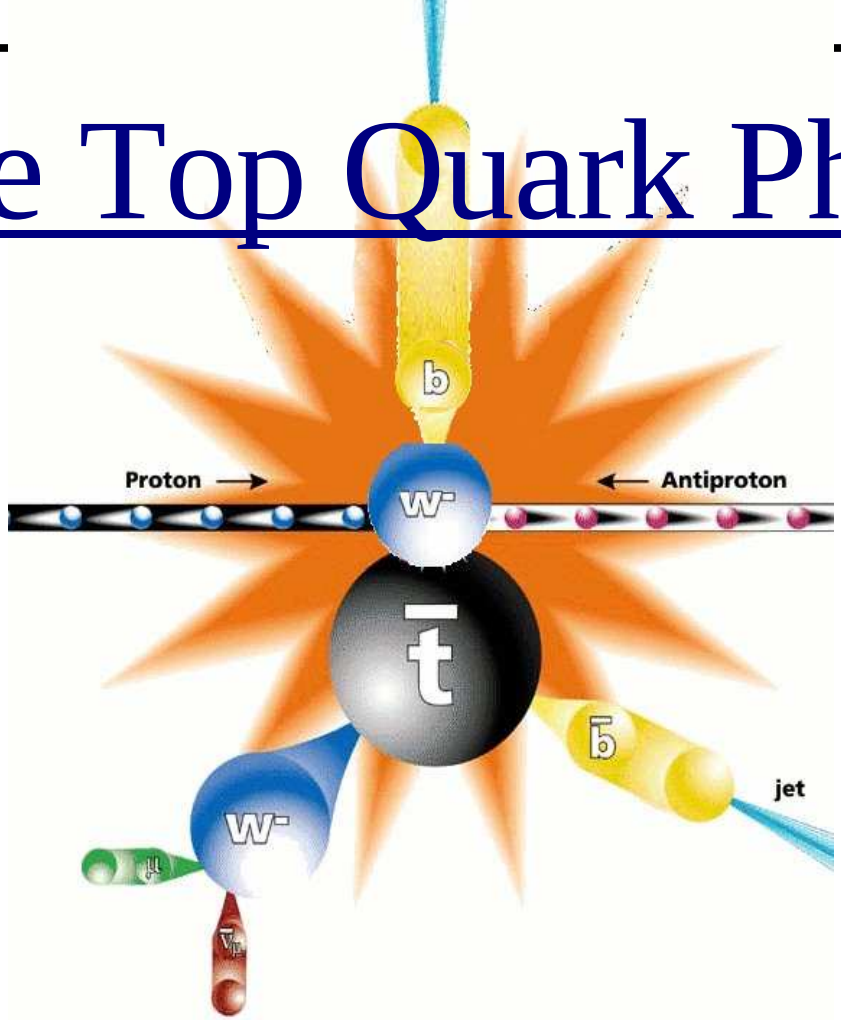
Single Top Quark Physics



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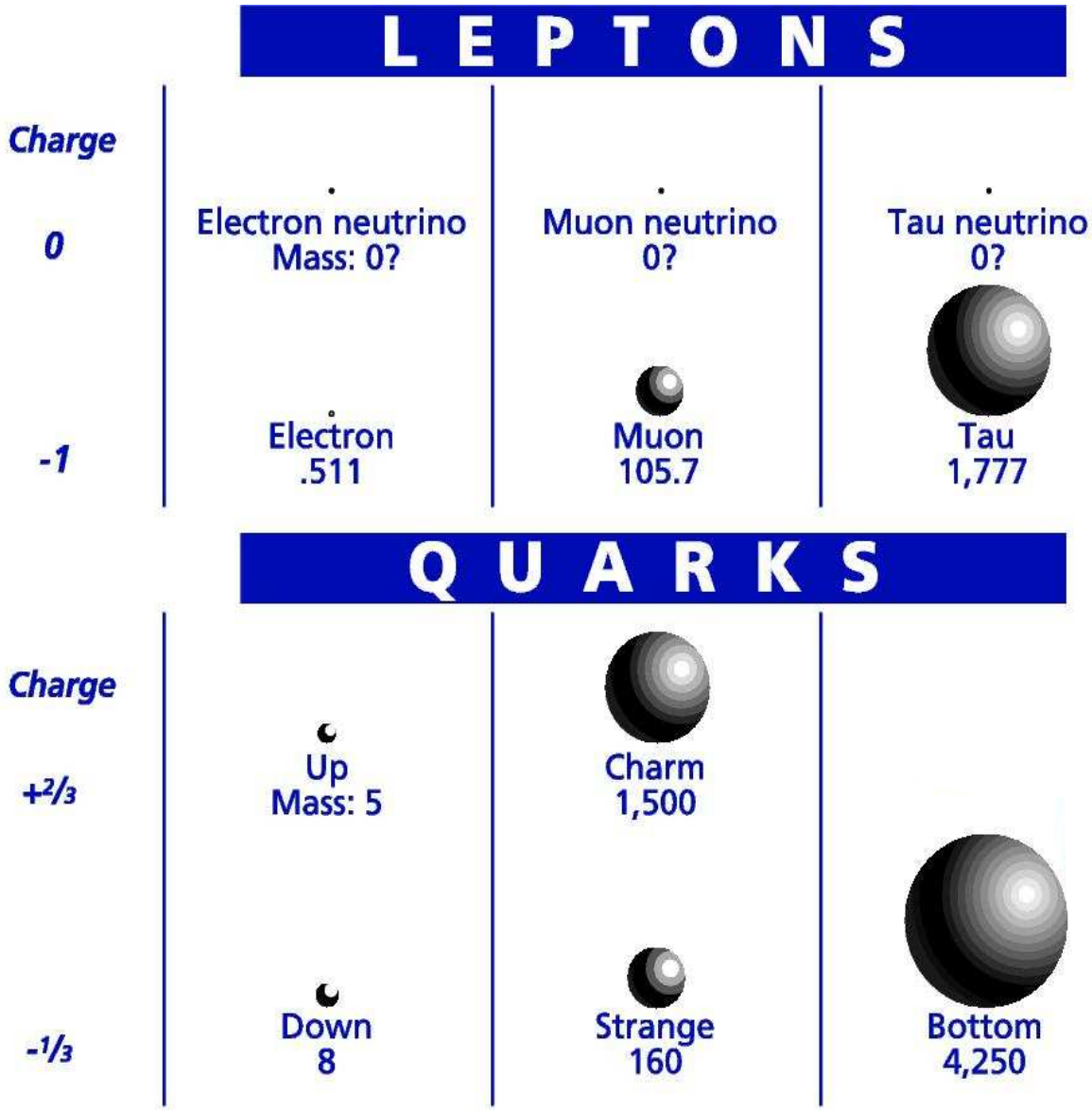
S. C. I. P. P.
Santa Cruz Institute for Particle Physics

UC Santa Cruz SCIPP seminar, 2/10/2006

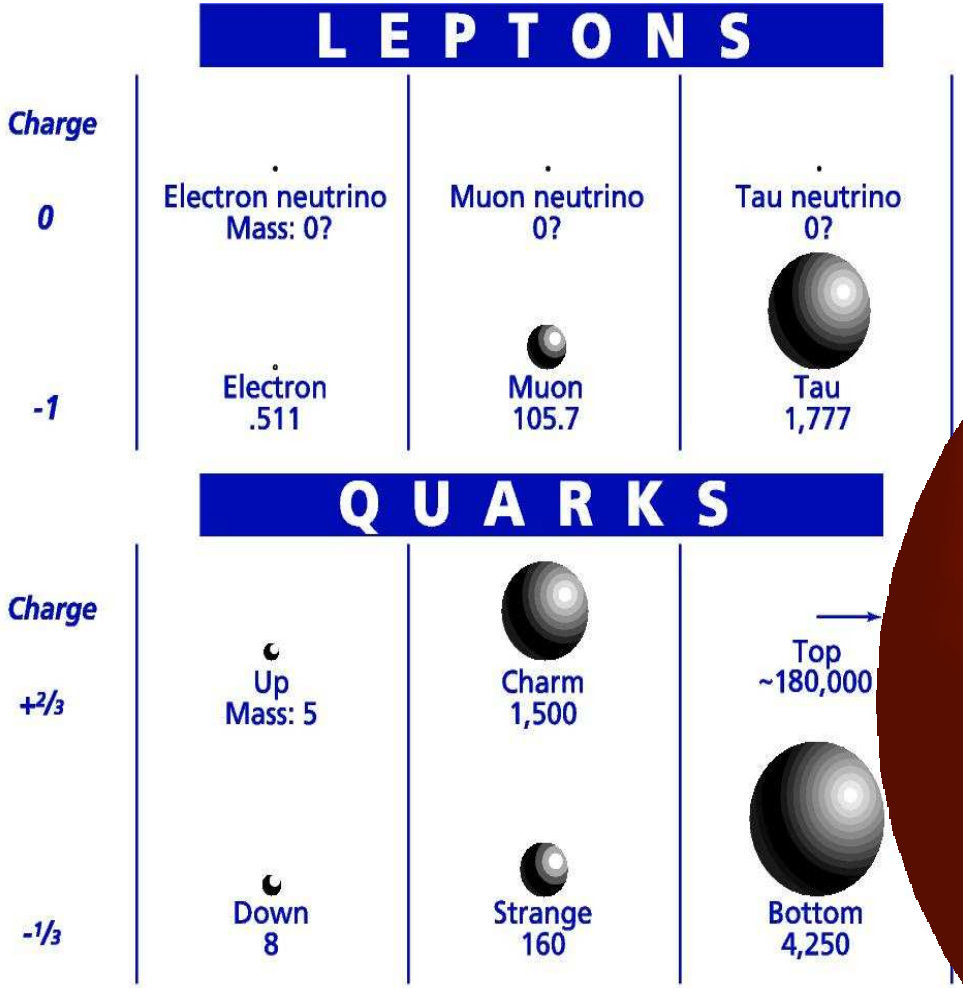
Outline

- The standard model of particle physics
  - Fundamental Fermions
  - The top quark
  - Single Top Quark Production
- The Energy Frontier
- Search for Single Top Quark Production
- Outlook
  - Fermilab
  - LHC
- Conclusions

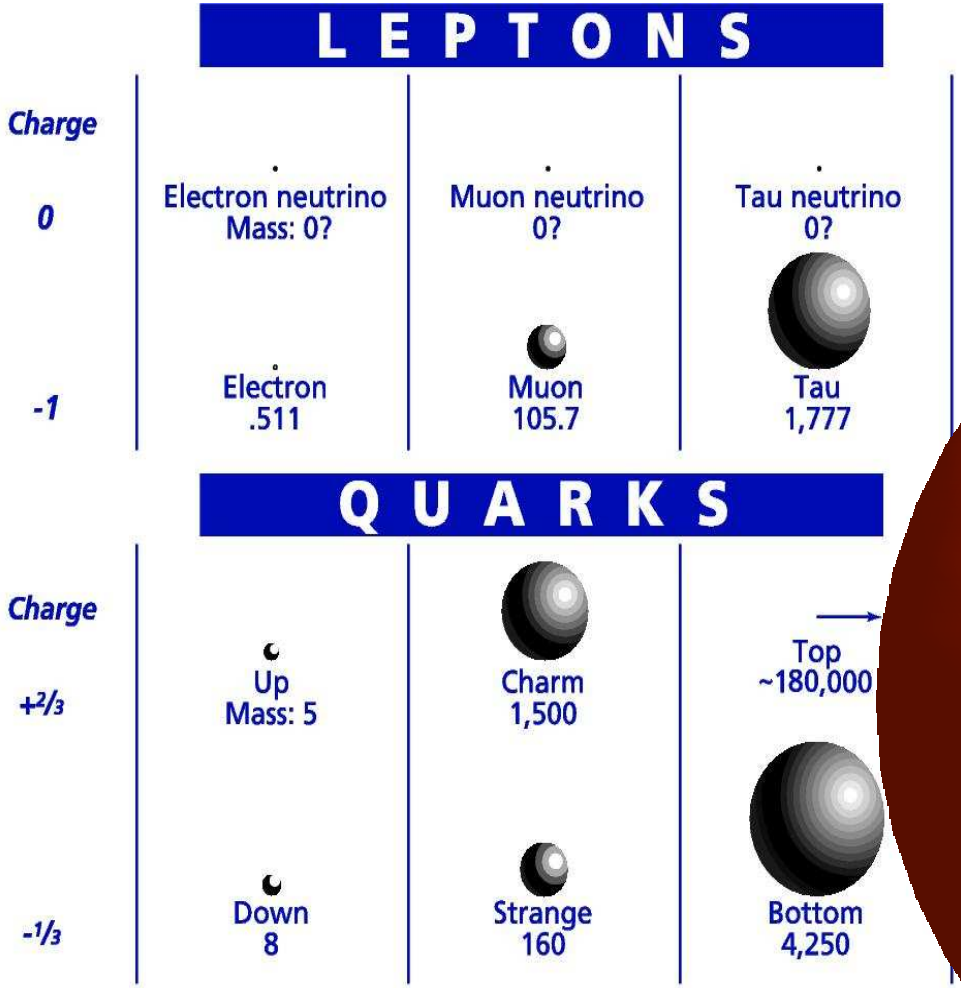
Fundamental Fermions

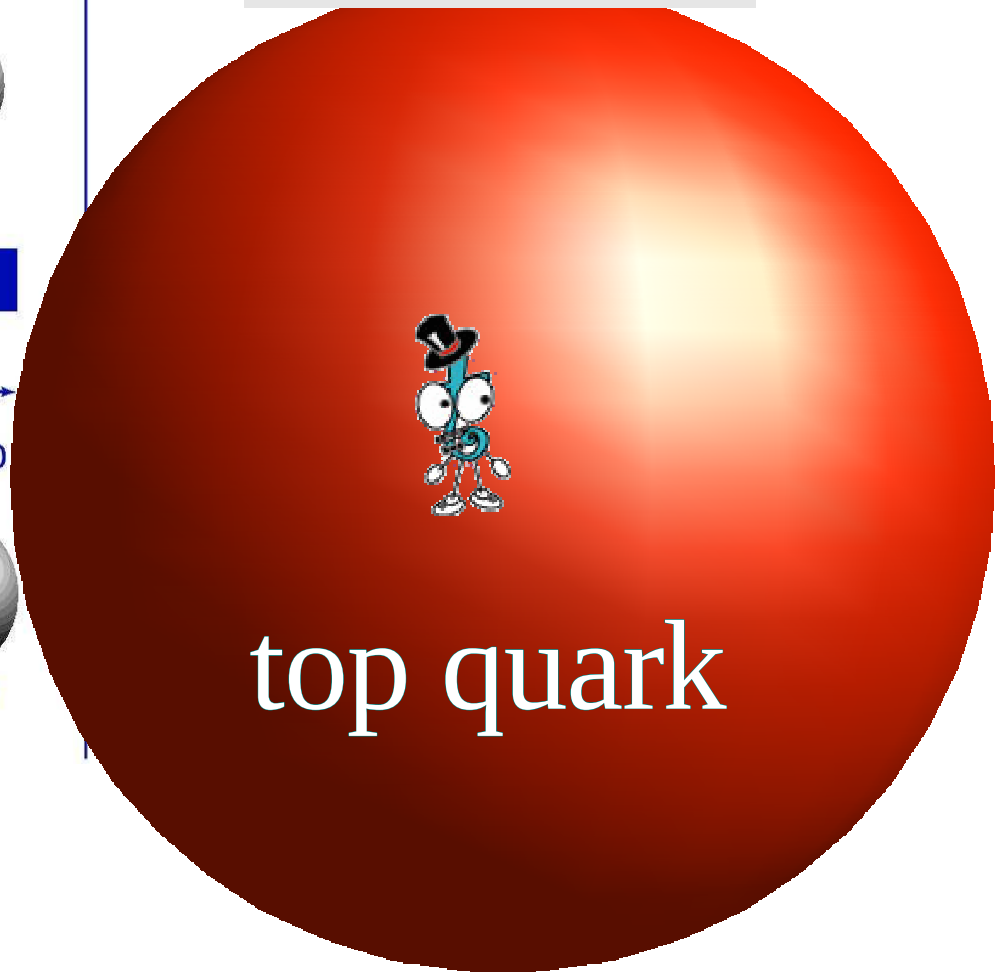


Fundamental Fermions



King of the Fermions





We assume but don't actually know:

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

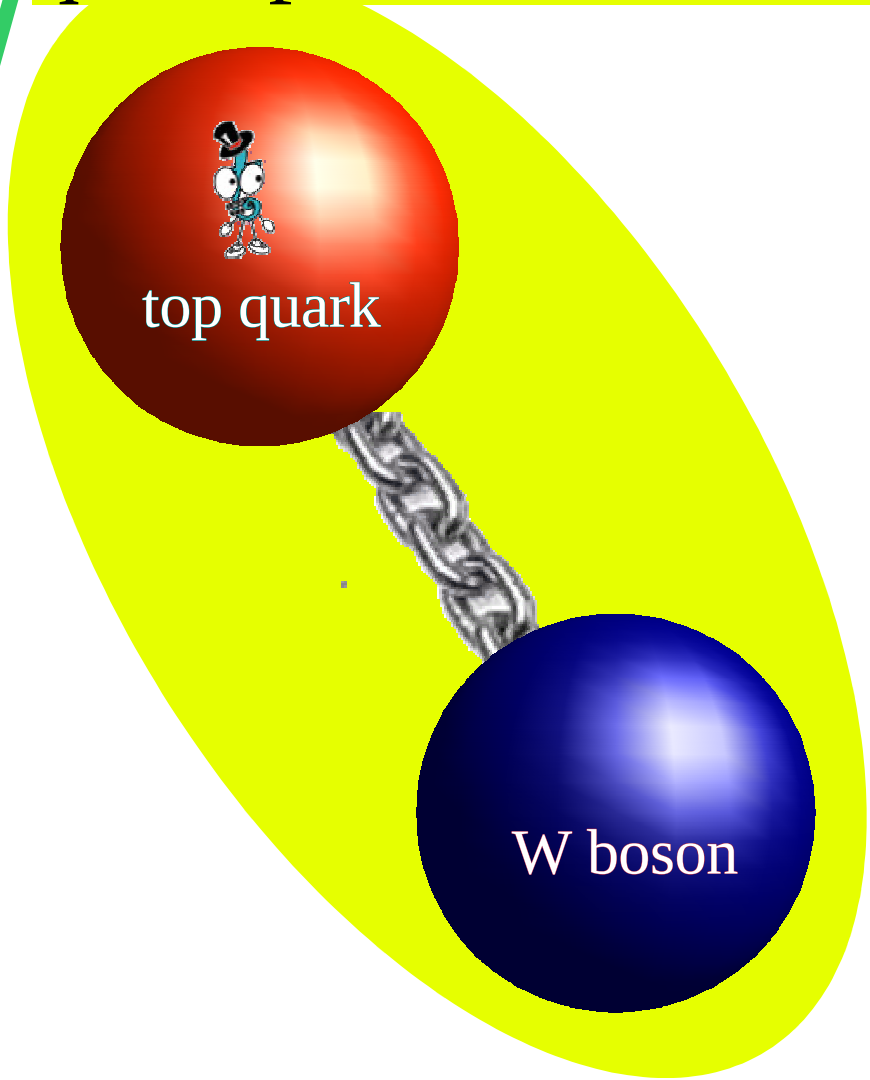
Really don't know:

- 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)

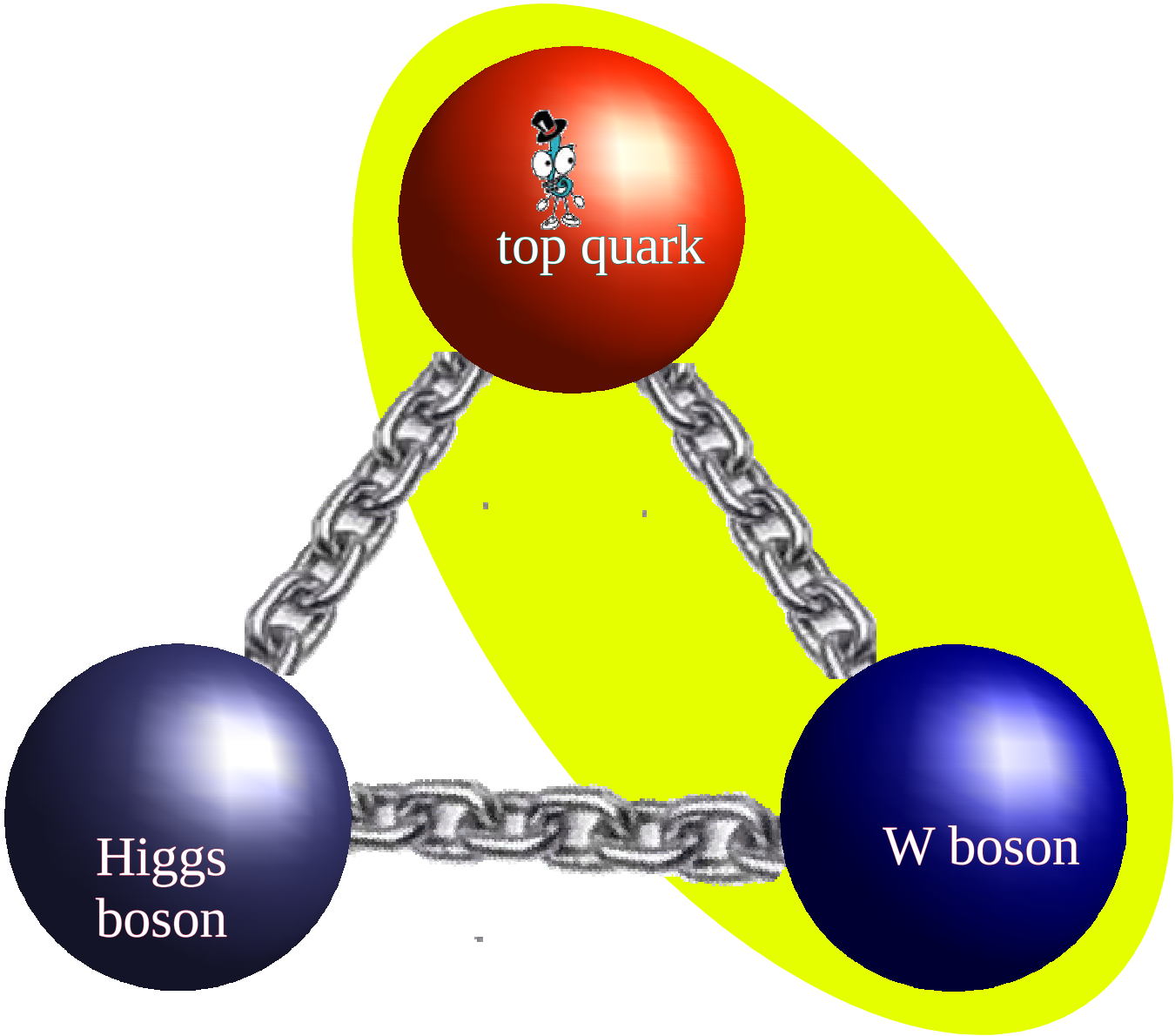
Study in single top quark production



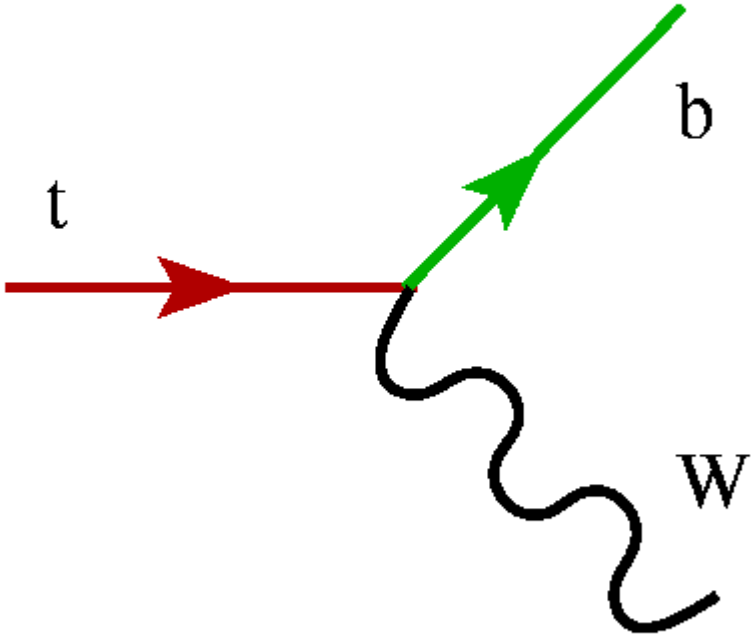
Really don't know:

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

Key to electroweak symmetry breaking



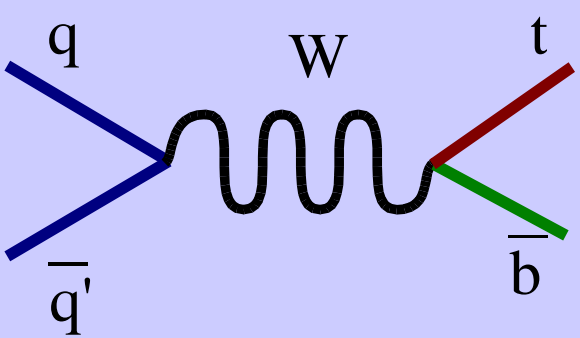
Top quark electroweak charged current interaction



top quark decay

SM single top quark production

s-channel



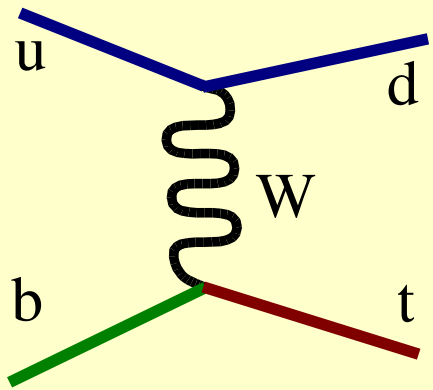
σ_{NLO}

TeV: 0.88 pb

LHC, t: 6.6 pb

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

t-channel



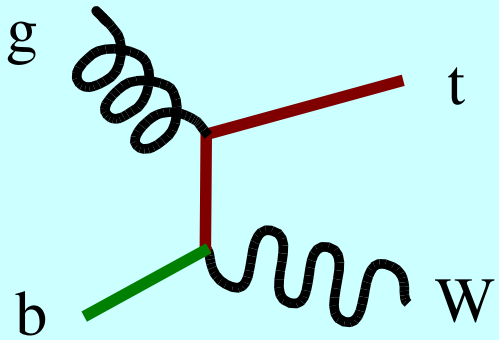
σ_{NLO}

1.98pb

156 pb

91 pb

Associated production



σ_{NLO}

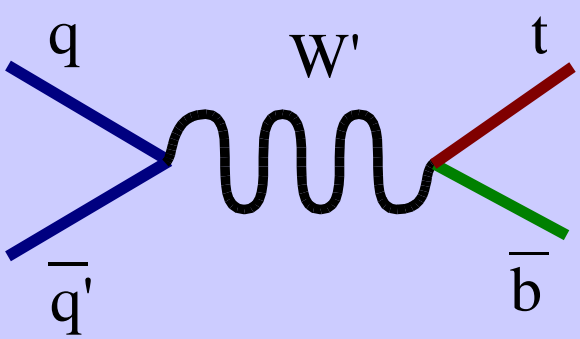
0.14 pb

34 pb

34 pb

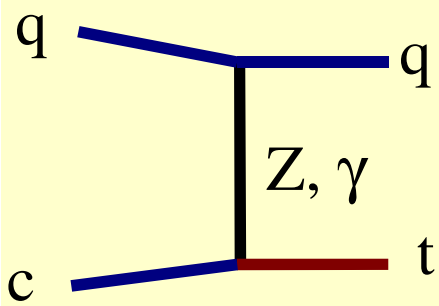
New physics

s-channel



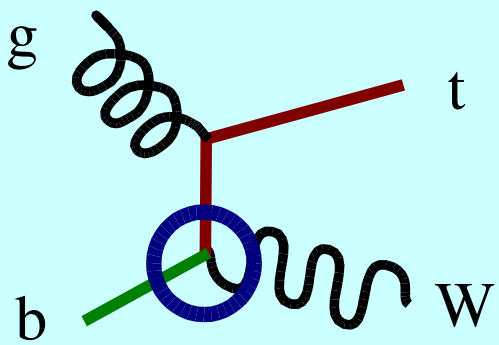
New heavy boson

t-channel

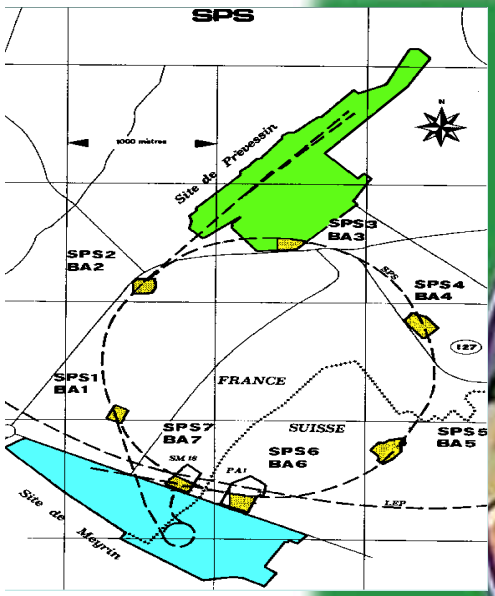


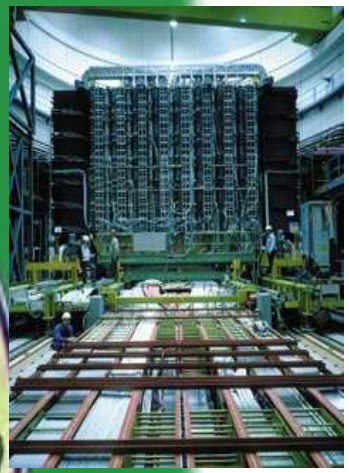
Flavor Changing Neutral Current

Associated production



Modified Wtb coupling


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



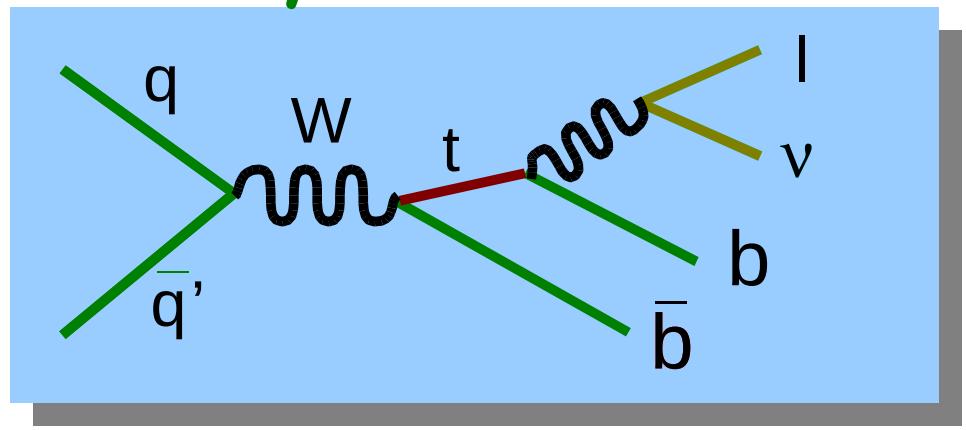
WHERE IN THE
WORLD

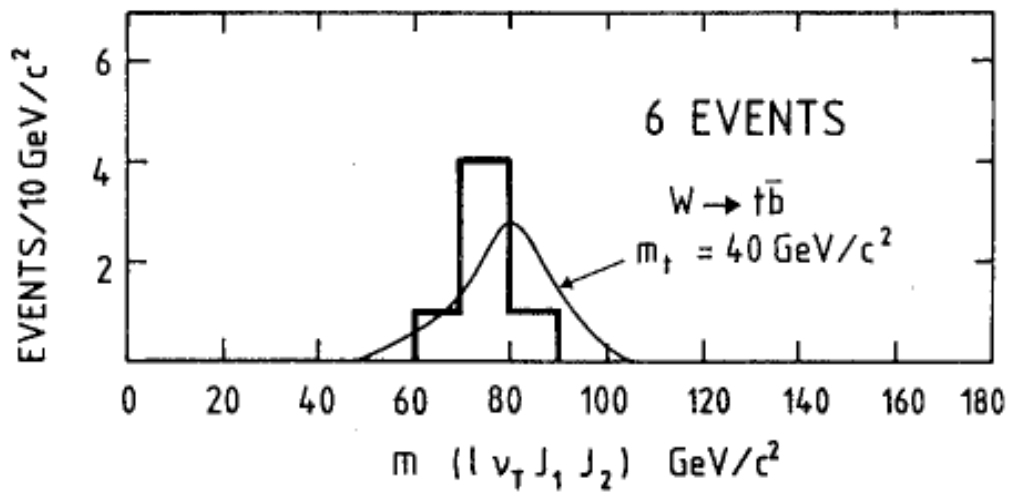
Single Top

HERA
PETRA

Top quark discovery in 1984?

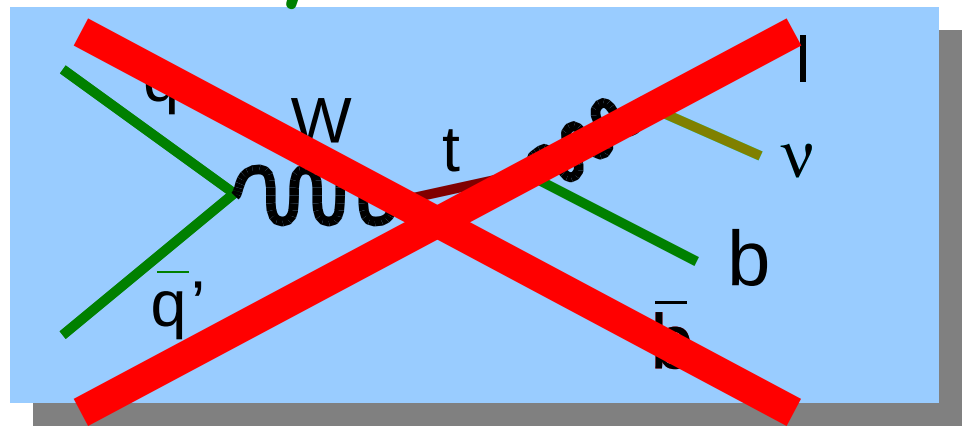
- Excess of lepton+MET+2jet events at UA1 in 1984
  - Consistent with production of single top quark
    - $M_{top} \approx 40GeV$

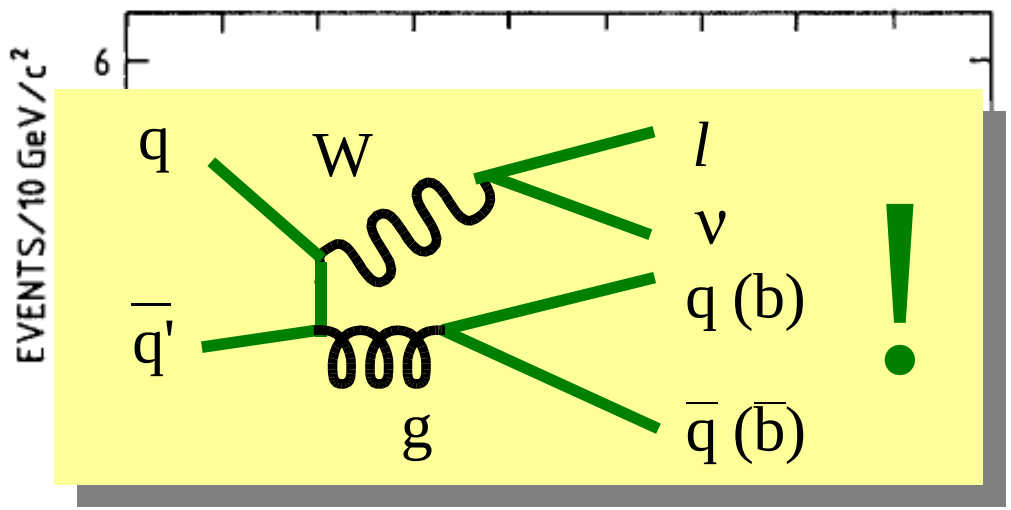




W+jets ~~Top quark discovery~~ in 1984?

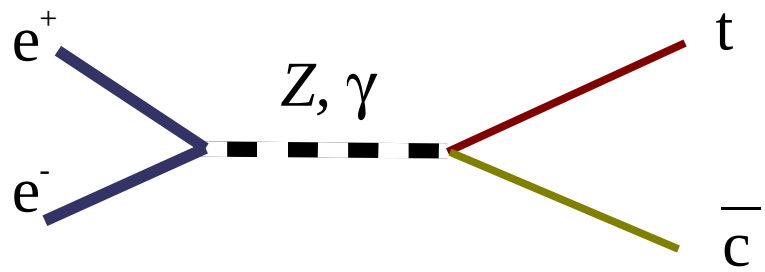
- Excess of lepton+MET+2jet events at UA1 in 1984
  - Consistent with production of single top quark
    - $M_{top} \approx 40GeV$



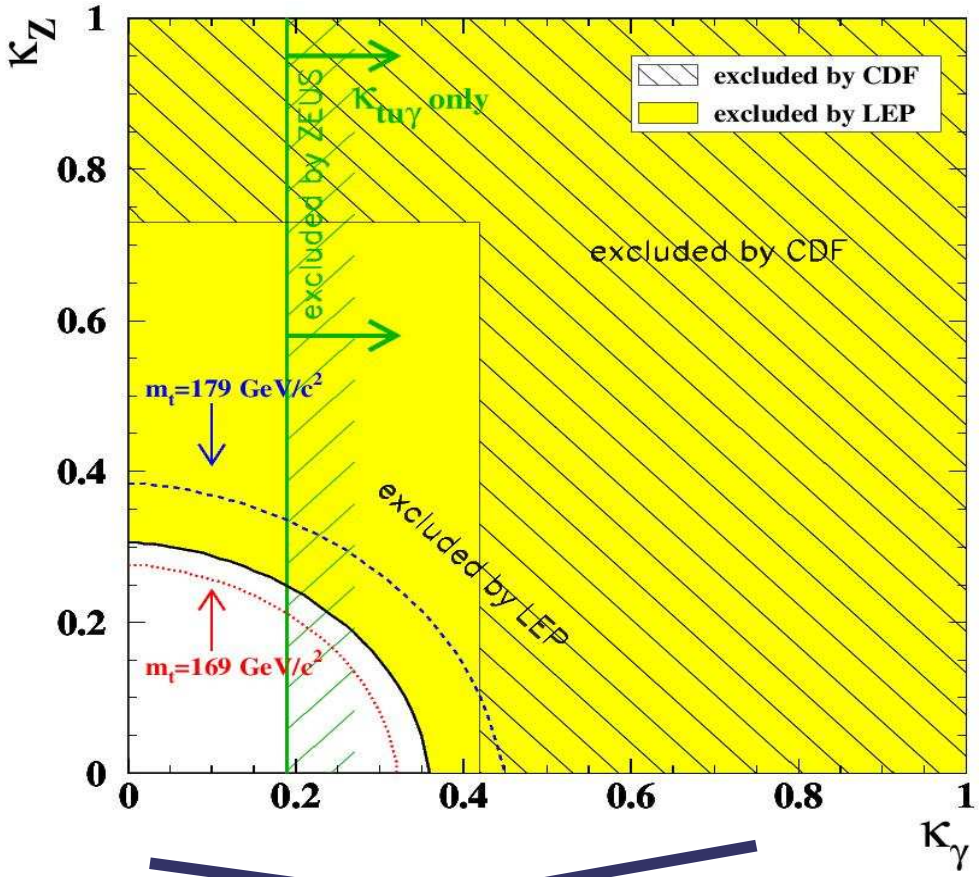


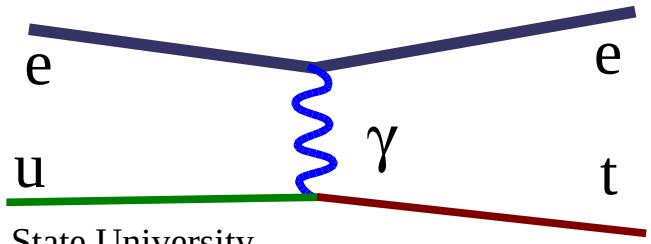
Single Top at LEP and Hera: FCNC

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

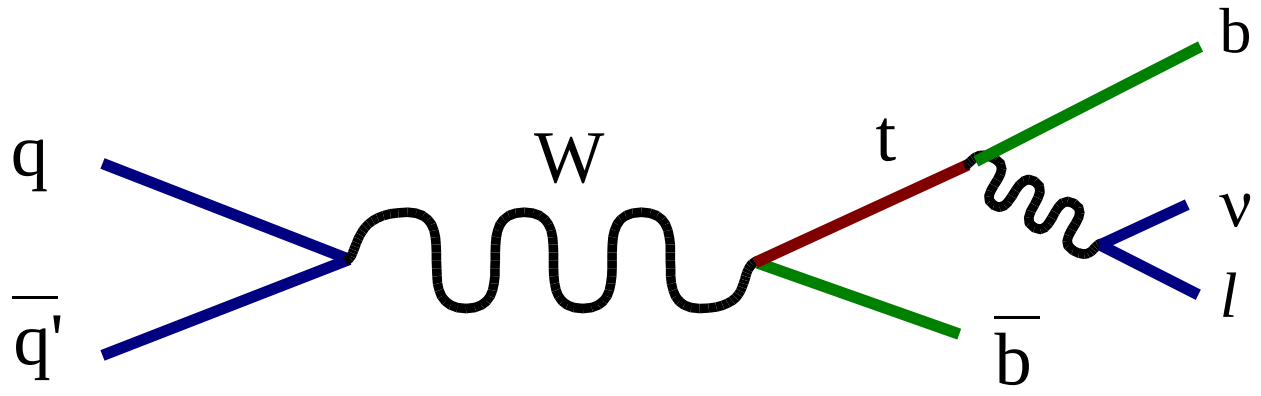


- Hera:
  - $ep \rightarrow et$

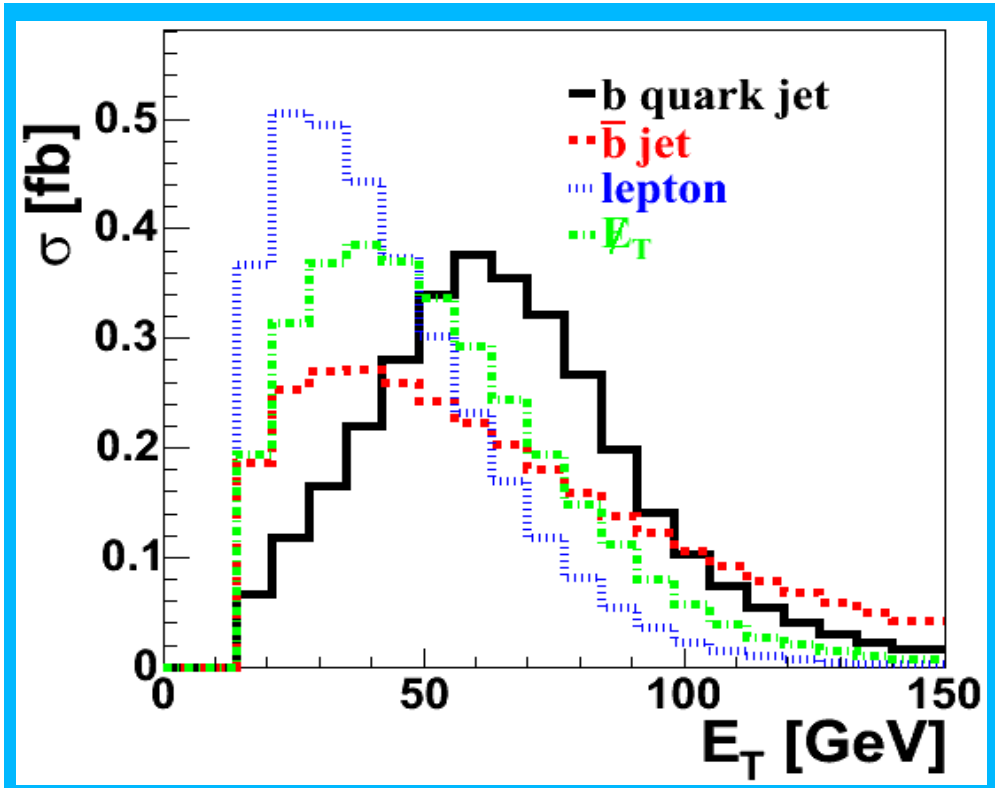




Tevatron s-channel signature

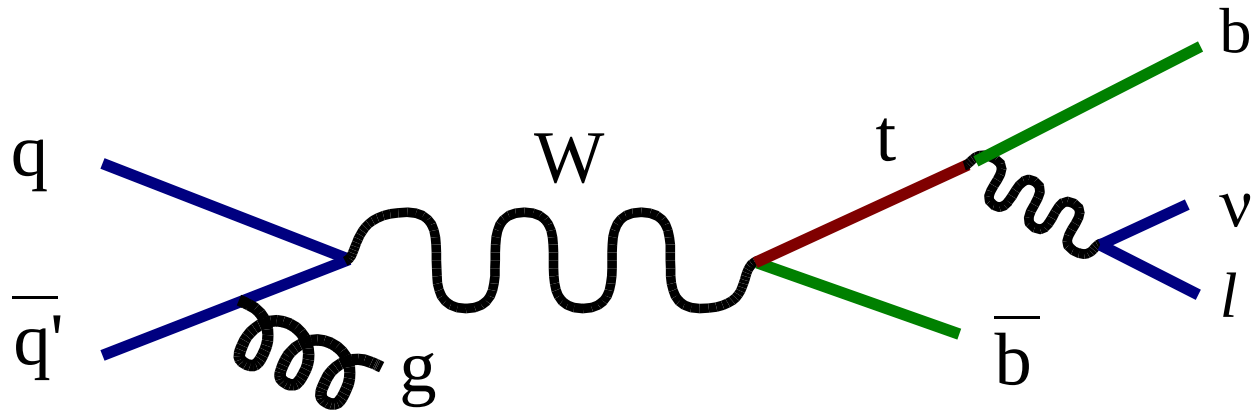


"tb"

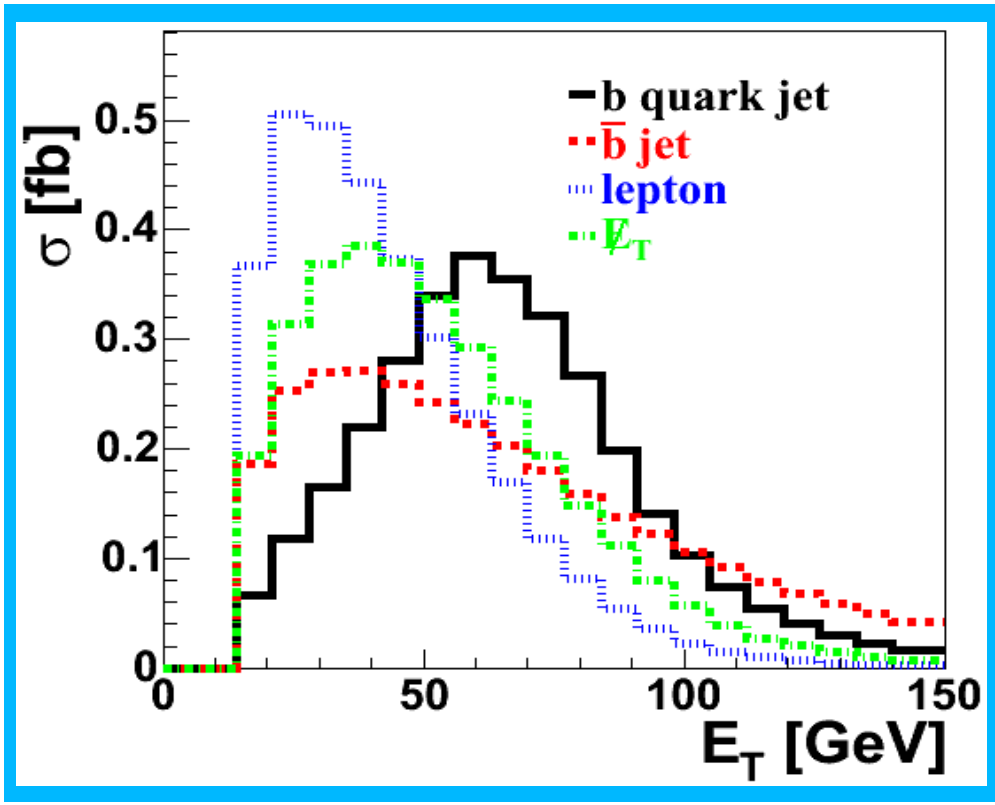


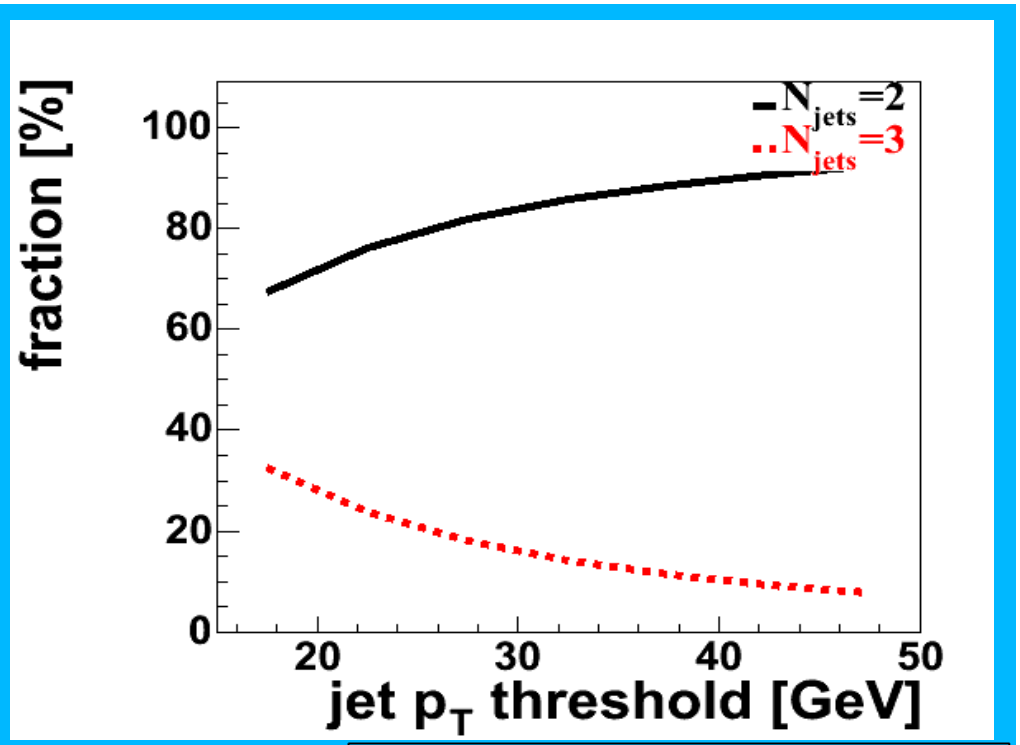
Cao, RS, Yuan PRD71, 054023 (2005)

Tevatron s-channel signature



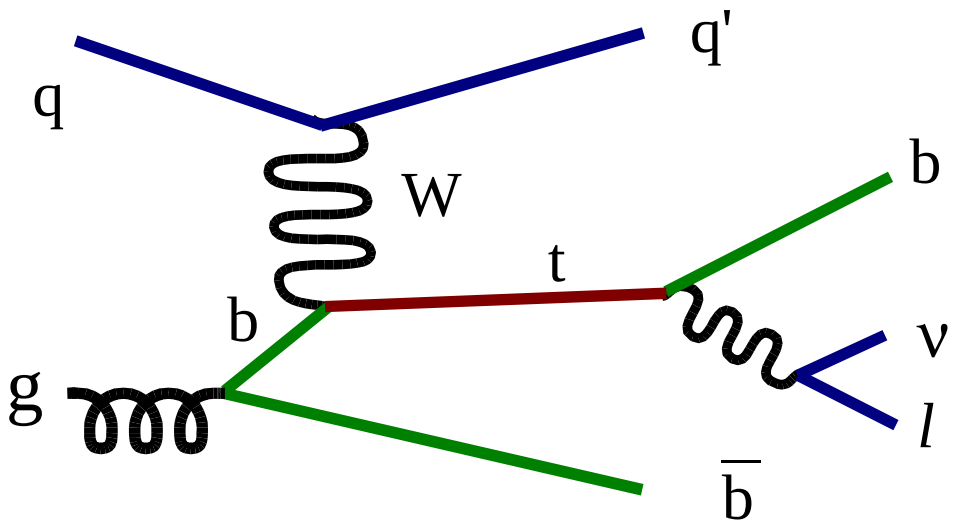
"*tb*"



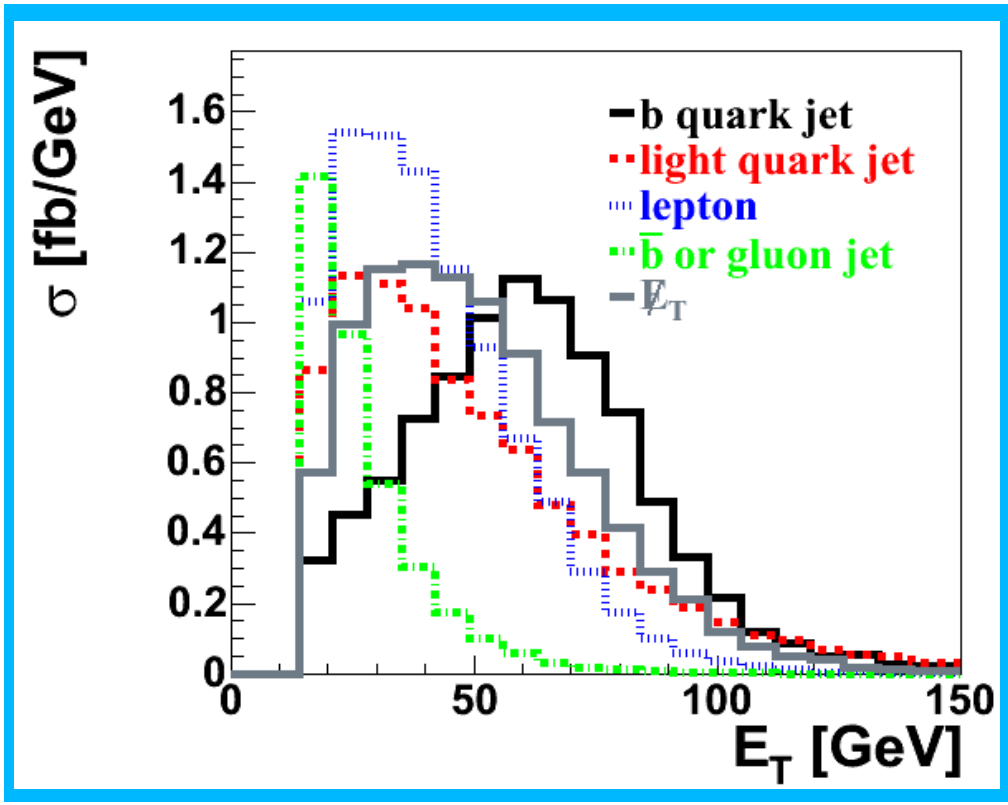


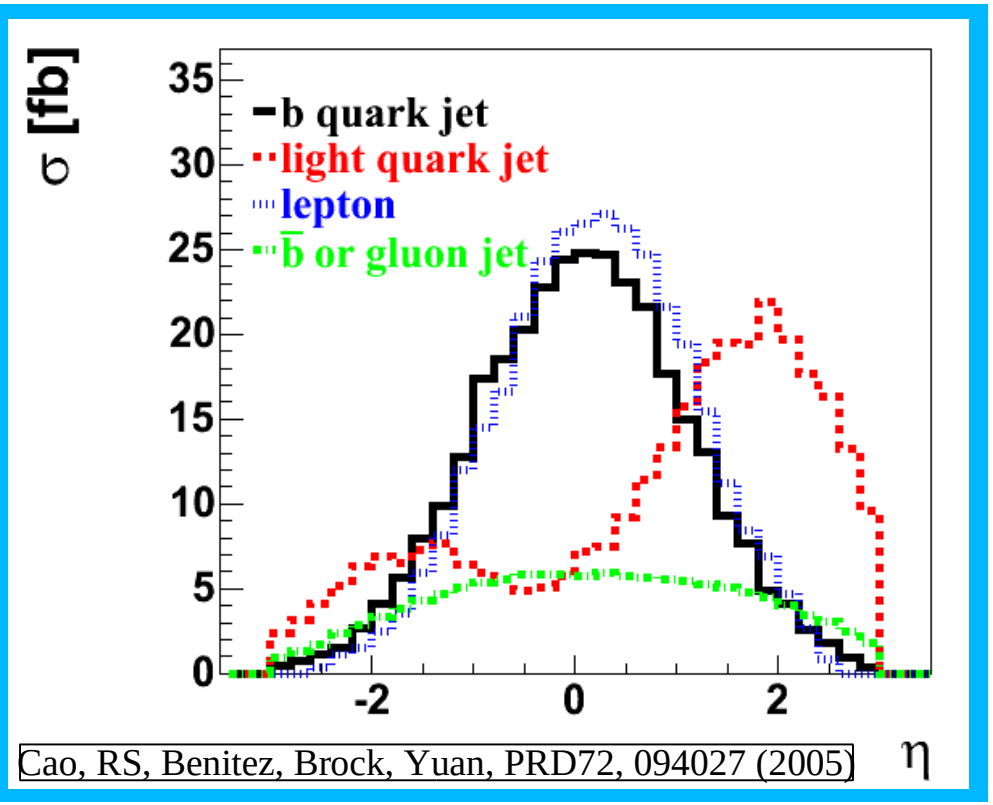
Cao, RS, Yuan PRD71, 054023 (2005)

Tevatron t-channel signature



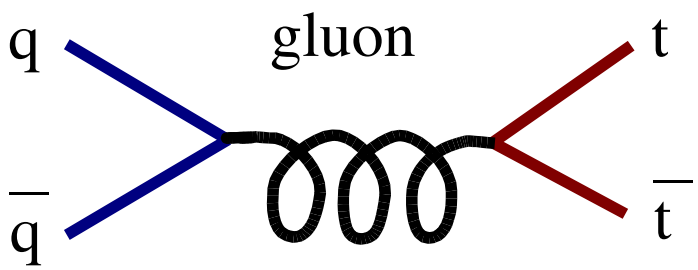
"tqb"





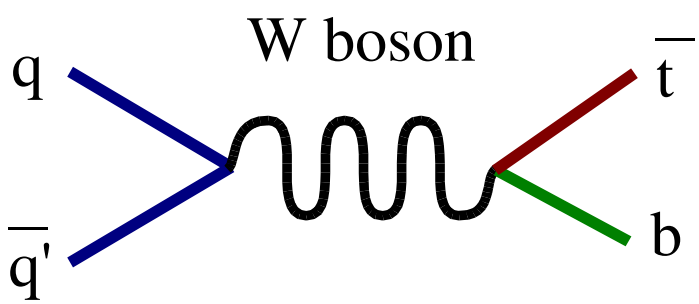
Cao, RS, Benitez, Brock, Yuan, PRD72, 094027 (2005)

Top quark pair production



$\sigma \sim 7$ pb

Single top quark production



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

Tevatron single top goals

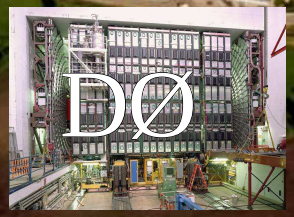
Production cross sections:	*s-channel*	*t-channel*	*s+t*
NLO calculation:	**0.88pb (±8%)**	**1.98pb (±11%)**	
Run I 95% CL limits, DØ:	< 17pb	< 22pb	
CDF:	< 18pb	< 13pb	< 14pb

- Observe single top quark production
  - Tevatron discovery!
- Measure production cross sections
  $\rightarrow$ 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

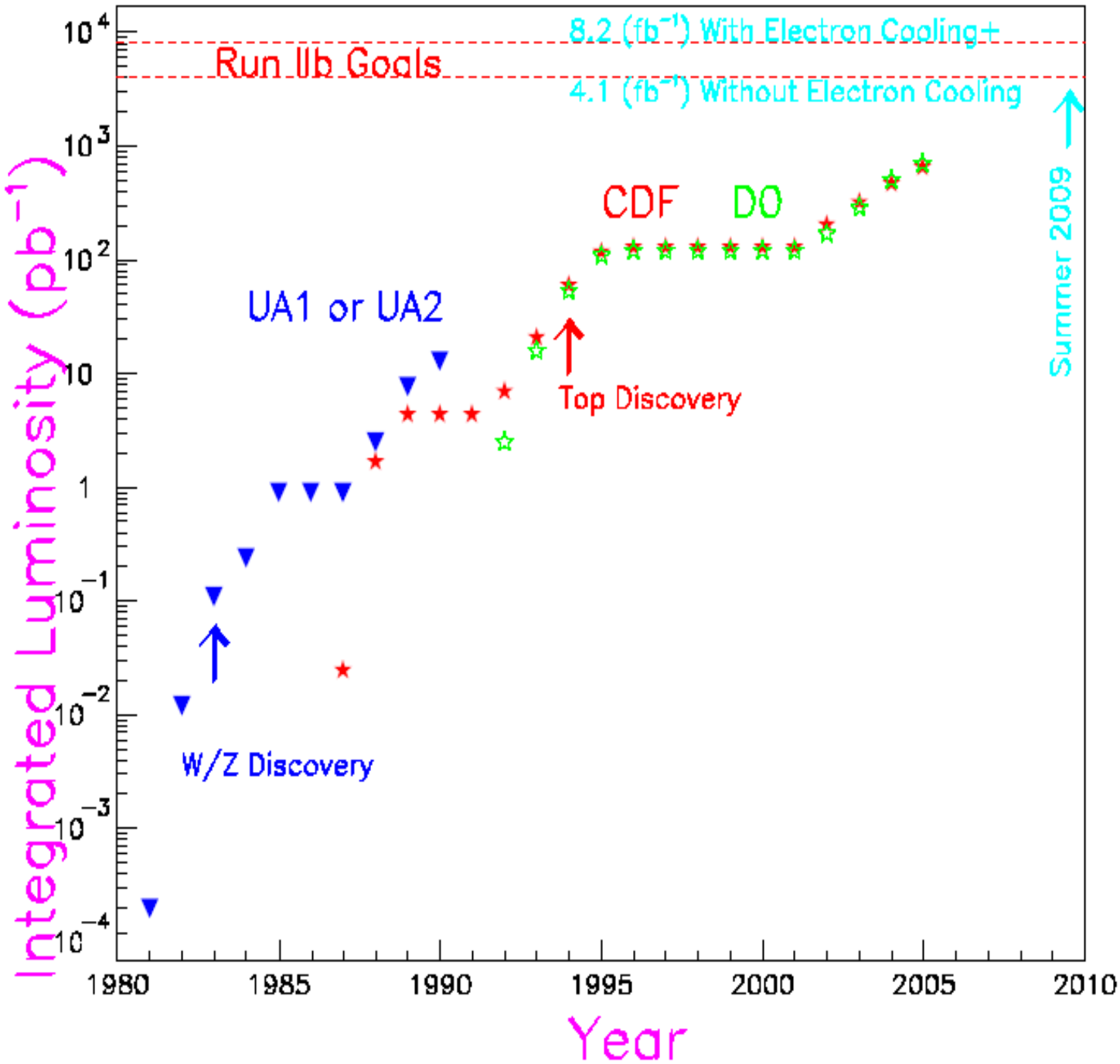
Experimental detection of single top quarks

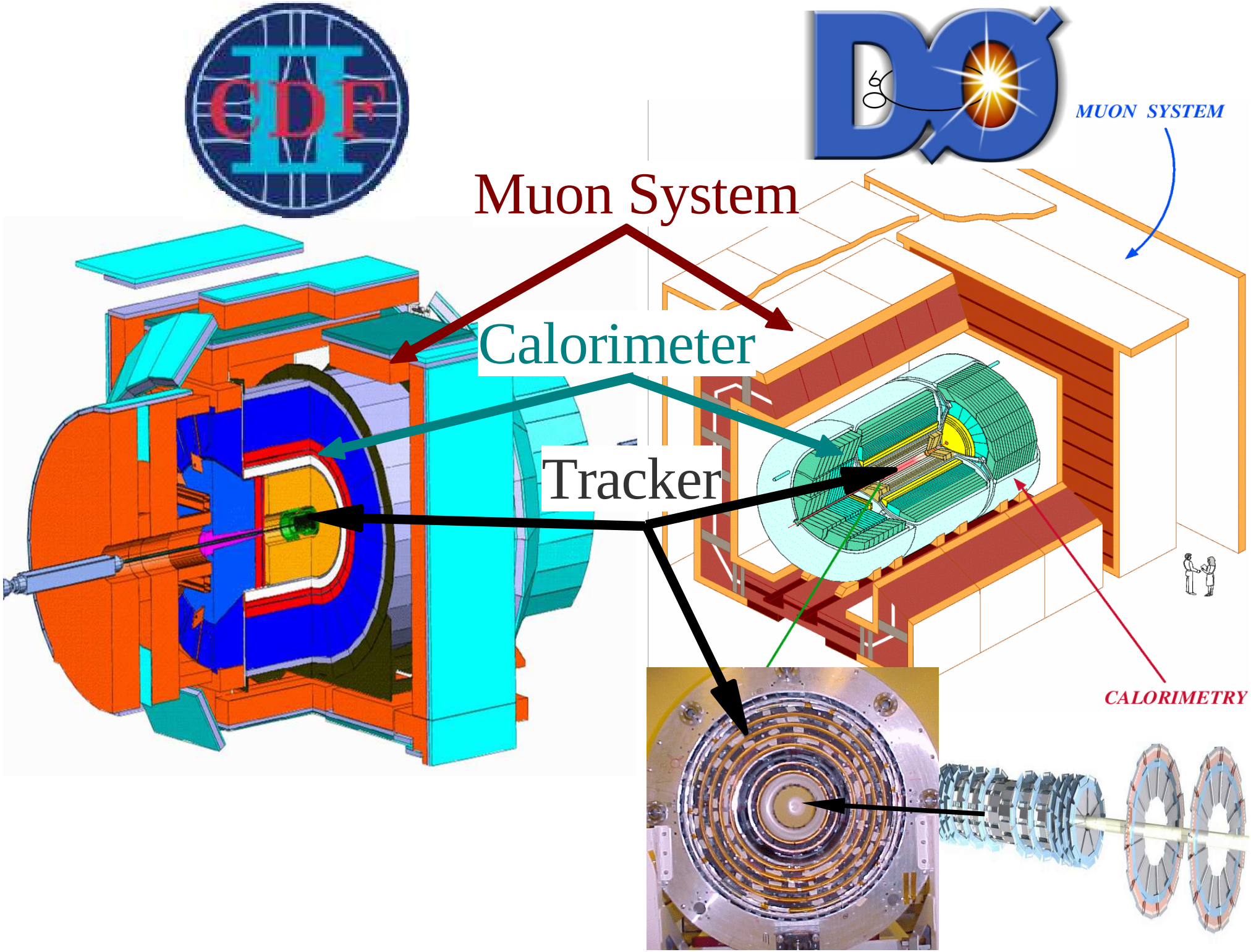
Experimental setup: Fermilab Tevatron in Run II

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***

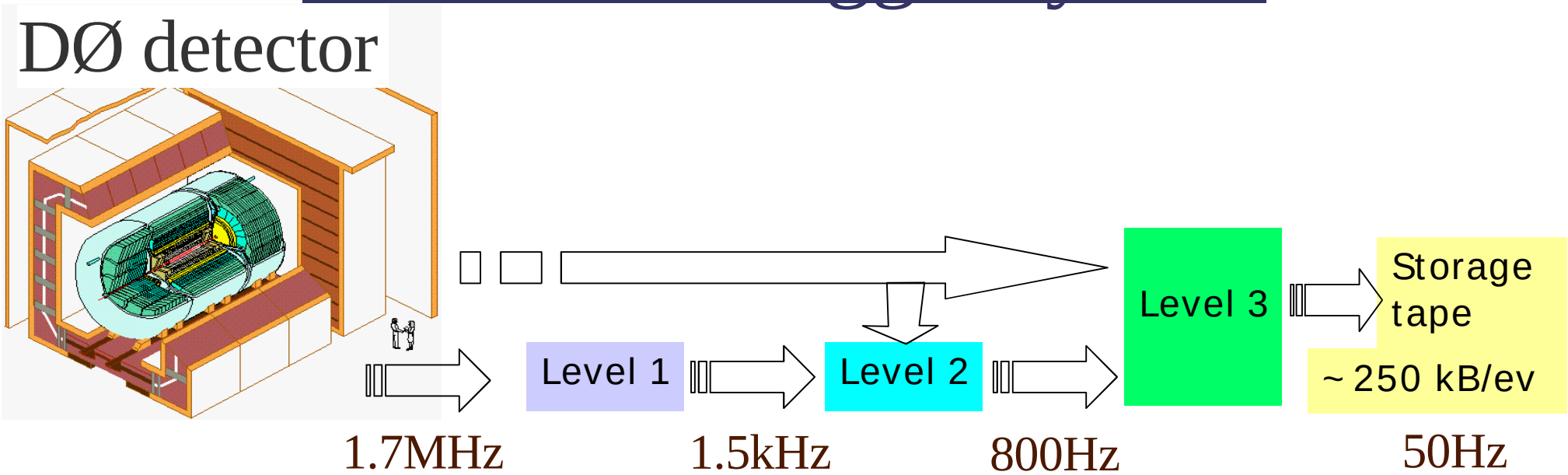


Hadron Collider Integrated Luminosity

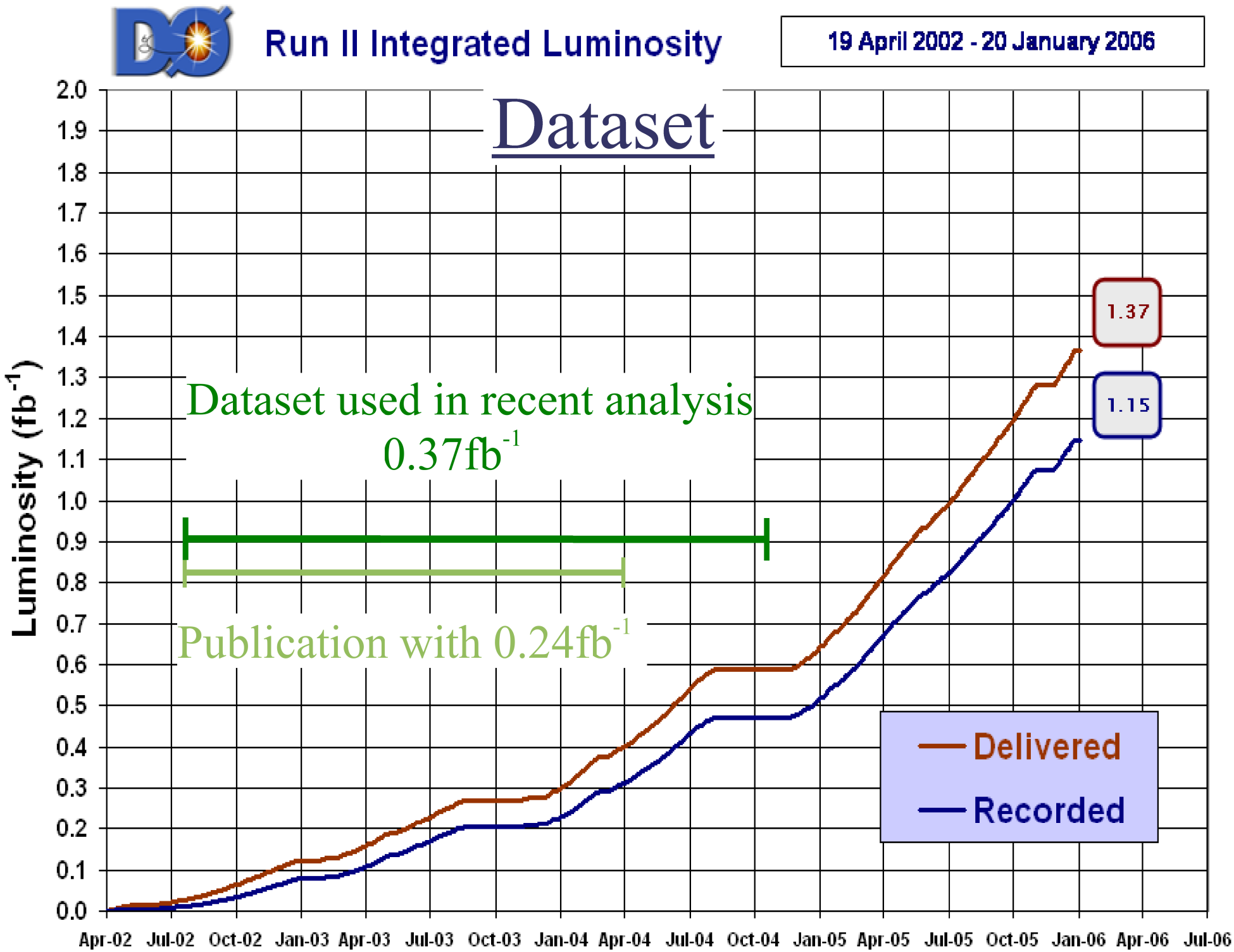



Muon System
Calorimeter
Tracker
MUON SYSTEM
CALORIMETRY

Three-level trigger system



- Level 1: identify basic hit patterns and measure energy
  - Hardware and FPGA firmware
- Level 2: reconstruct basic physics objects
  - Fast, simple processing on PCs interfaced to hardware
- Level 3: full detector reconstruction
  - Linux filter farm, fast version of offline reconstruction


Run II Integrated Luminosity
19 April 2002 - 20 January 2006
Dataset
Dataset used in recent analysis
0.37fb-1
Publication with 0.24fb-1
1.37
1.15
Delivered
Recorded
Luminosity (fb-1)
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
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
Jan-06
Apr-06
Jul-06

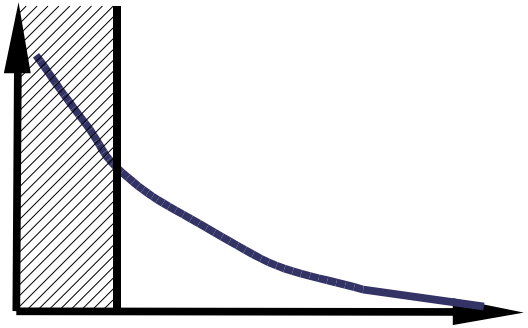
Current Results

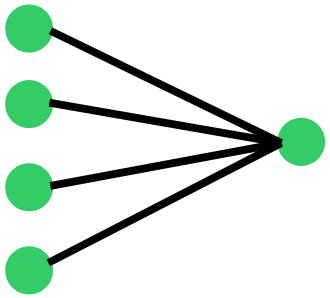
Precious Data!

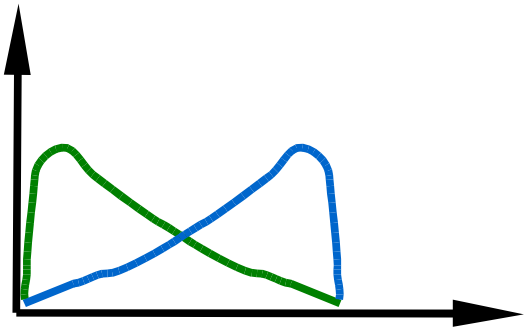
Analysis Outline

Goal:

Maximize Sensitivity

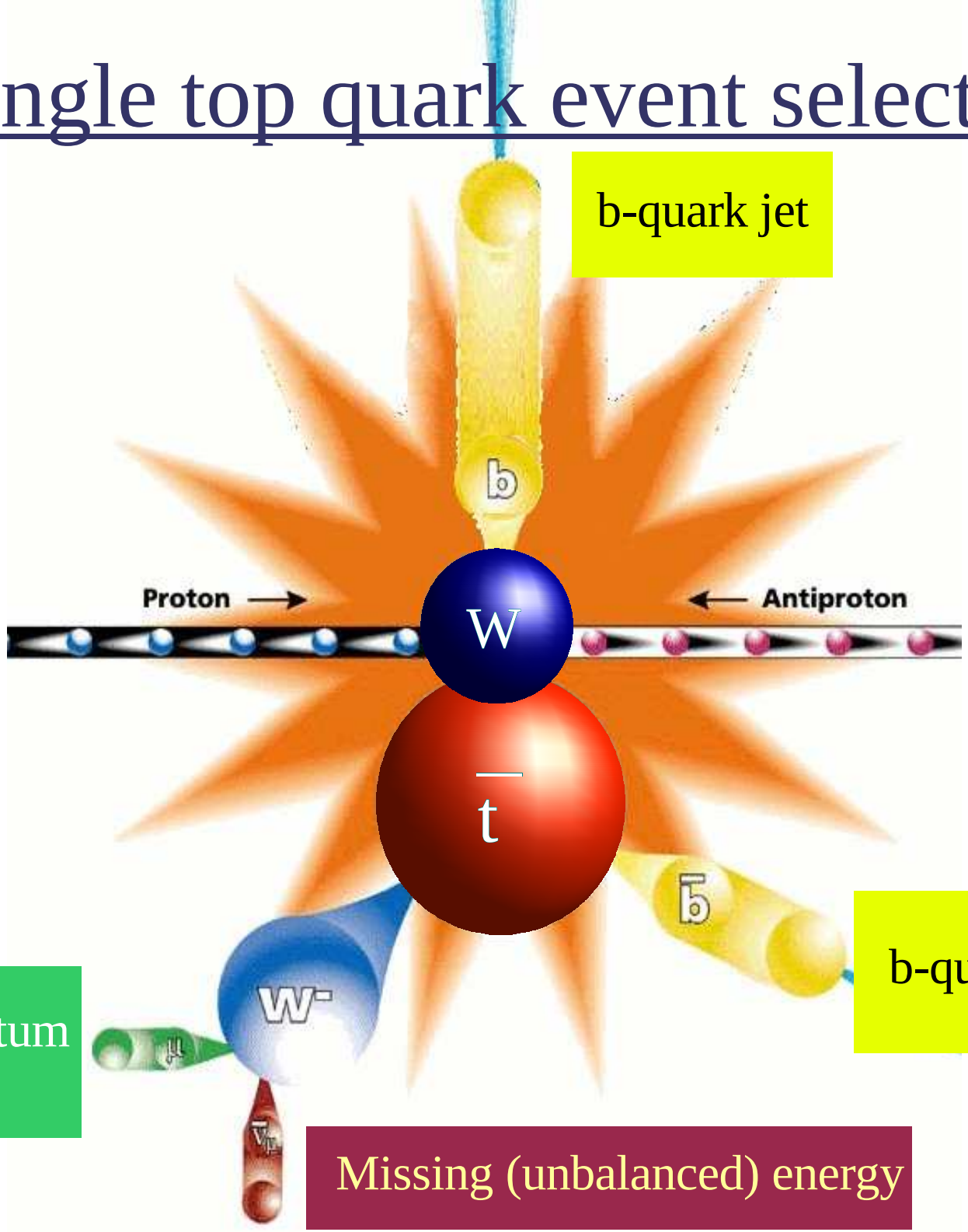






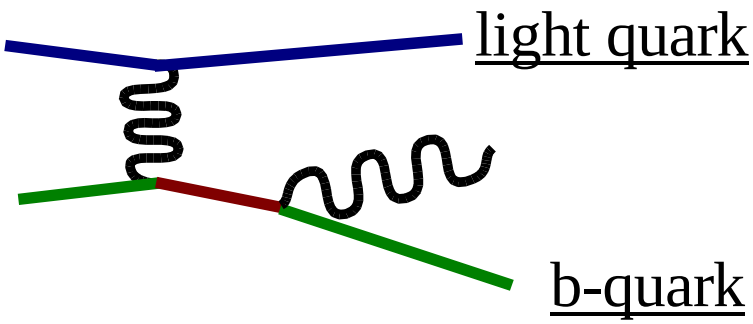
1. Event Selection
   - Select *W*-like events
   - Maximize acceptance
   - Model backgrounds
2. Event Analysis
   - Find discriminating variables
   - Cut/combine in multivariate analysis
3. Determine cross section
   - Event counting or binned likelihood
   - Separately for s-channel, t-channel, and combined

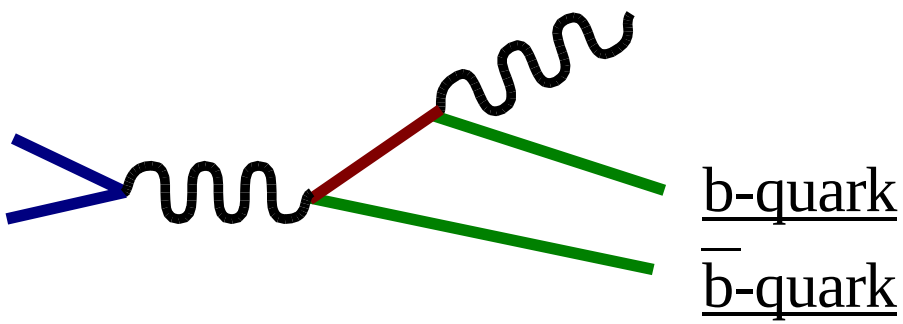
Single top quark event selection



Event Selection

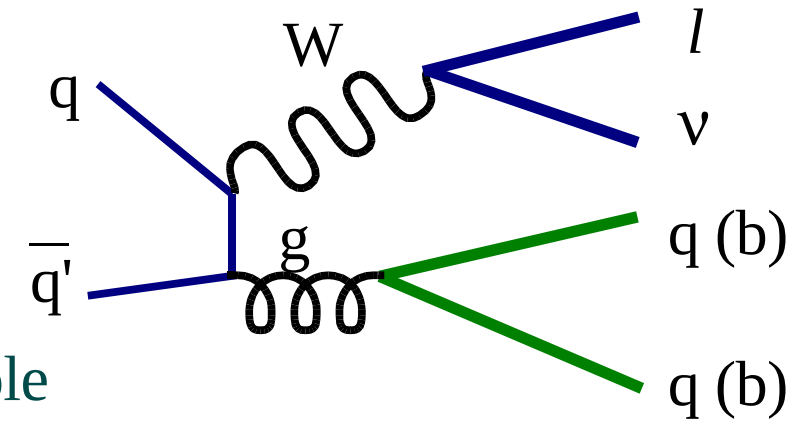
- Trigger:
  - Electron + ≥1 jets, muon + ≥1 jets
- Lepton:
  - 1 electron: $p_T > 15\text{GeV}$, $|\eta^{det}|<1.1$
  - 1 muon: $p_T > 15\text{GeV}$, $|\eta^{det}|<2.0$
- Neutrino: $\not{E}_T > 15\text{GeV}$
- Jets:
  - $p_T > 15\text{GeV}$, $|\eta^{det}|<3.4$, p_T (jet 1)> 25GeV $|\eta^{det}(\text{jet1})|<2.5$
  - $2 \leq n_{jets} \leq 4$
  - ≥ 1 b-tagged jet
- Reject mis-reconstructed events



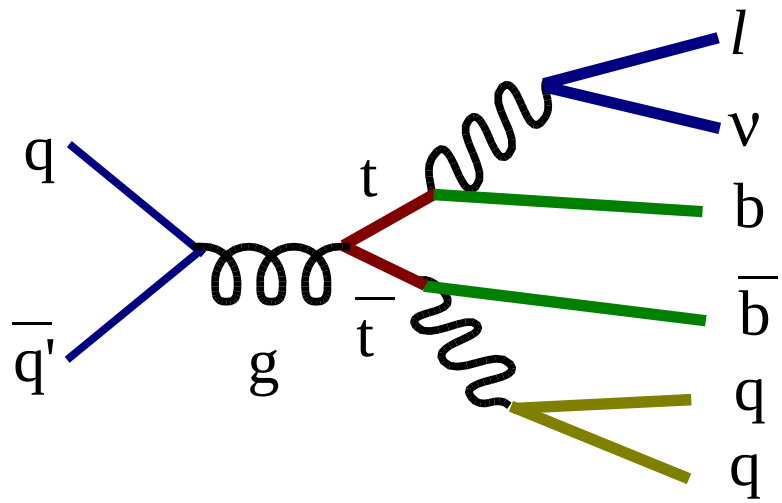


Background Modeling

- Based on data as much as possible
- W/Z+jets production
  - Estimated from MC/data
    - Distributions from MC
    - Normalization from pre-tagged sample
    - Flavor fractions from NLO

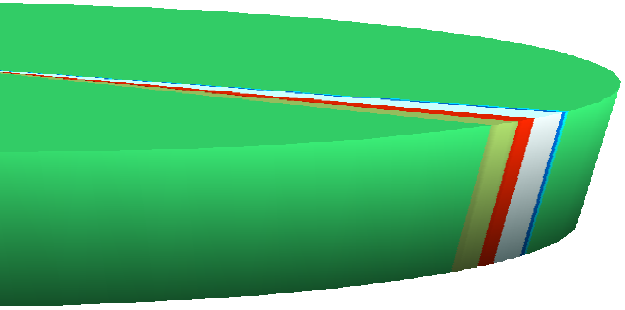


- Multijet events (misidentified lepton)
  - Estimated from data
- Top pair production
  - Estimated from MC
- Diboson (WZ, WW)
  - Estimated from MC

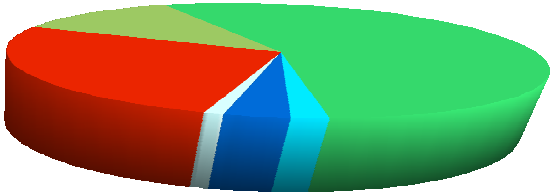


Single top quark events in data (230pb^{-1})

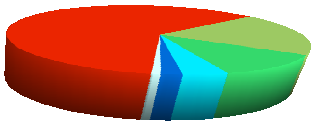
All:
10,000 events



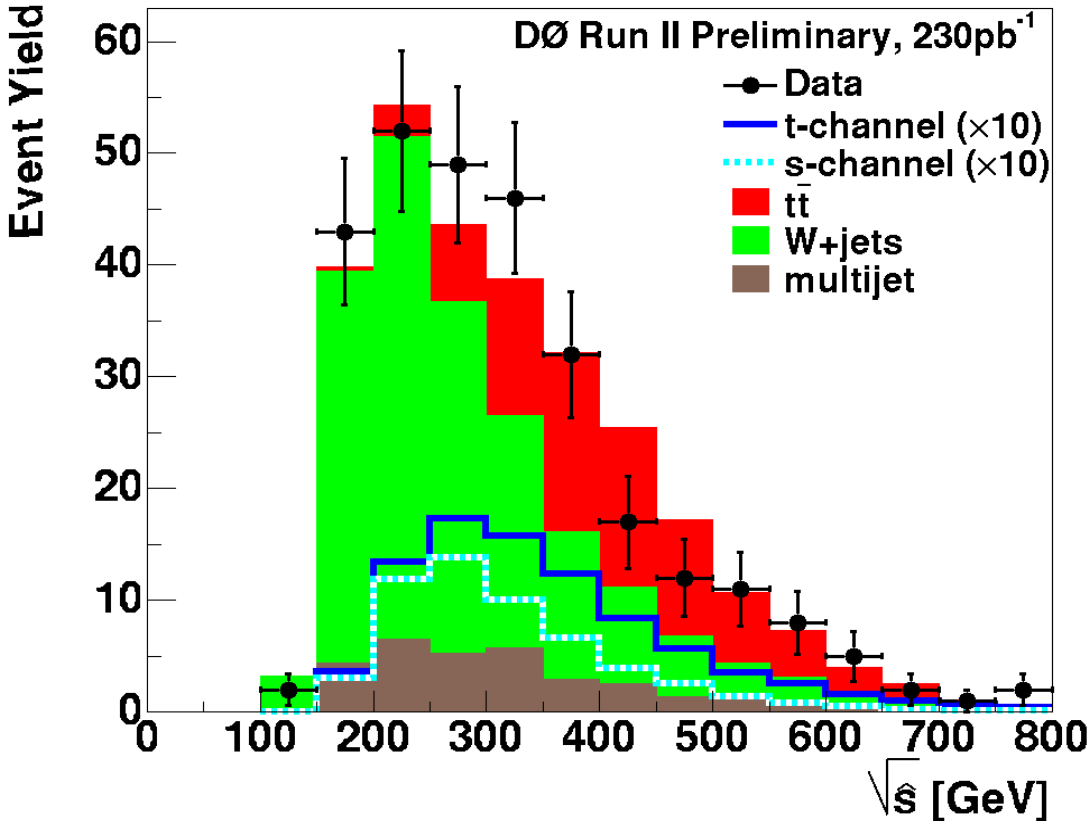
=1 b-tag:
367 events



=2 b-tags:
76 events



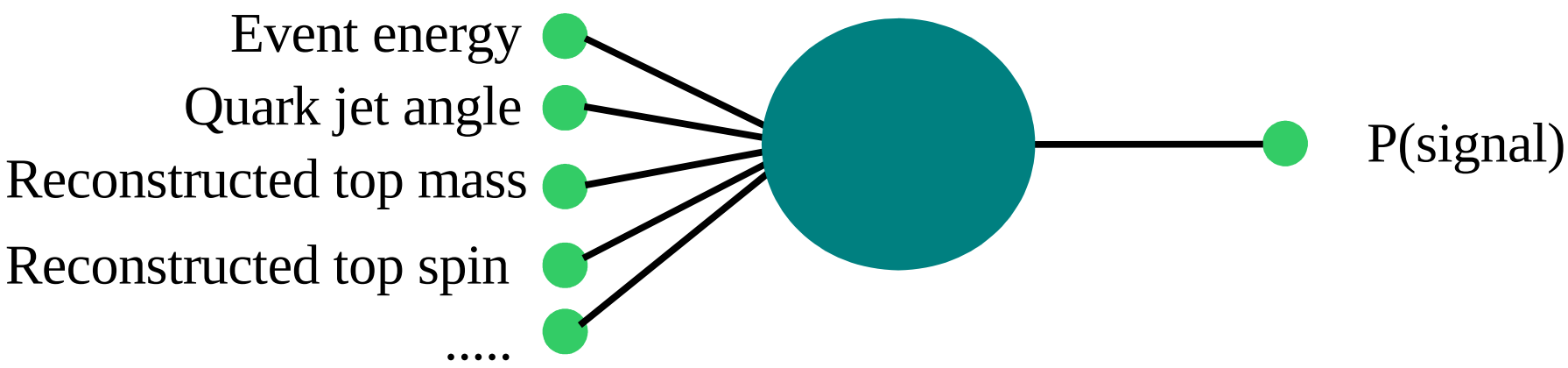
Top quark pairs
W+jets and
other non-top
Single top



Separating Signal from Backgrounds

- Optimized event analysis

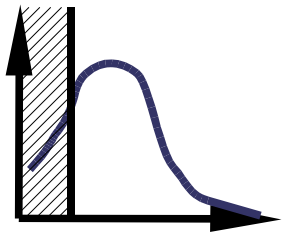
Input:	Method:	Output:
discriminating variables	multivariate analysis	signal probability



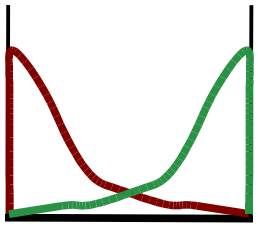
Event Analysis

- Advanced analysis techniques

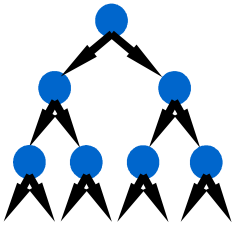
Cut-Based



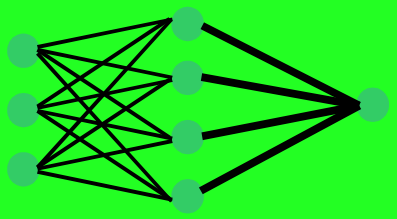
Likelihoods



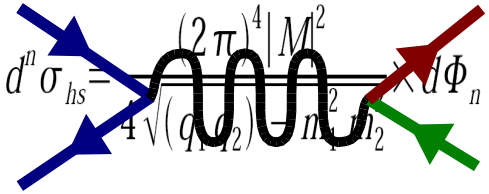
Decision Trees



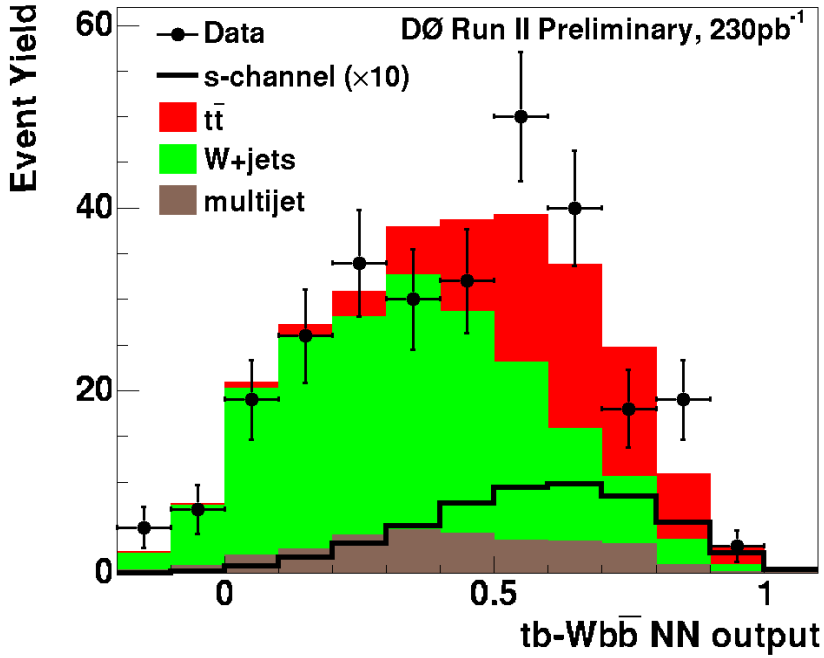
Neural Networks

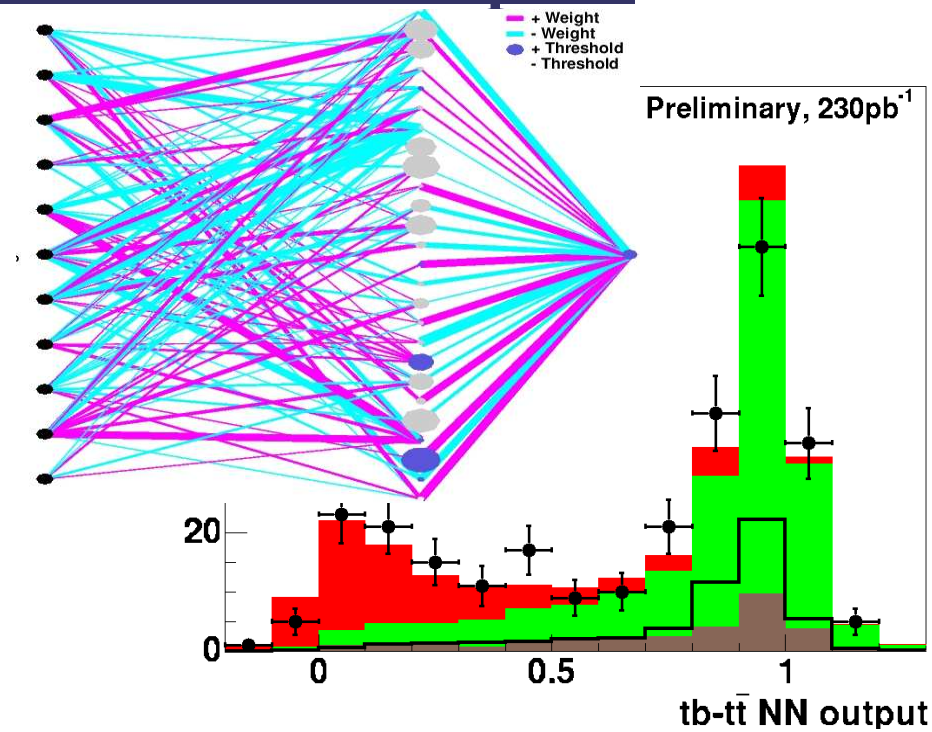


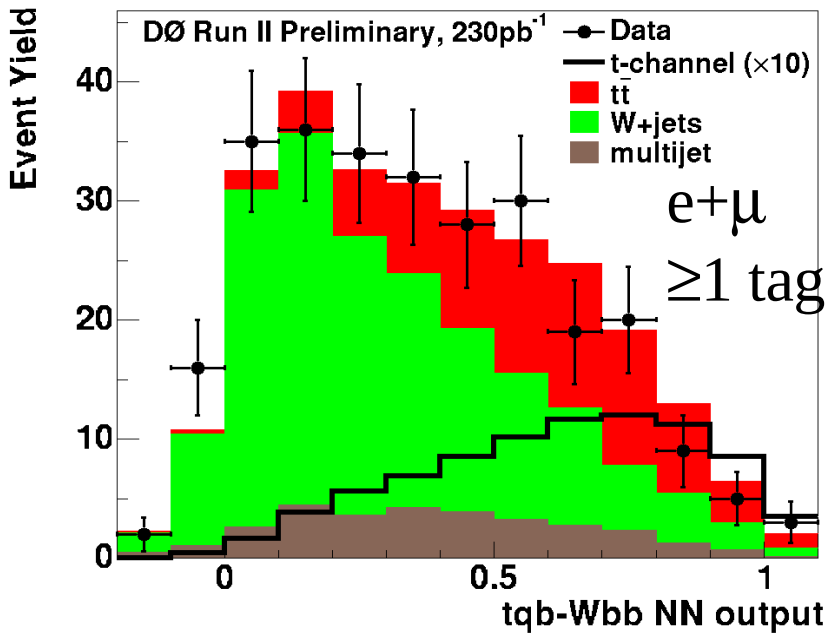
Matrix Elements

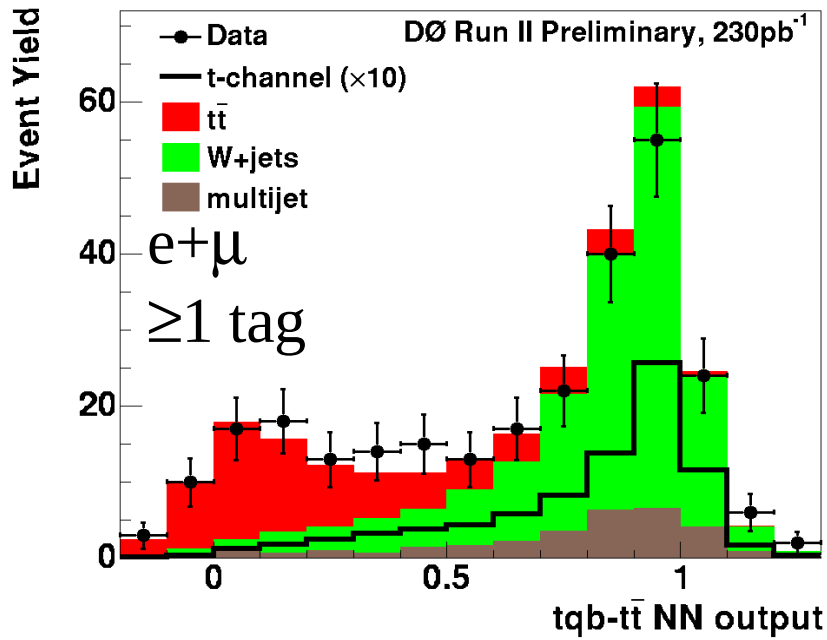


Neural Network Output

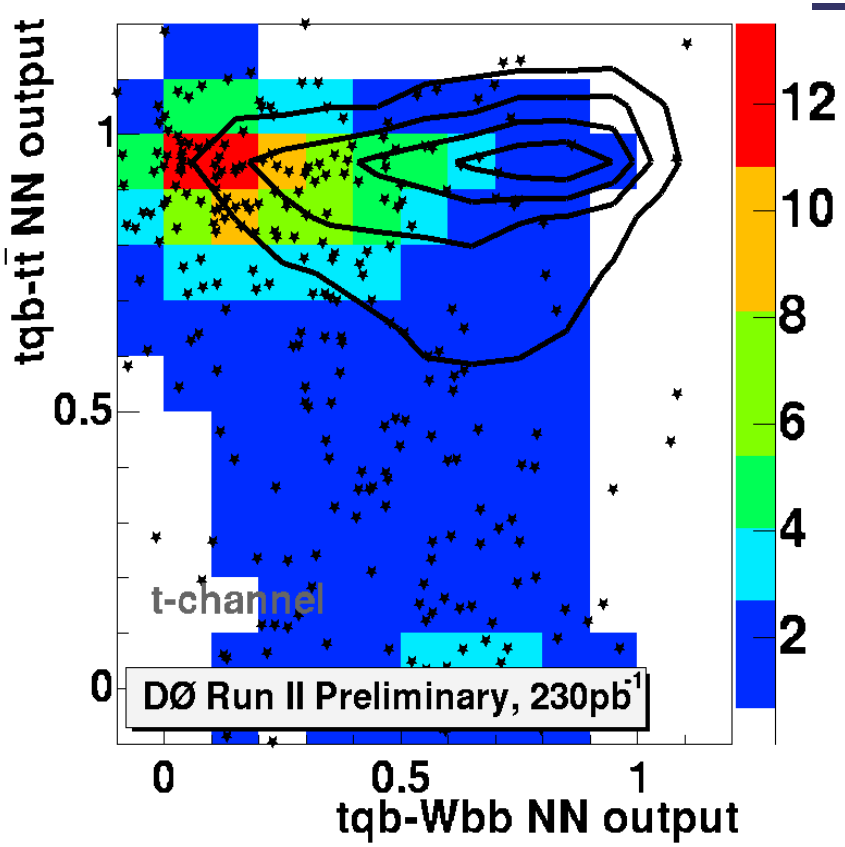




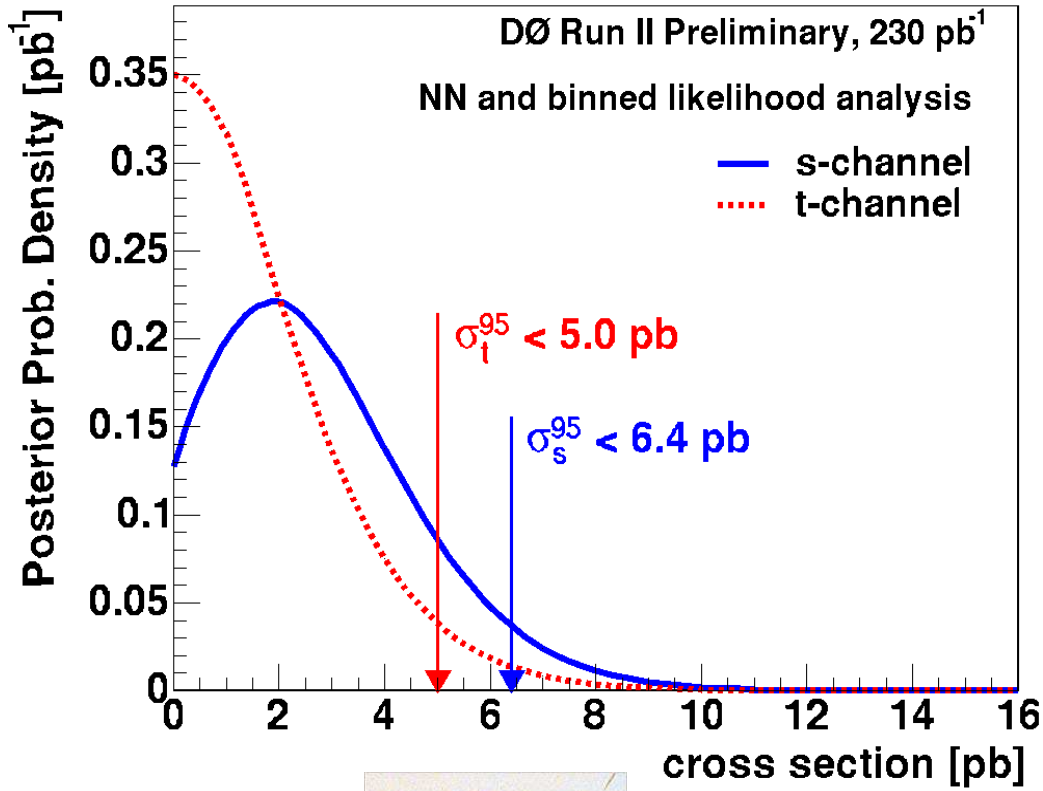




Result



- Bayesian statistical analysis
- Systematic uncertainty ~20%



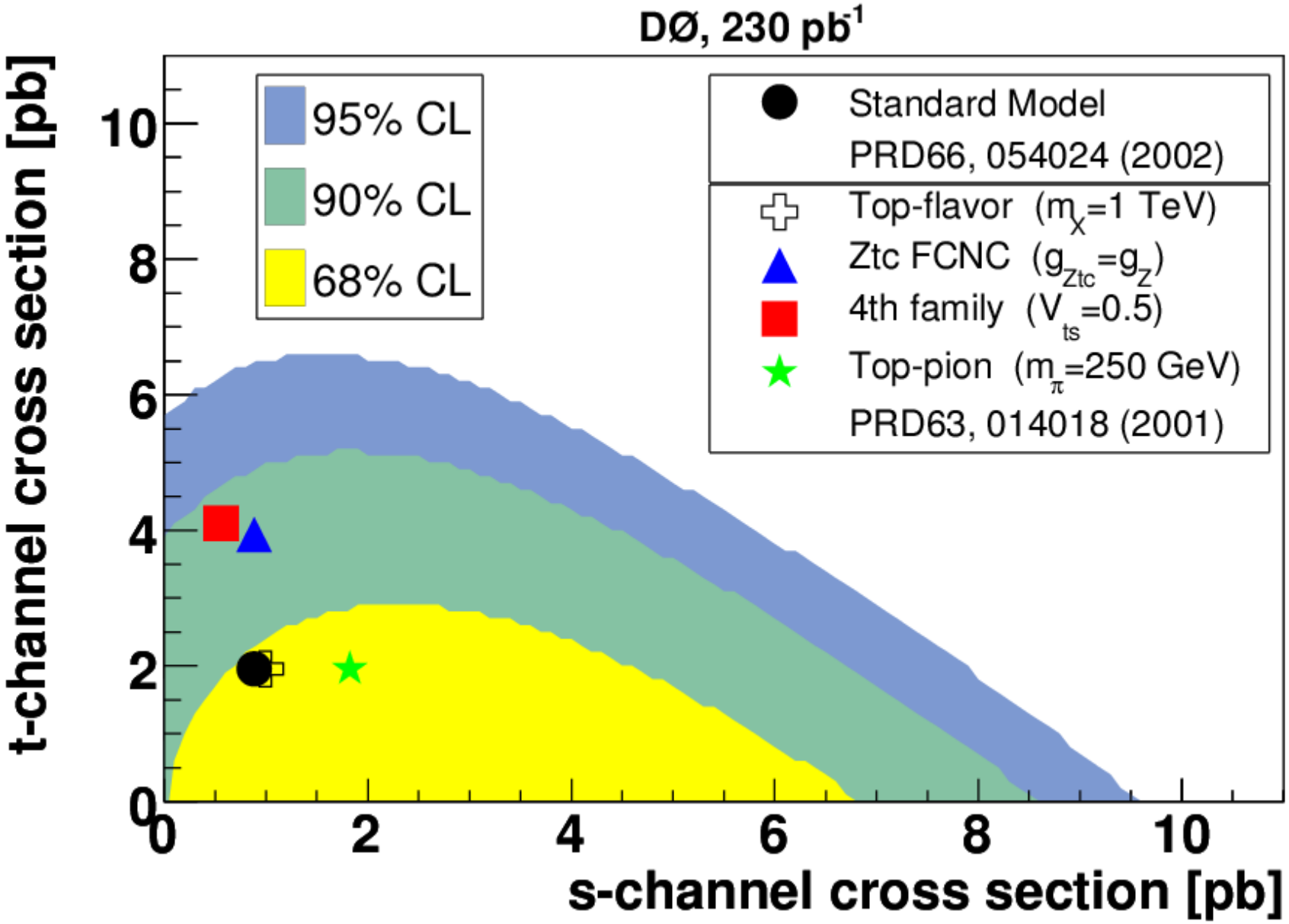
Expected/Observed limit:

σ_s < 4.5 / 6.4 pb

σ_t < 5.8 / 5.0 pb

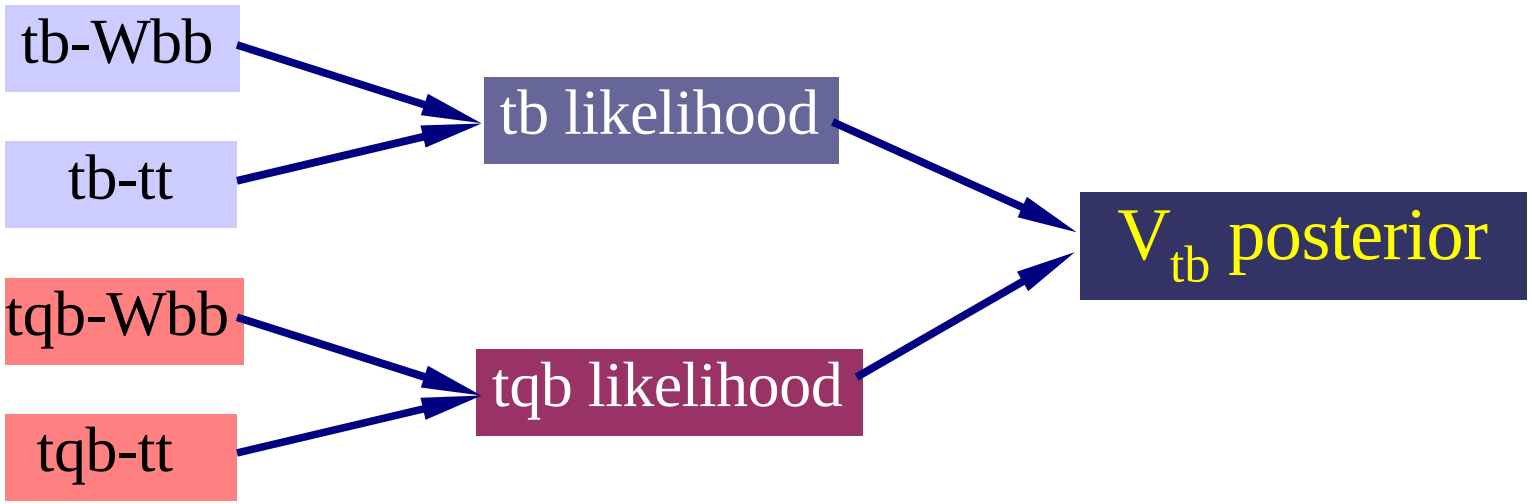
Published in PLB 622, 265 (2005)

Sensitivity to non-SM Single Top



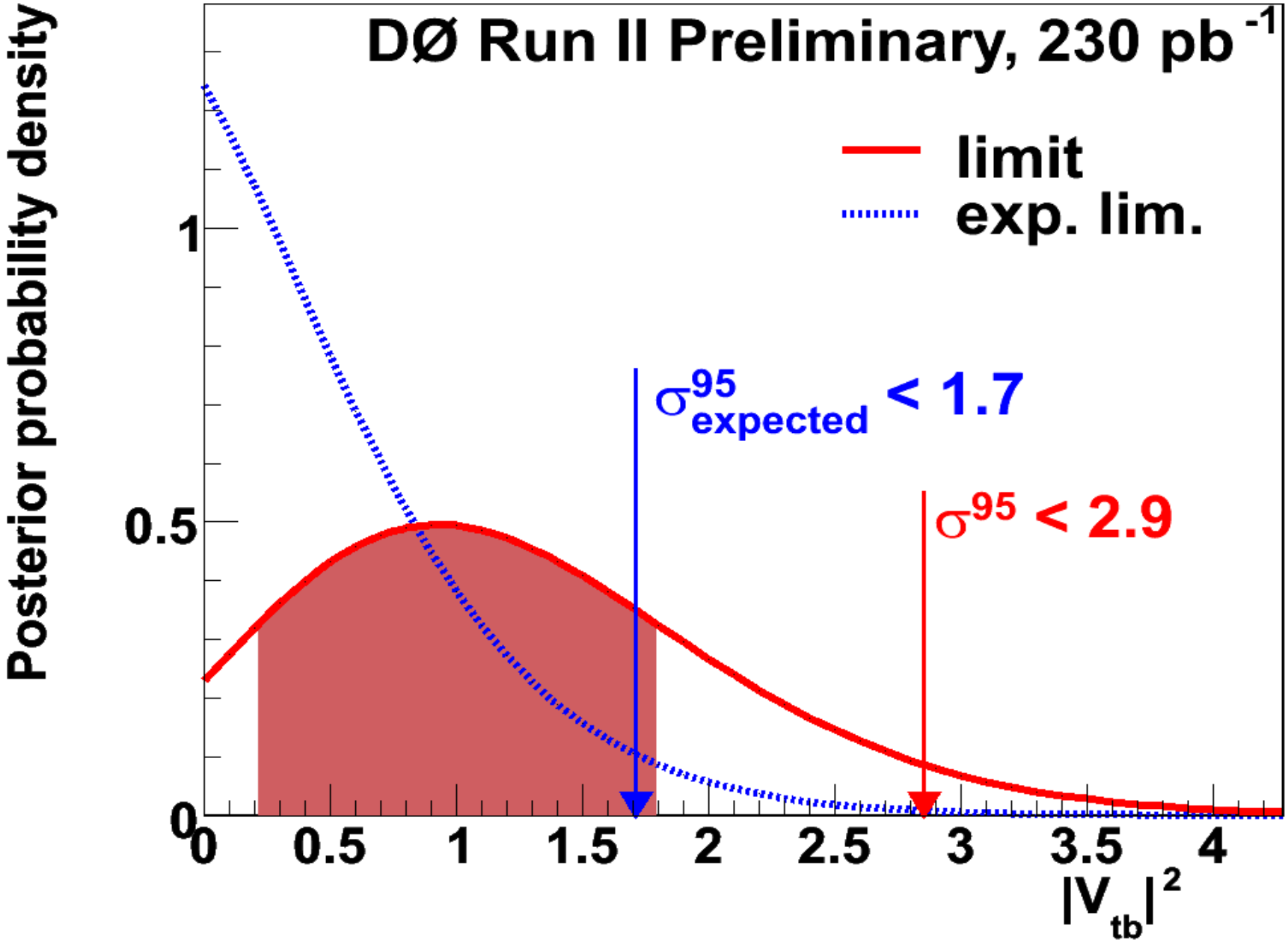
V_{tb} Coupling Limit

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



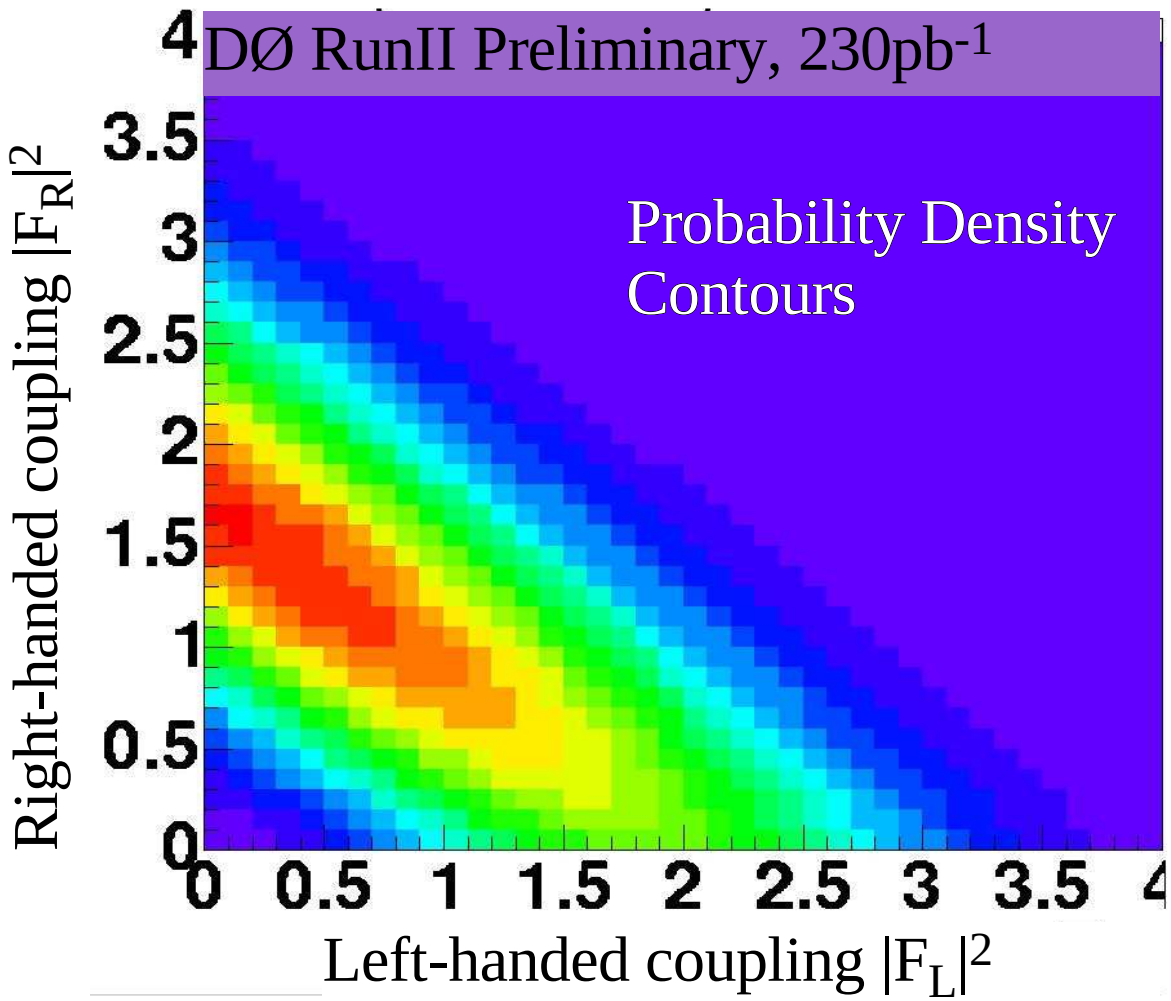
  - Need to assume SM ratio of cross sections

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

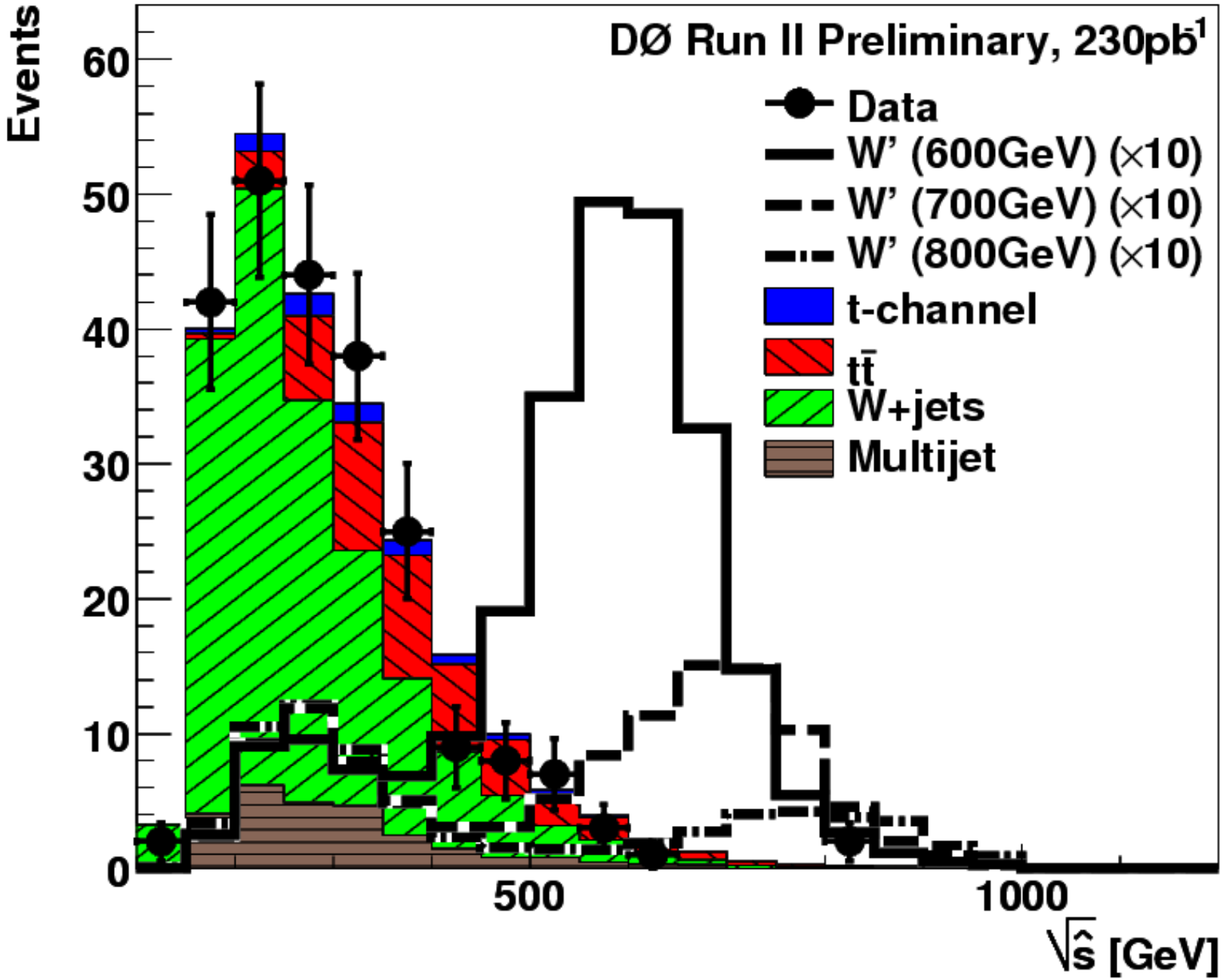


Left-handed or right-handed *W* coupling?

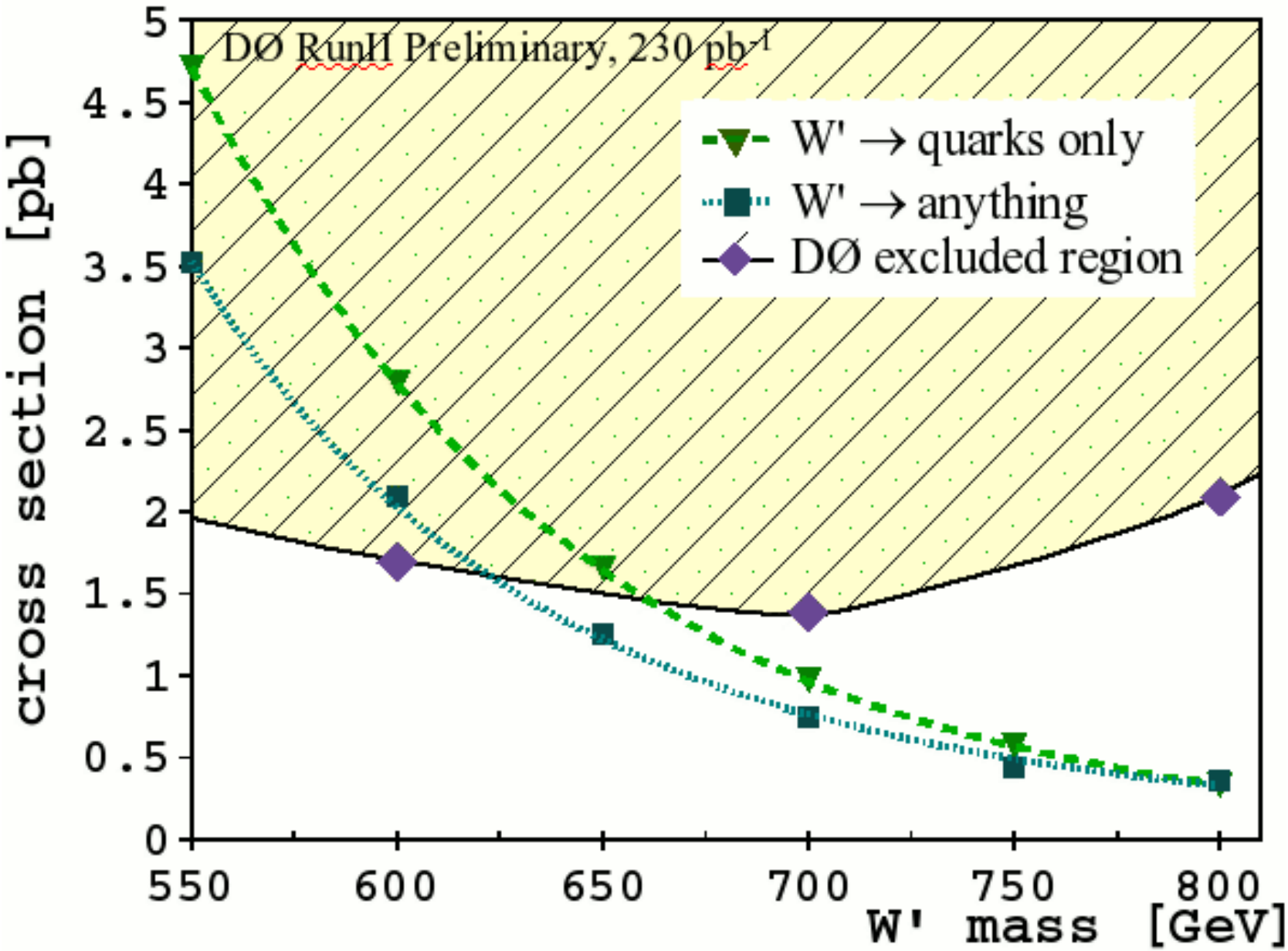
- Extremely preliminary
  - No systematic uncertainties, no full MC simulation



Extra heavy boson *W'*?



W' mass limit

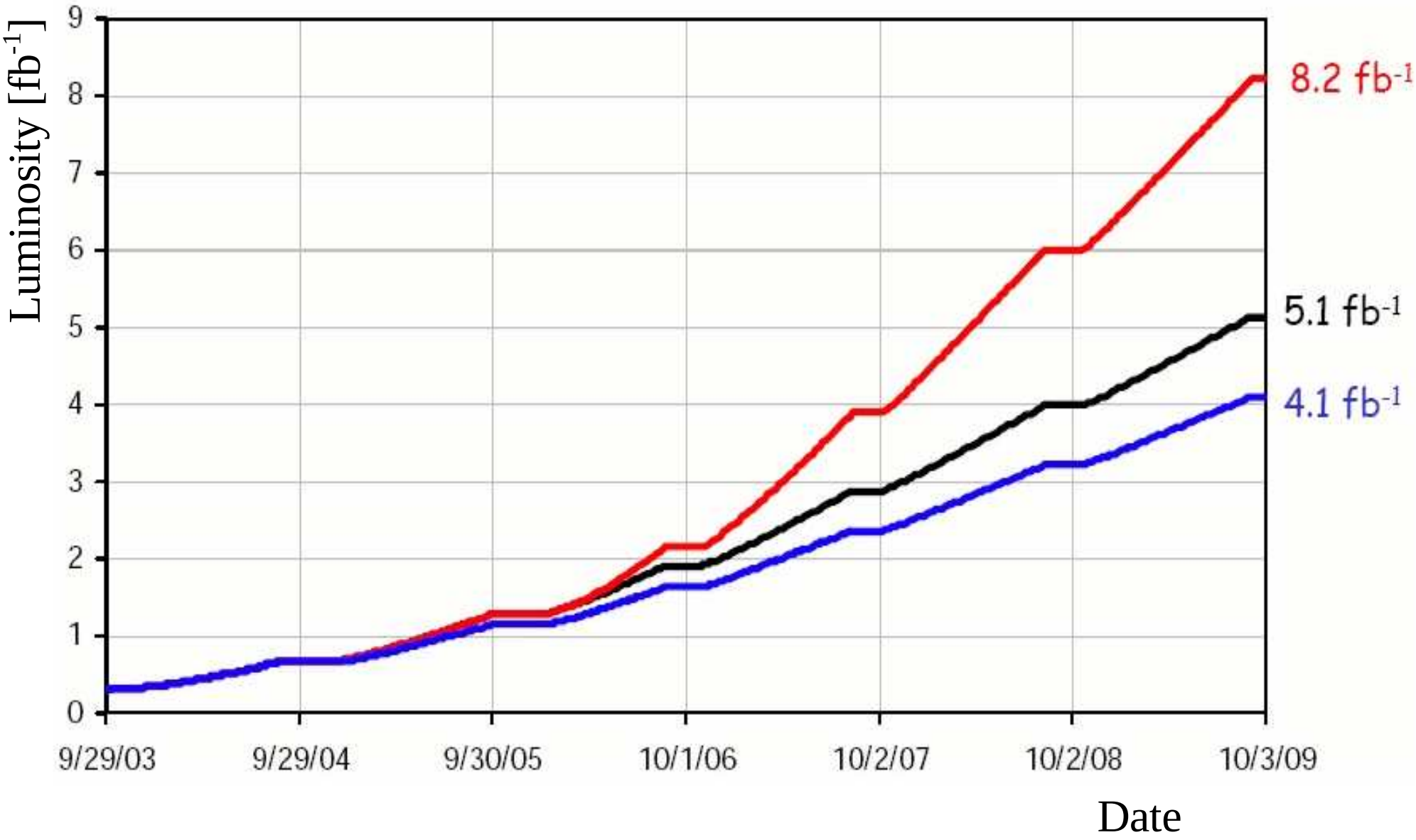

DØ RunII Preliminary, 230 pb-1
W' → quarks only
W' → anything
DØ excluded region
cross section [pb]
W' mass [GeV]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
550
600
650
700
750
800

Outlook

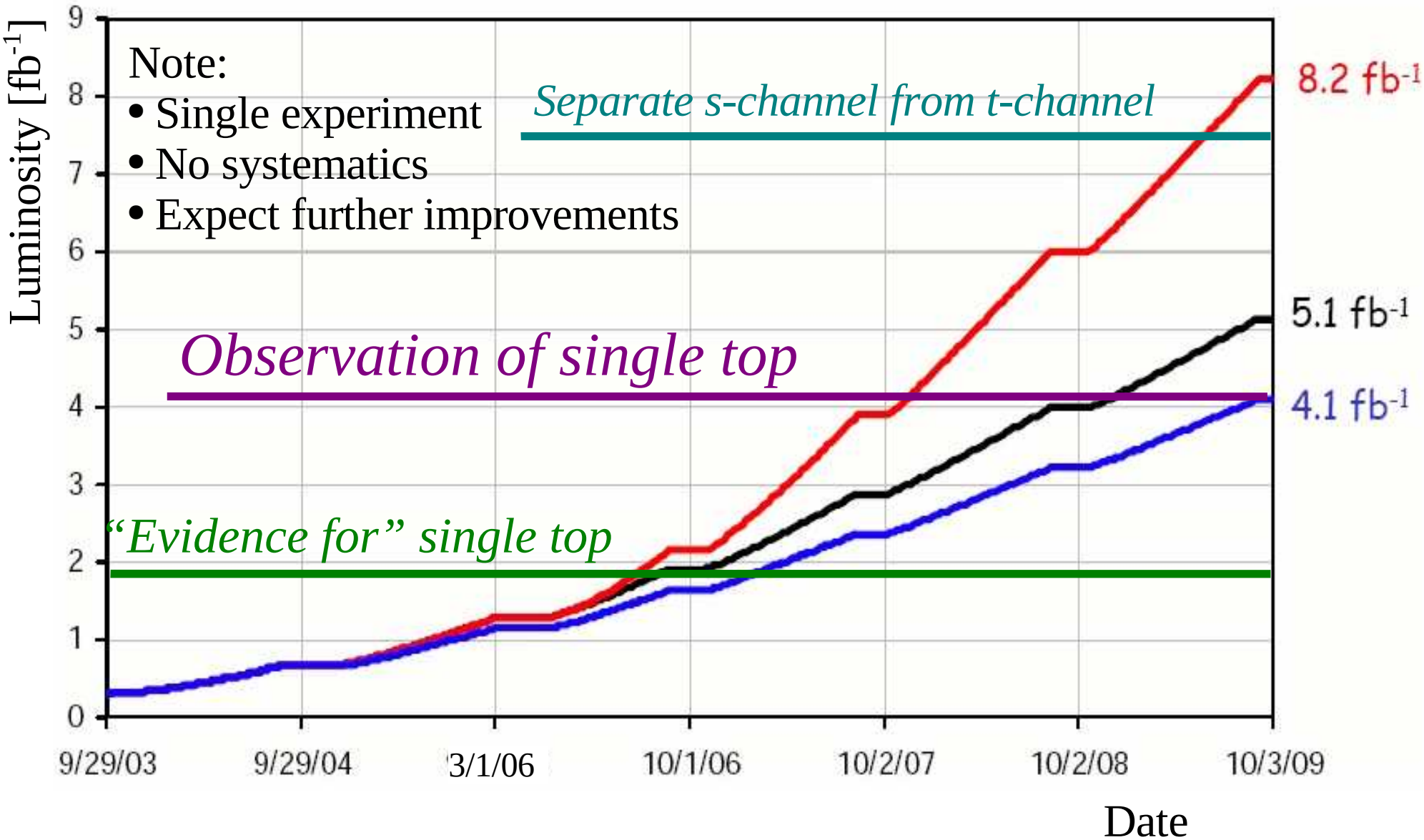
How will we find out more?

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

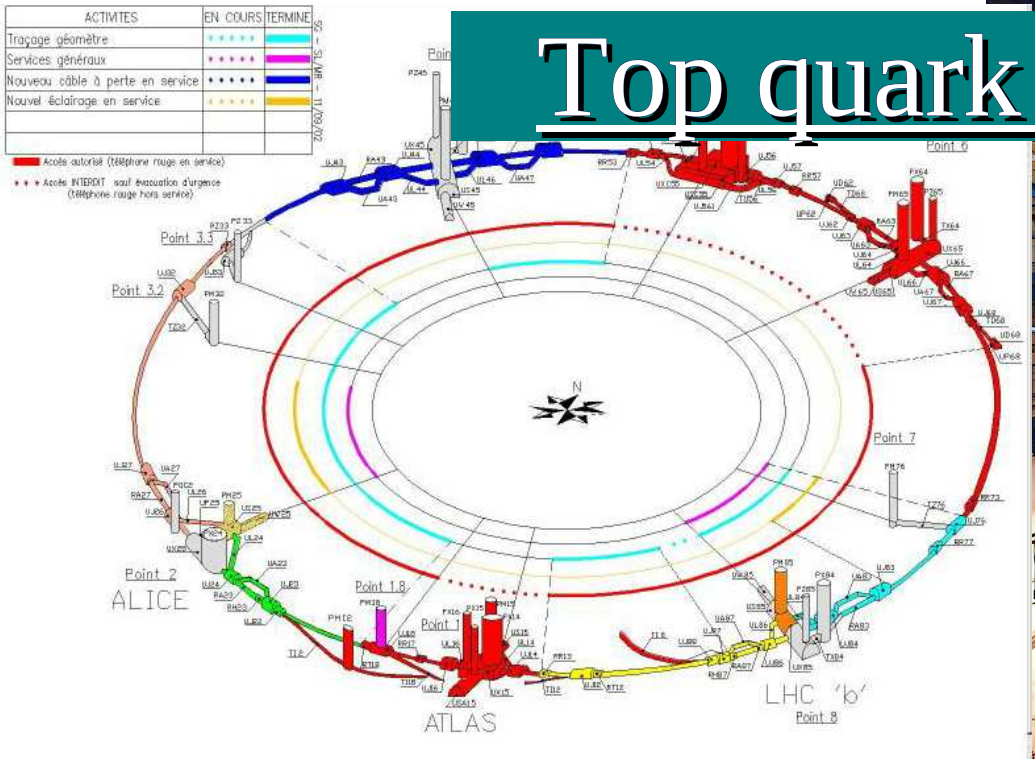
Tevatron luminosity projection

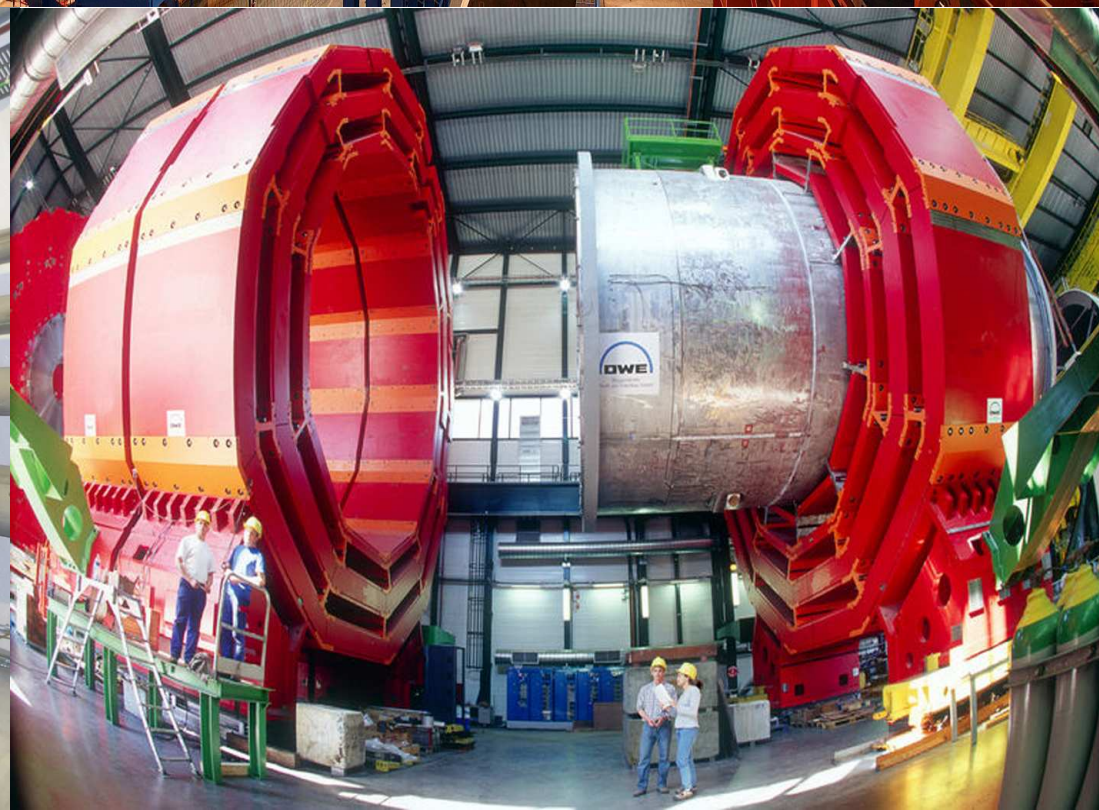


Tevatron luminosity projection

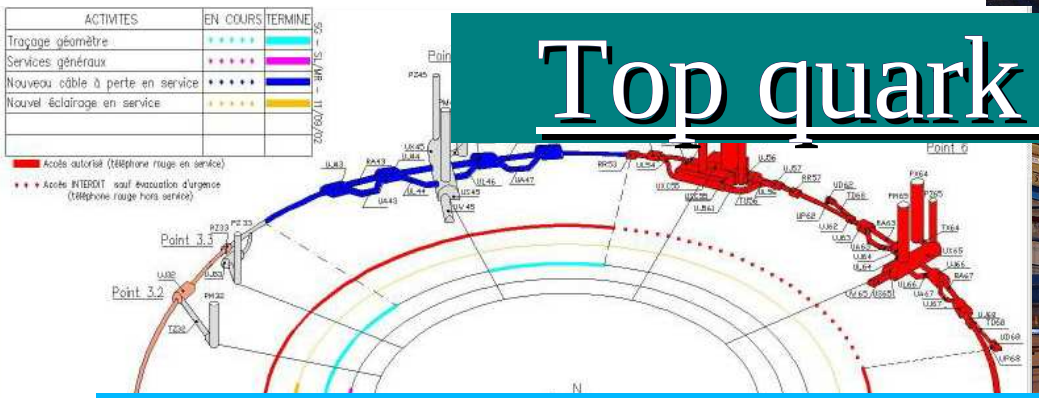


Top quark future: LHC

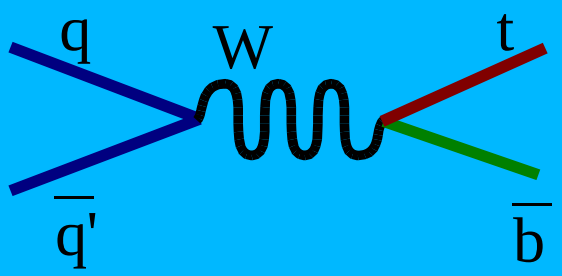




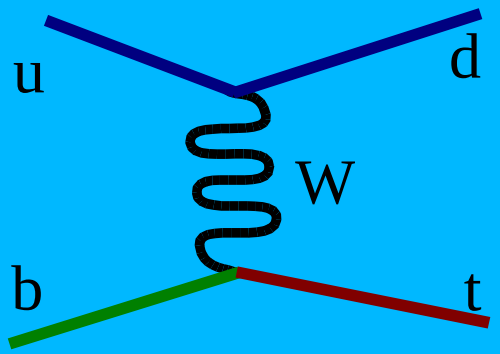
Top quark future: LHC



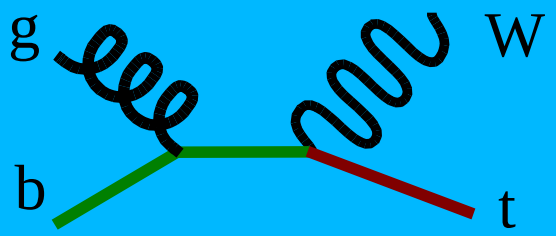
s-channel: 10.7pb



t-channel: 247pb



associated production: 68pb

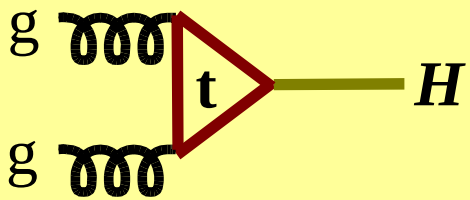


- Observe three single top production modes separately
  - t-channel: easy s-channel and assoc. prod: harder
- Observe new physics *(if it can be seen)*
- Measure V_{tb} to few %
- Study spin correlations

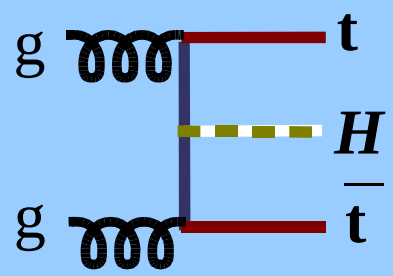
Top as the gateway to Higgs

Neutral Higgs

Higgs production mechanism at the LHC:



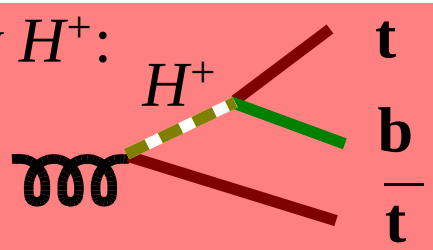
Top-Higgs Yukawa coupling measurement



Discover with ~30fb^{-1}

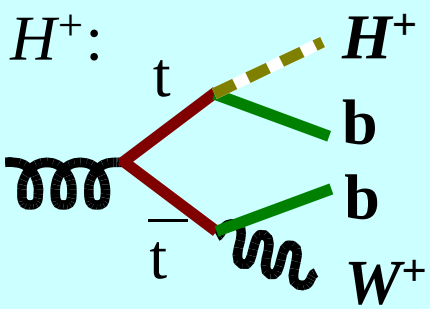
Supersymmetry: Charged Higgs

Heavy H^+:



Discover with ~30fb^{-1}

Light H^+:



Discover with ~30fb^{-1}

Conclusions

- Electroweak top quark production is a key observation for the Tevatron
- Run II single top analysis going well
  - World's best limits are from DØ: $\sigma_s < 5.0$ pb, $\sigma_t < 4.4$ pb
  - Experiments will be close to "evidence for" this summer
  - Already reaching sensitivity to new physics
- Understanding top is a key to understanding Higgs or other new physics
  - Study in detail at future colliders

Dawn of Discoveries

Backup Slides

Summary

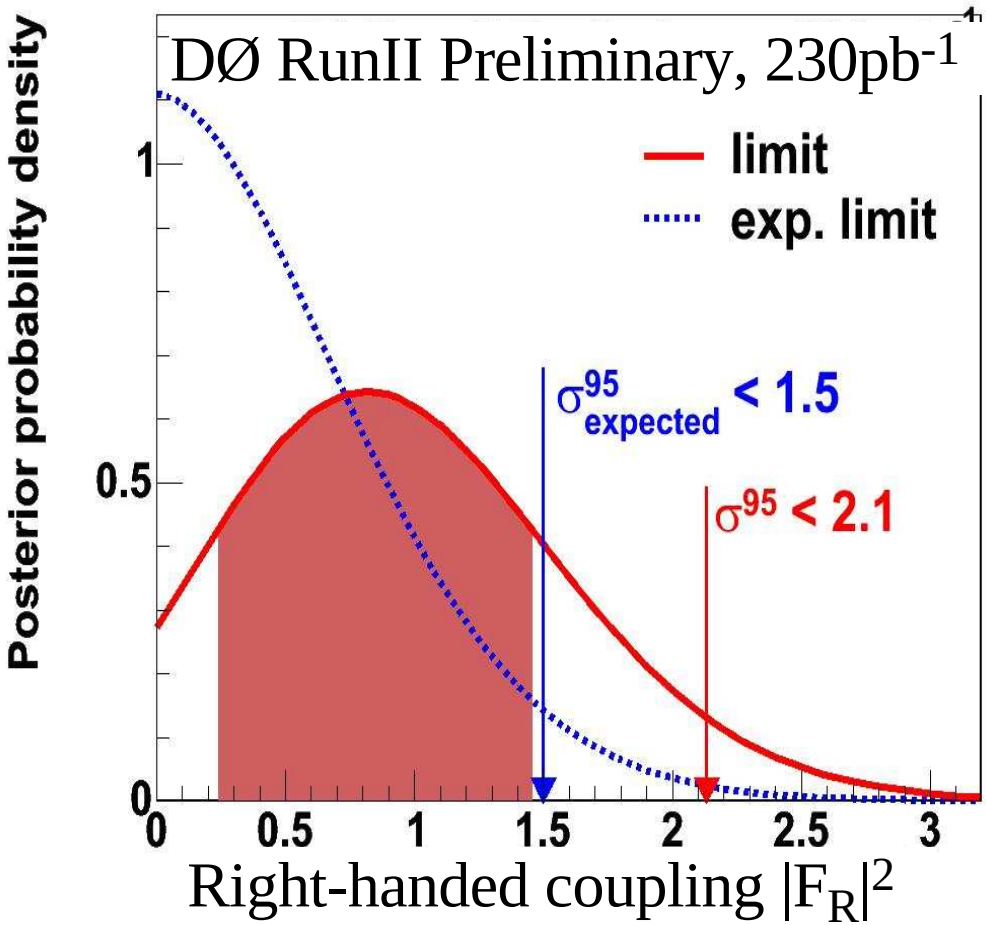
	s-channel	t-channel
NLO cross section	0.88 pb	1.98 pb

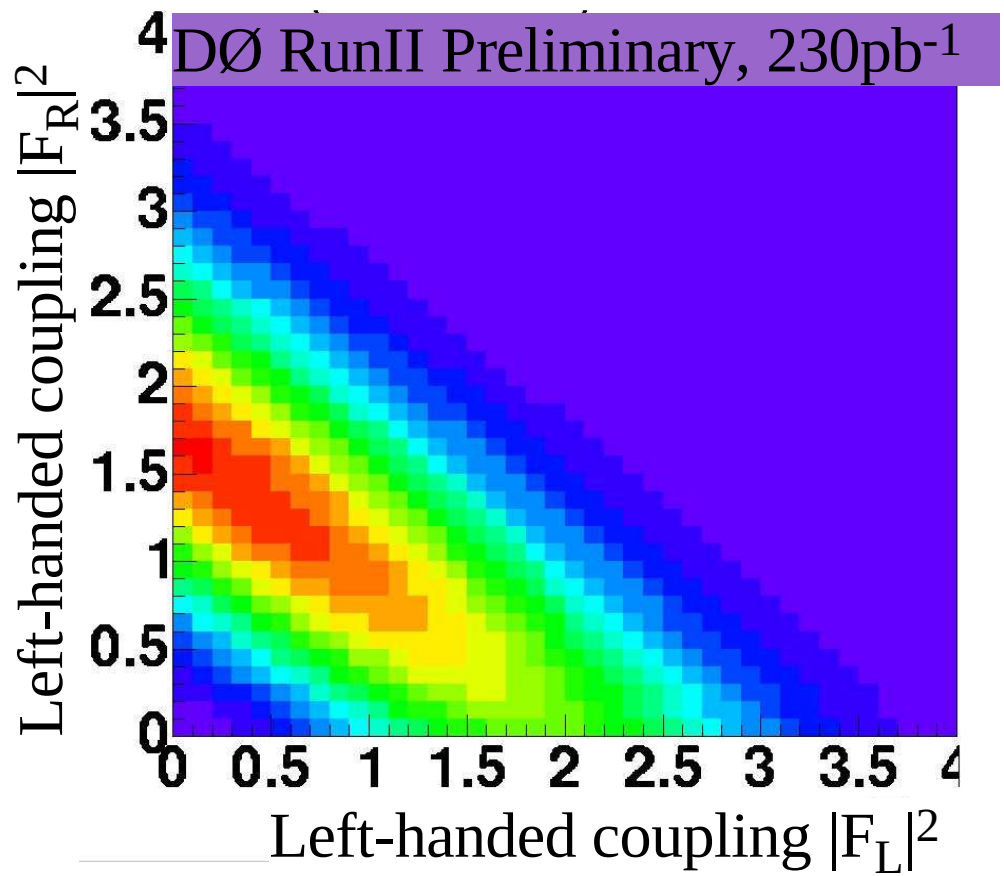
95% CL upper cross section limits [pb]

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

Left-handed or right-handed W coupling?

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





2005 2006 2007 2008 2010 2013 20??

First top results

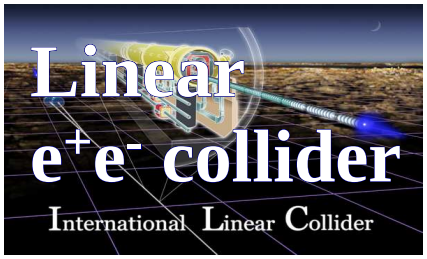
Single top observation

Top mass ± 1.5GeV

First top results

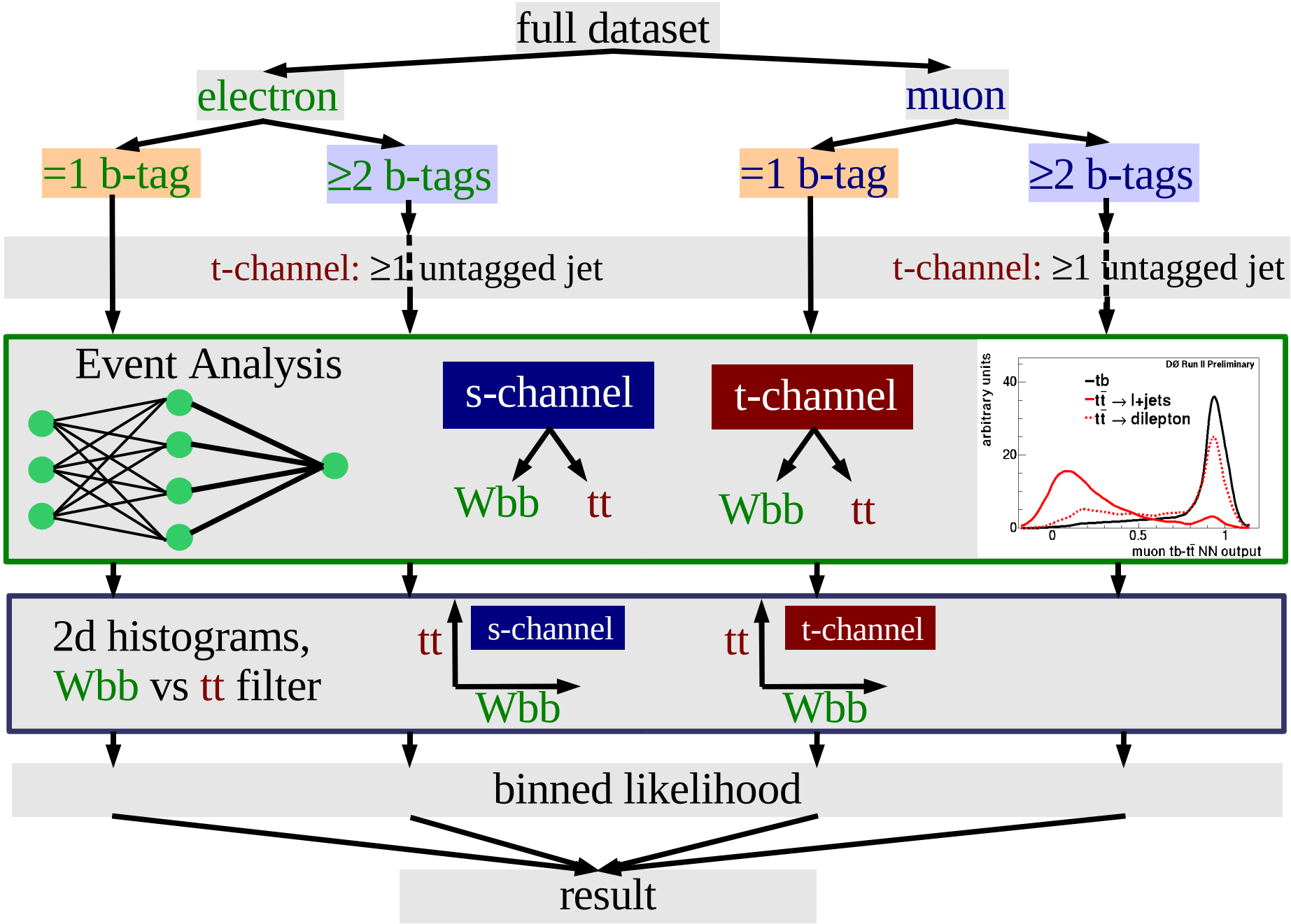
Single top, top mass

New top couplings



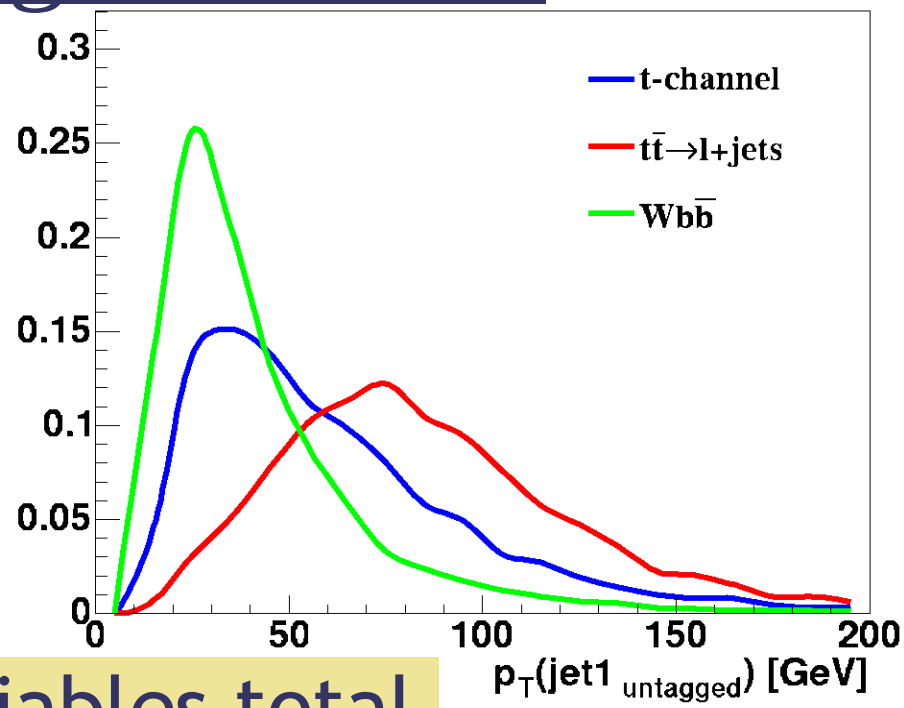
Precision top measurements

Analysis Strategy

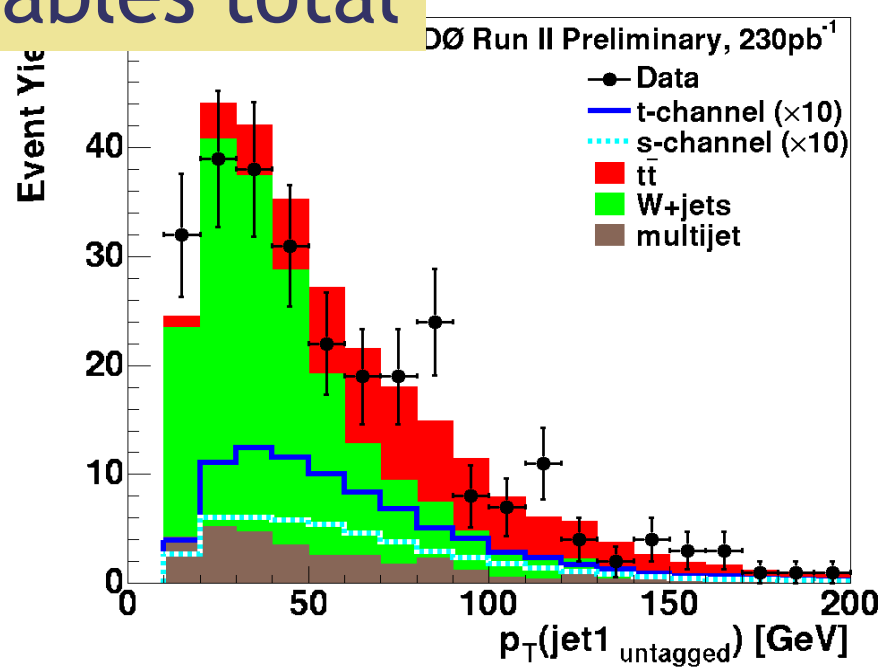


Discriminating Variables

- 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
  - Sphericity, aplanarity

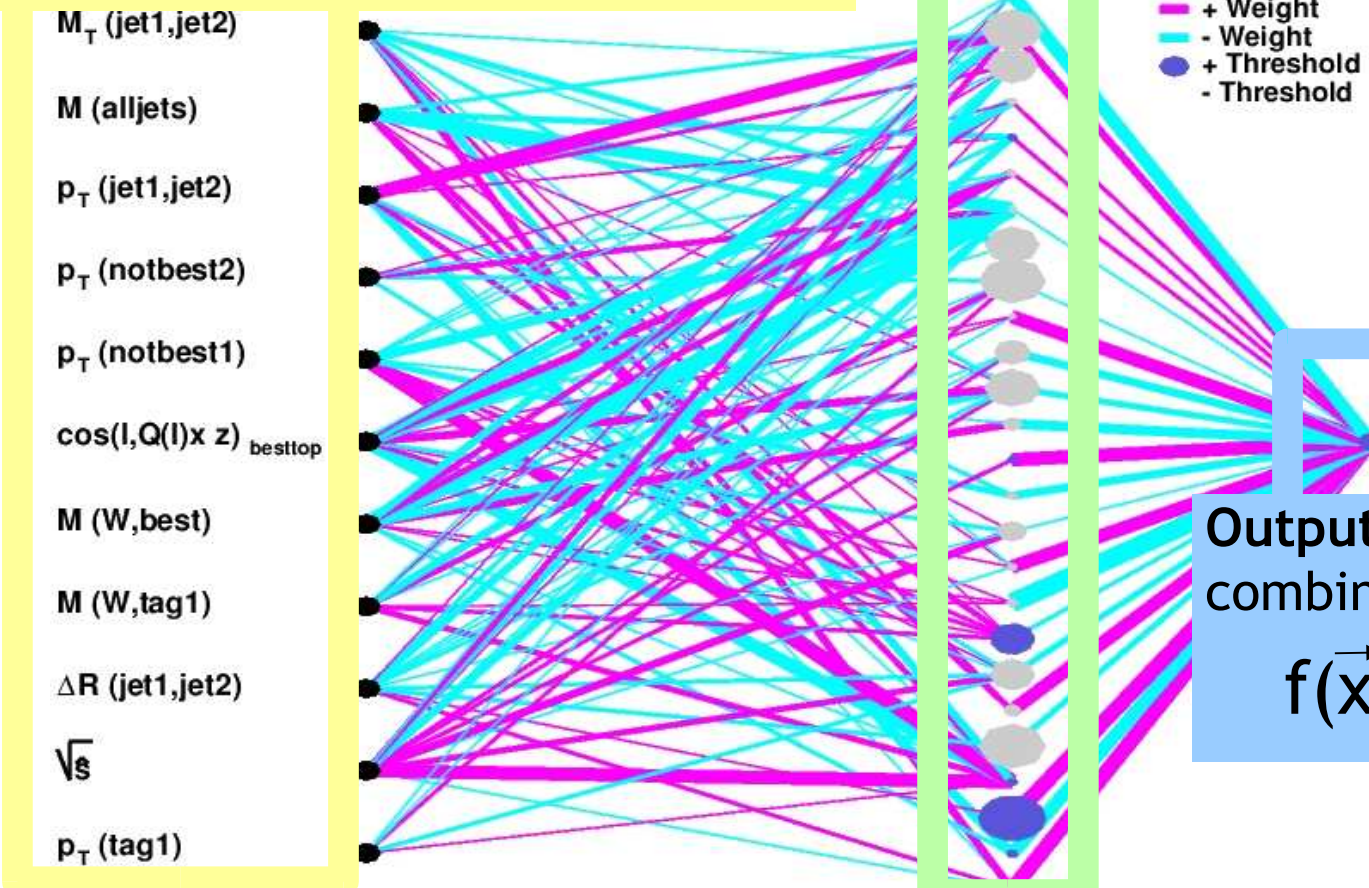


25 variables total



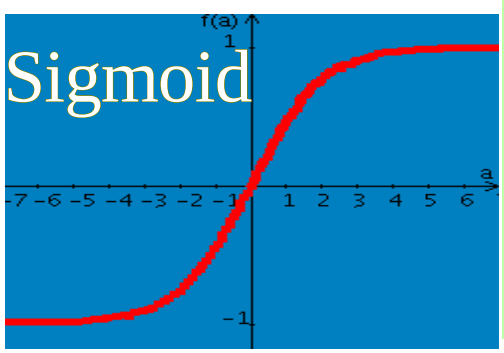
Neural Networks

Input Nodes: One for each variable x_i



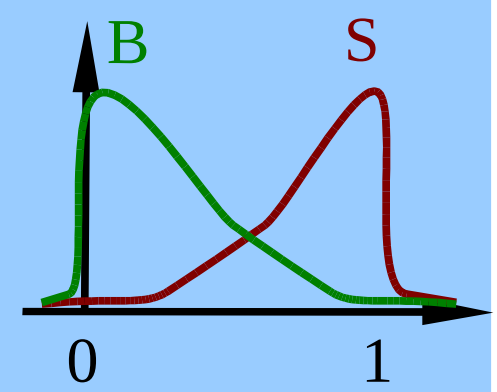
Output Node: linear combination of hidden nodes

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

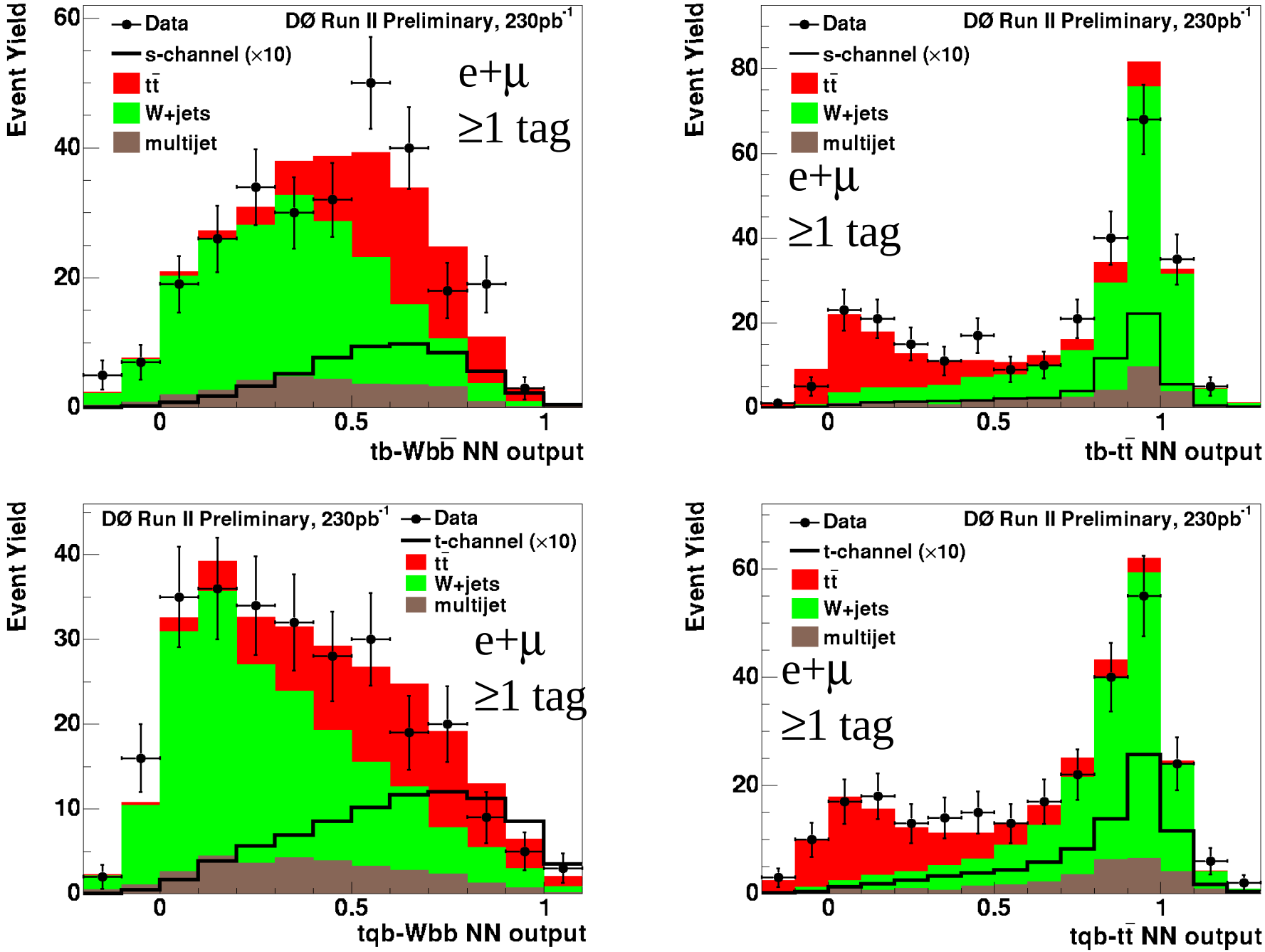


Hidden Nodes: Each is a sigmoid dependent on the input variables

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



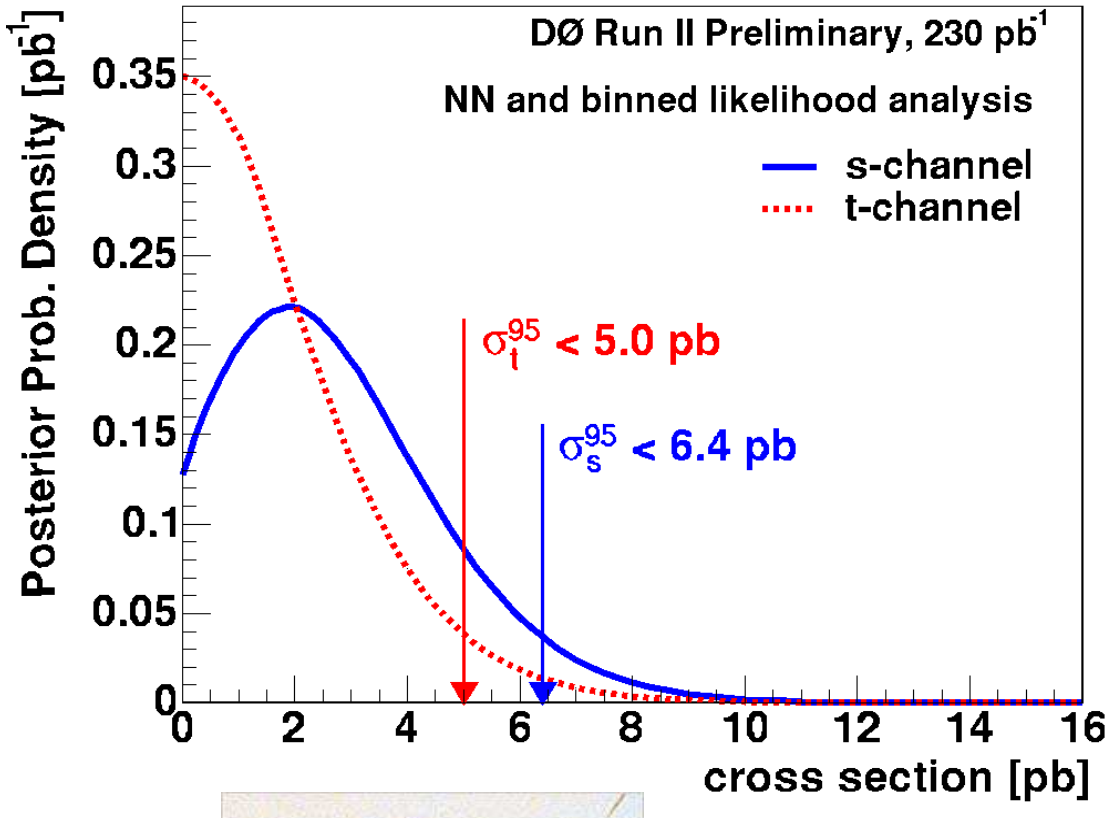
Neural Network Output



Neural Network Result

- Dominant systematics
  - Jet energy scale, b-ID: 10%
  - Background norm: 15-20%
  - Object ID: 5%
- Total systematic

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



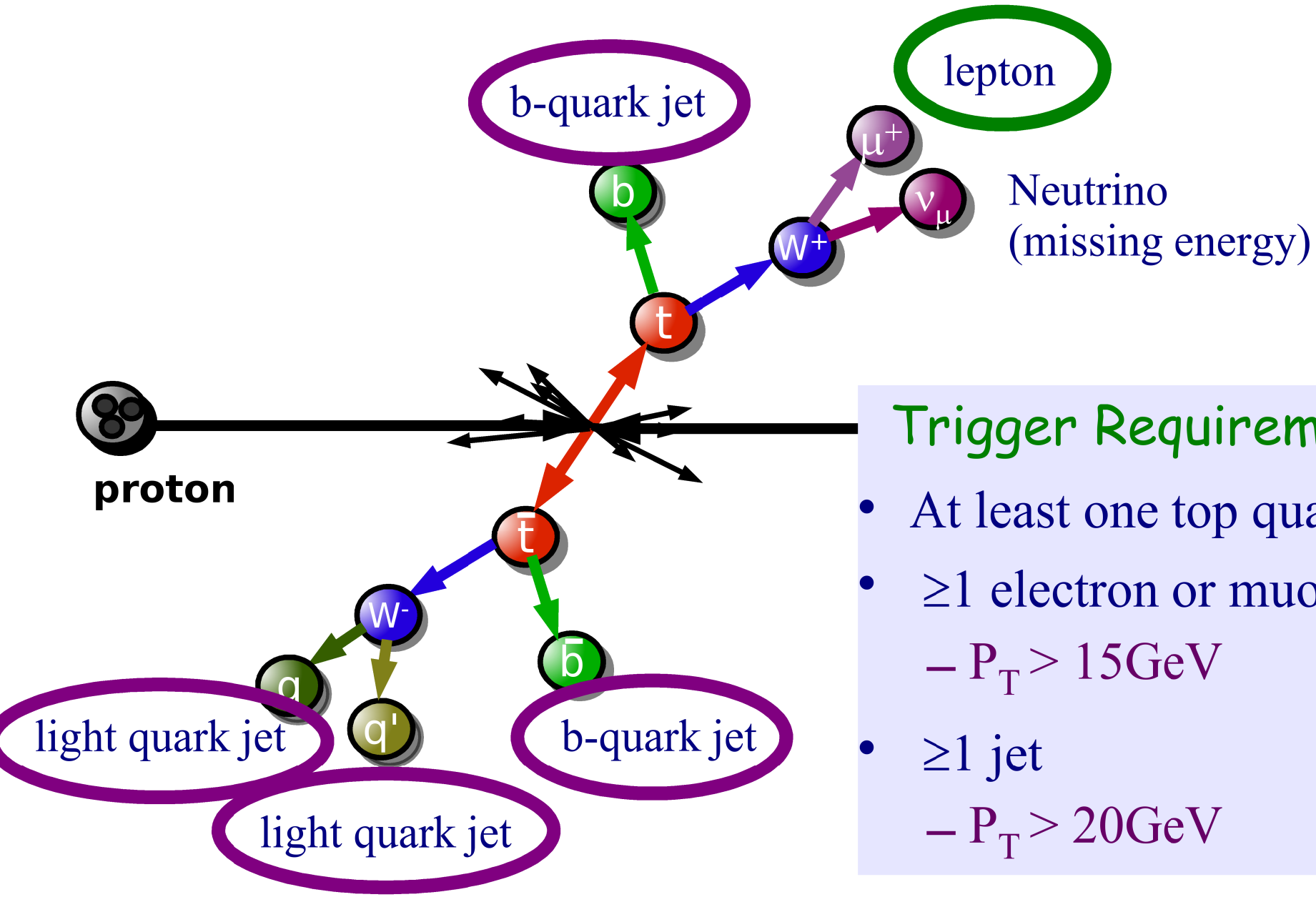
Expected/Observed limit:

σ_s < 4.5 / 6.4 pb

σ_t < 5.8 / 5.0 pb

Published in PLB 622, 265 (2005)

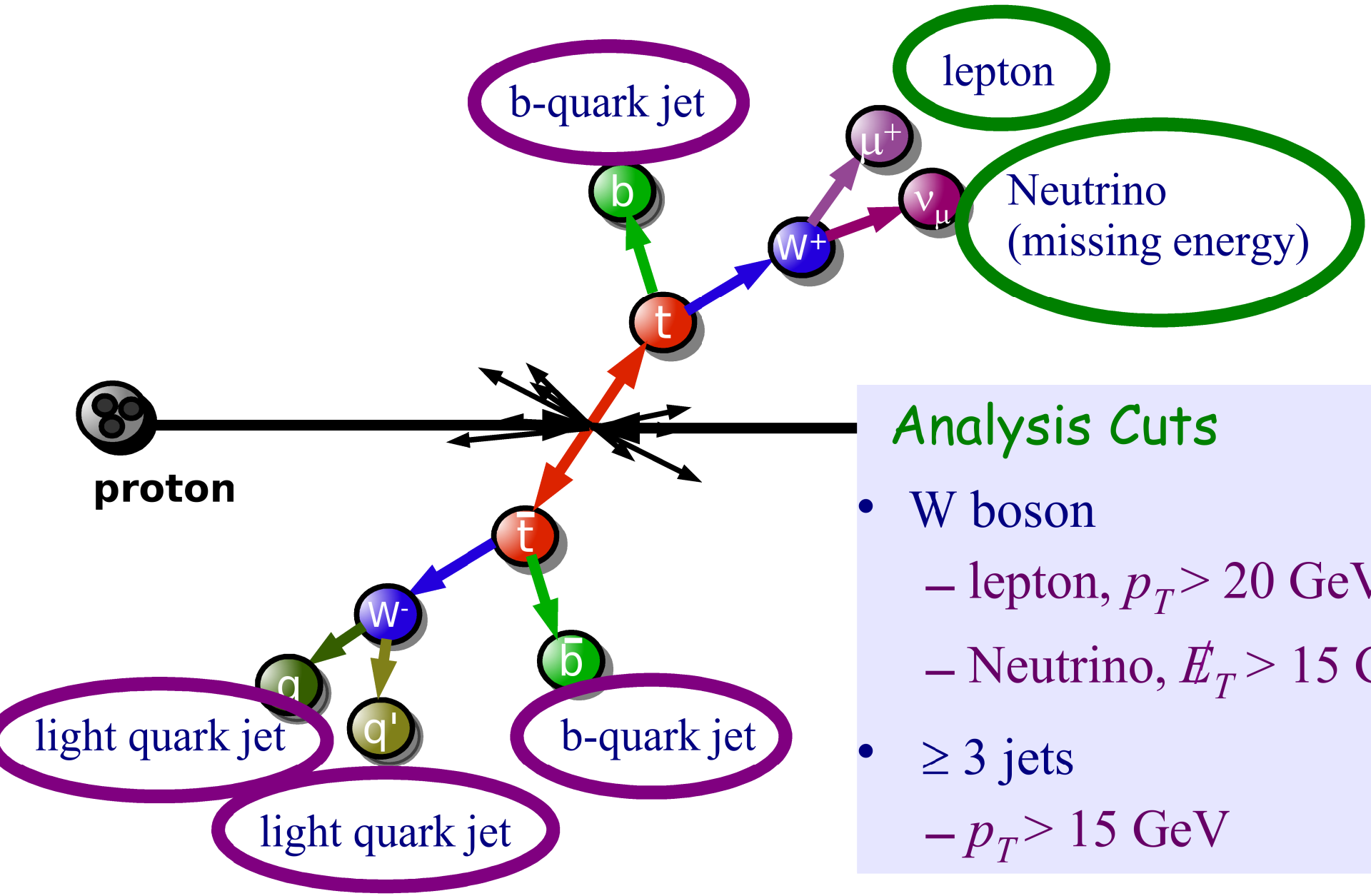
Trigger selection



Trigger Requirements

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

Analysis event selection



Analysis Cuts

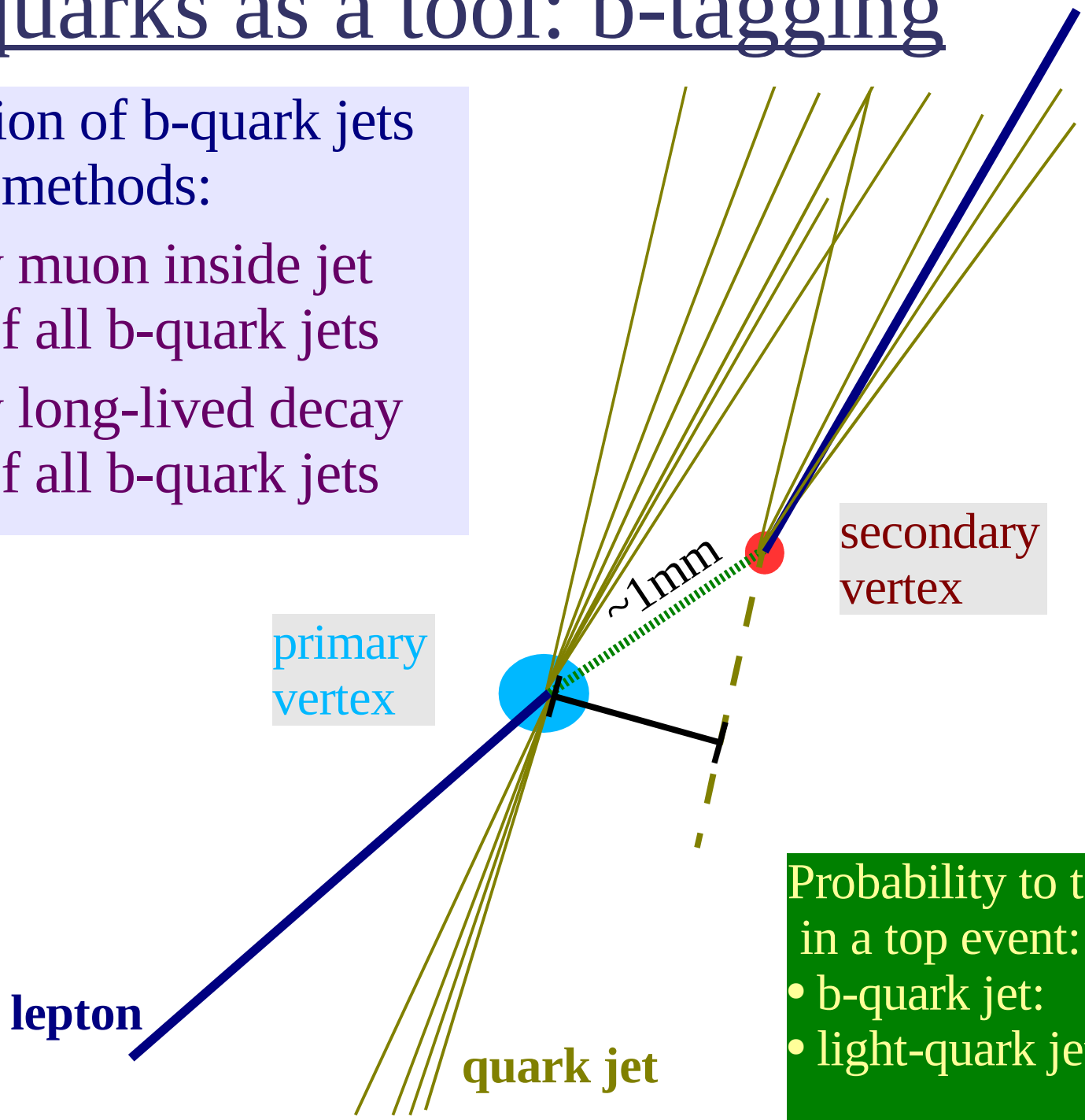
- W boson
  - lepton, $p_T > 20$ GeV
  - Neutrino, $\not{E}_T > 15$ GeV
- ≥ 3 jets
  - $p_T > 15$ GeV

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 172.7 GeV

b quarks as a tool: b-tagging

- Identification of b-quark jets
  2 possible methods:
  - Identify muon inside jet
    ~20% of all b-quark jets
  - Identify long-lived decay
    ~35% of all b-quark jets

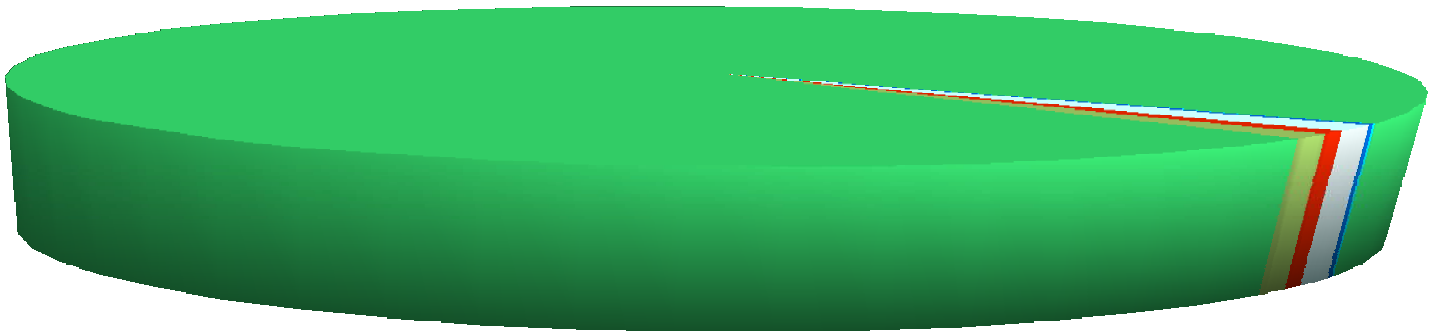


Probability to tag a jet
in a top event:
- b-quark jet: ~55%
- light-quark jet: ~0.5%

Event selection result

10,000 events with lepton, neutrino, ≥ 2 jets

expect ~250 top quarks



Top quark pairs

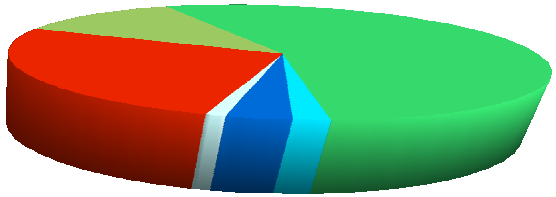
Backgrounds

In 360pb^{-1}, lepton+jets

Top Quark Events

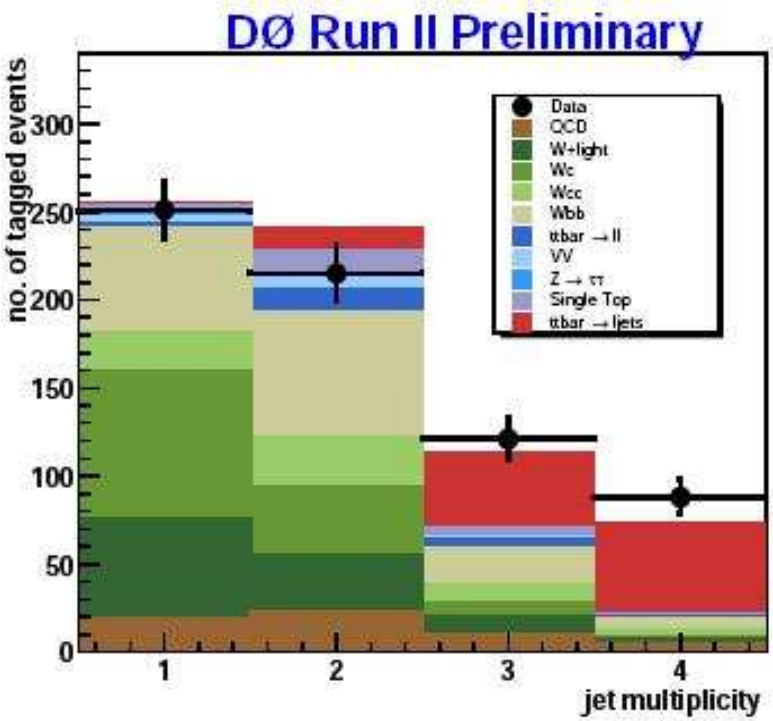
=1 b-tag:
367 events

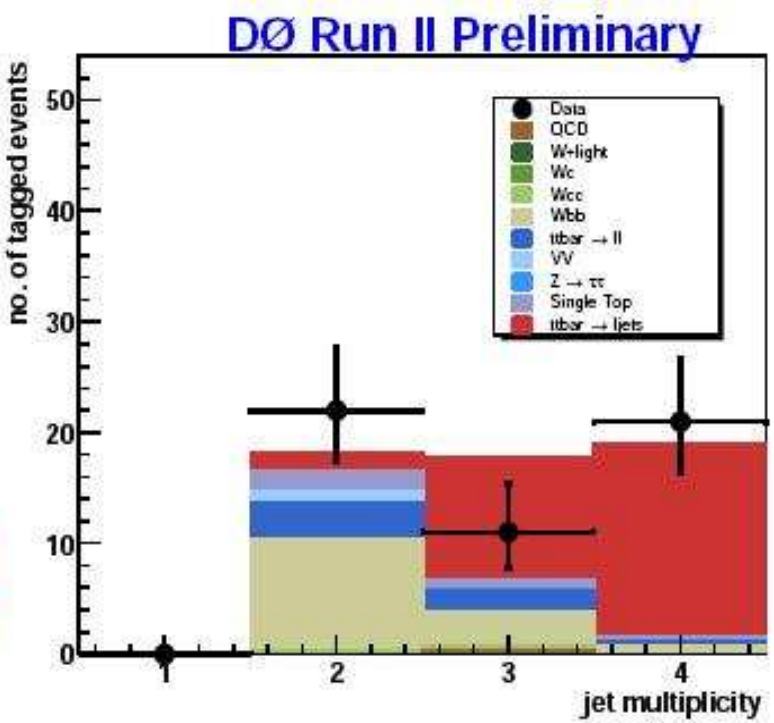
=2 b-tags:
76 events



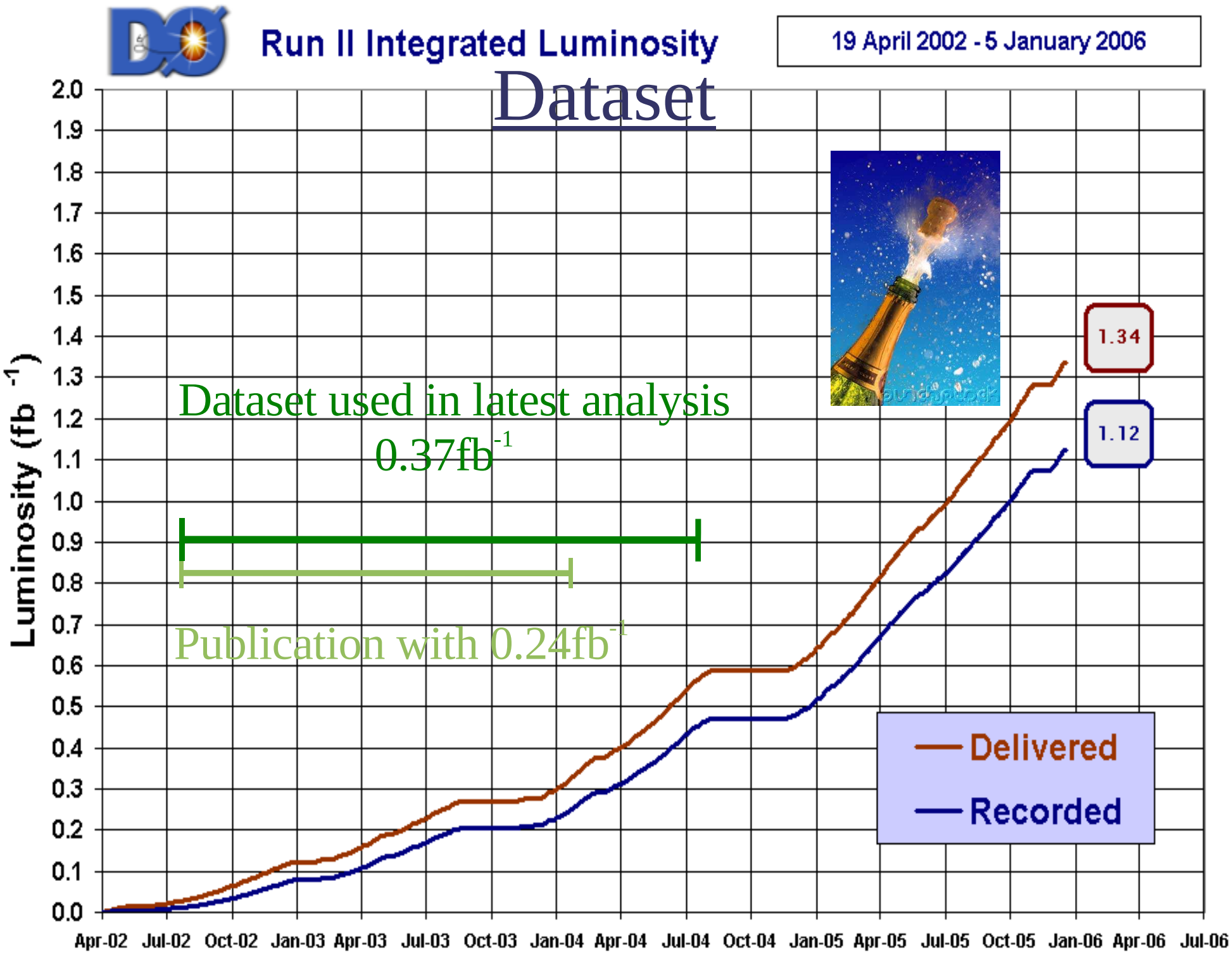
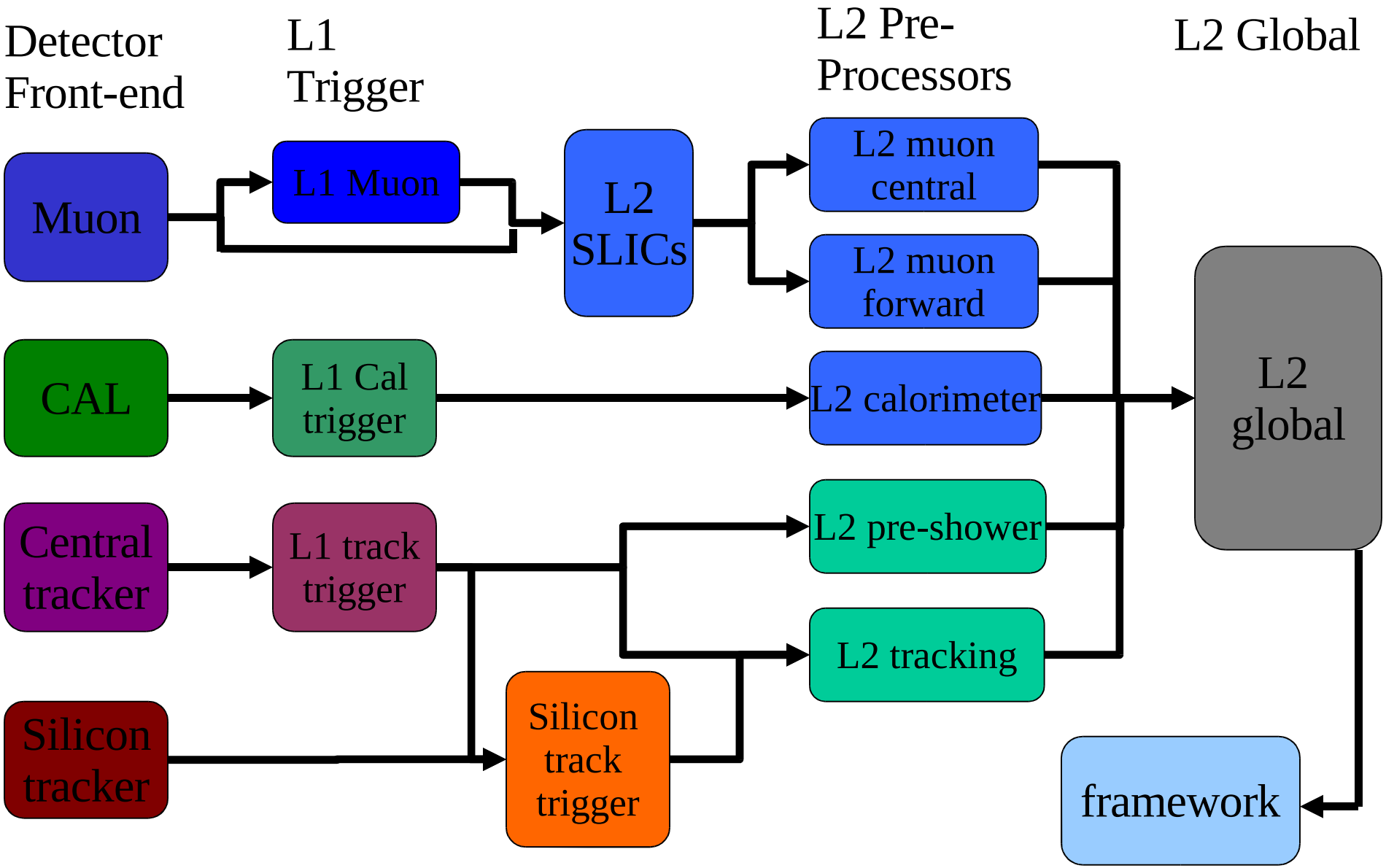
Top quark pairs

Backgrounds





Dataset


Run II Integrated Luminosity
19 April 2002 - 5 January 2006
Luminosity (fb -1)
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
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
Jan-06
Apr-06
Jul-06
1.34
1.12
Delivered
Recorded
Dataset used in latest analysis
0.37fb-1
Publication with 0.24fb-1

Level 2 Trigger System