Physics in the Third Generation

Testing the Standard Model at the Energy Frontier

Reinhard Schwienhorst

Northern Illinois University Physics Colloquium, May 24, 2005

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!

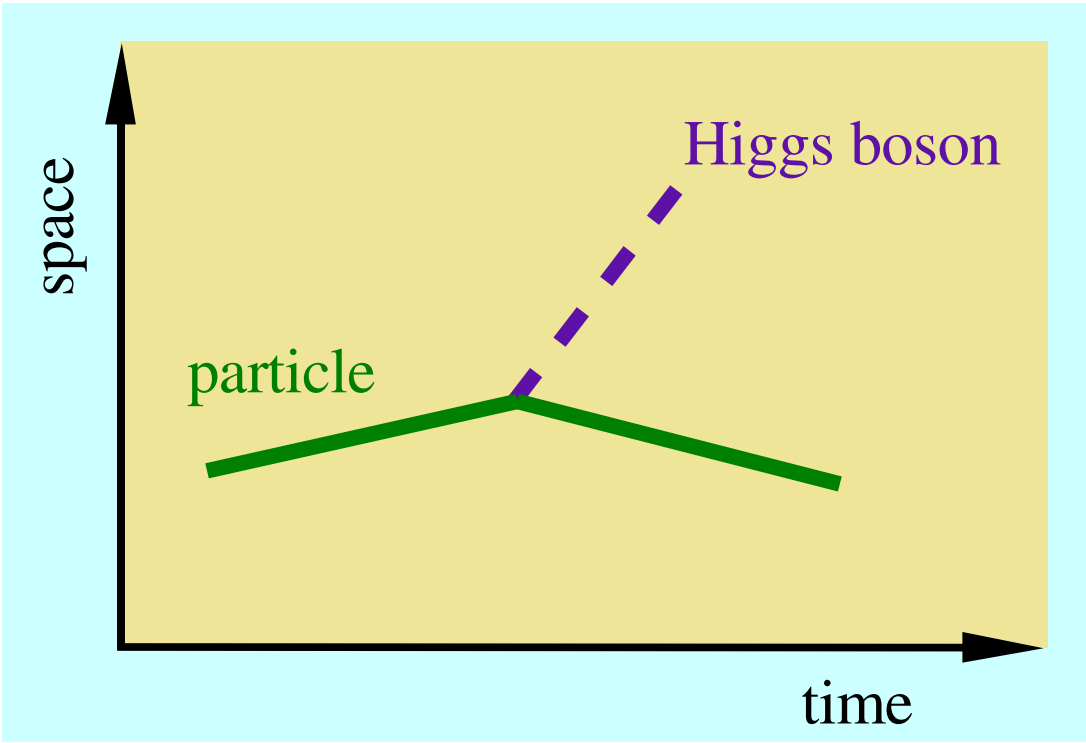
Homer J Simpson

Fundamental Questions

What do I want to know?

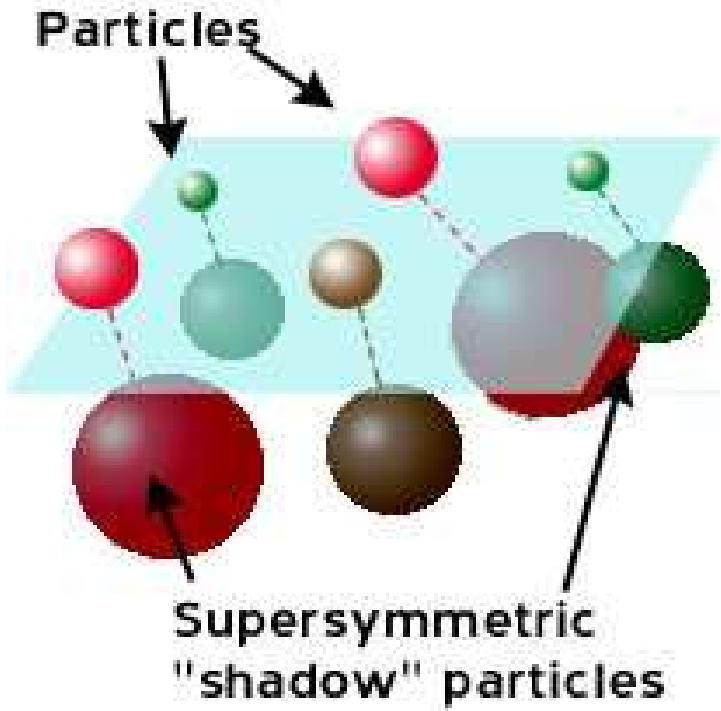
Fundamental questions

- What is the origin of mass?
  - What is the origin of electroweak symmetry breaking?
    - Higgs Mechanism?



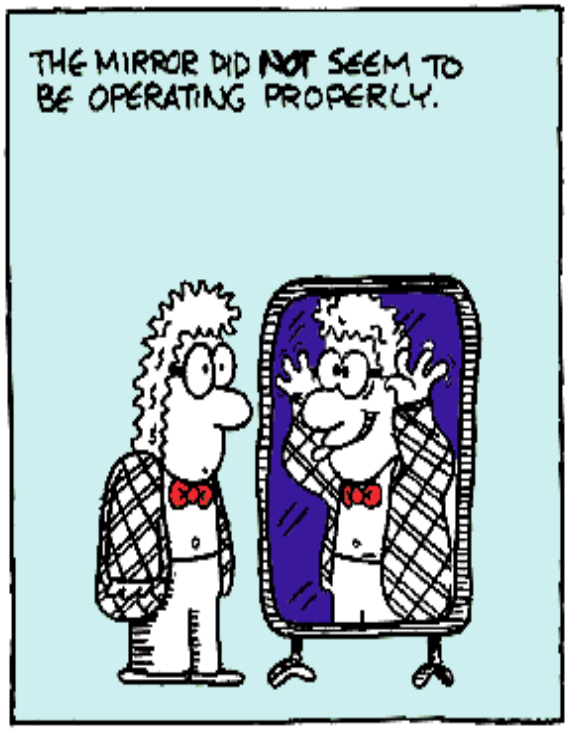
Fundamental questions

- What is the origin of mass?
  - What is the origin of electroweak symmetry breaking?
- Is there an underlying symmetry?
  - Supersymmetry?
  - String Theory?
  - .....



Fundamental questions

- What is the origin of mass?
  - What is the origin of electroweak symmetry breaking?
- Is there an underlying symmetry?
- The Cosmological Connection:
  - Why is there more matter in the universe than anti-matter?
    - Why does anti-matter not behave like matter?
  - What is dark matter?
  - What is dark energy?



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

This talk will be about those limited questions and how we go about answering them

The minute particular

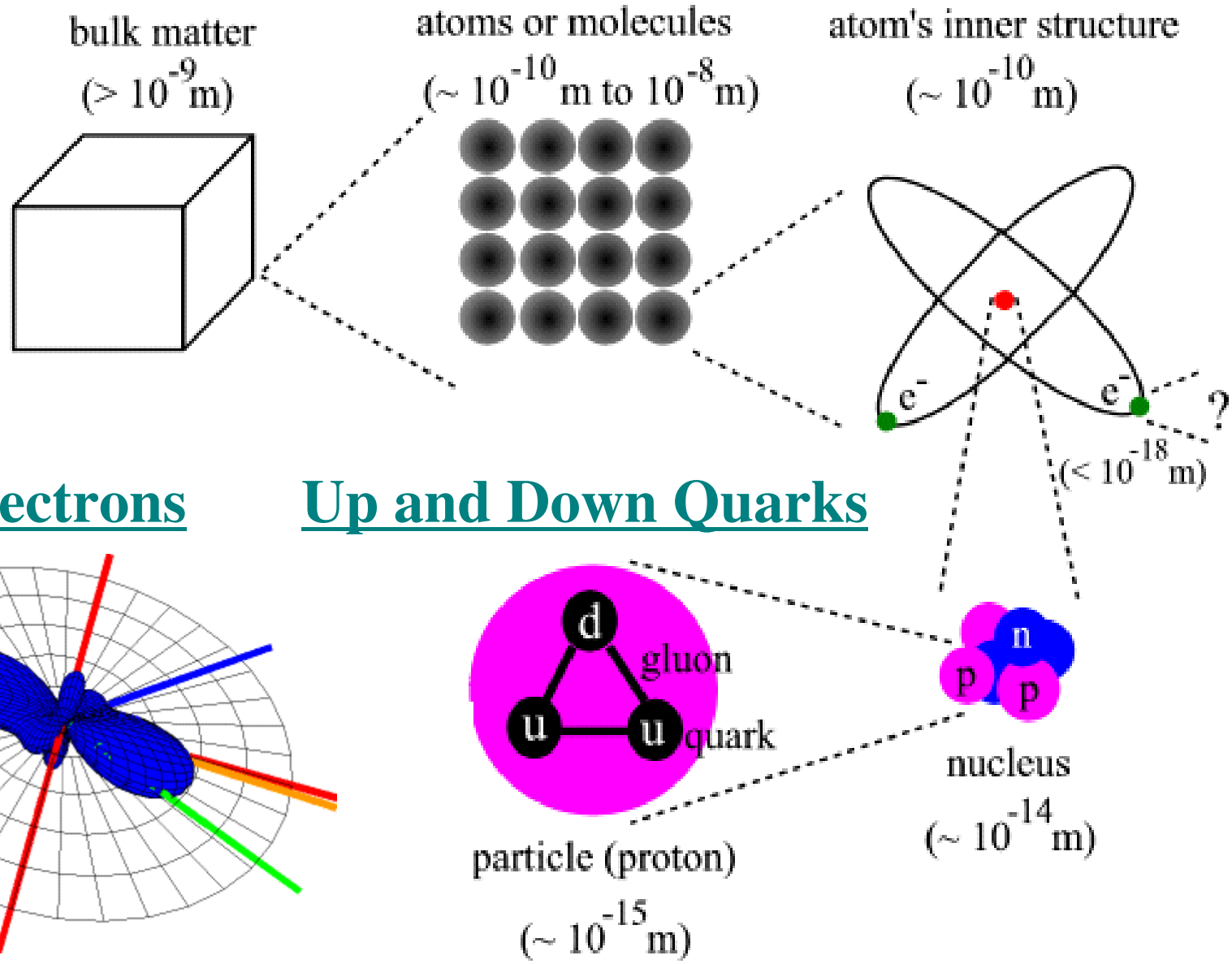
Outline

- Introduction
  - Three Generations of elementary particles
  - Electroweak top quark interactions
- The Energy Frontier
  - Fermilab Tevatron
  - Dzero experiment
- Results
- Outlook
- Conclusions

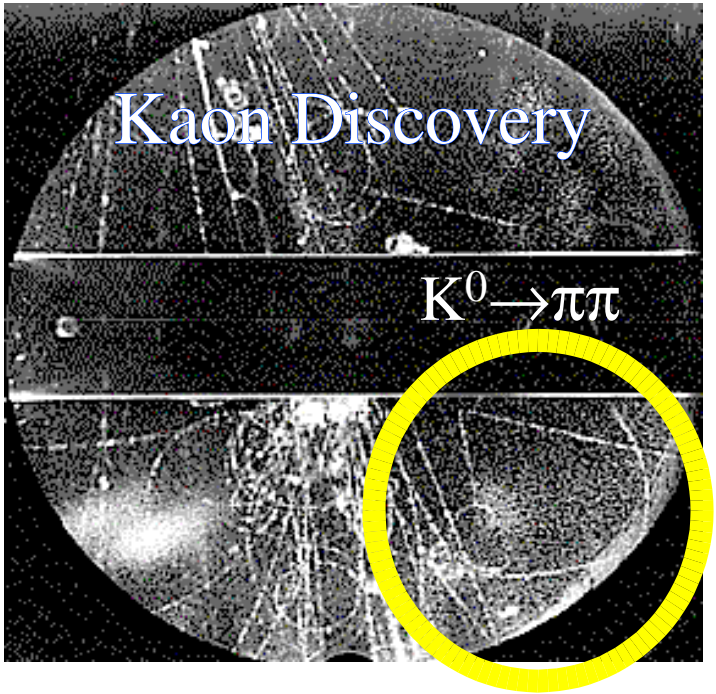
State of the art

What do we know already?

What matter is made of: The 1st generation

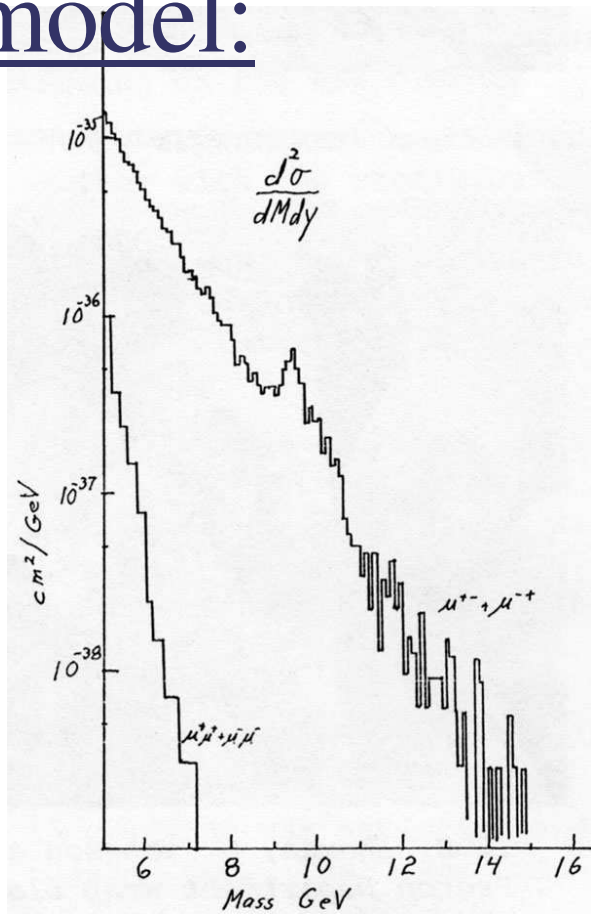


Exciting discoveries: The 2nd generation

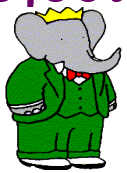


- Another set of leptons and quarks
  - Strange and charm quarks
    - Kaon discovery in 1947
  - Muon and muon neutrino
- Duplication of 1st generation, but at higher mass
- Today subject of detailed measurements
    - Muon magnetic moment (g-2)
    - CP-violation in the Kaon sector

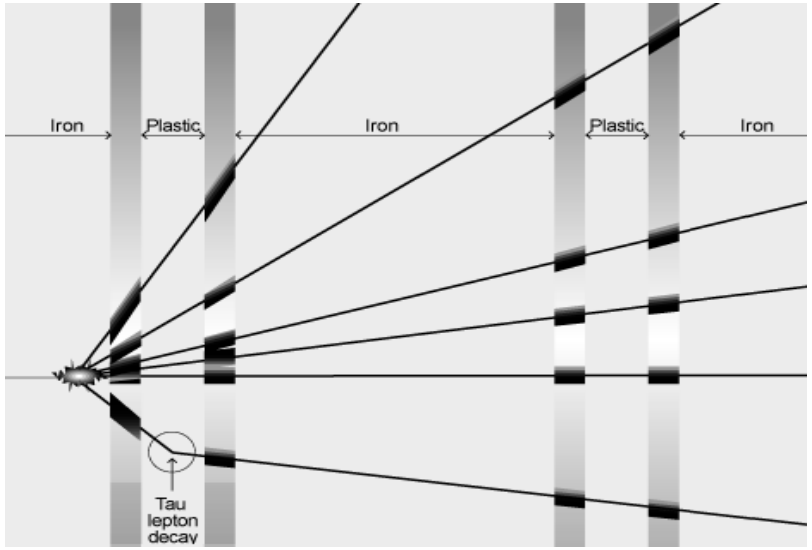
Completing the standard model: The 3rd generation

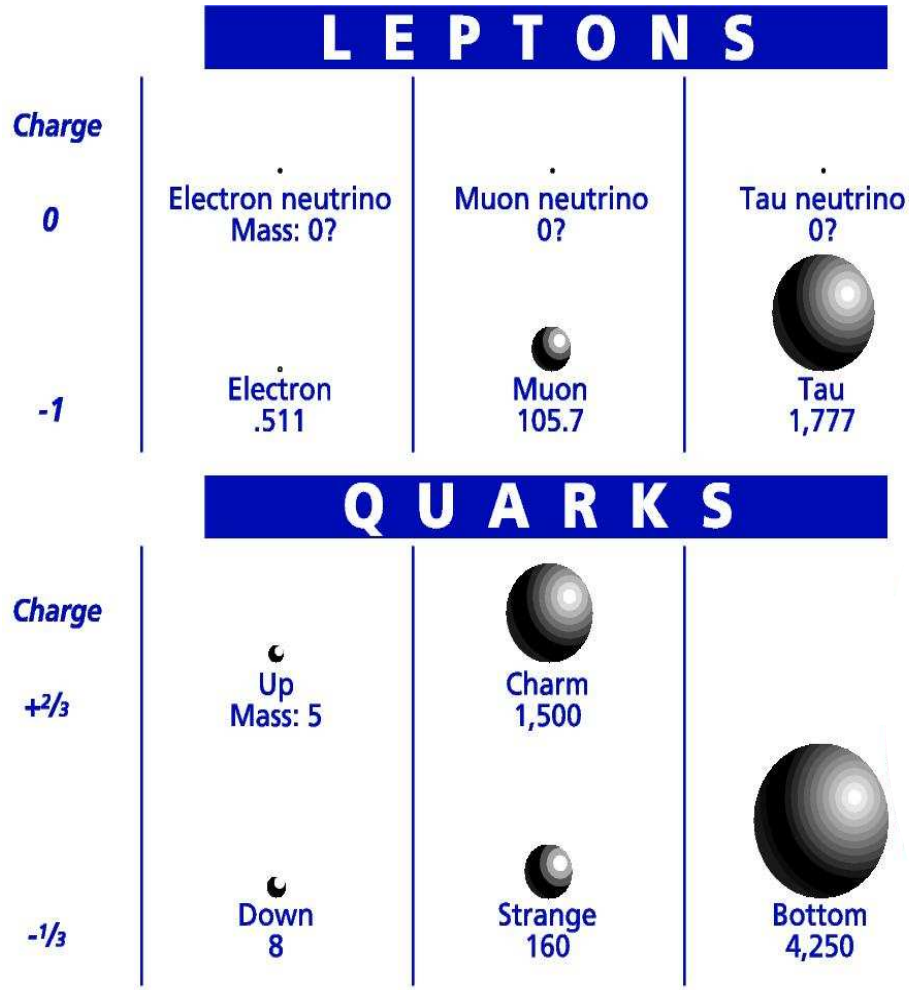


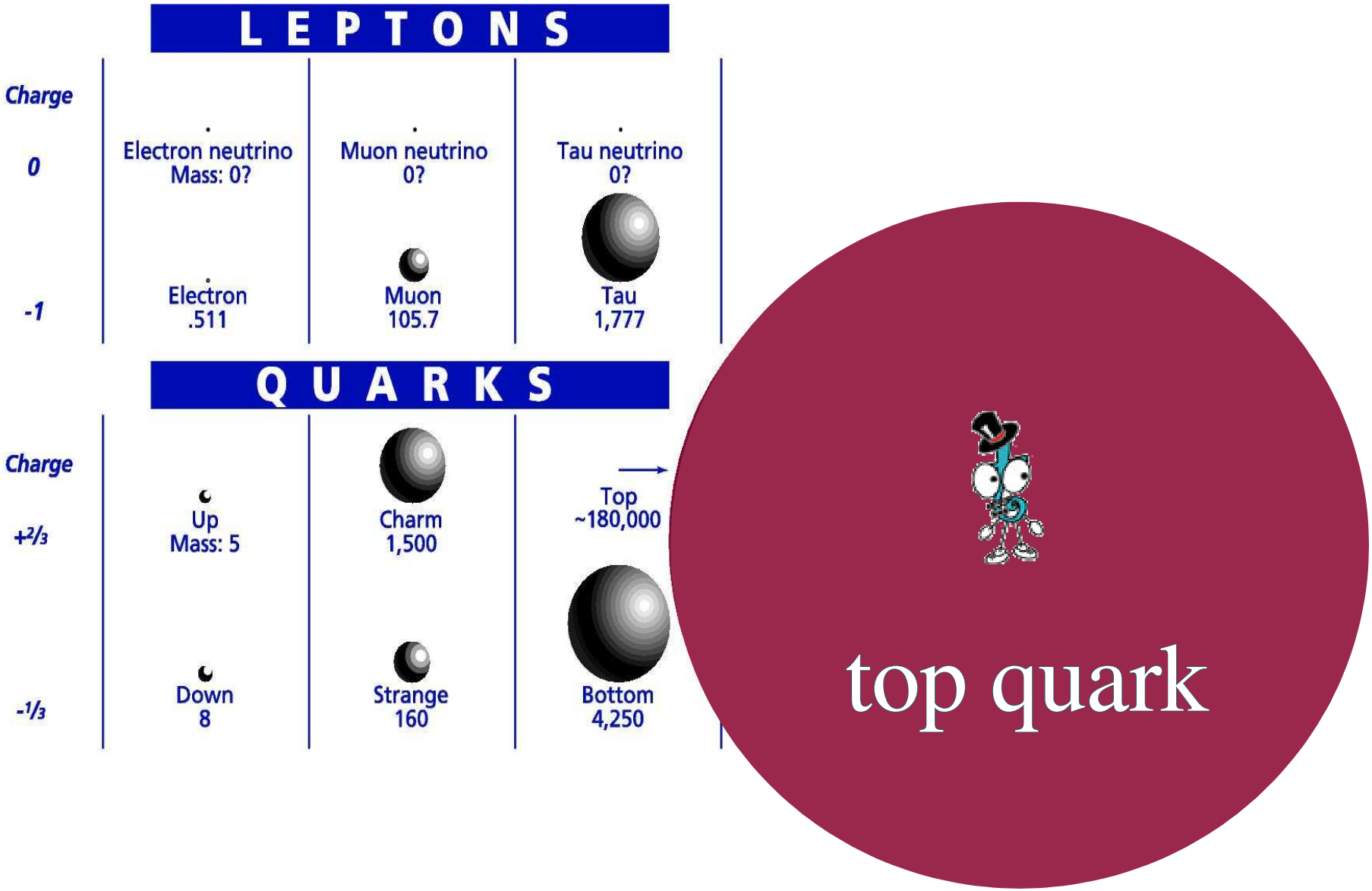
- Another set of leptons and quarks
- Tau lepton
  - Discovered 1975 at SLAC
- Bottom quark
  - Discovered 1977 at Fermilab
  - Today the subject of high-precision experiments

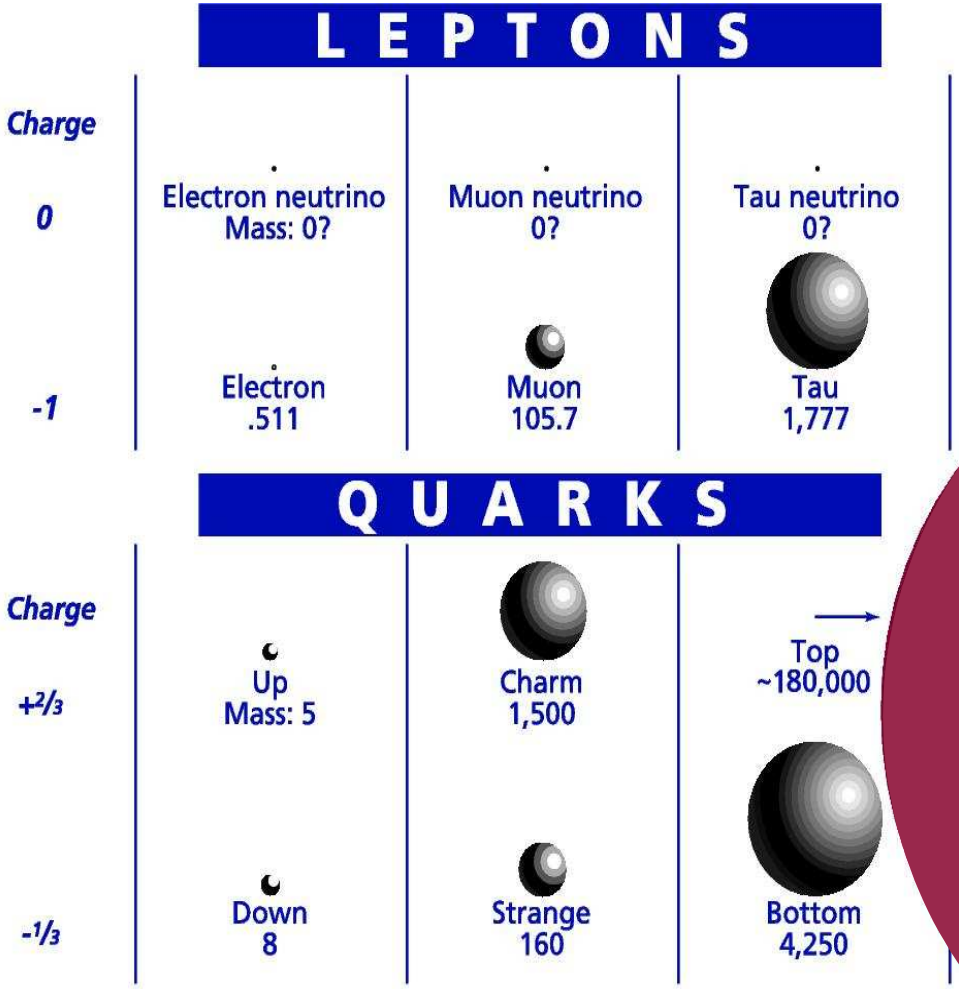


- Top quark
  - Discovered 1995 at Fermilab
- Tau neutrino
  - Discovered 2000 at Fermilab

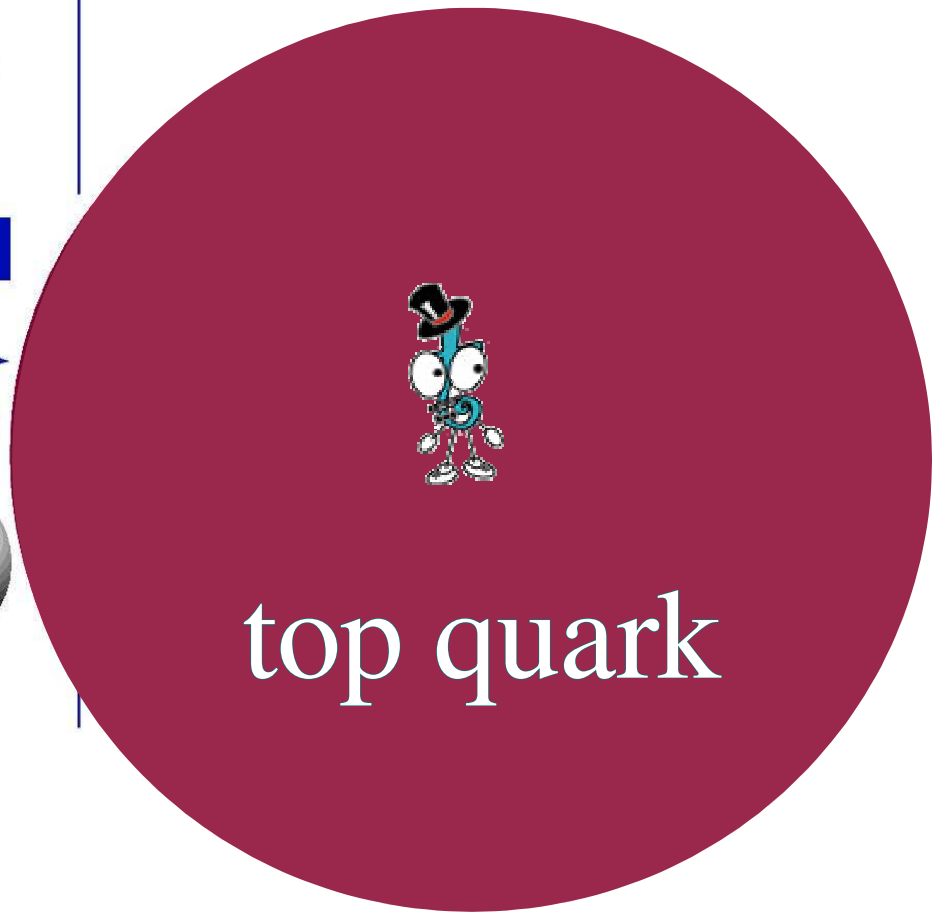


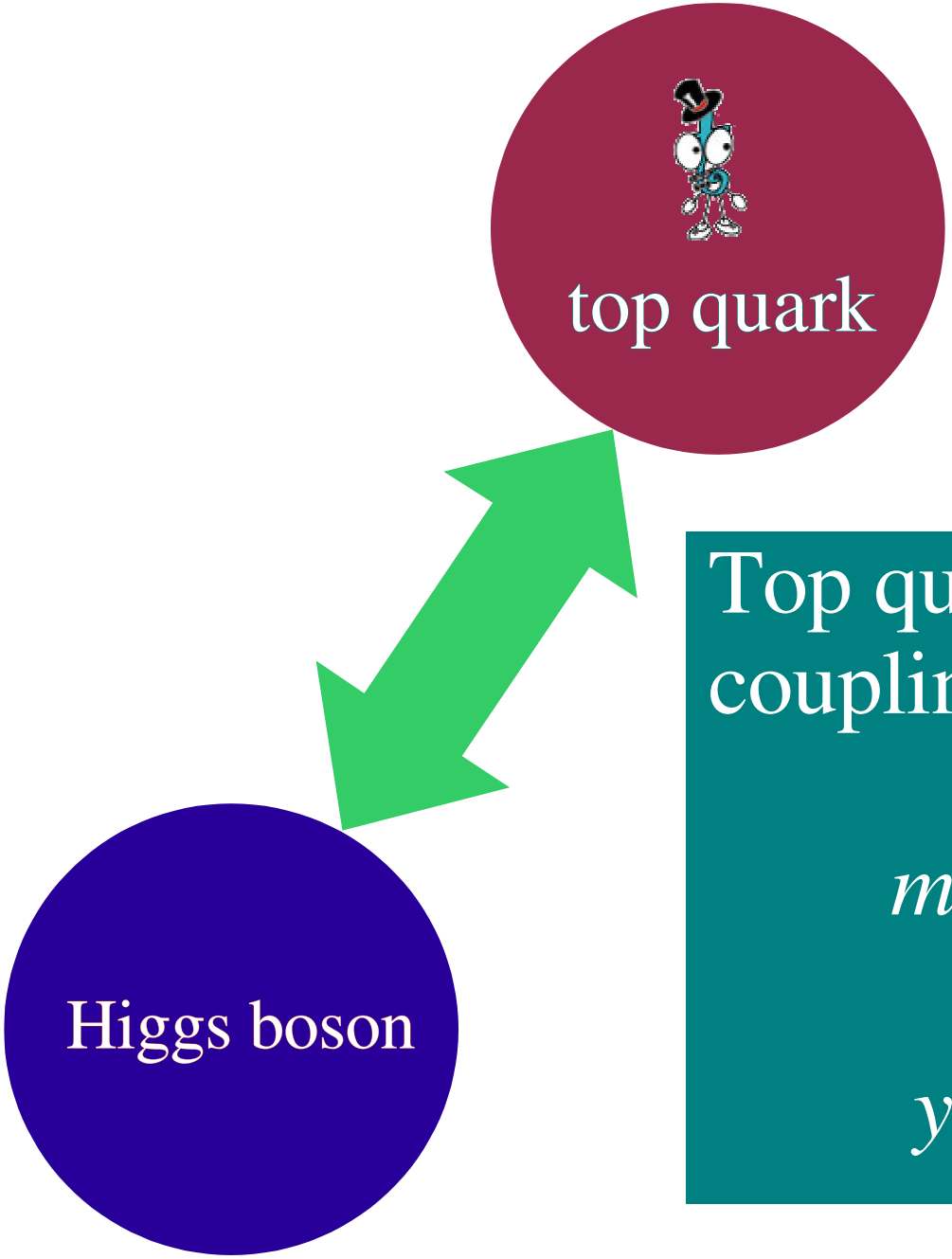

LEPTONS
Charge
0
Electron neutrino
Mass: 0?
Muon neutrino
0?
Tau neutrino
0?
-1
Electron
.511
Muon
105.7
Tau
1,777
QUARKS
Charge
+2/3
Up
Mass: 5
Charm
1,500
-1/3
Down
8
Strange
160
Bottom
4,250


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
top quark



KING OF FERMIONS

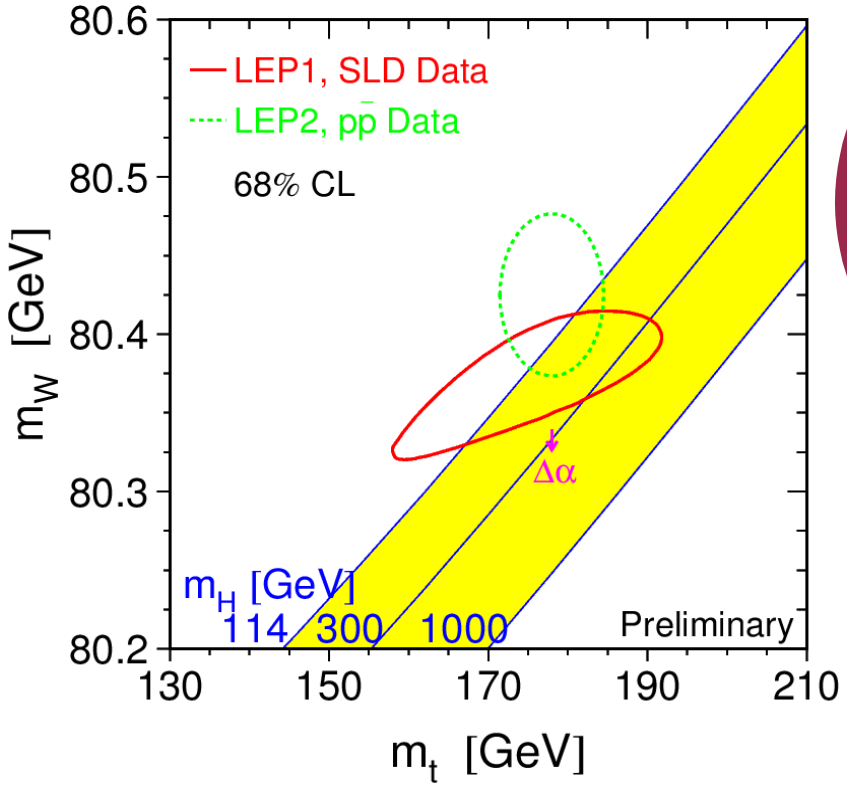


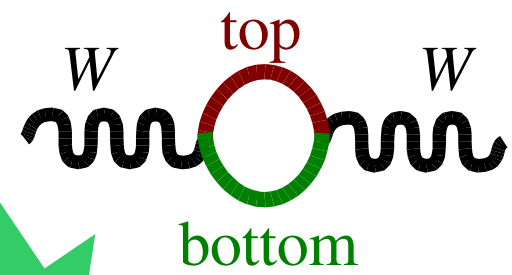


Top quark mass through coupling to Higgs field

$$m_t = y_t \, v$$

$$y_t \sim 1$$

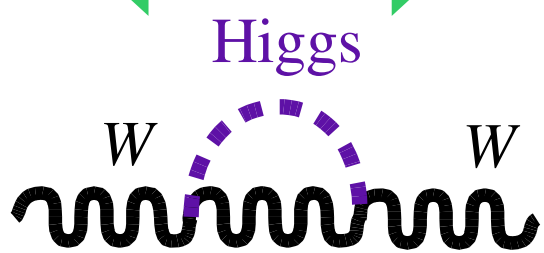


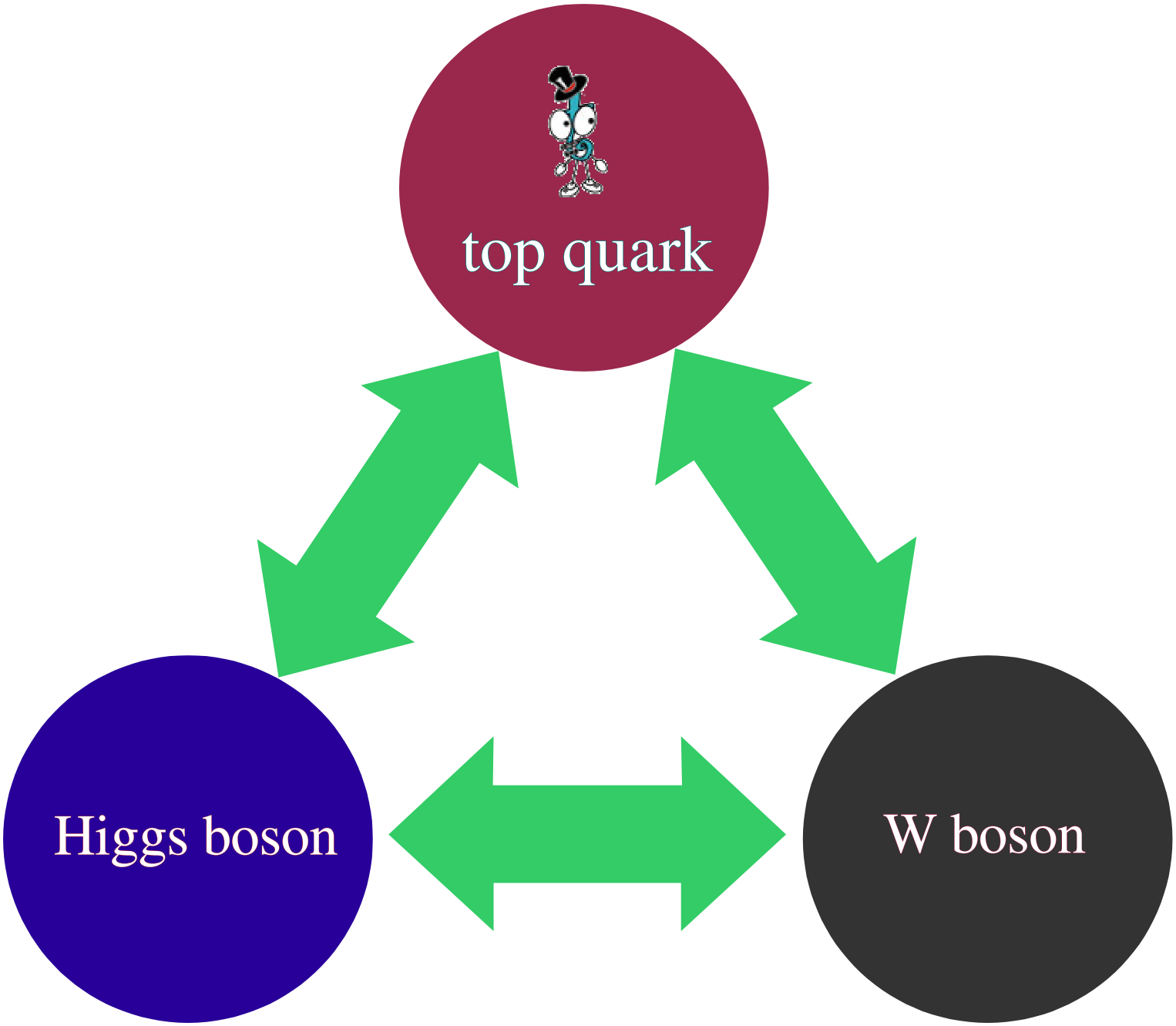


SM Higgs boson mass estimate

Higgs boson

W boson

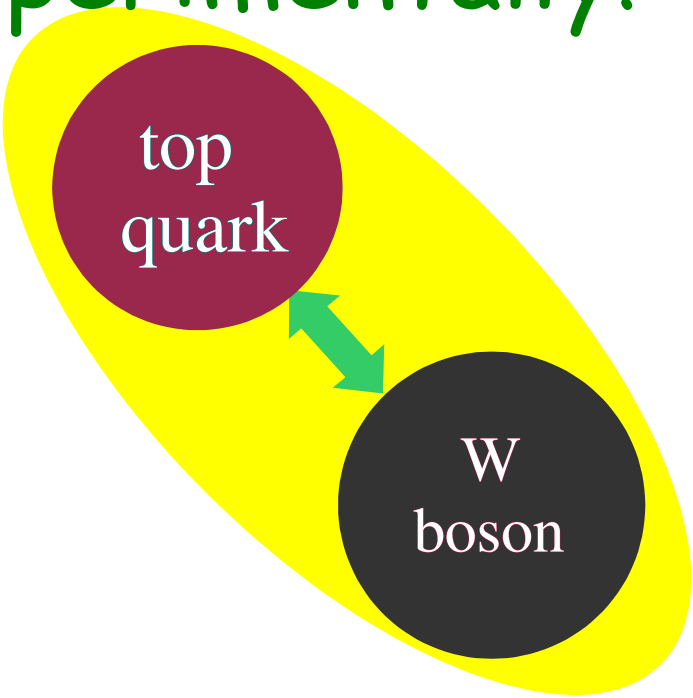




Key to the origin of particle masses

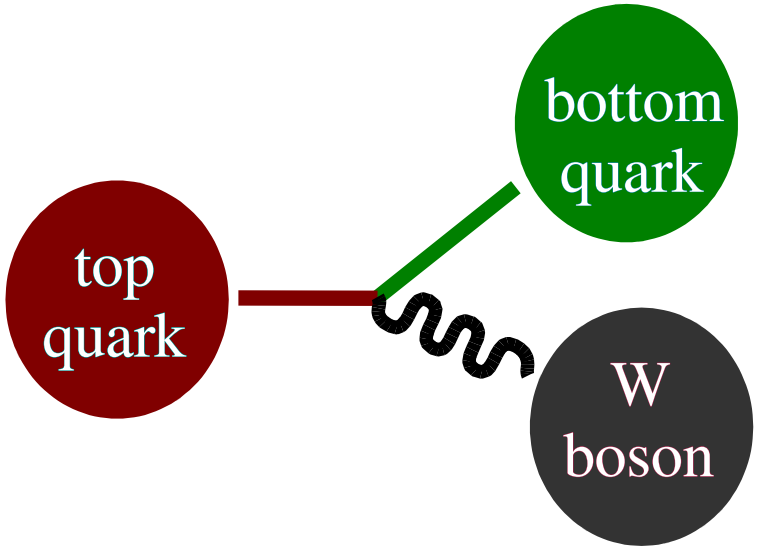
Very little known experimentally!

- Top quark mass 178.0 ± 4.3 GeV
- SM strong interaction
- Typically decays to W boson and b quark



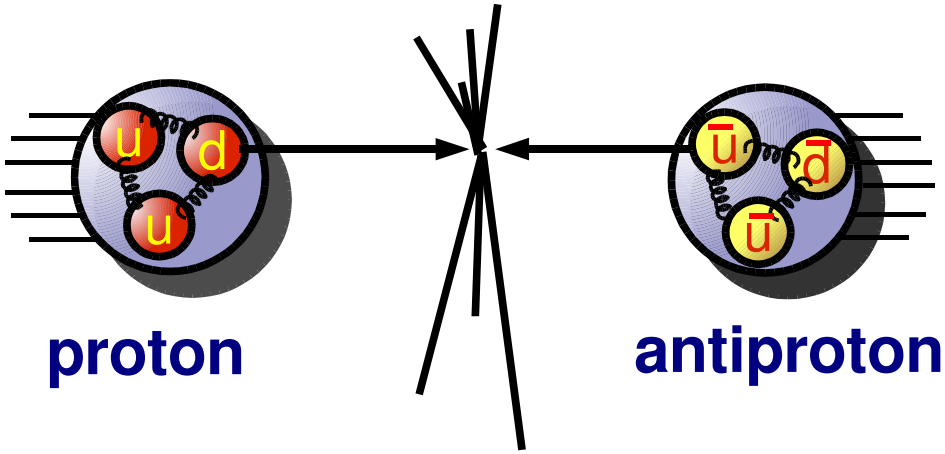
Top quark unknowns:

- Electroweak interaction?
  - Total width?
  - Decay branching ratios?
  - V-A Structure?
- Other couplings?
  - Z, γ, H? – New physics?



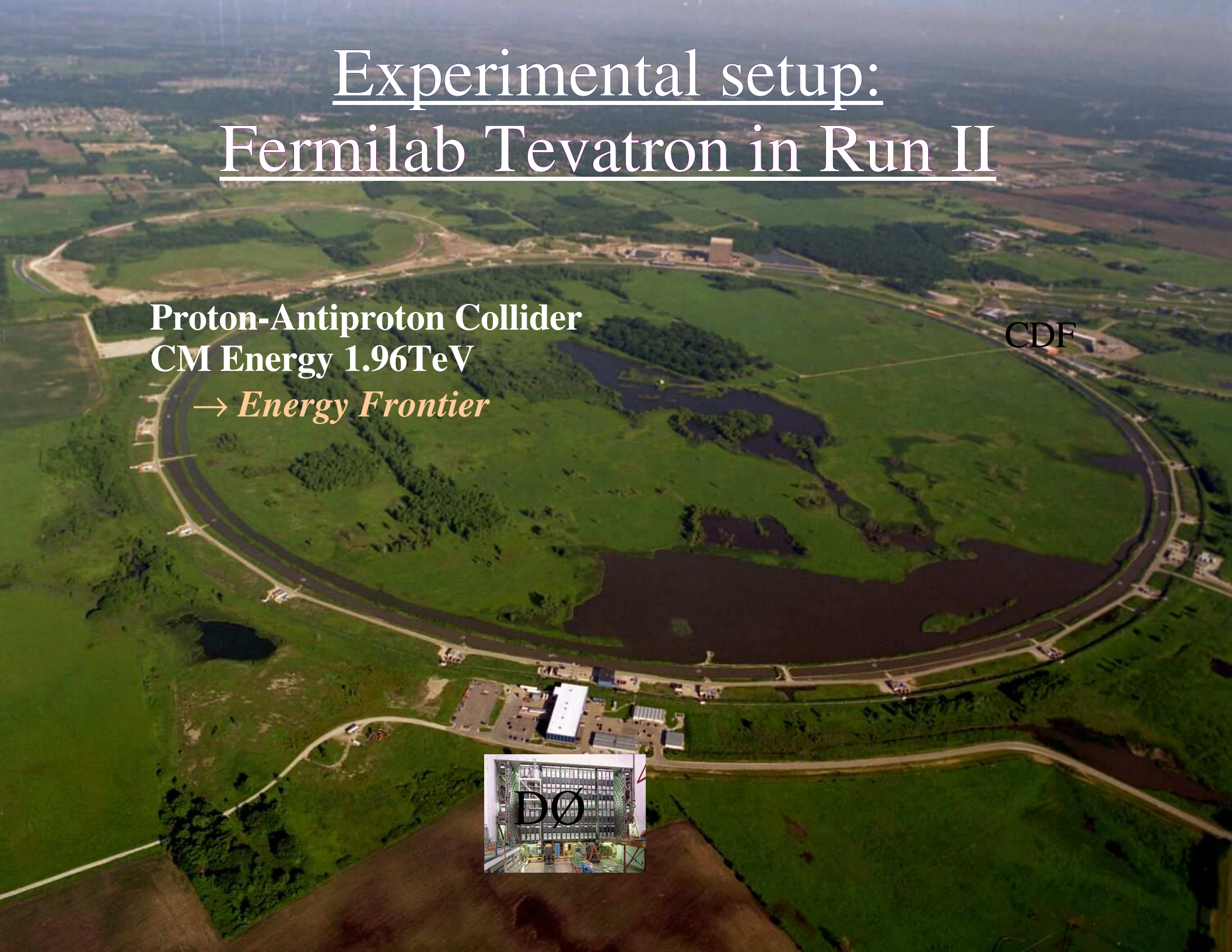
Experimental setup: the energy frontier

Probe Physics at small distance scales by colliding particles at high energy



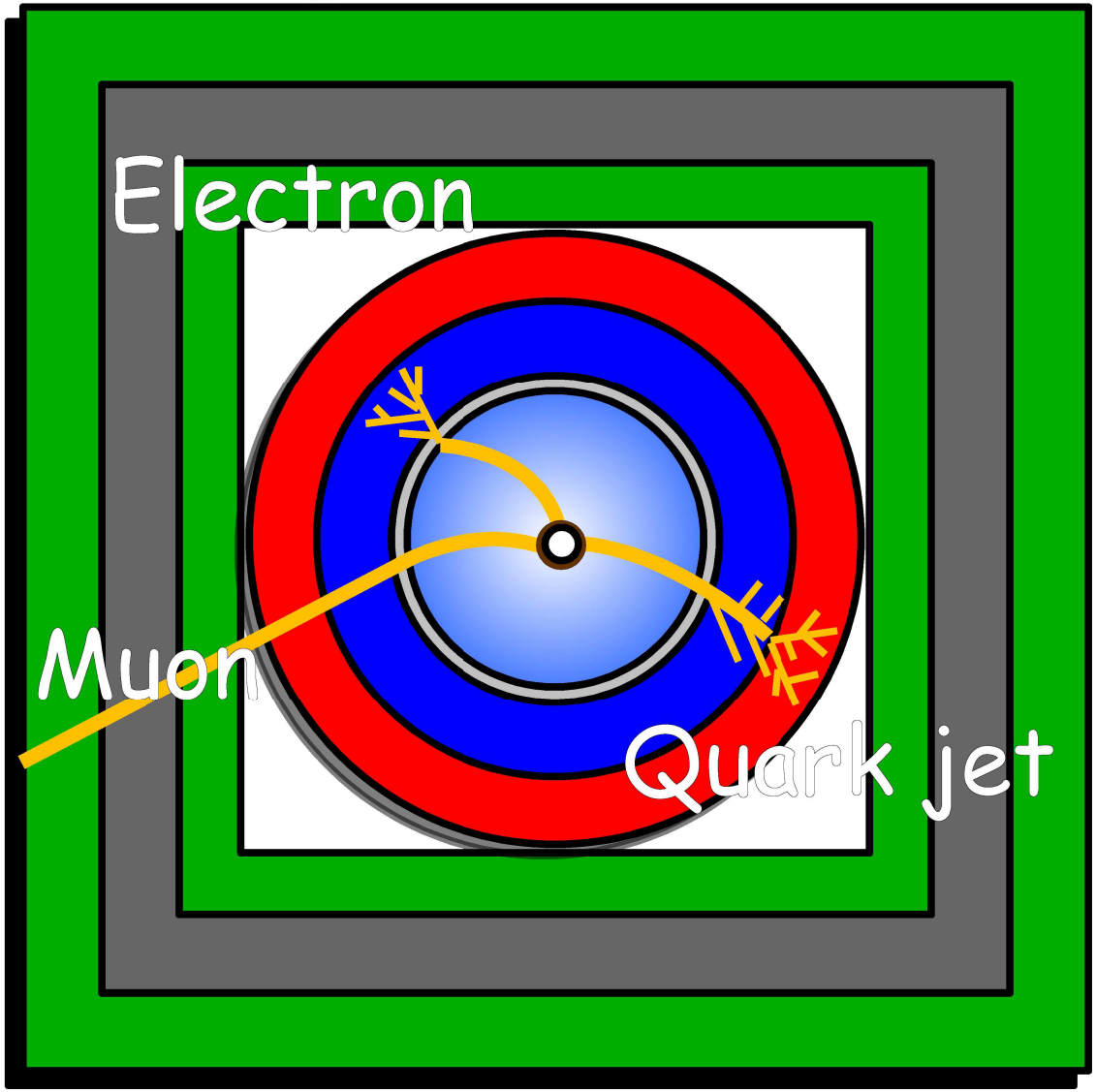
Experimental setup: Fermilab Tevatron in Run II

Proton-Antiproton Collider
CM Energy 1.96TeV
→ ***Energy Frontier***

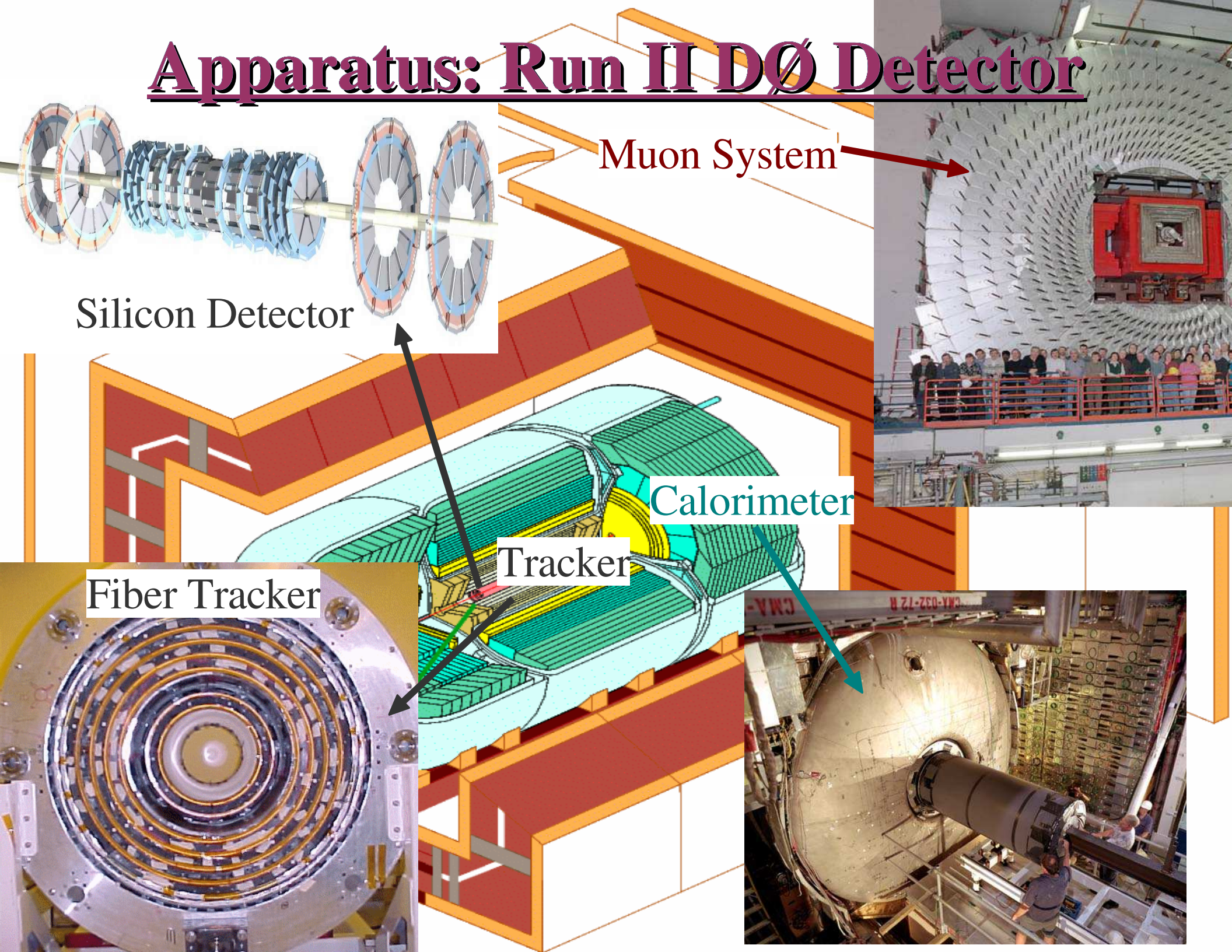


Experimental setup: detector configuration

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



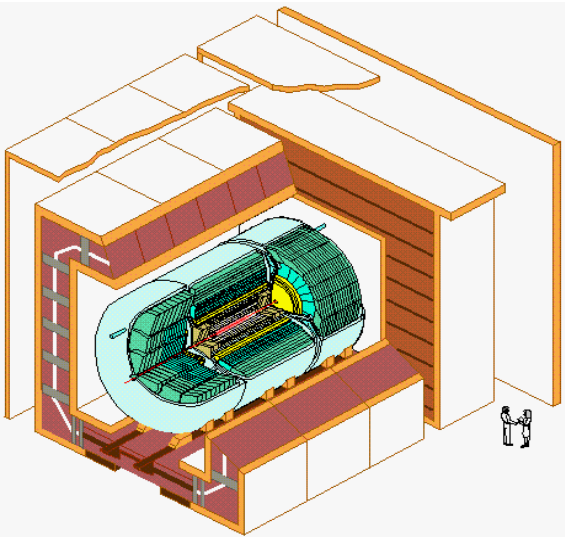
Apparatus: Run II DØ Detector



Experimenters

- 19 countries
- 80 institutions
- 670 physicists

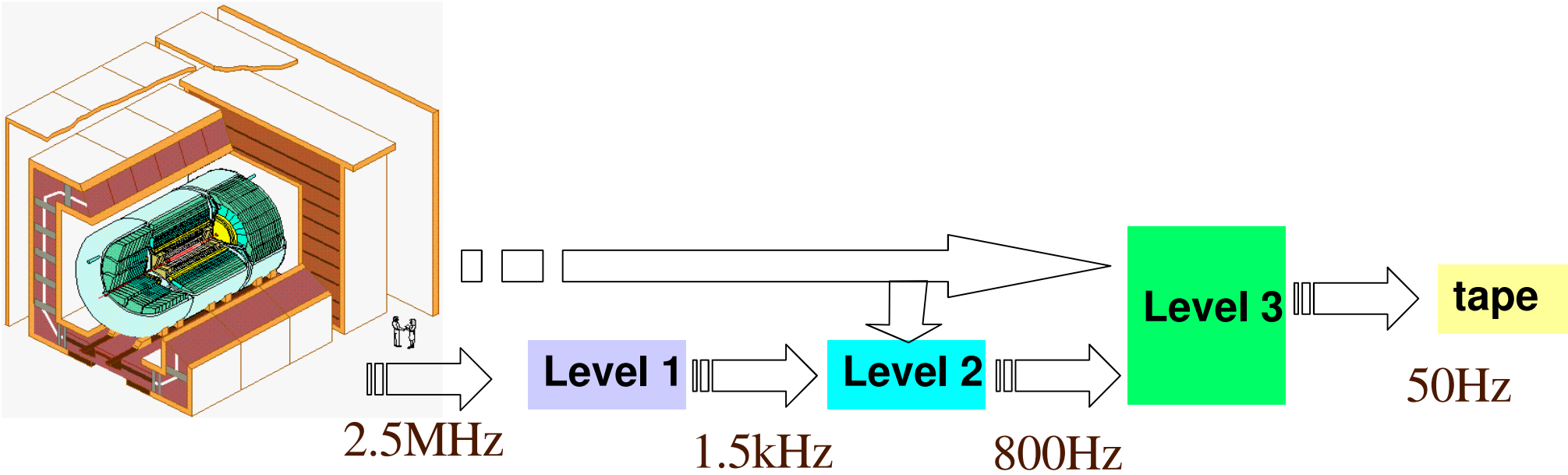
Collecting interesting events: Trigger System



2.5MHz → **Select interesting events** → 50Hz → **Storage tape**

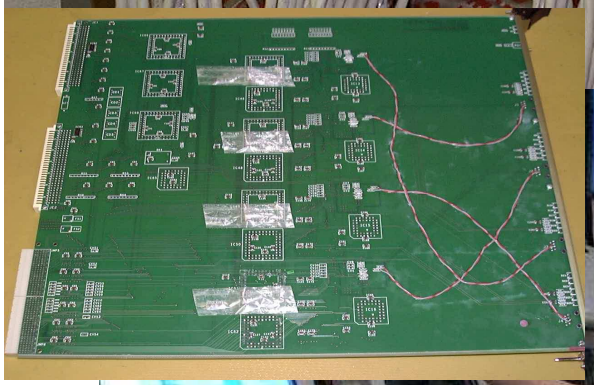
- Reduce rate of interactions (inelastic collision rate) to manageable level that can be stored
- Record "interesting" events
  - Select events containing high-energy final state objects
    - Electrons, muons, quark jets

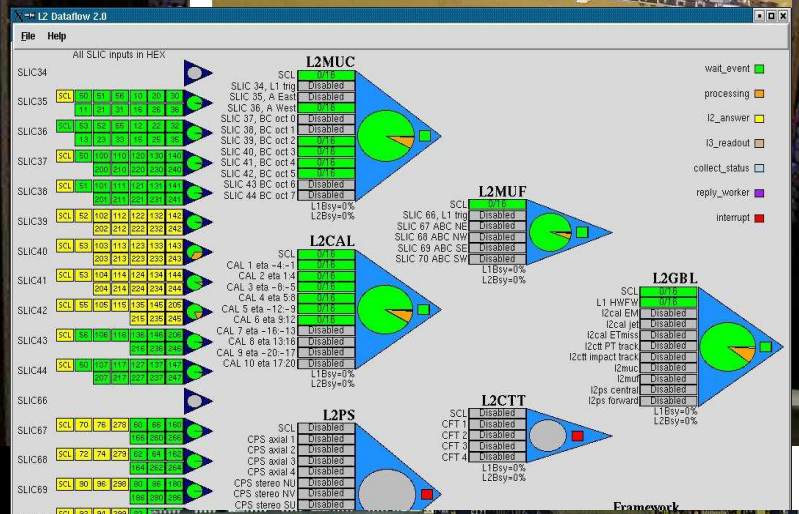
Collecting interesting events: Trigger System

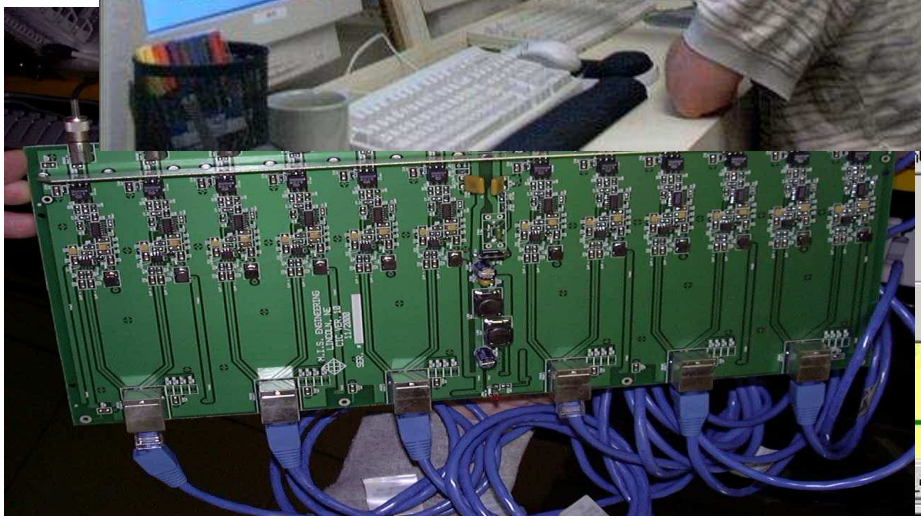


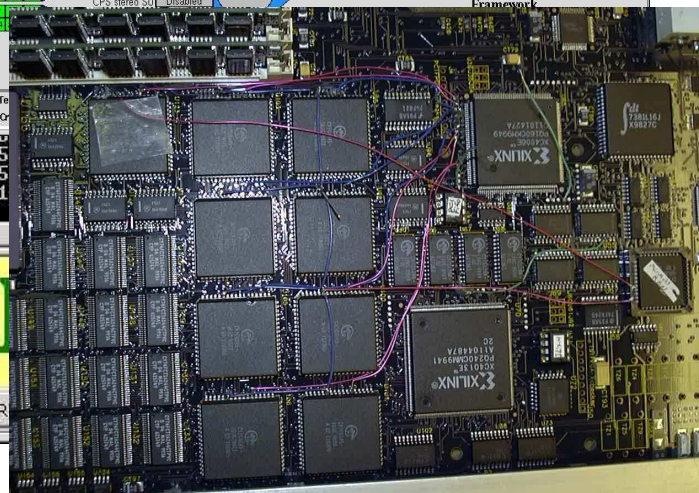
- DØ experiment: three-level trigger system
  - Reconstruct objects at every level
    - Decreasing event accept rate
    - Increasing time per decision
    - Increasing level of sophistication

Trigger commissioning



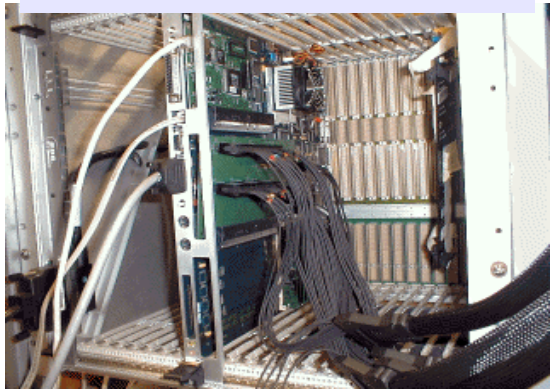






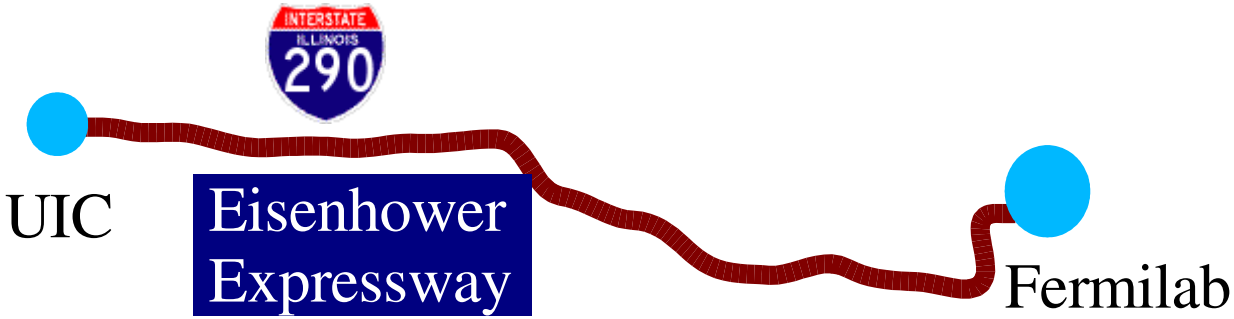
Eisenhower test

Test processor board at UIC



Load into car

Transport to Fermilab



Test processor board again at DØ

Eisenhower test

Test processor board

Load

Commissioning challenges

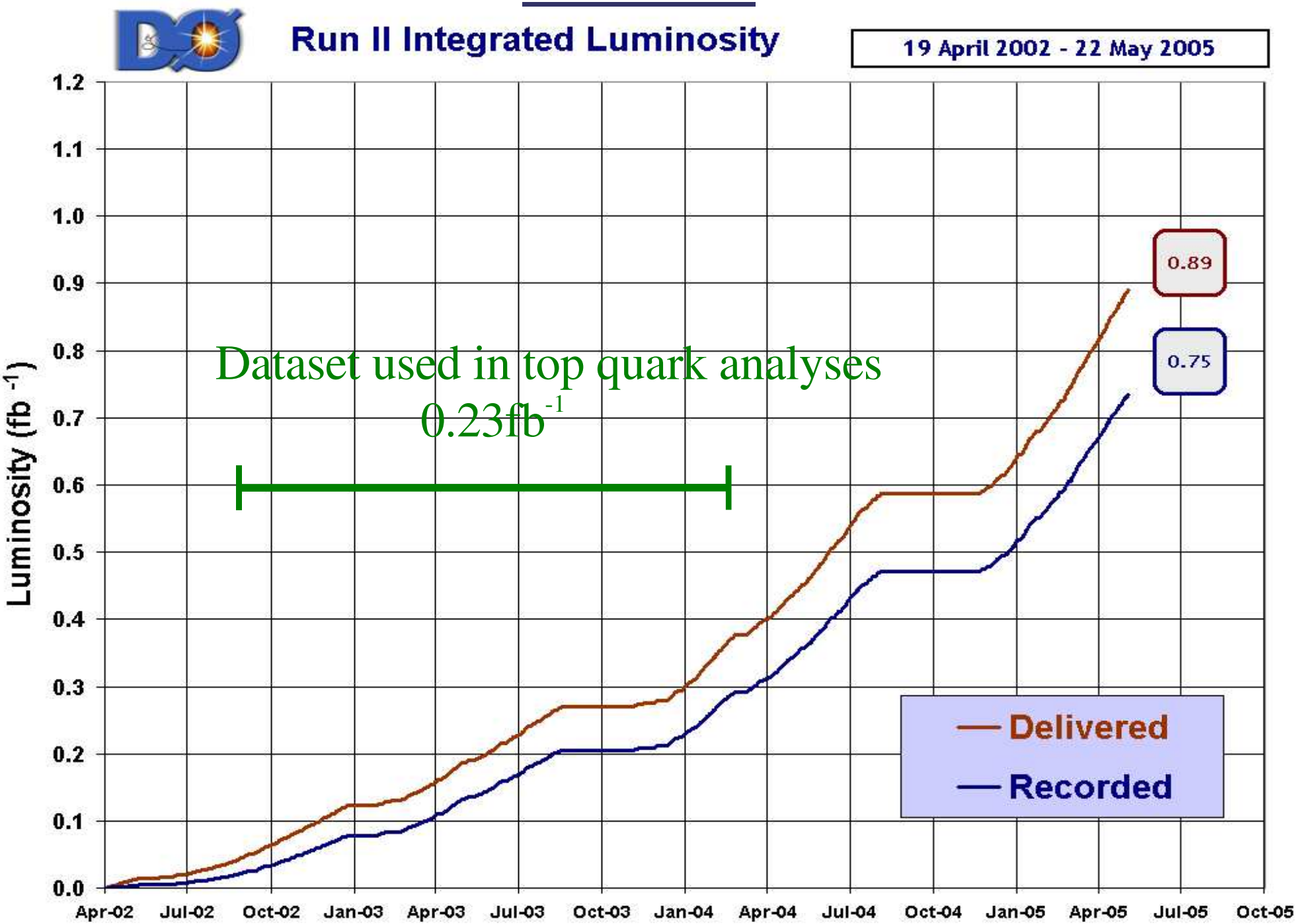
I bet Einstein turned himself all kinds of colors before he invented the light bulb.

Homer J Simpson
to his son Bart after a failed science experiment

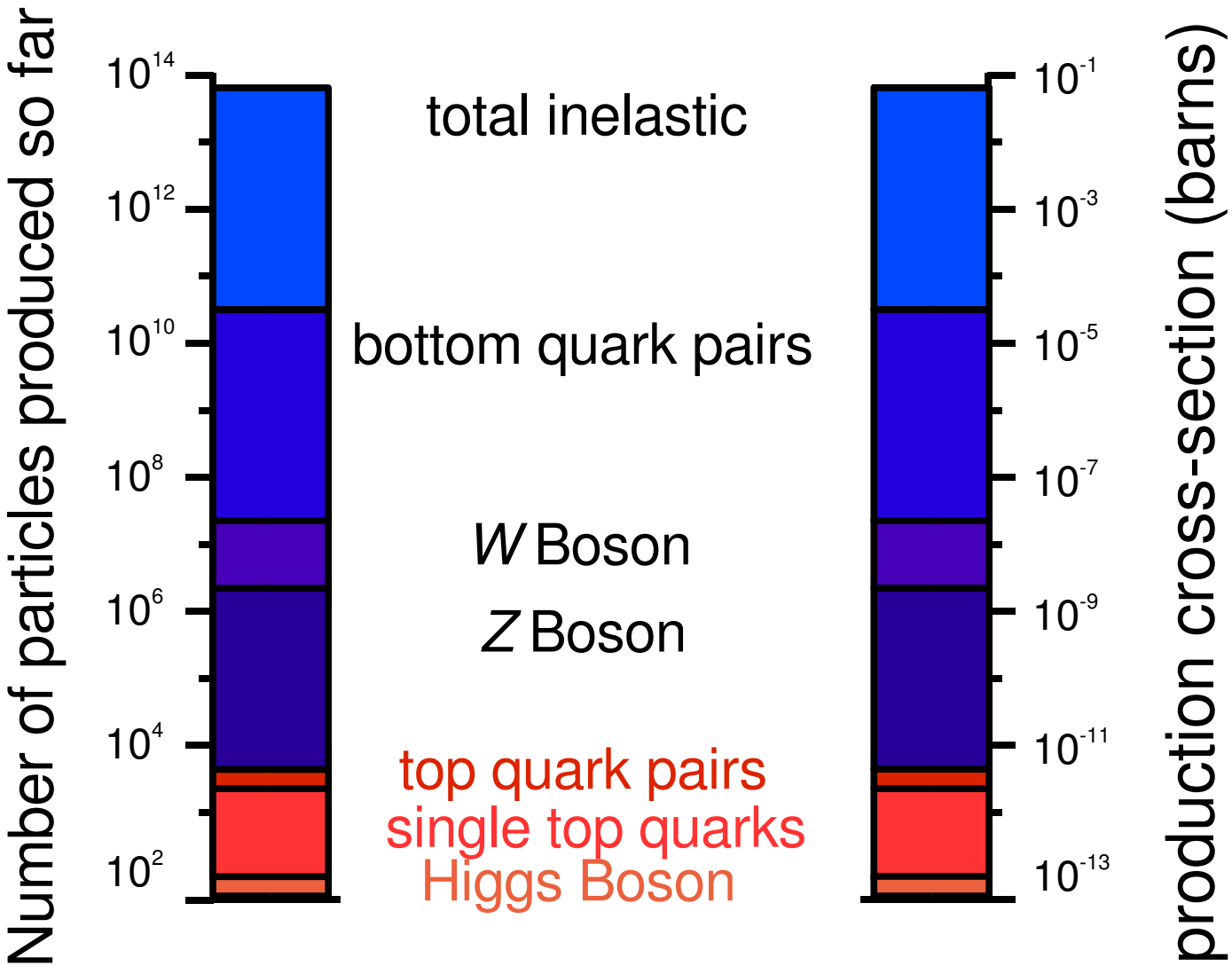
essor
ain

ab

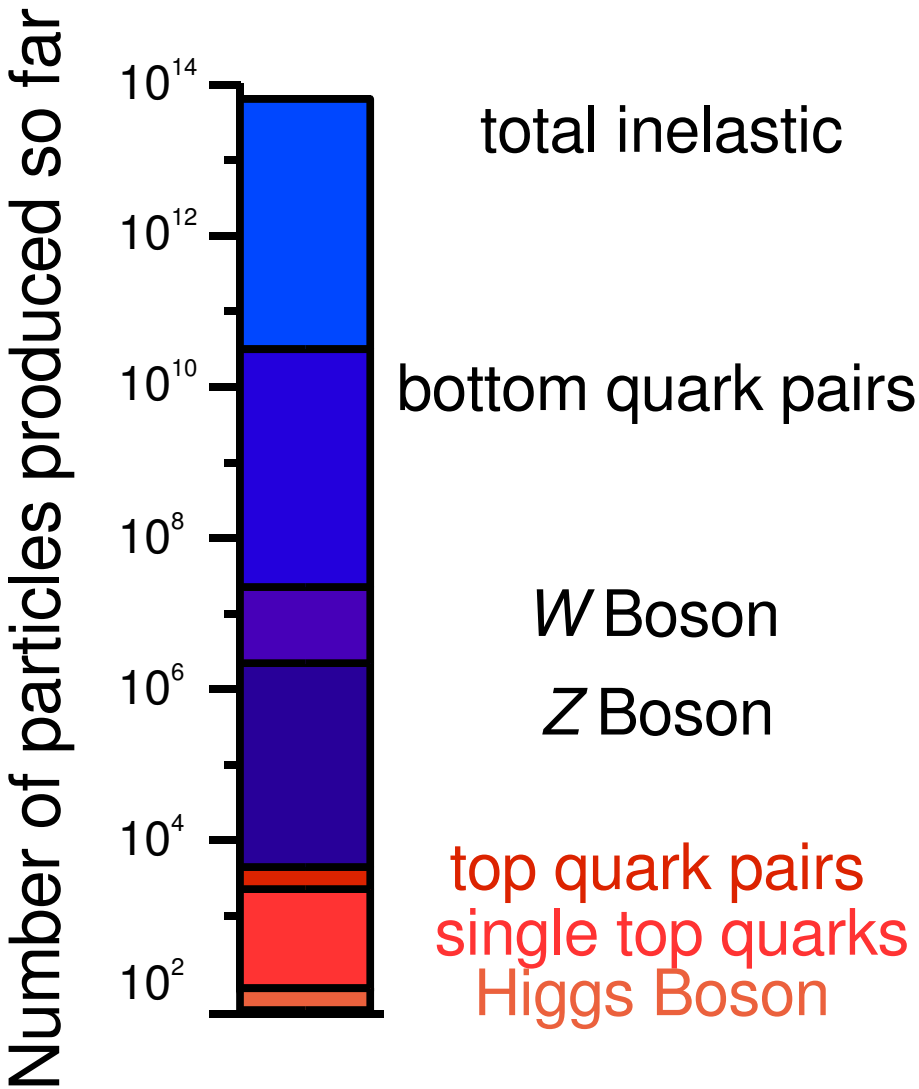
Dataset


Run II Integrated Luminosity
19 April 2002 - 22 May 2005
Luminosity (fb -1)
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Apr-02
Jul-02
Oct-02
Jan-03
Apr-03
Jul-03
Oct-03
Jan-04
Apr-04
Jul-04
Oct-04
Jan-05
Apr-05
Jul-05
Oct-05
0.89
0.75
Delivered
Recorded
Dataset used in top quark analyses
0.23fb-1

Particle production at the Tevatron



Tevatron physics program



Precision QCD physics

Bottom quark physics

Precision electroweak physics

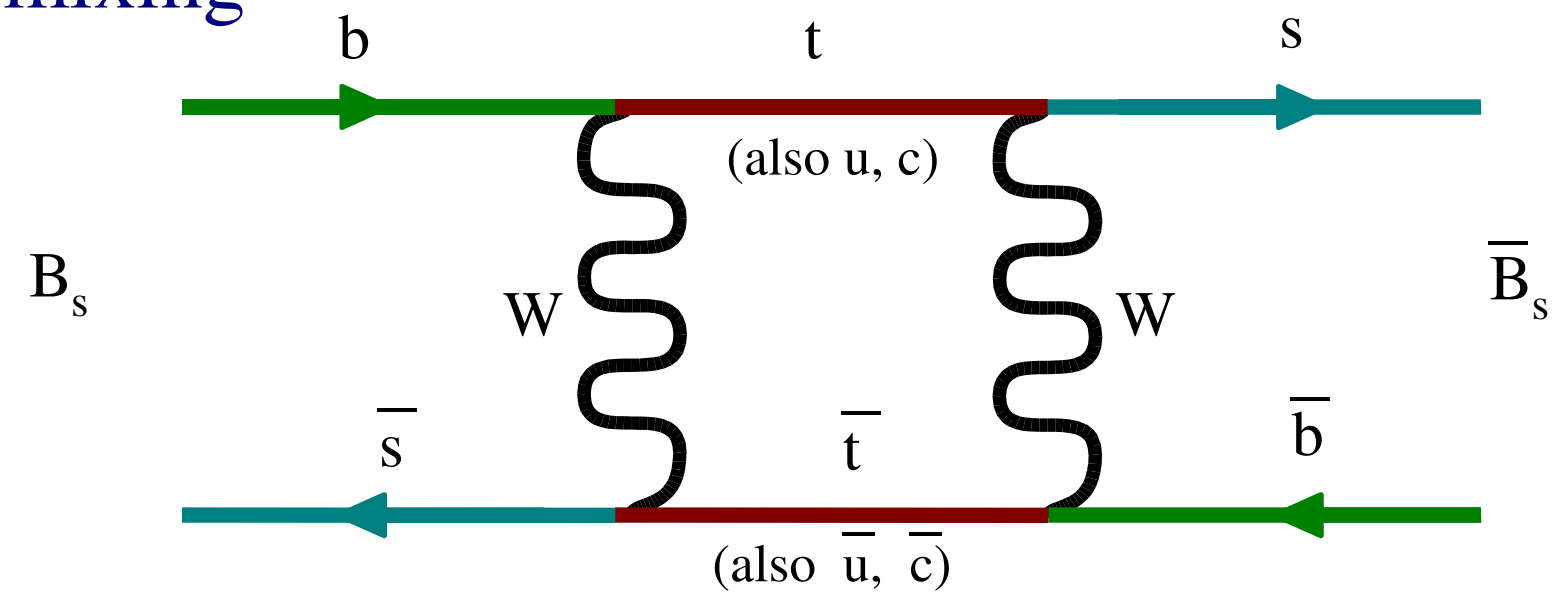
Top quark measurements

Searches for new physics

Higgs boson searches

Bottom quark physics

- B_s mixing

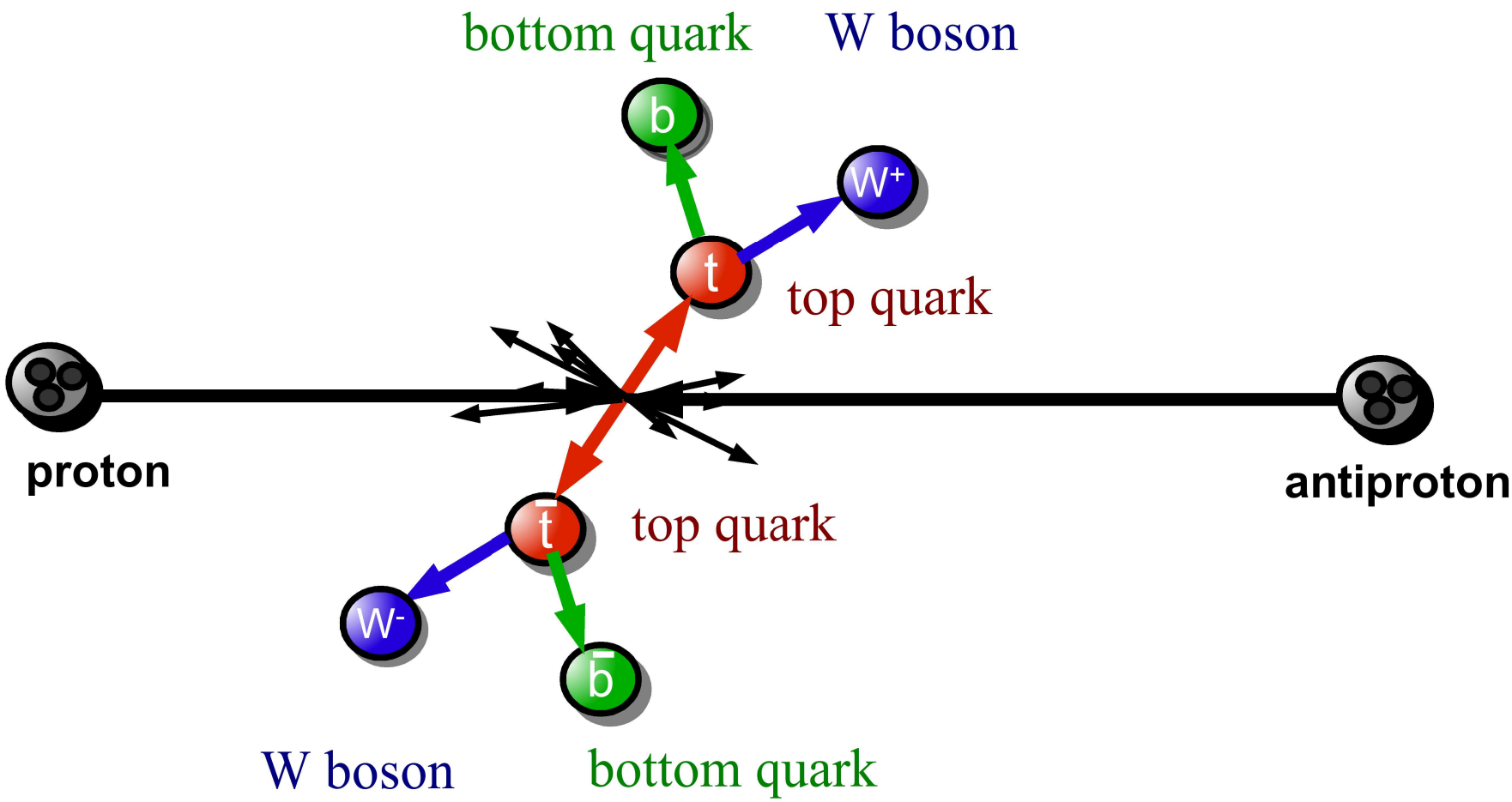


  - Study Wtb vertex
  - Mass Eigenstates: B_{Light}, B_{Heavy} $\Delta m = m_{B_H} - m_{B_L}$
    - Global fit assuming Standard Model: $\Delta m \sim 18 ps^{-1}$

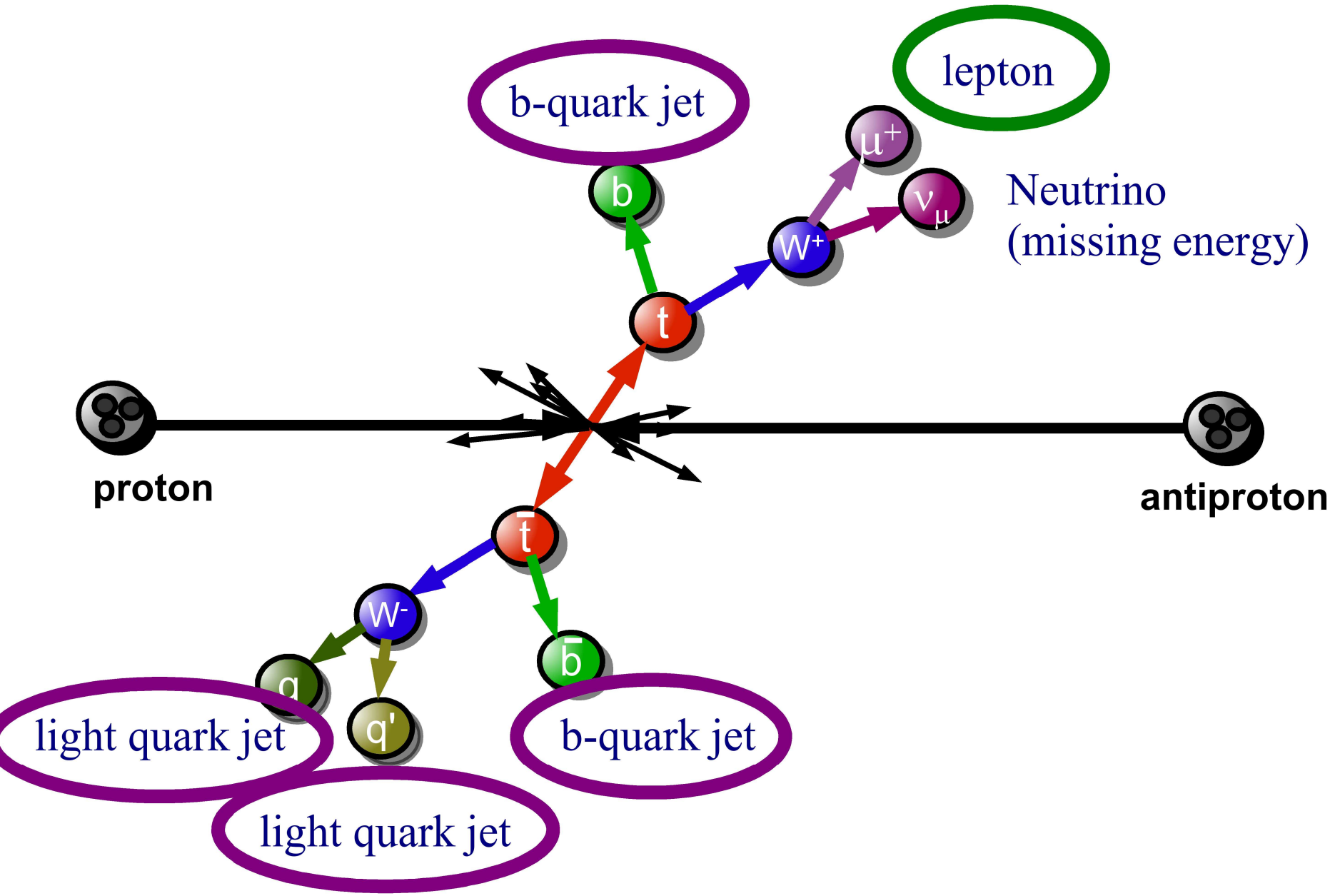
DØ Run II preliminary

$\Delta m_s > 5.0\ ps^{-1}$

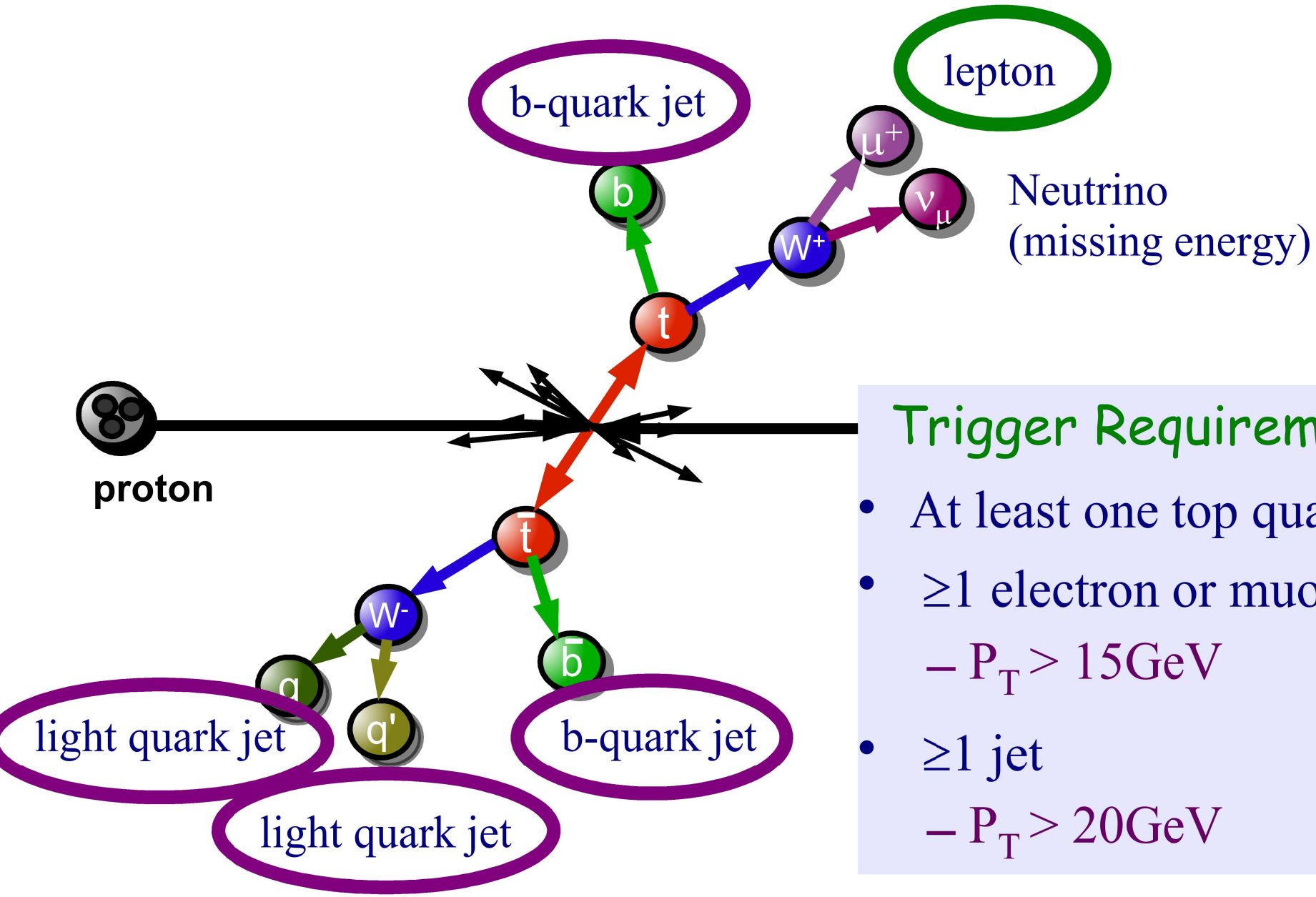
Top quark pair physics



Top quark pair selection: lepton+jets



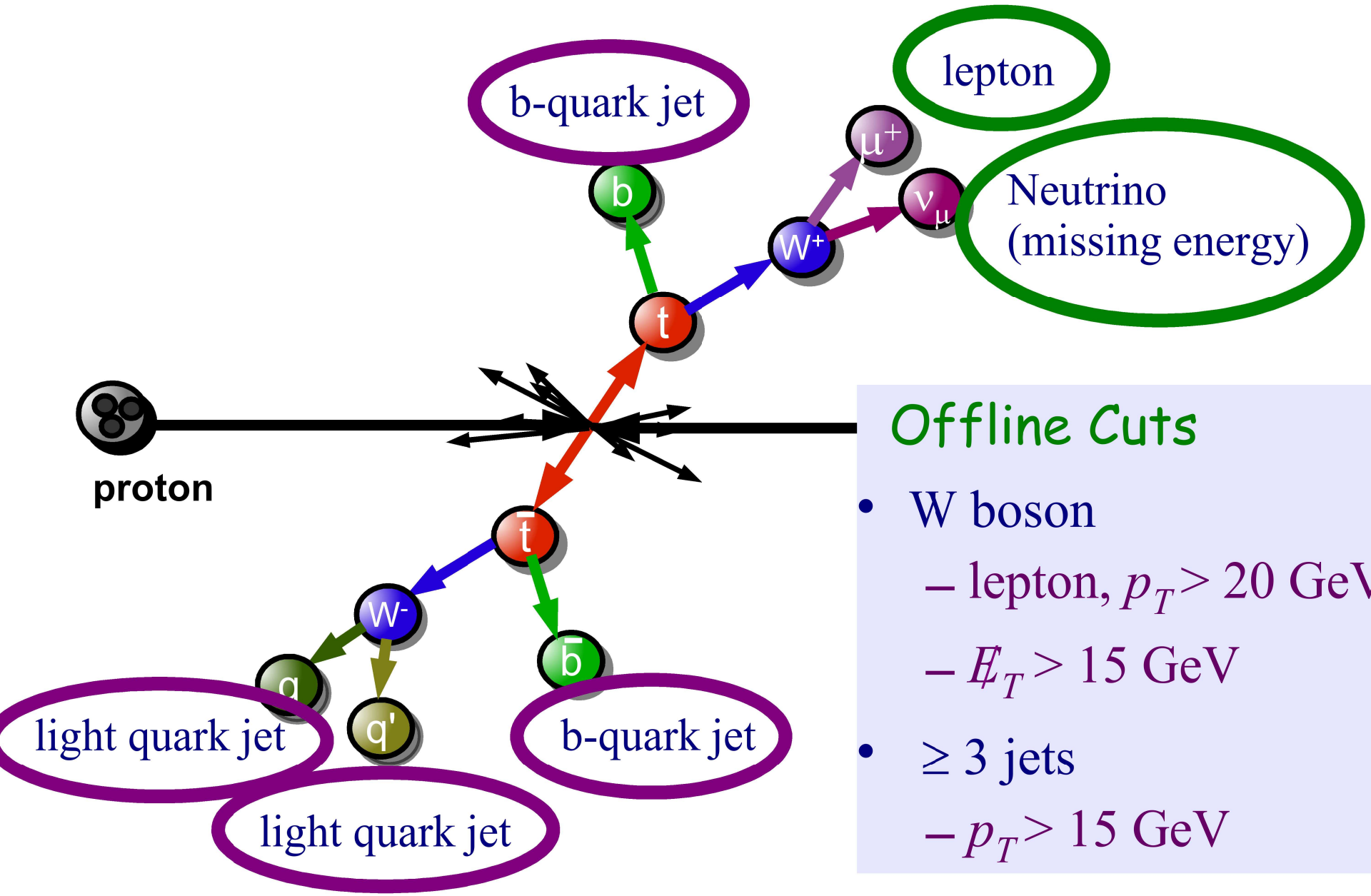
Trigger selection



Trigger Requirements

- At least one top quark
- ≥1 electron or muon
  - $P_T > 15$GeV
- ≥1 jet
  - $P_T > 20$GeV

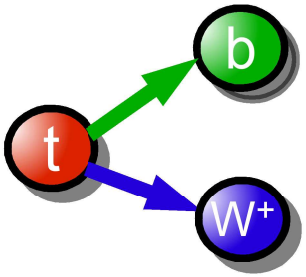
Analysis event selection

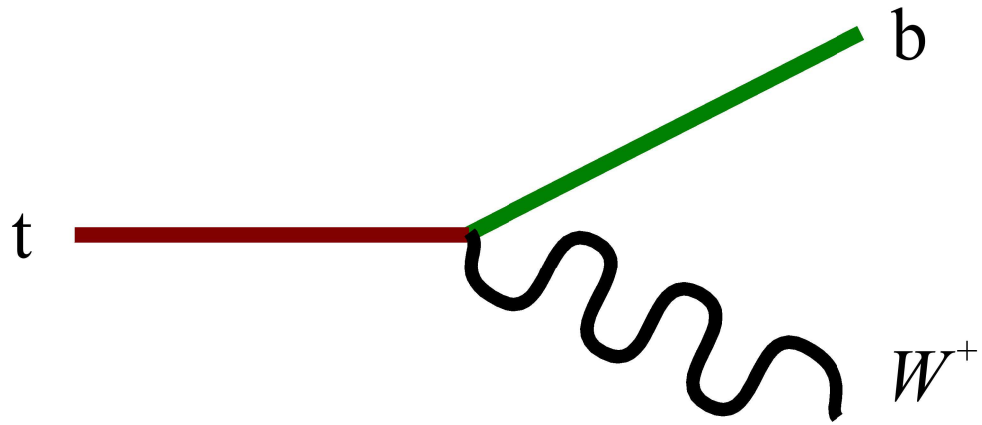


Offline Cuts

- W boson
  - lepton, $p_T > 20$ GeV
  - $\not{E}_T > 15$ GeV
- ≥ 3 jets
  - $p_T > 15$ GeV

Top quark electroweak charged current interaction

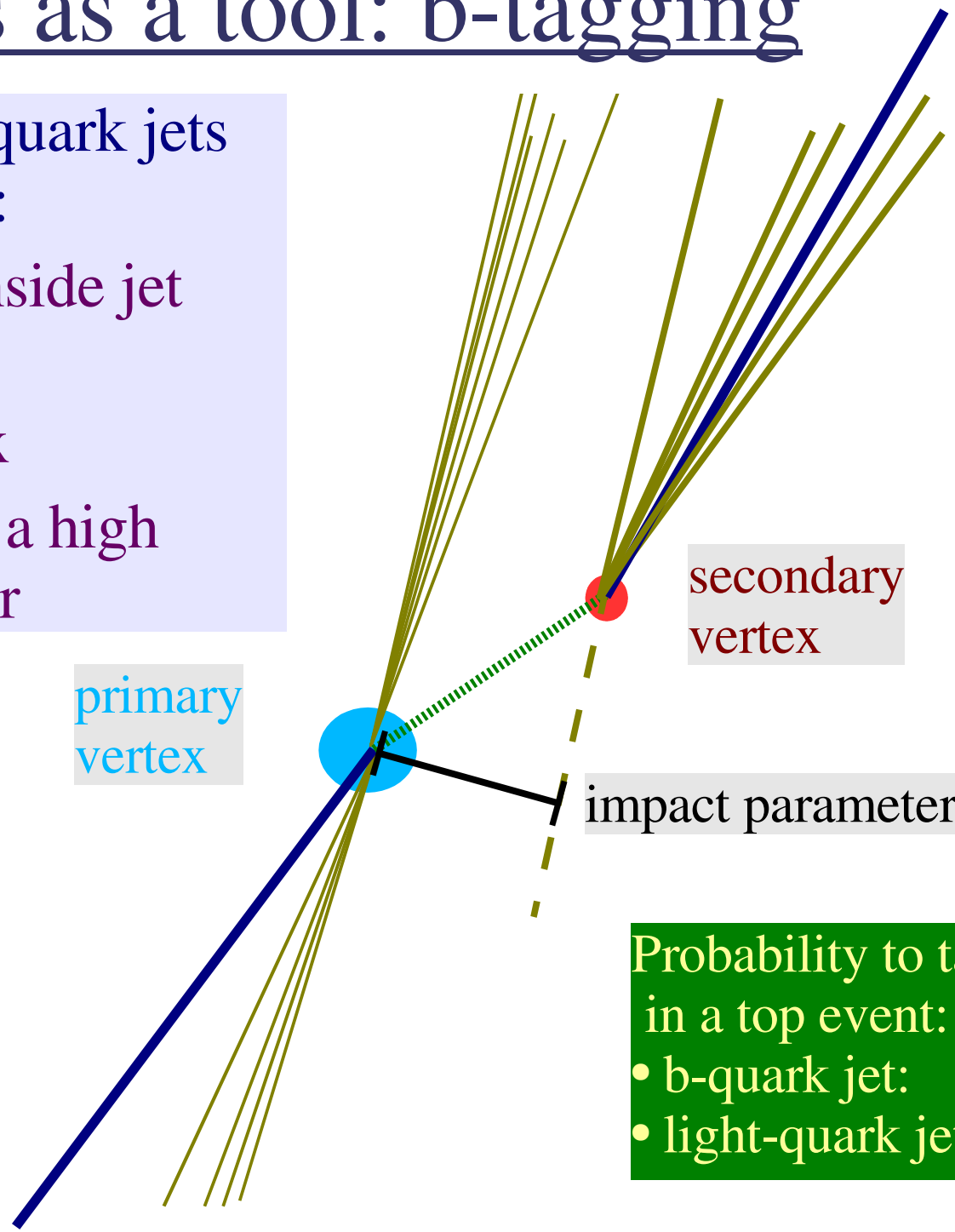




Top quark decay

b quarks as a tool: b-tagging

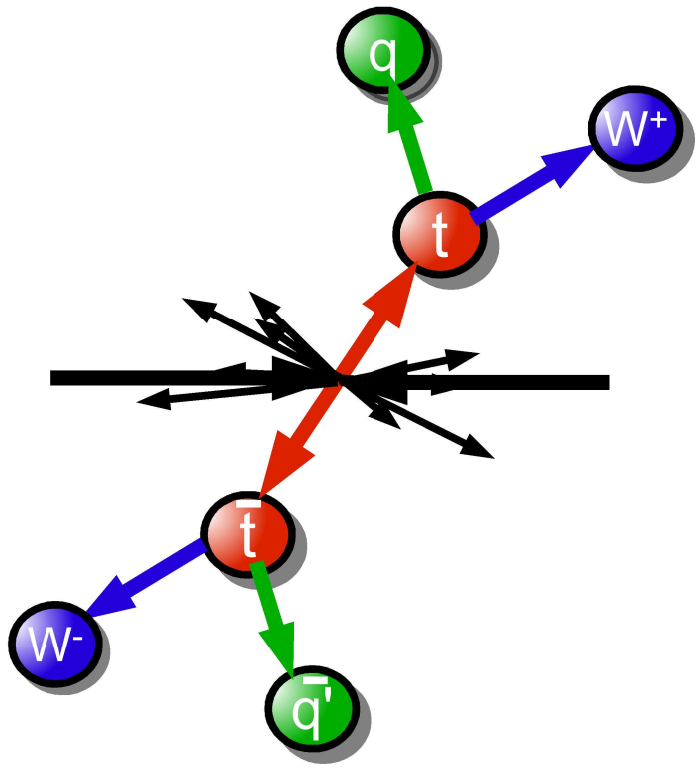
- Identification of b-quark jets
  3 possible methods:
  - Identify muon inside jet
  - Reconstruct secondary vertex
  - Find tracks with a high impact parameter



Probability to tag a jet in a top event:
- b-quark jet: ~55%
- light-quark jet: ~0.5%

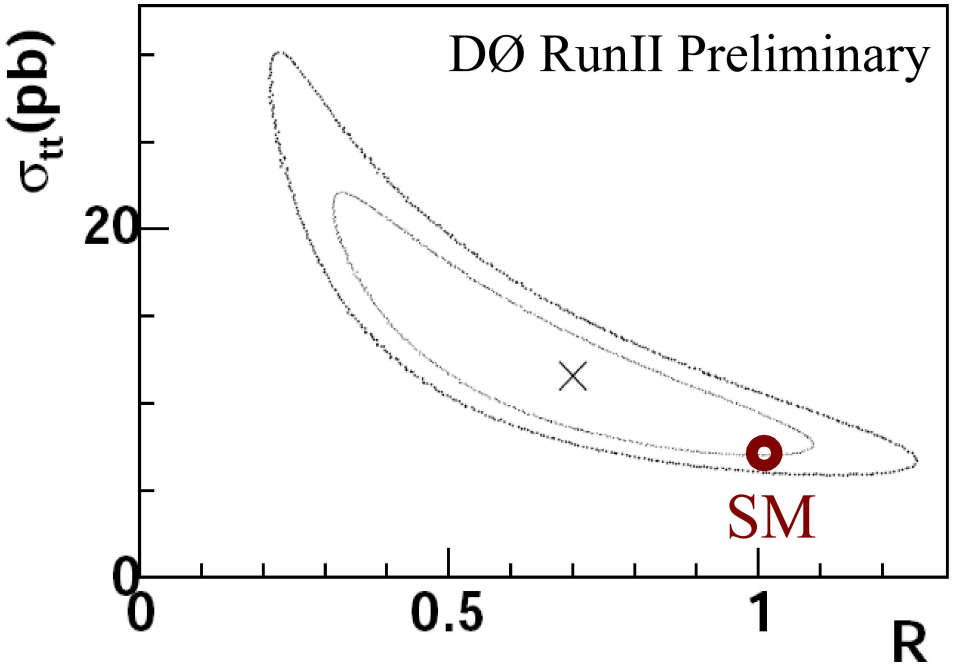
Top quark decay branching ratios

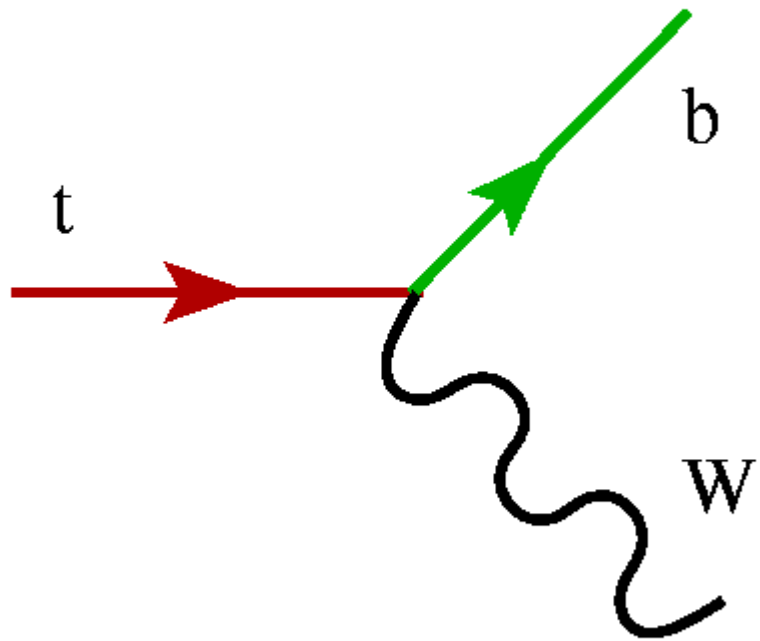
b quark or other flavor?



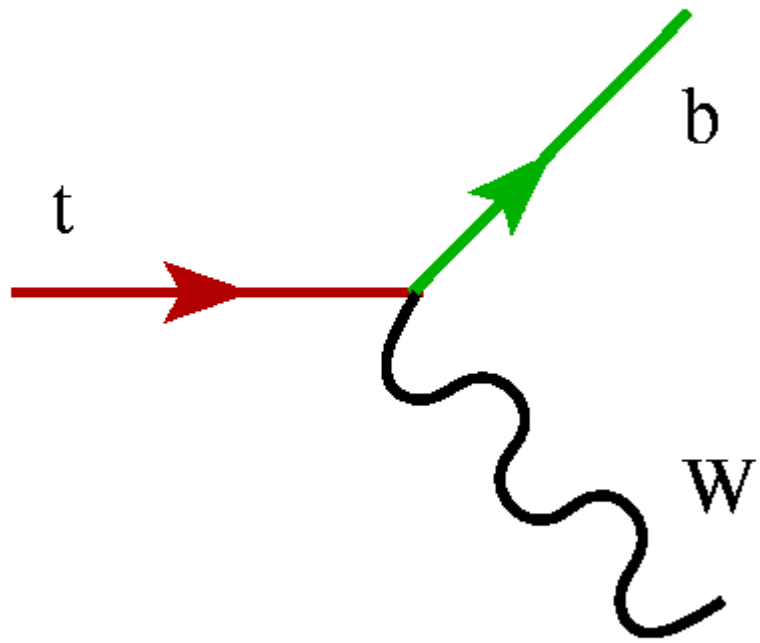
b quark or other flavor?

$$R = \frac{t \rightarrow W + b\ \text{quark}}{t \rightarrow W + \text{any quark}} \sim \frac{\#\ \text{with 2 b-tagged jets}}{\#\ \text{with 1 b-tagged jets}}$$





top quark decay

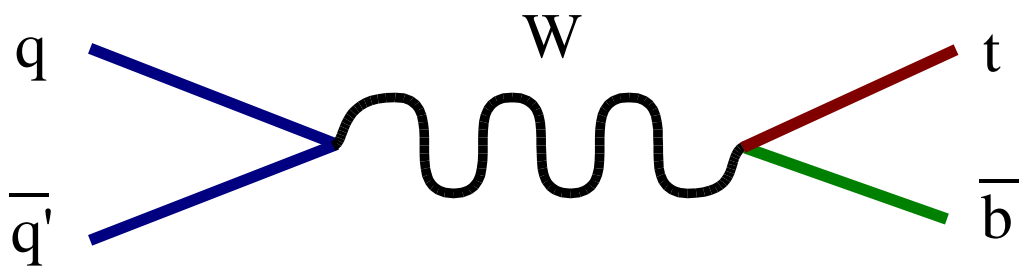


top quark decay

Wtb vertex has many angles

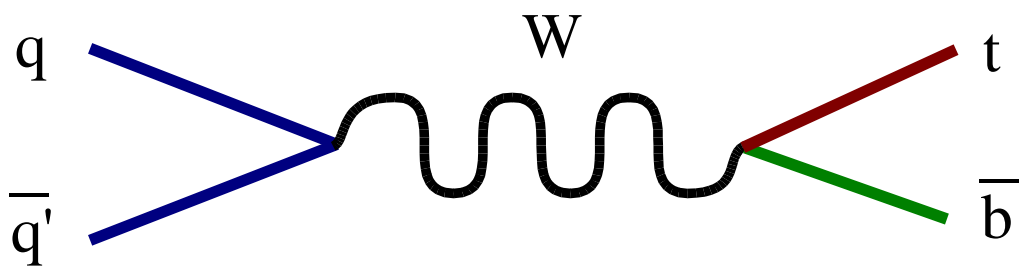
Electroweak production of top at the Tevatron

s-channel

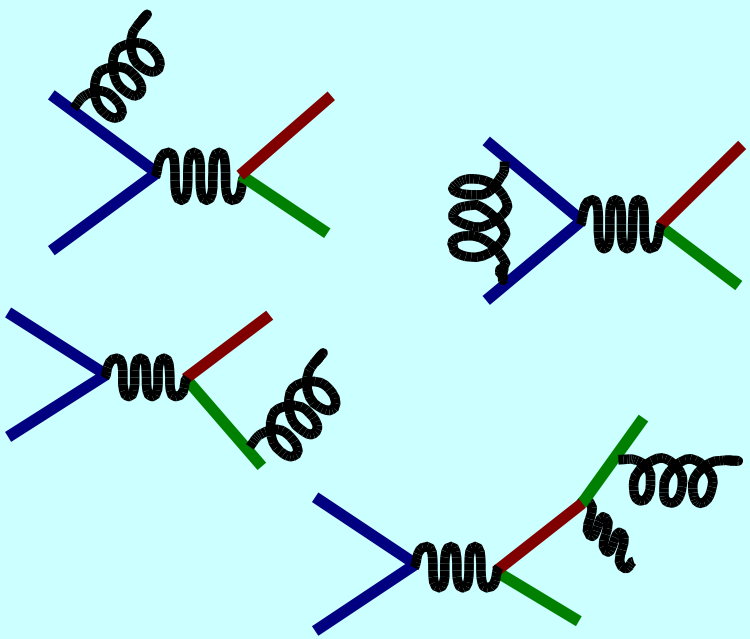


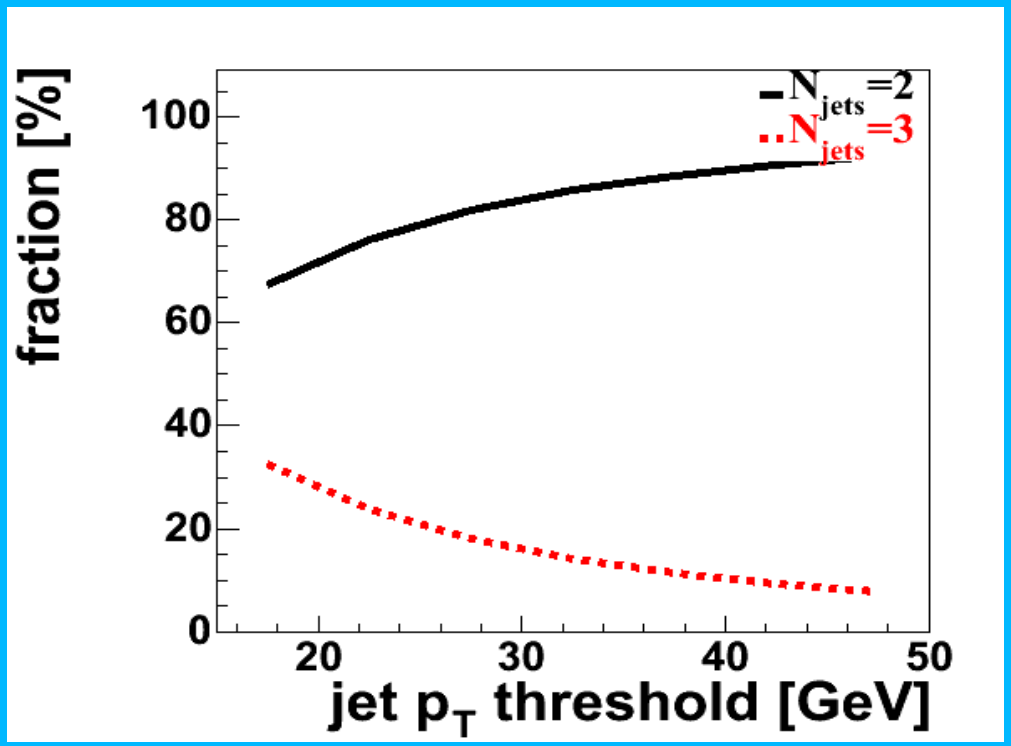
Electroweak production of top at the Tevatron

s-channel



$O(\alpha_s)$ corrections

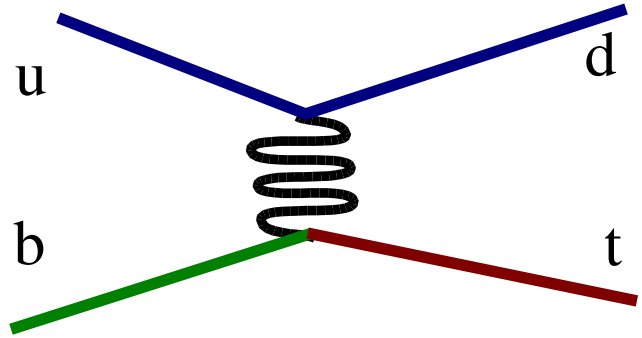




Cao, RS, Yuan hep-ph/0409040

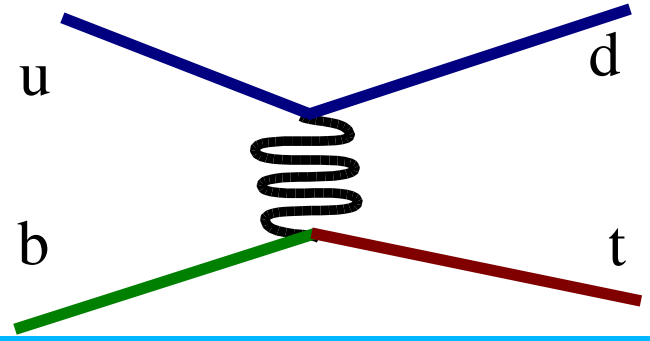
Electroweak production of top at the Tevatron

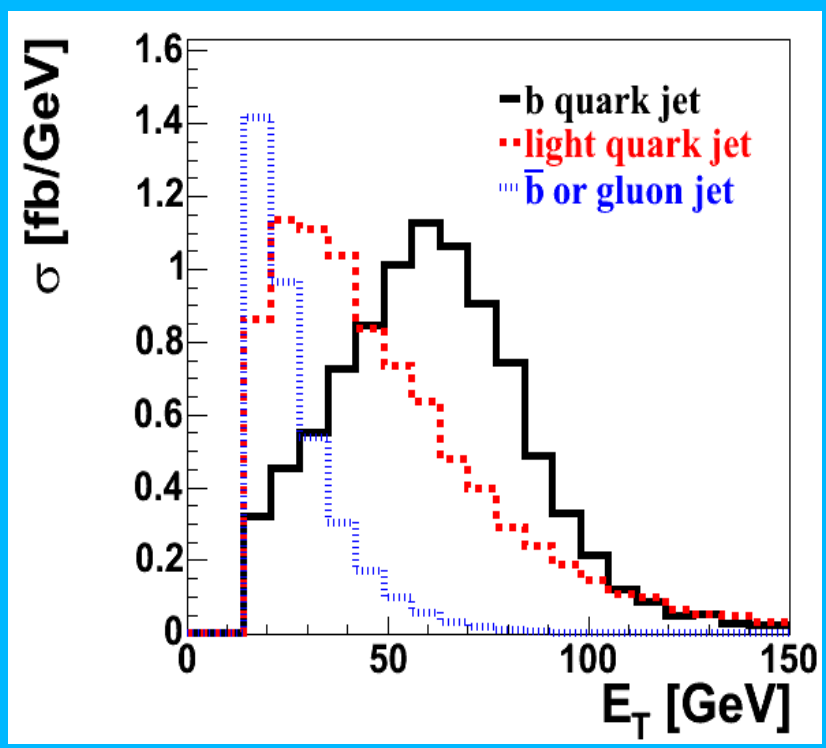
t-channel

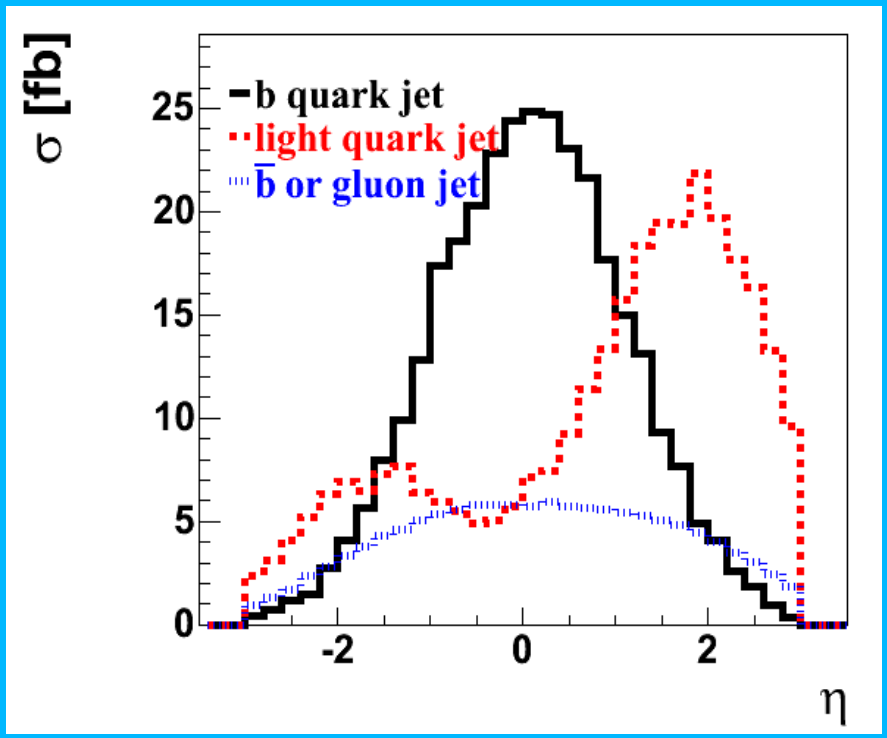


Electroweak production of top at the Tevatron

t-channel







Cao, RS, Benitez, Brock, Yuan hep-ph/0504230

Tevatron single top goals

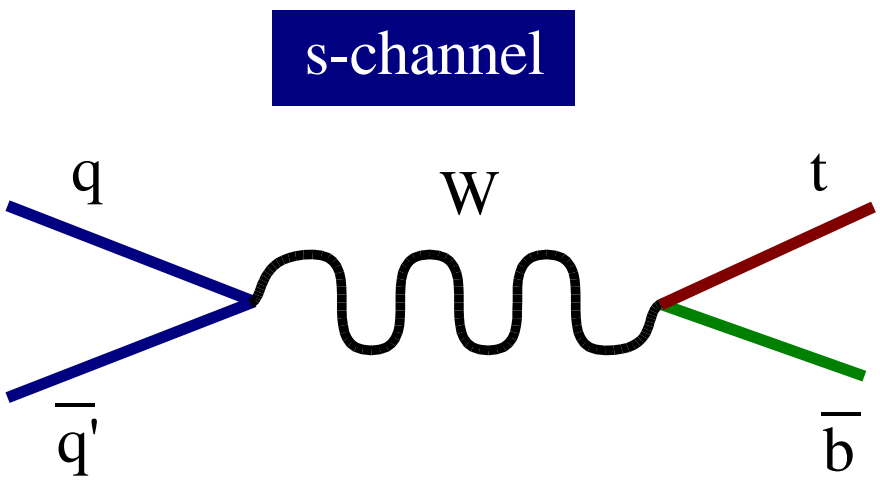
- Observe single top quark production

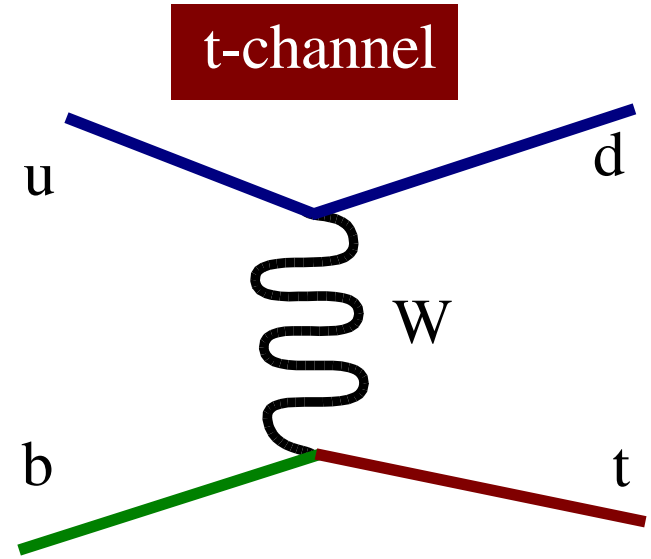
  NLO cross section: σ_s **= 0.88pb** σ_t **= 1.98pb**

  Run II CDF 95% CL limits: < 14pb < 10pb

- Measure production cross sections
  - Direct measurement of Wtb vertex
- Look for physics beyond the Standard Model
- Study top quark spin correlations
  - Physics with ~100% polarized top quarks
- Irreducible background to associated Higgs production

Single top status





- Production cross section:

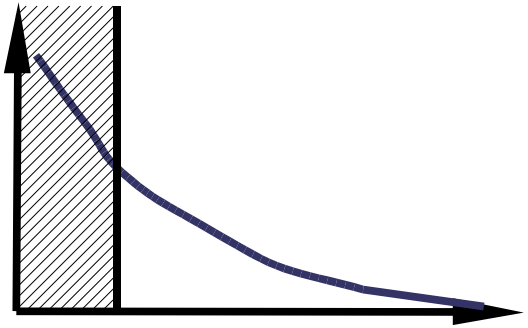
	s-channel	*t-channel*	*s+t*
–			
– Run I 95% CL limits, DØ:	< 17pb	< 22pb	
CDF:	< 18pb	< 13pb	< 14pb
– Run II CDF 95% CL limits:	< 14pb	< 10pb	< 18pb

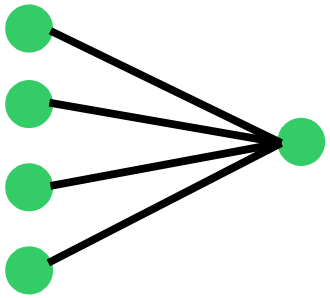
- Other Standard Model production mode (*Wt*) negligible

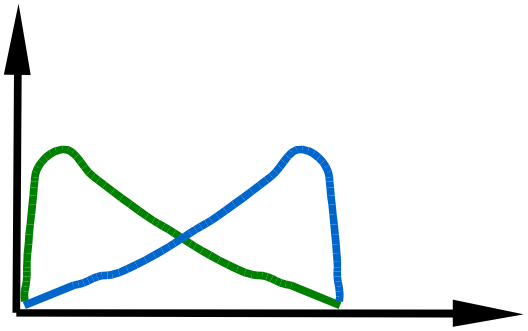
Analysis outline

Goal:

Maximize Sensitivity





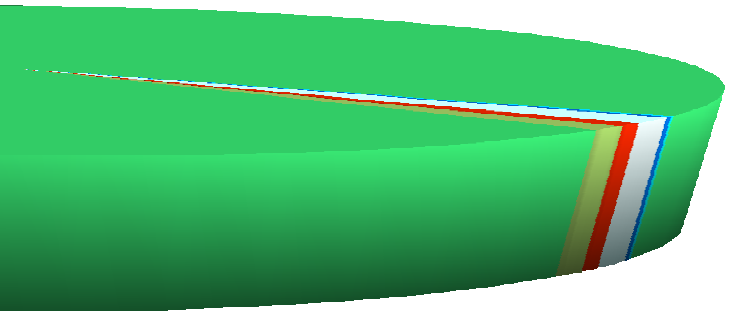


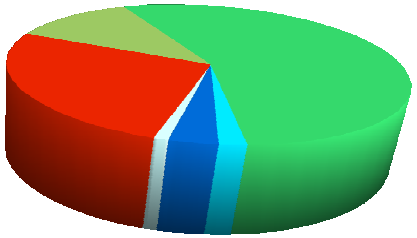
1. Event Selection
   - Select *W*-like events
   - Maximize acceptance
   - Model backgrounds
2. Separate signal from backgrounds
   - Find discriminating variables
   - Cut/combine in multivariate analysis
3. Determine cross section
   - Using shape information
   - Bayesian statistical analysis

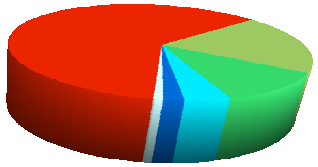
1. Event selection

1 lepton, $p_T > 15$ GeV, $2 \leq$ njets ≤ 4, $p_T > 15$ GeV

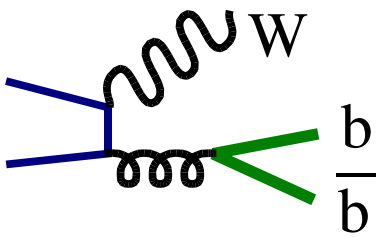
Pre-tagged	=1 b-tag	≥2 b-tags
7100 events	252 events	31 events

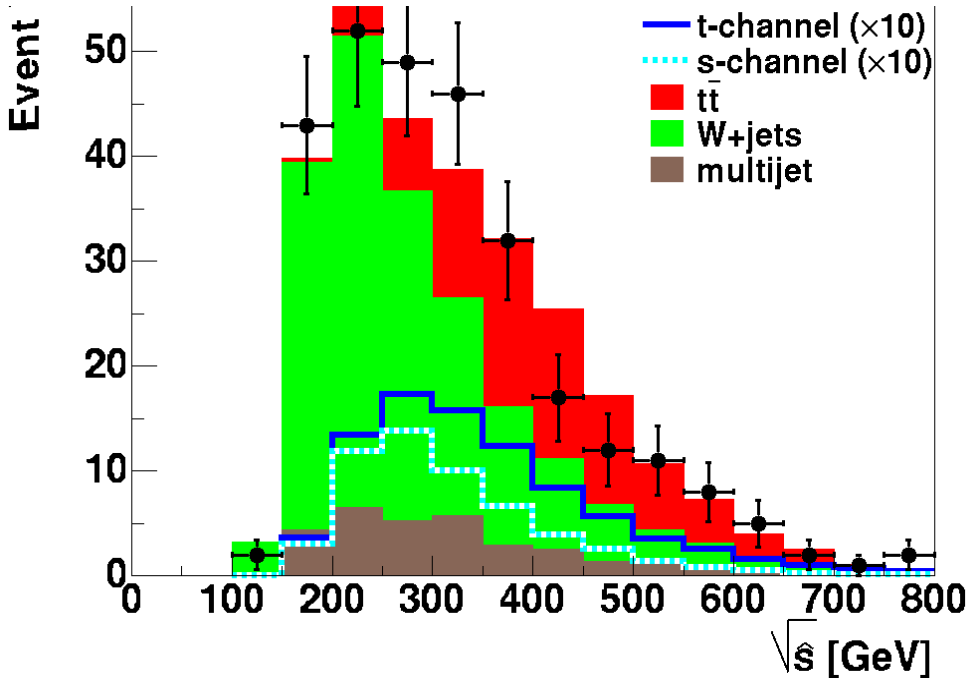






- Wjj
- Wbb
- $t\bar{t}$
- WW/WZ
- t-channel
- s-channel

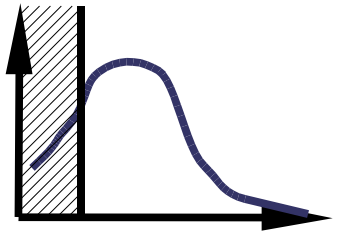




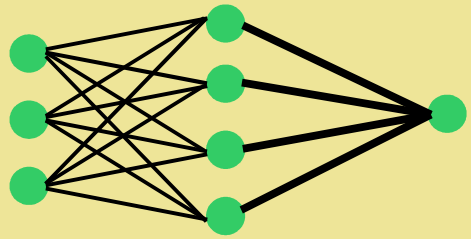
2. Separating signal from backgrounds

- Three analysis methods

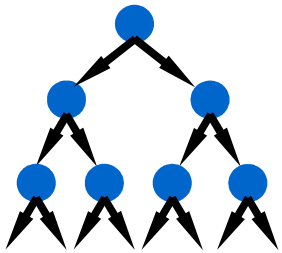
Cut-Based



Neural Networks



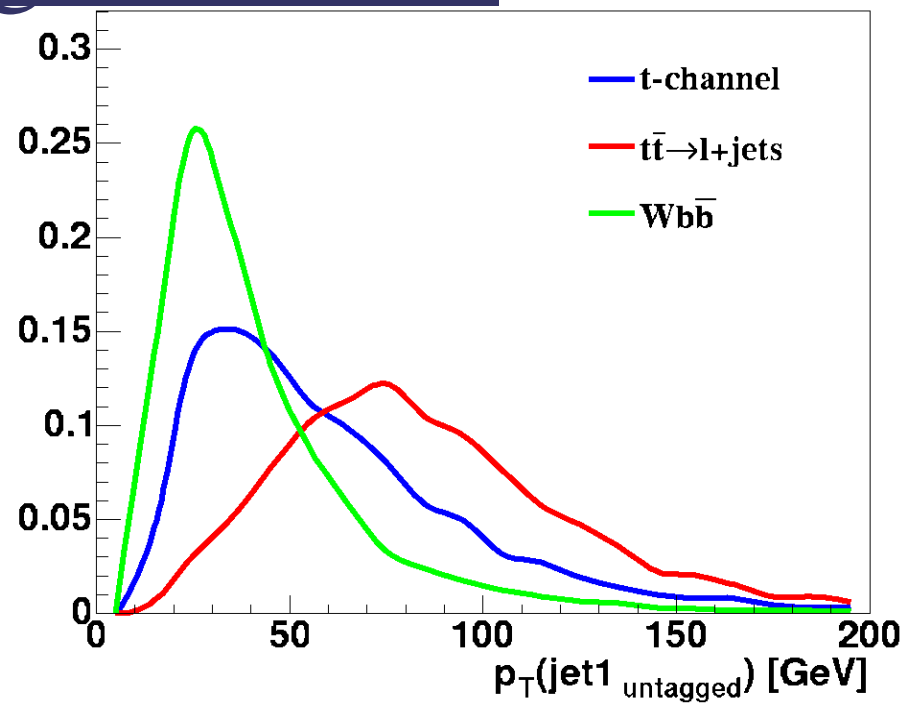
Decision Trees

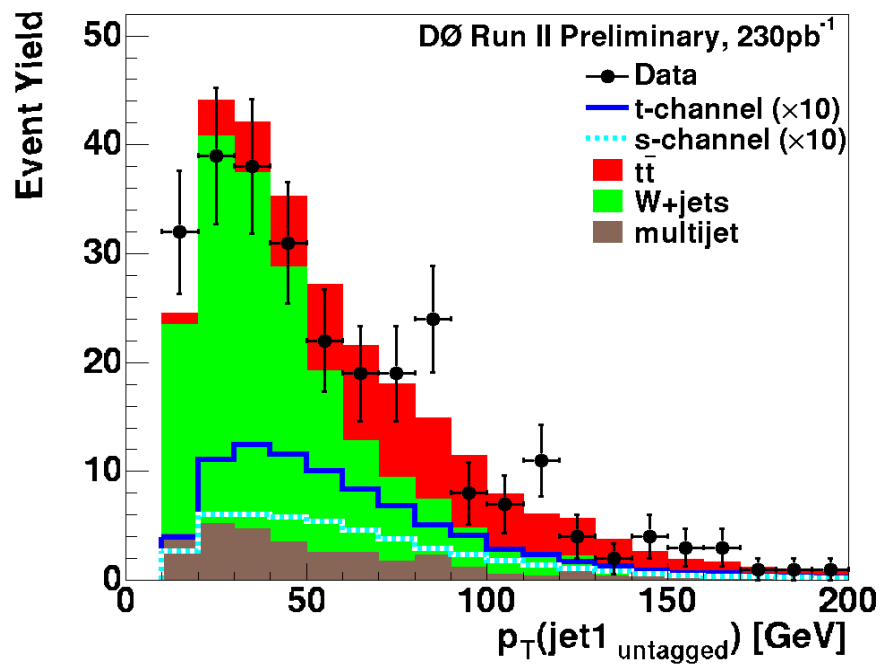


- Each using the same structure:
  - Optimize separately for s-channel and t-channel
    - Optimize separately for electron and muon channel (same variables)
  - Focus on dominant backgrounds W+jets, tt
  - ➔ 8 separate sets of cuts/networks/trees

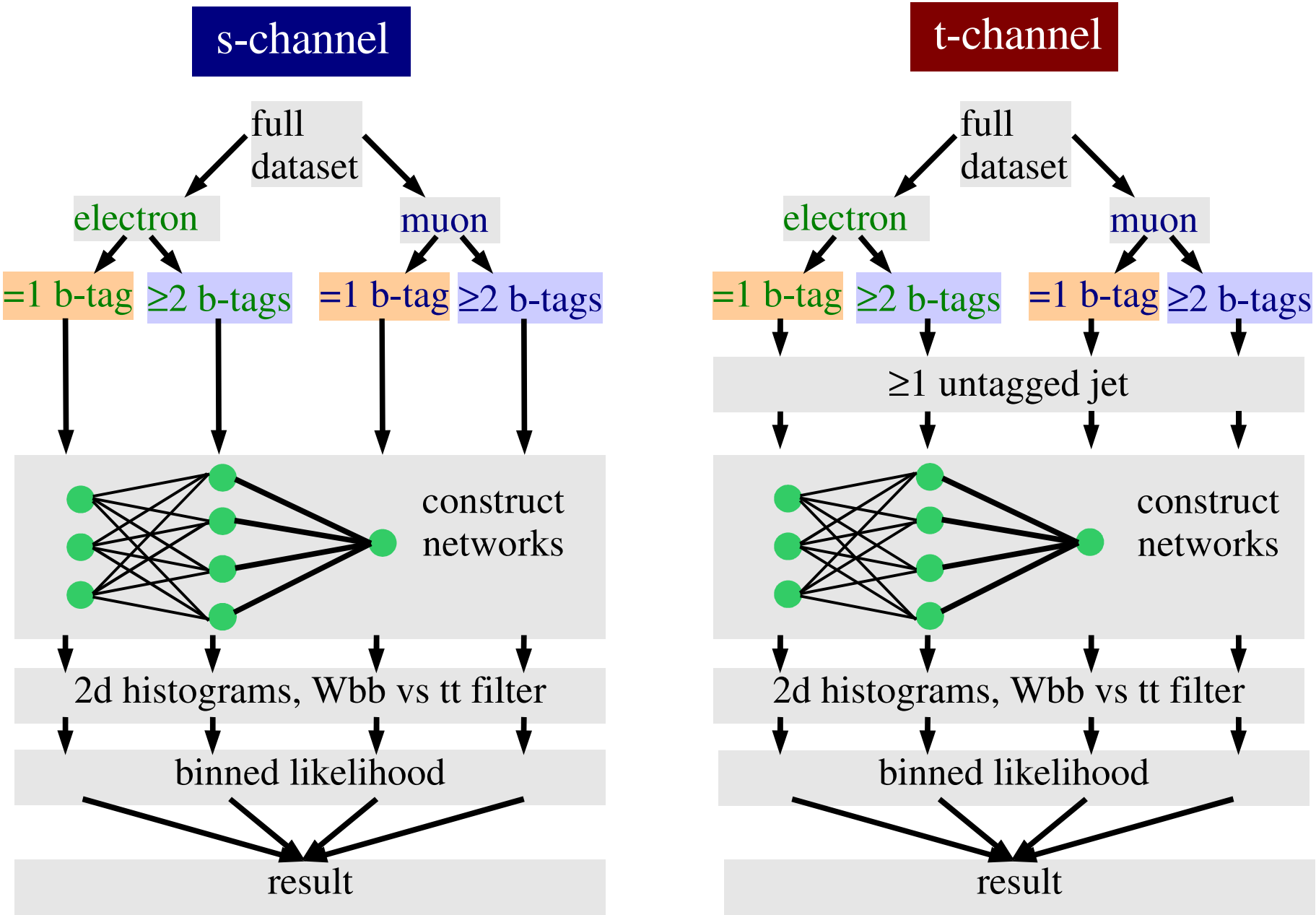
Discriminating variables

- Object kinematics
  - Jet p_T for different jets
    - Tagged, untagged,...
- Event kinematics
  - H (total energy)
  - H_T (transverse energy)
  - M (invariant mass)
  - M_T (transverse mass)
  - Summing over various objects in the event
- Angular variables
  - Jet-jet separation
  - Jet pseudorapidity (t-channel)
  - Top quark spin



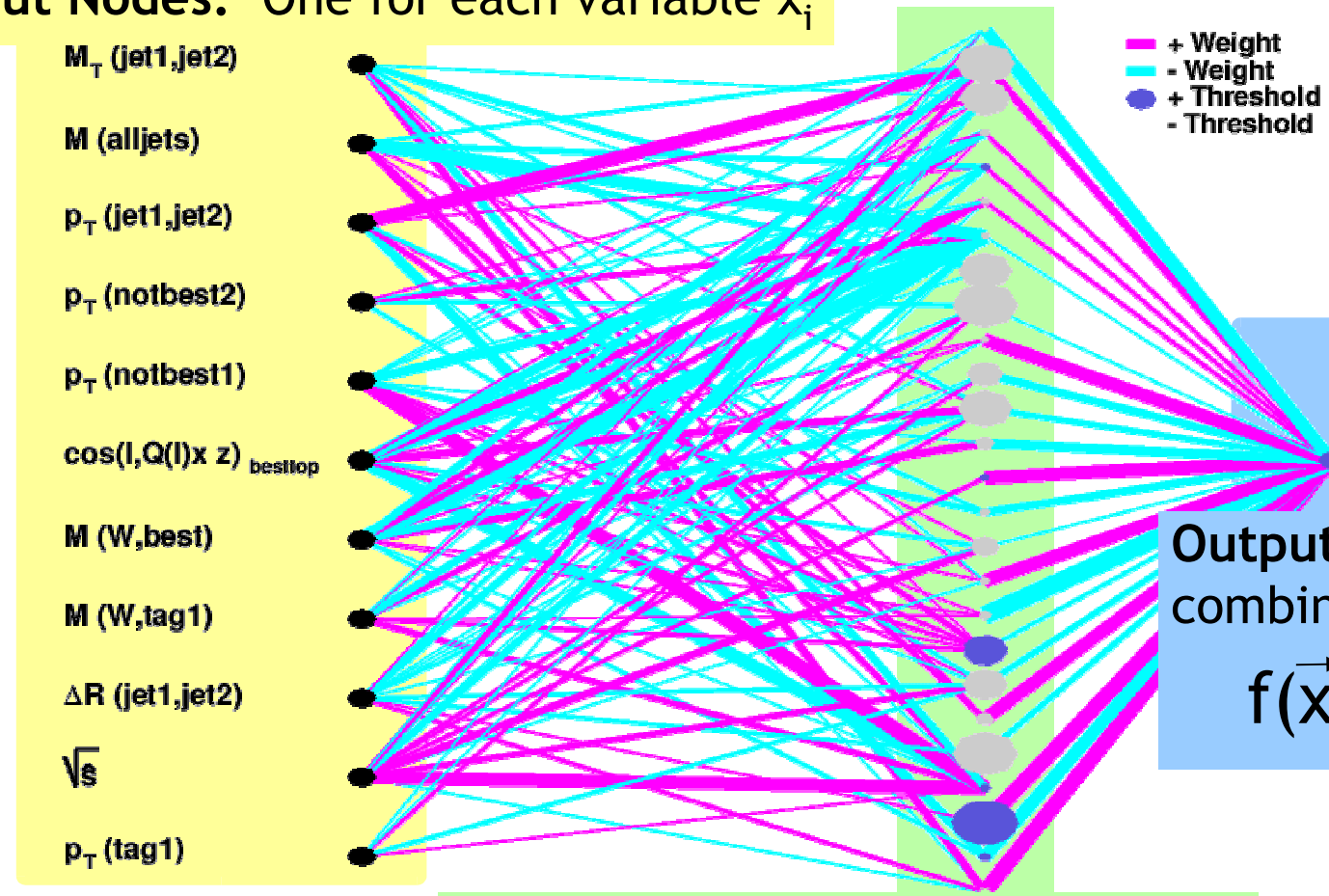


Neural network analysis



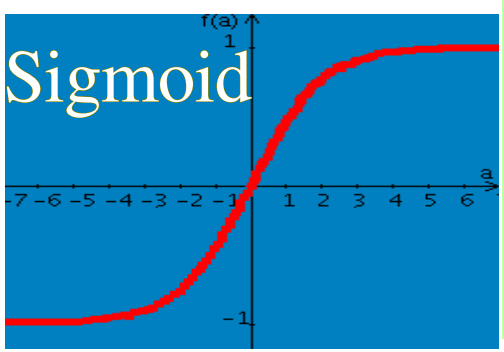
Neural networks

Input Nodes: One for each variable x_i



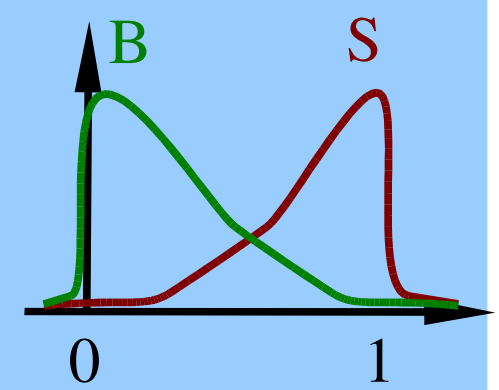
Output Node: linear combination of hidden nodes

$$f(\vec{x}) = \Sigma\, w'_k\, n_k(\vec{x}, \vec{w}_k)$$

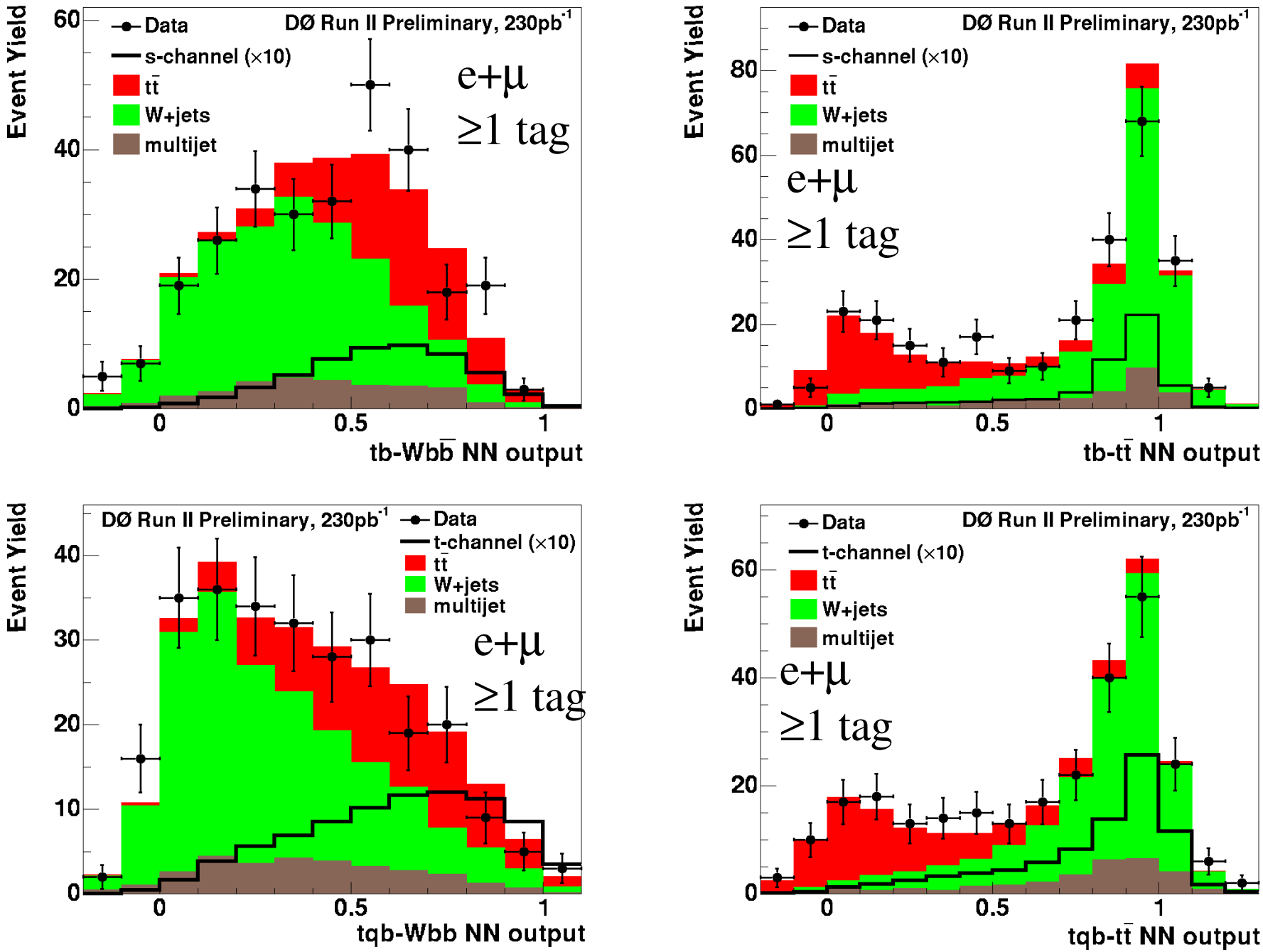


Hidden Nodes: Each is a sigmoid dependent on the input variables

$$n_k(\vec{x}, \vec{w}_k) = \frac{1}{1 + e^{-\Sigma\, w_{ik}\, x_i}}$$



Neural network output

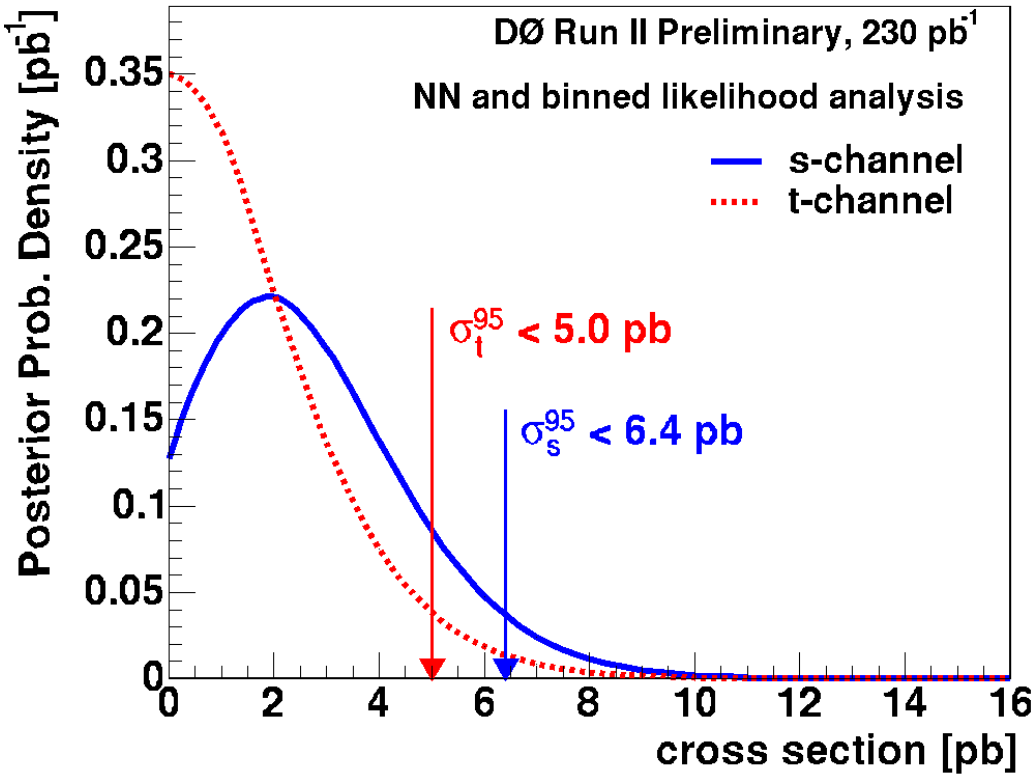


3. Result

Expected/Observed limit:

$\sigma_s < 4.5 / 6.4$ pb

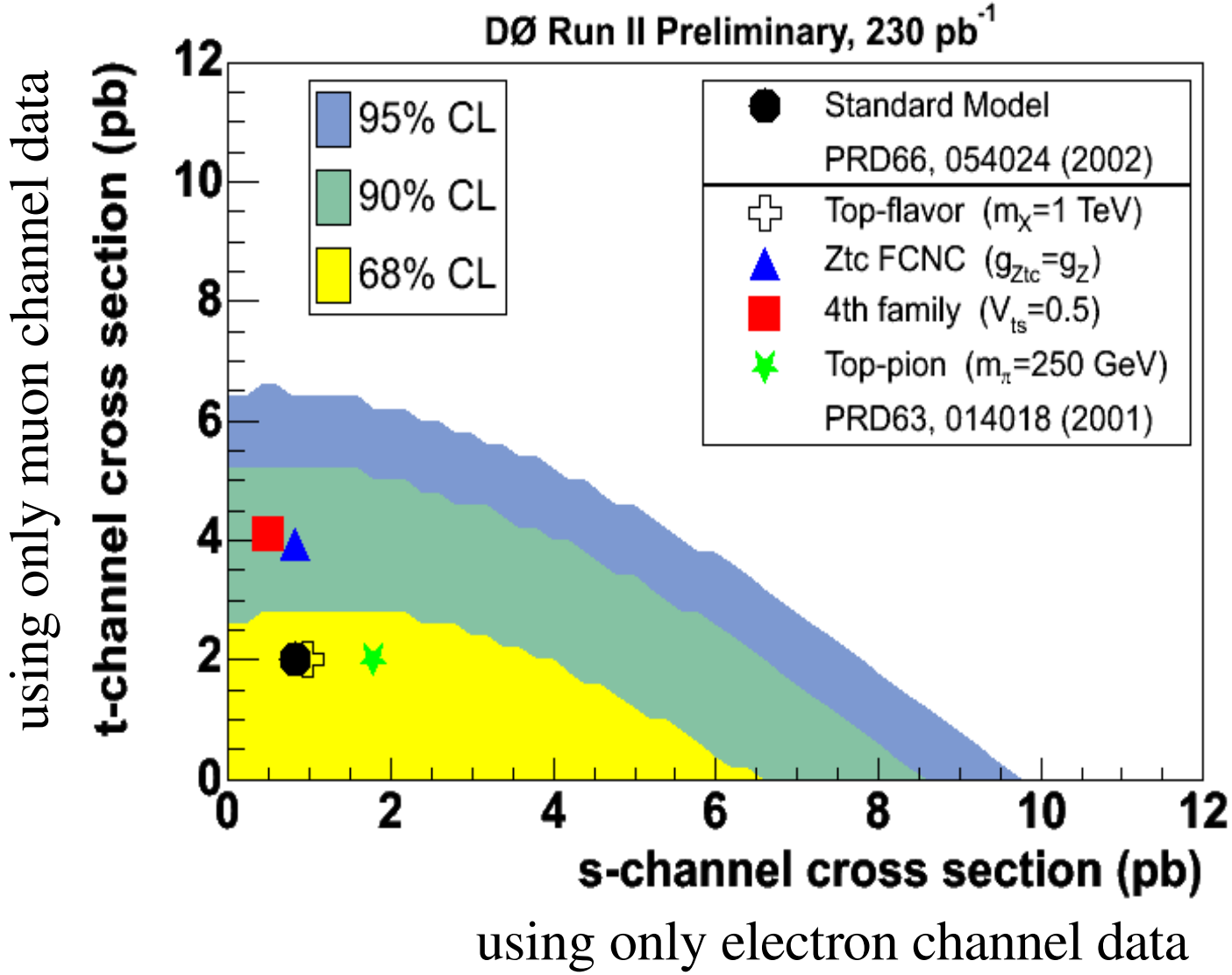
$\sigma_t < 5.8 / 5.0$ pb



- Most sensitive analysis method
- Factor 2 improvement over previous limits

DØ collaboration, hep-ex/0505063

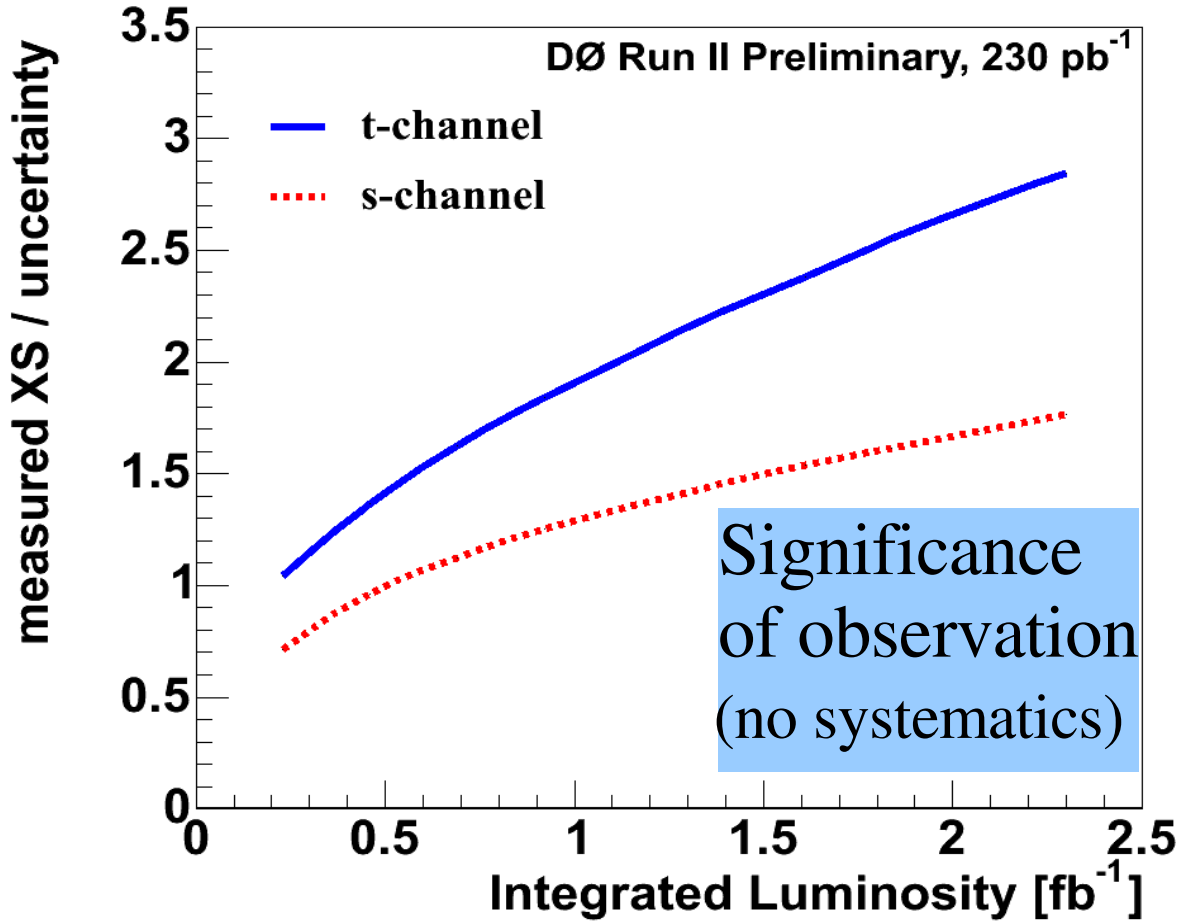
Sensitivity to non-SM single top



using only muon channel data

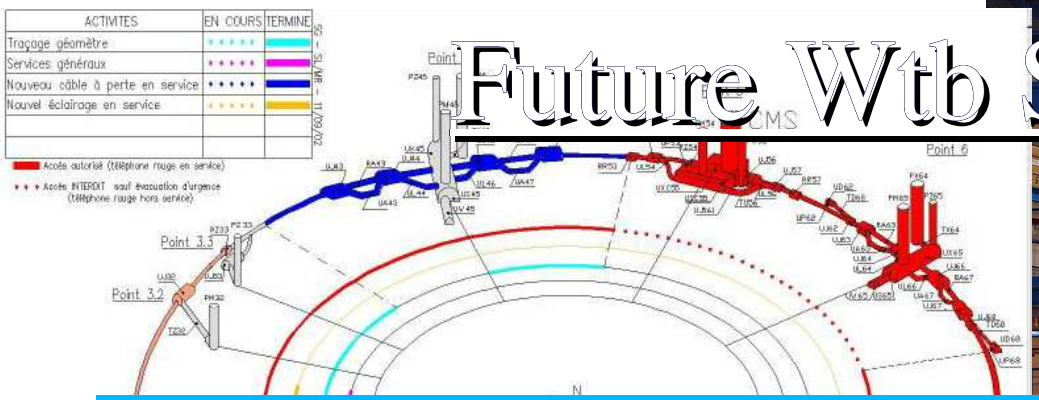
using only electron channel data

Tevatron single top prospects

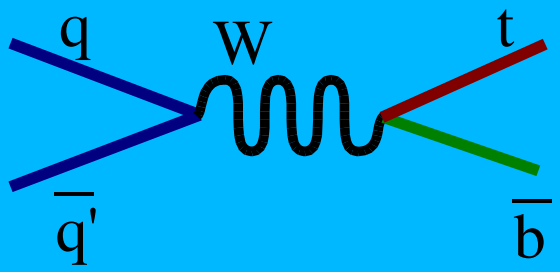


- Observe single top production in Run II
  - Observe new physics (if it's there)
- Measure V_{tb} to ~10%

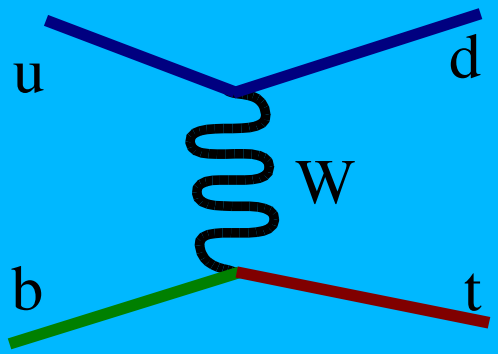
Future Wtb Studies: LHC



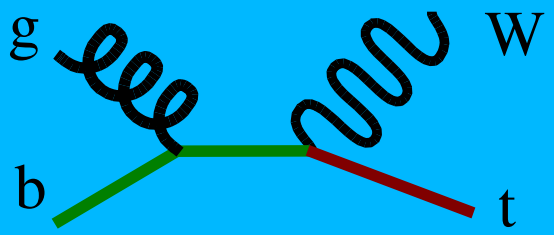
s-channel



t-channel



associated production



- Observe all three single top production modes
- Measure V_{tb} to few %

Conclusions

- DØ Run II now producing many results
  - Precision top quark measurements
  - Single top quark production search with 230pb^{-1} completed
    - 95% CL single top cross section limits
      $\sigma_s < 6.4$ pb, $\sigma_t < 5.0$ pb
    - Factor 2 improvement over previous limits
    - Reaching sensitivity to new physics
- The Wtb vertex is an exciting opportunity for Run II
  - New and old (SM) physics
- This is just the beginning
  - Expect ×3 dataset by end of year
  - LHC is just around the corner

Dawn of Run II Discoveries

Resources

- Quantum Universe
  http://interactions.org/quantumuniverse/
- Quarks Unbound
  http://www.aps.org/units/dpf/quarks_unbound/index.html
- Particle Adventure
  http://particleadventure.org/particleadventure/index.html
- Fermilab
  http://www.fnal.gov
- DØ
  http://www-d0.fnal.gov
- Cern
  http://www.cern.ch

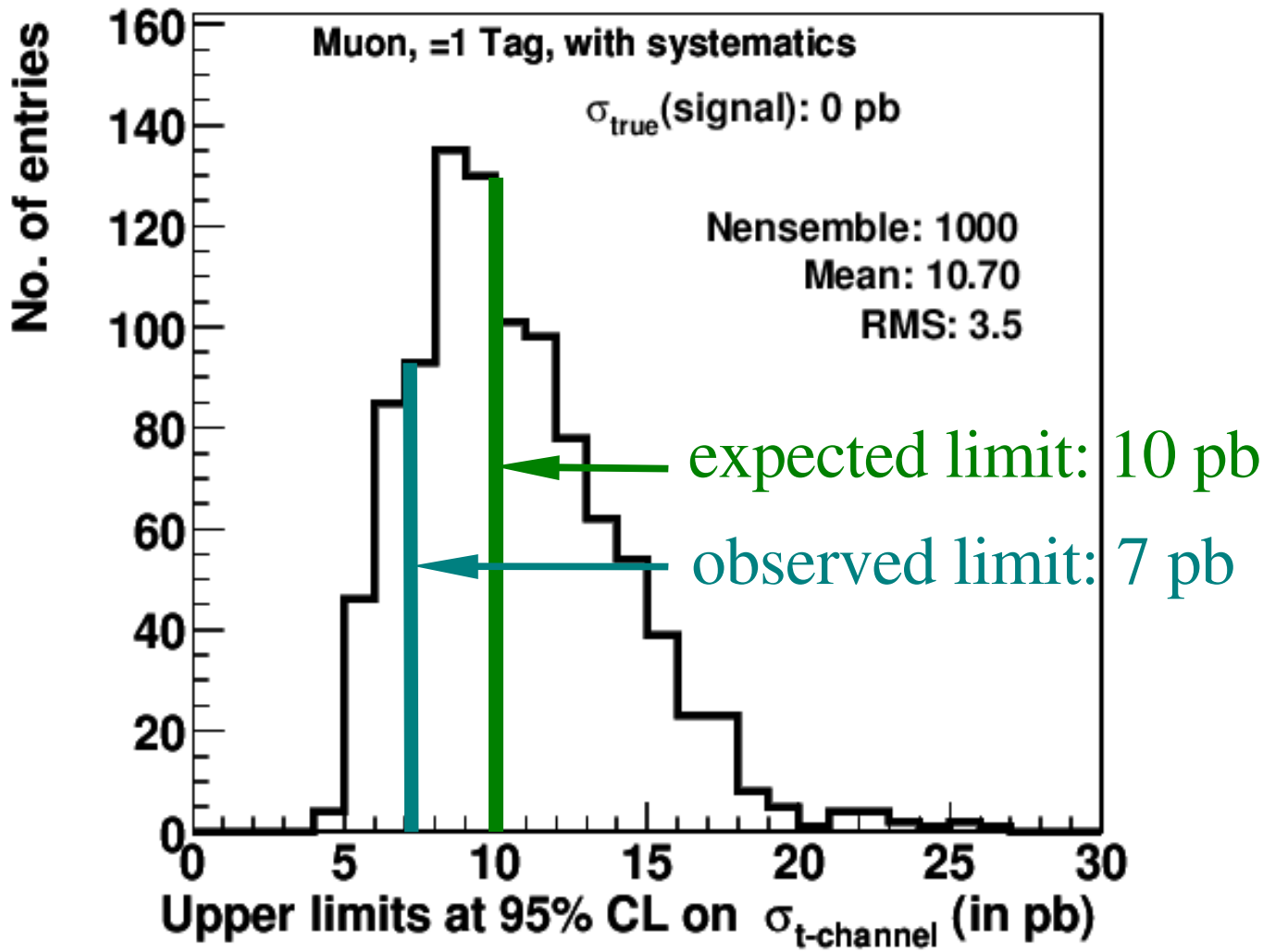
Credits

- Thanks to the many people that have helped me put this talk together
  - Including Brigitte Vachon, John Womersley, Dugan O'Neil
- Some of the material was adopted from the web pages listed on the previous page
- Some of the material was adopted from the ICHEP 2004 and Vietnam 2004 conferences
- The latest DØ top quark results can be found at http://www-d0.fnal.gov/Run2Physics/top/index.html

Backup Slides

Ensemble Tests

- Limits from pseudo-experiments
  - Vary count in each bin according to Poisson distribution



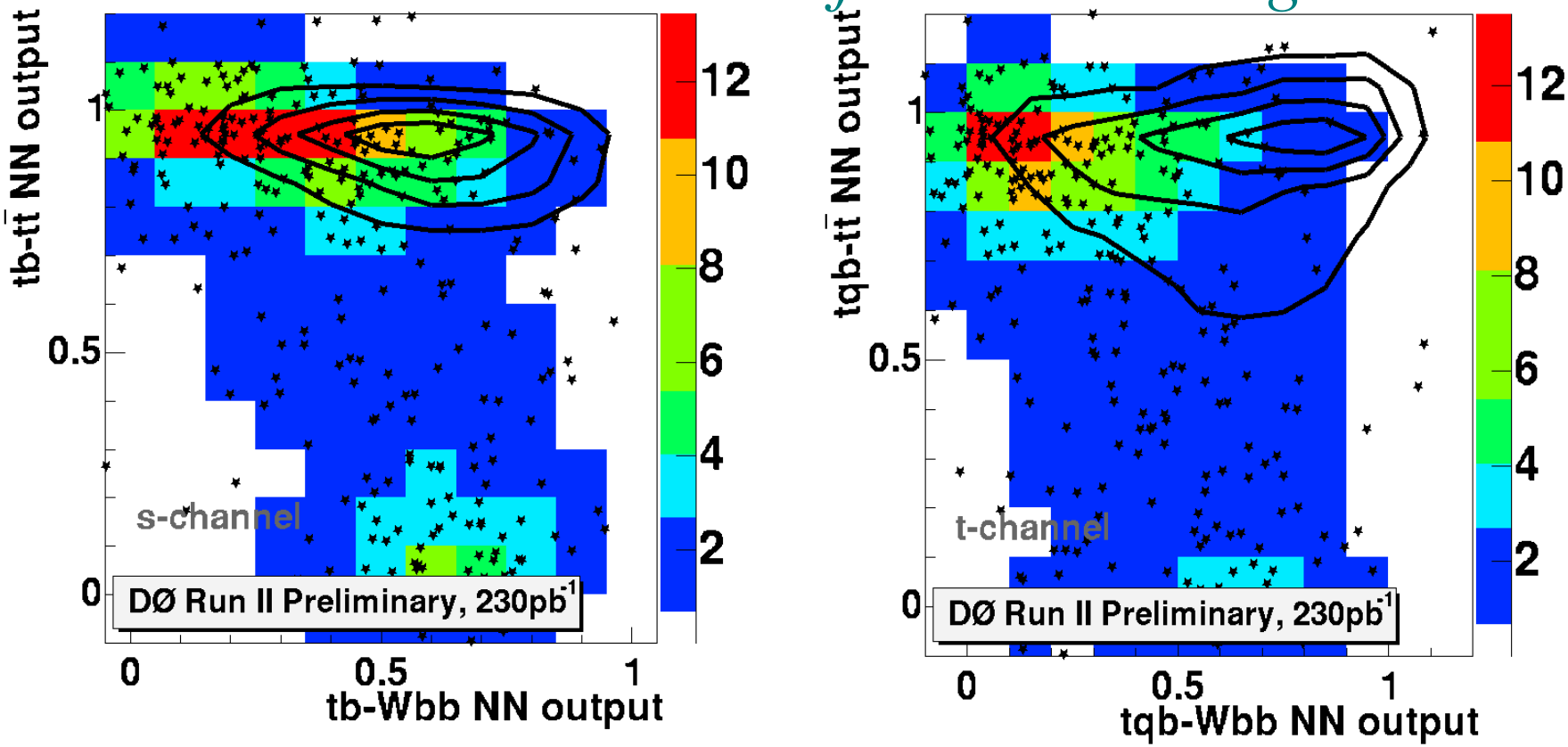
Summary

	s-channel	t-channel
NLO cross section	0.88 pb	1.98 pb
	95% CL upper cross section limits [pb]	
DØ Run I	17	22
CDF Run II (160pb^{-1})	13.6	10.1
This analysis (230pb^{-1})		
cut-based	10.6	11.3
DTs & binned likelihood	8.3	8.1
NNs & binned likelihood	6.4	5

Result

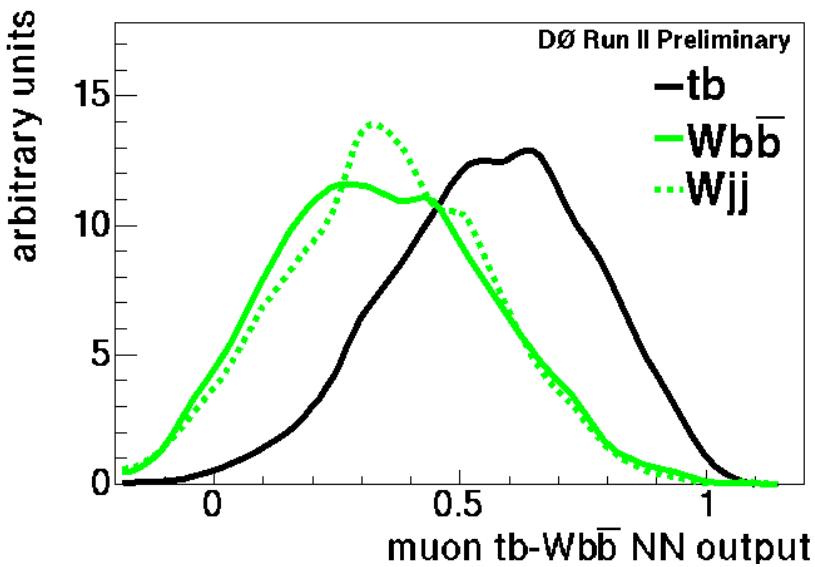
- No evidence for single top signal
  - ➔ Set 95% CL upper cross section limit
  - – Using Bayesian approach and binned likelihood
  - – Including bin-by-bin systematics and correlations

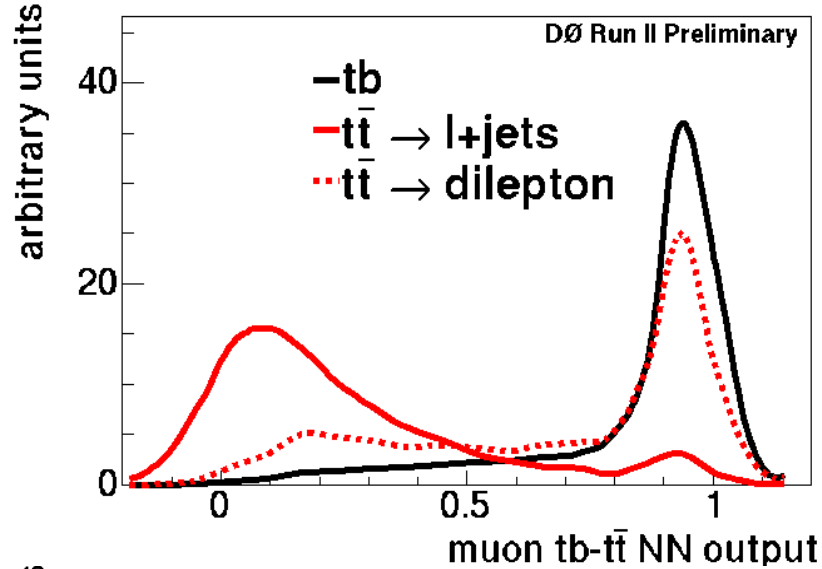
Build binned likelihood from 2-d histograms

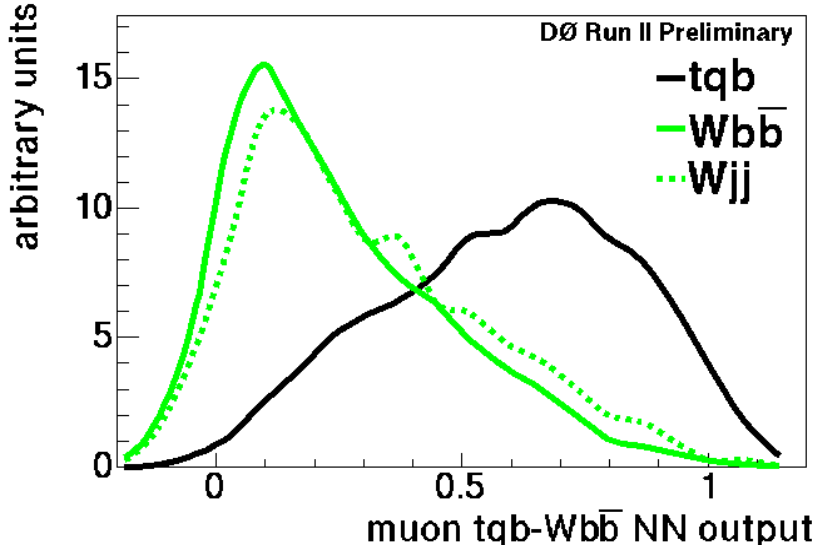


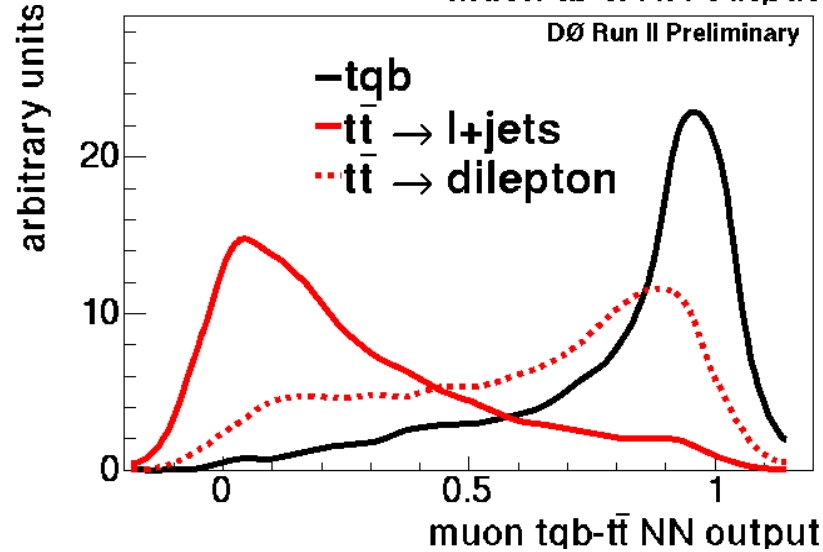
Neural Network Filters

- Focus on the largest backgrounds: Wbb and tt→*l*+jets
- Same variables for electron and muon channel
- Same filter for =1 tag and ≥2 tags



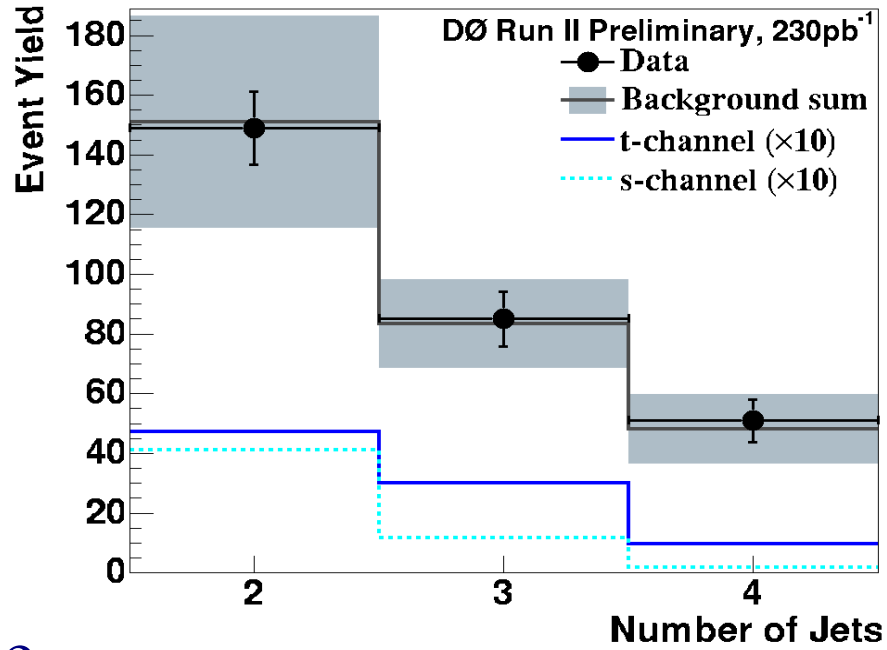






Systematic Uncertainties

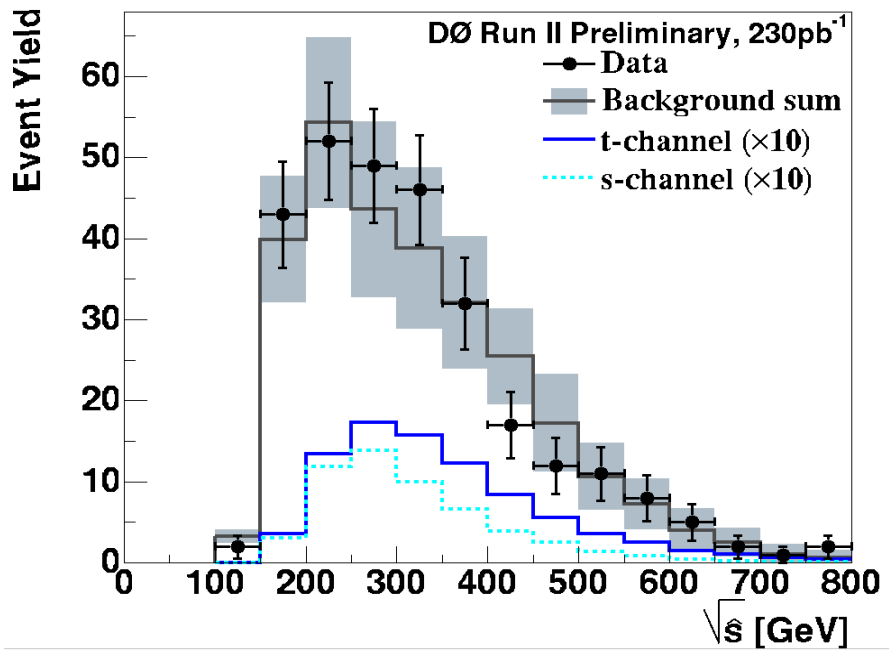
Monte Carlo Systematic Uncertainties	
Theory cross sections	15 %
SVT modeling, single (double) tag	10 %(20 %)
Jet Energy Scale	10 %
Trigger Modeling	6 %
Jet Fragmentation	6 %
Jet ID	5 %
ℓ ID	5 %



- Some uncertainties also affect shape
  - JES, b-tag and trigger modeling
- Total Uncertainty

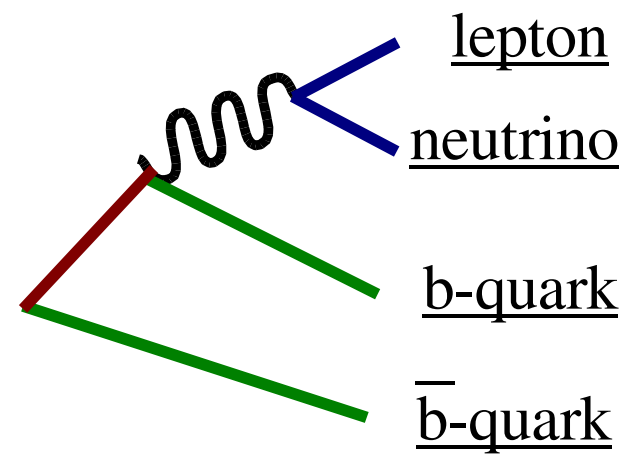
	=1 tag	≥2 tags
Signal acceptance	15%	25%
Background sum	10%	26%

Result is statistics limited



Event Selection

- Trigger:
  - Electron + ≥1 jets, muon + ≥1 jets
- Lepton:
  - 1 electron: $p_T > 15\text{GeV}$, $|\eta^{det}|<1.1$
  - 1 muon: $p_T > 15\text{GeV}$, $|\eta^{det}|<2.0$
- Neutrino: $\not{E}_T > 15\text{GeV}$
- Jets:
  - $p_T > 15\text{GeV}$, $|\eta^{det}|<3.4$, p_T (jet 1)> 25GeV
  - $2 \leq n_{jets} \leq 4$
- Reject mis-reconstructed events

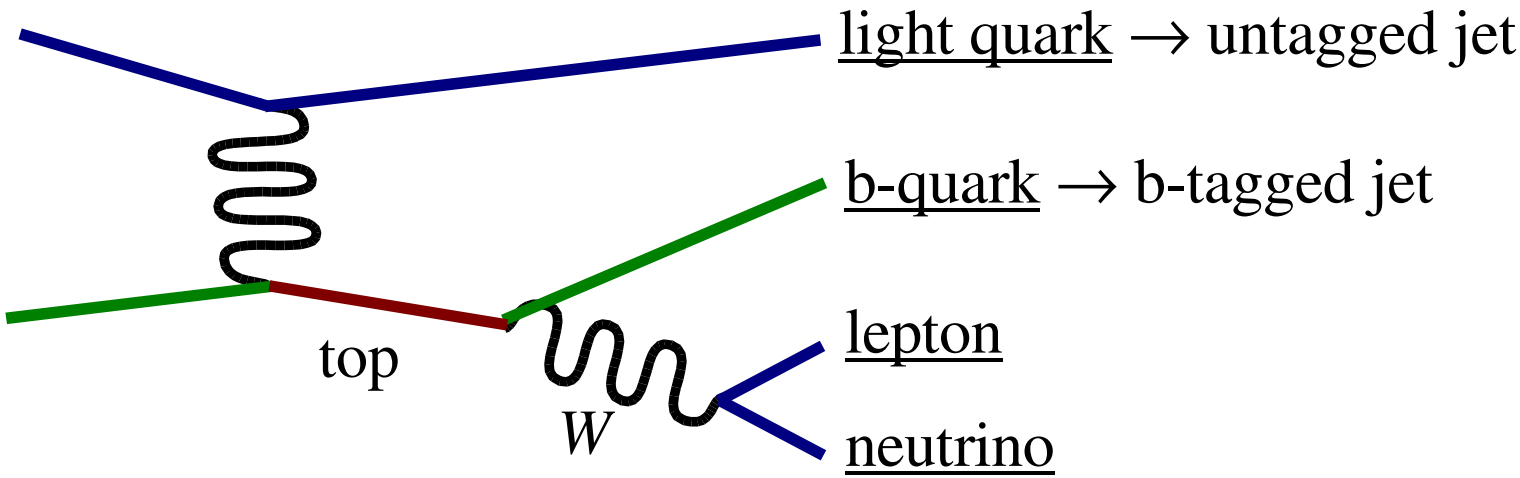


Variables:

	Signal-Background Pairs			
	tb		tqb	
	Wbb	$t\bar{t}$	Wbb	$t\bar{t}$
Individual object kinematics				
$p_T(\mathrm{jet1}_{\mathrm{tagged}})$	$\surd$	$\surd$	$\surd$	—
$p_T(\mathrm{jet1}_{\mathrm{untagged}})$	—	—	$\surd$	$\surd$
$p_T(\mathrm{jet2}_{\mathrm{untagged}})$	—	—	—	$\surd$
$p_T(\mathrm{jet1}_{\mathrm{nonbest}})$	$\surd$	$\surd$	—	—
$p_T(\mathrm{jet2}_{\mathrm{nonbest}})$	$\surd$	$\surd$	—	—
Global event kinematics				
$M_T(\mathrm{jet1},\mathrm{jet2})$	$\surd$	—	—	—
$p_T(\mathrm{jet1},\mathrm{jet2})$	$\surd$	—	$\surd$	—
$M(\mathrm{alljets})$	$\surd$	$\surd$	$\surd$	$\surd$
$H_T(\mathrm{alljets})$	—	—	$\surd$	—
$M(\mathrm{alljets}-\mathrm{jet1}_{\mathrm{tagged}})$	—	—	—	$\surd$
$H(\mathrm{alljets}-\mathrm{jet1}_{\mathrm{tagged}})$	—	$\surd$	—	$\surd$
$H_T(\mathrm{alljets}-\mathrm{jet1}_{\mathrm{tagged}})$	—	—	—	$\surd$
$p_T(\mathrm{alljets}-\mathrm{jet1}_{\mathrm{tagged}})$	—	$\surd$	—	$\surd$
$M(\mathrm{alljets}-\mathrm{jet}_{\mathrm{best}})$	—	$\surd$	—	—
$H(\mathrm{alljets}-\mathrm{jet}_{\mathrm{best}})$	—	$\surd$	—	—
$H_T(\mathrm{alljets}-\mathrm{jet}_{\mathrm{best}})$	—	$\surd$	—	—
$M(\mathrm{top}_{\mathrm{tagged}}) = M(W,\mathrm{jet1}_{\mathrm{tagged}})$	$\surd$	$\surd$	$\surd$	$\surd$
$M(\mathrm{top}_{\mathrm{best}}) = M(W,\mathrm{jet}_{\mathrm{best}})$	$\surd$	—	—	—
$\sqrt{\hat{s}}$	$\surd$	—	$\surd$	$\surd$
Angular variables				
$\Delta R(\mathrm{jet1},\mathrm{jet2})$	$\surd$	—	$\surd$	—
$Q(\mathrm{lepton}) \times \eta(\mathrm{jet1}_{\mathrm{untagged}})$	—	—	$\surd$	$\surd$
$\cos(\mathrm{lepton}, Q(\mathrm{lepton}) \times z)_{\mathrm{top}_{\mathrm{best}}}$	$\surd$	—	—	—
$\cos(\mathrm{lepton},\mathrm{jet1}_{\mathrm{untagged}})_{\mathrm{top}_{\mathrm{tagged}}}$	—	—	$\surd$	—
$\cos(\mathrm{alljets},\mathrm{jet1}_{\mathrm{tagged}})_{\mathrm{alljets}}$	—	—	$\surd$	$\surd$
$\cos(\mathrm{alljets},\mathrm{jet}_{\mathrm{nonbest}})_{\mathrm{all\ jets}}$	—	$\surd$	—	—

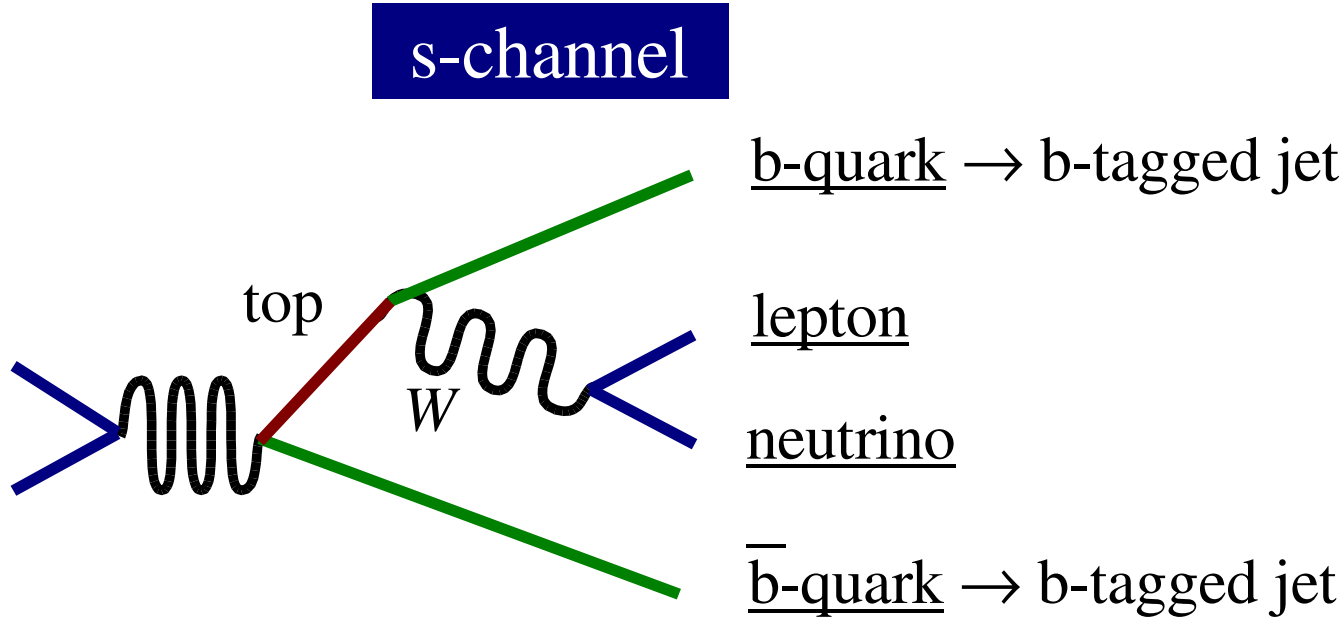
Final State Reconstruction

t-channel



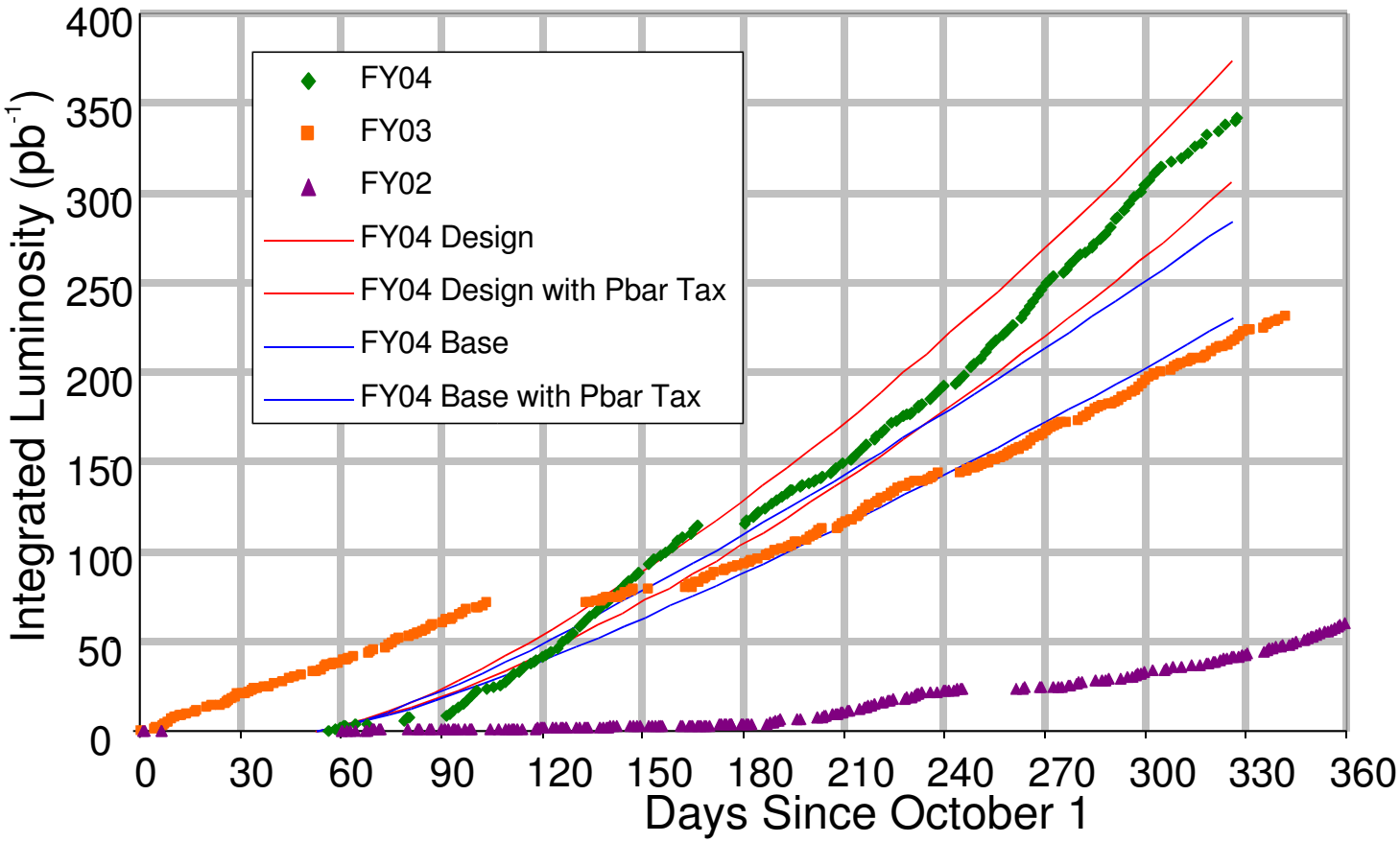
- Reconstruct W from lepton and $\not{E}_T$
- Reconstruct top quark from W and leading b-tagged jet
- Reconstruct light quark as leading untagged jet

Final State Reconstruction



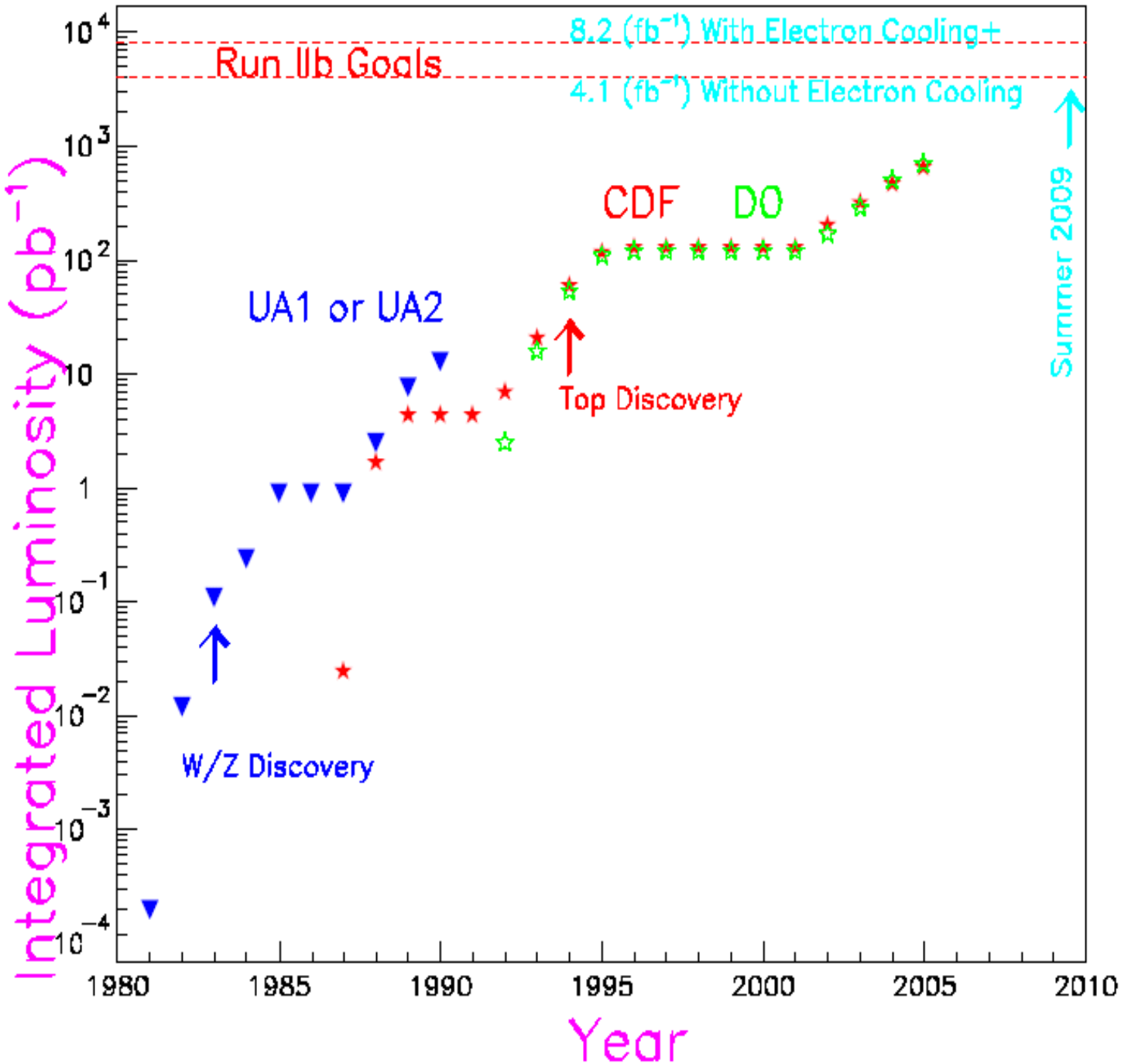
- Reconstruct W from lepton and $\not{E}_T$
- Reconstruct top quark from W and one of the jets using Best Jet Algorithm:
  - Pick jet for which $M(W,\text{jet})$ is closest to true top mass (175GeV)
- Reconstruct $\bar{b}$-quark as leading non-best jet

Tevatron Integrated Luminosity per year



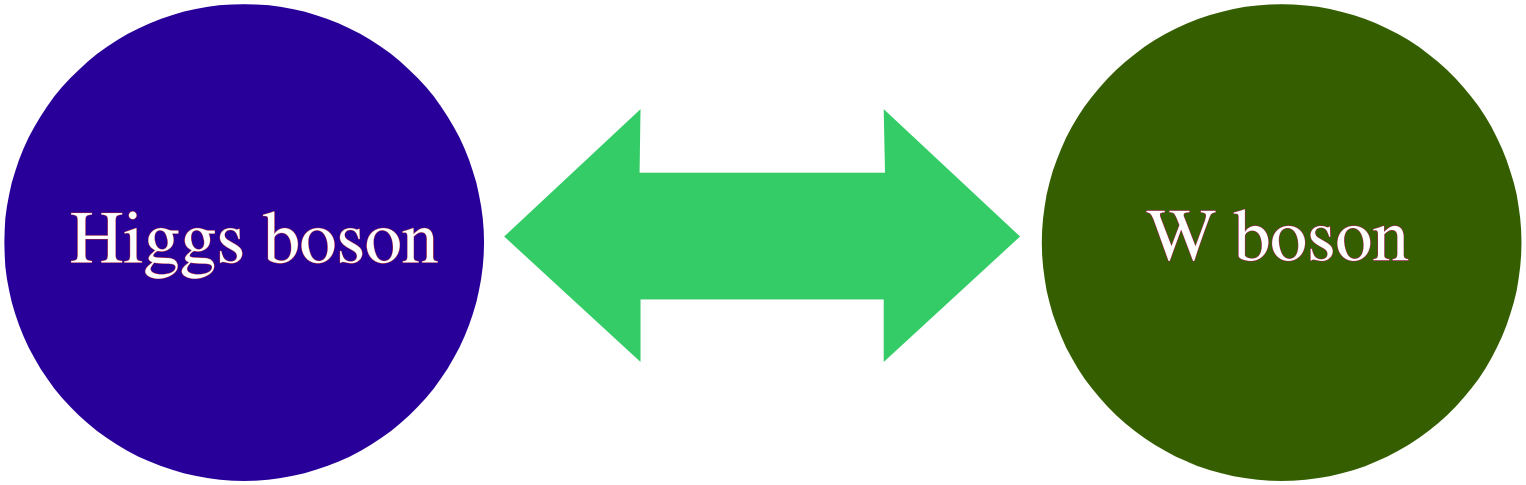
- Tevatron delivered luminosity is exceeding "baseline" and "design" projections

Hadron Collider Integrated Luminosity



Electroweak Symmetry Breaking

Gauge boson coupling to Higgs field



Nacht.

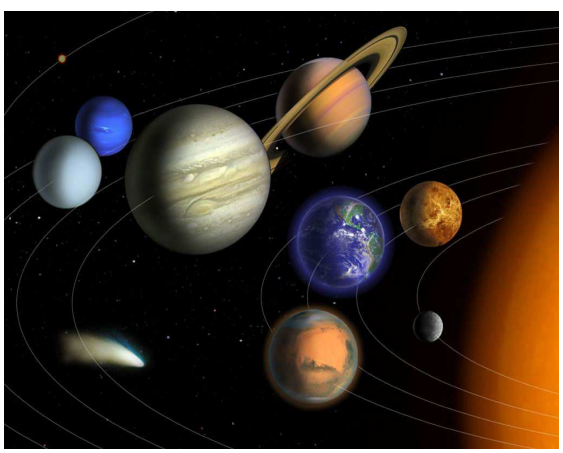
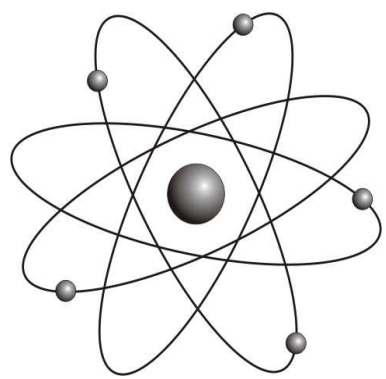
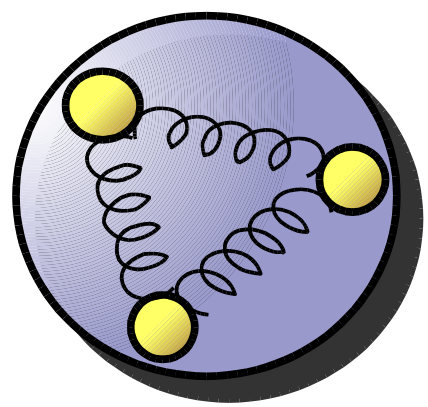
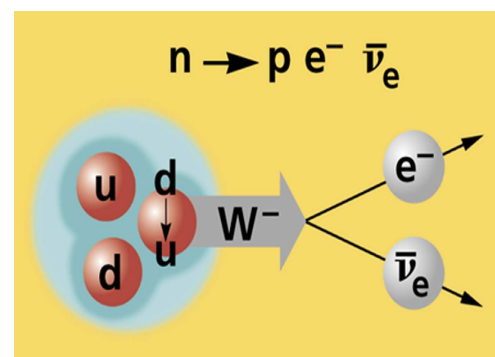
In einem hochgewölbten, engen gotischen Zimmer Faust, unruhig auf seinem Sessel am Pulte.

FAUST: Habe nun, ach! Philosophie,
Juristerei und Medizin,
Und leider auch Theologie
Durchaus studiert, mit heißem Bemühn.
Da steh ich nun, ich armer Tor!
Und bin so klug als wie zuvor;
Heiße Magister, heiße Doktor gar
Und ziehe schon an die zehen Jahr
Herauf, herab und quer und krumm
Meine Schüler an der Nase herum-
Und sehe, daß wir nichts wissen können!
Das will mir schier das Herz verbrennen.
Zwar bin ich gescheiter als all die Laffen,
Doktoren, Magister, Schreiber und Pfaffen;
Mich plagen keine Skrupel noch Zweifel,
Fürchte mich weder vor Hölle noch Teufel-
Dafür ist mir auch alle Freud entrissen,
Bilde mir nicht ein, was Rechts zu wissen,
Bilde mir nicht ein, ich könnte was lehren,
Die Menschen zu bessern und zu bekehren.
Auch hab ich weder Gut noch Geld,
Noch Ehr und Herrlichkeit der Welt;
Es möchte kein Hund so länger leben!
Drum hab ich mich der Magie ergeben,
Ob mir durch Geistes Kraft und Mund
Nicht manch Geheimnis würde kund;
Daß ich nicht mehr mit saurem Schweiß
Zu sagen brauche, was ich nicht weiß;
Daß ich erkenne, was die Welt
Im Innersten zusammenhält,
Schau alle Wirkenskraft und Samen,
Und tu nicht mehr in Worten kramen.

O sähst du, voller Mondenschein,
Zum letzenmal auf meine Pein,
Den ich so manche Mitternacht
An diesem Pult herangewacht:
Dann über Büchern und Papier,
Trübsel'ger Freund, erschienst du mir!
Ach! könnt ich doch auf Bergeshöhn
In deinem lieben Lichte gehn,
Um Bergeshöhle mit Geistern schweben,
Auf Wiesen in deinem Dämmer weben,
Von allem Wissensqualm entladen,
In deinem Tau gesund mich baden!

Weh! steck ich in dem Kerker noch?
Verfluchtes dumpfes Mauerloch,
Wo selbst das liebe Himmelslicht
Trüb durch gemalte Scheiben bricht!
Beschränkt mit diesem Bücherhauf,
den Würme nagen, Staub bedeckt,
Den bis ans hohe Gewölb hinauf
Ein angeraucht Papier umsteckt;
Mit Gläsern, Büchsen rings umstellt,
Mit Instrumenten vollgepfropft,
Urväter Hausrat drein gestopft-
Das ist deine Welt! das heißt eine Welt!

Generations of particles

quarks	up	charm	top
	down	strange	bottom
fermions			
leptons	electron neutrino	muon neutrino	tau neutrino
	electron	muon	tau

Interactions