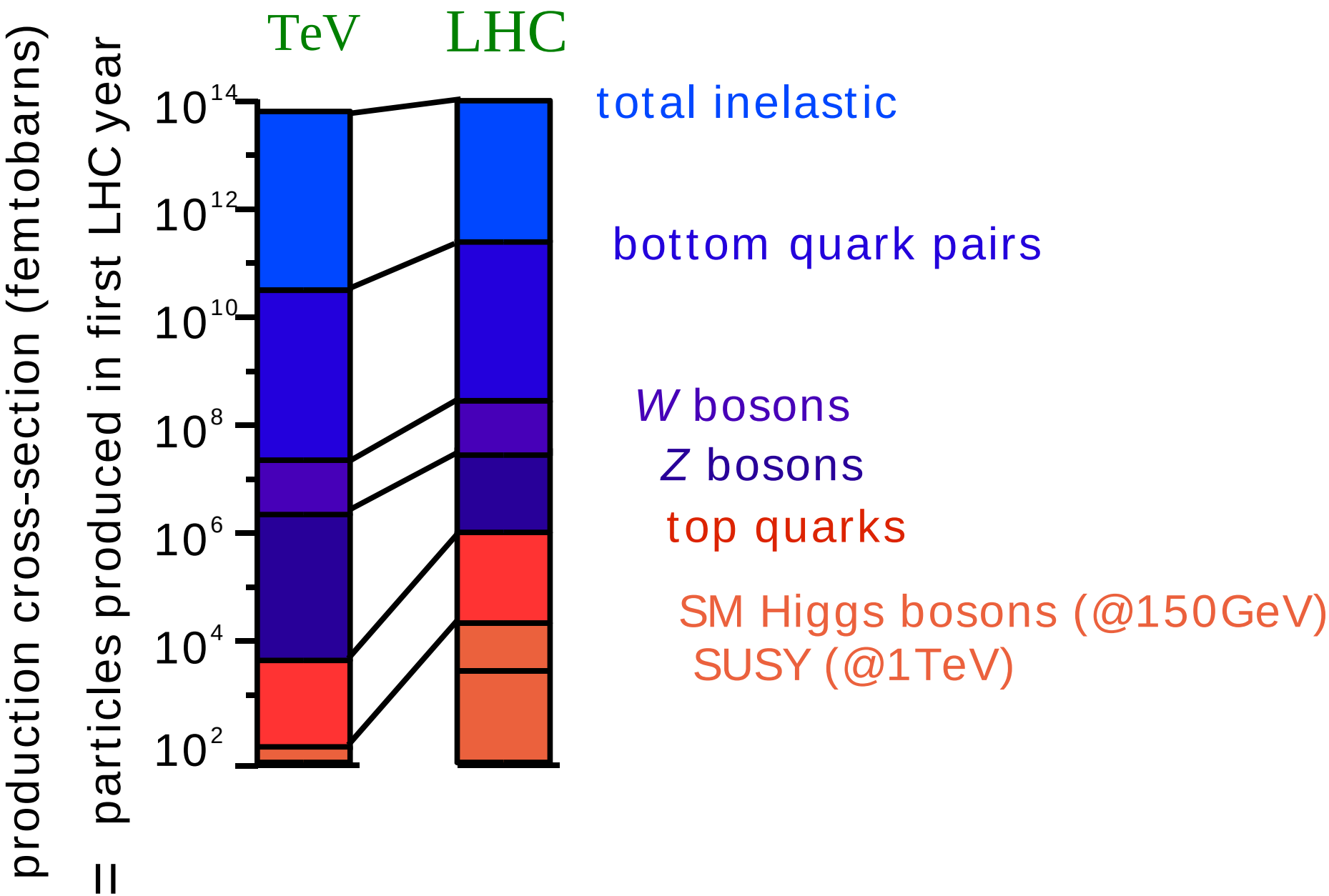
I never think of the future. It comes soon enough.
Albert Einstein

Future energy frontier: LHC



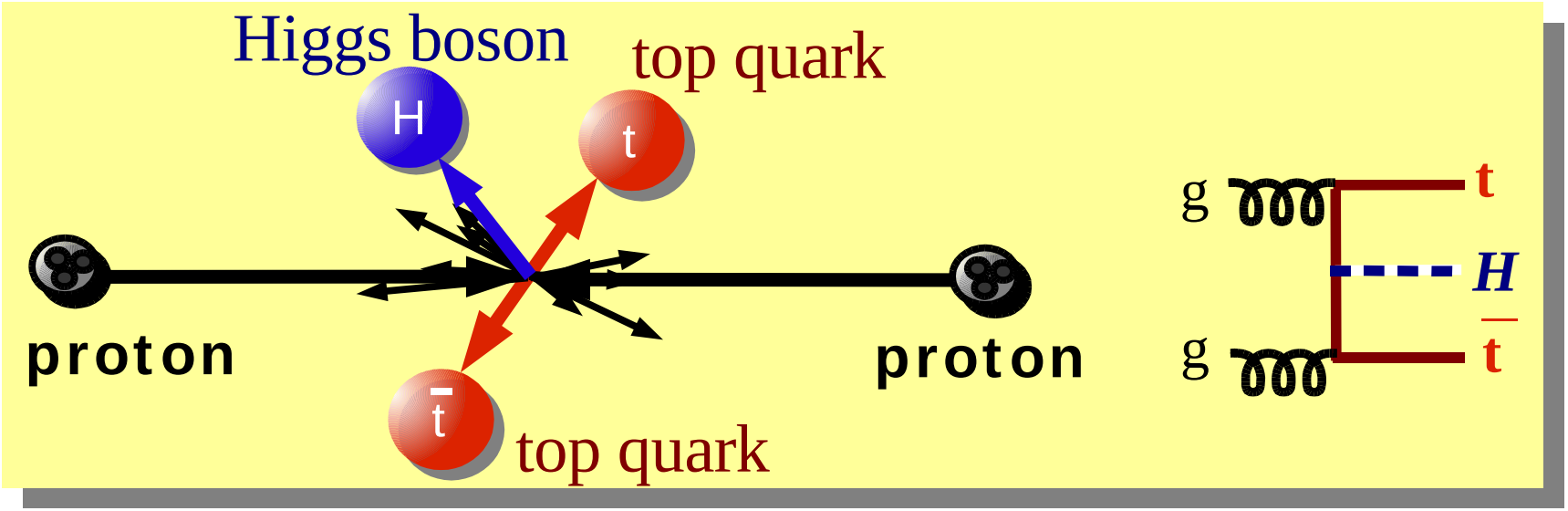


Particle production at the LHC

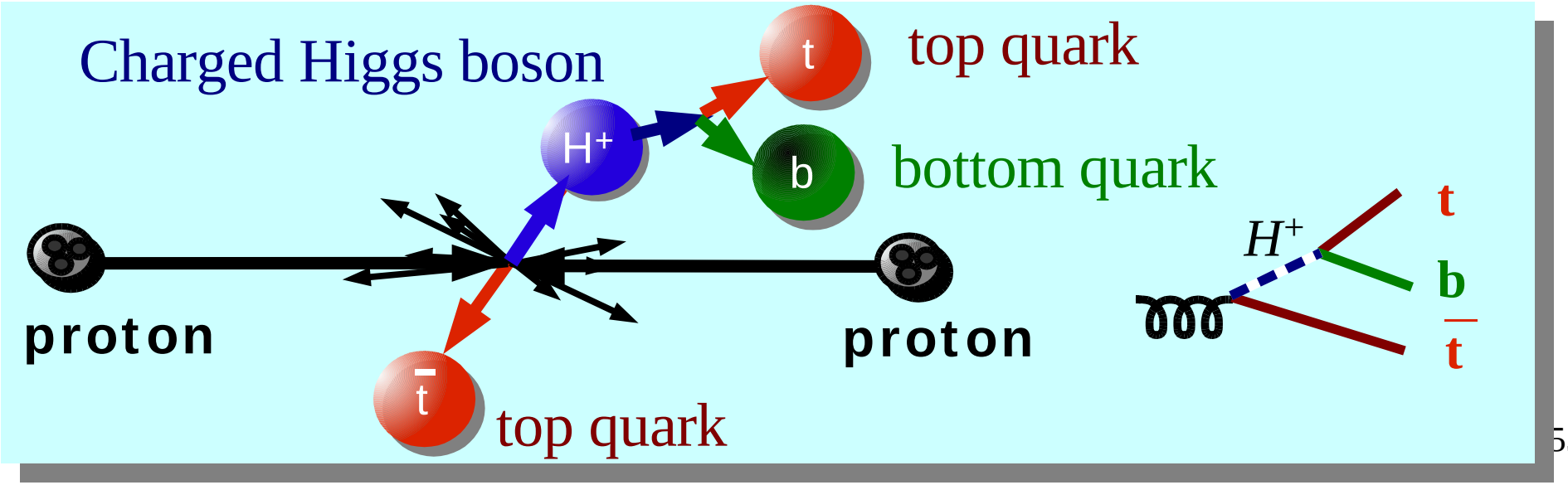


Top as the gateway to Higgs

Neutral SM Higgs

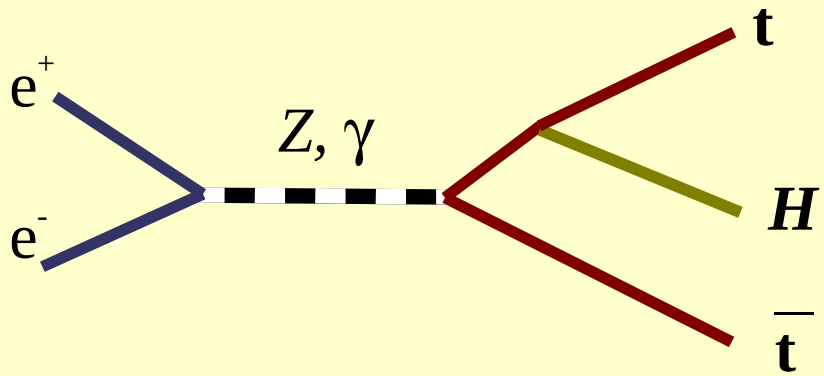


Supersymmetry: Charged Higgs



High precision top quark physics

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



International Linear 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