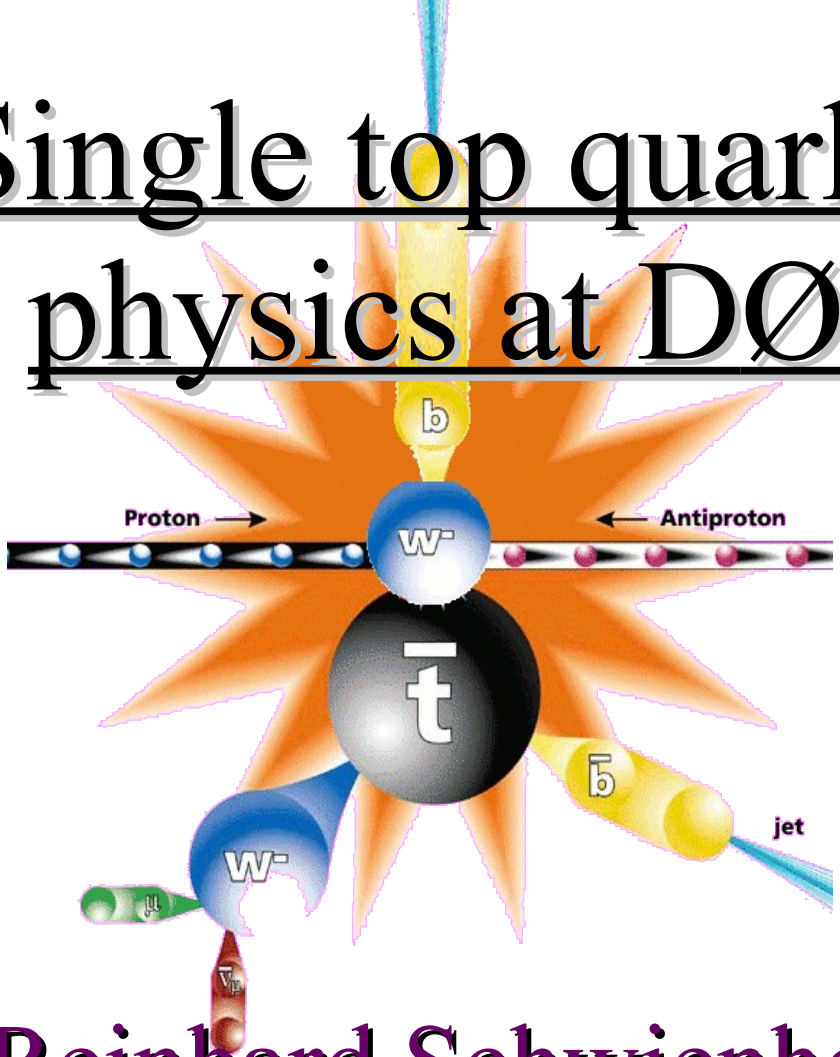
Single top quark physics at DØ



Reinhard Schwienhorst

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IPNL seminar, July 20, 2007

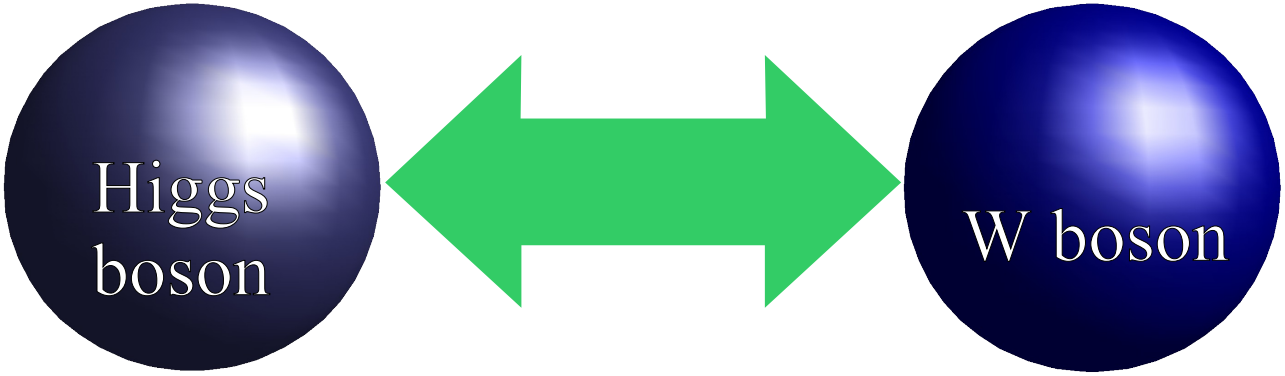
Outline

- Introduction
- Tevatron and DØ
- Single top quark production
  - Event Selection
  - Optimized event analysis
  - |Vtb|
- Conclusions

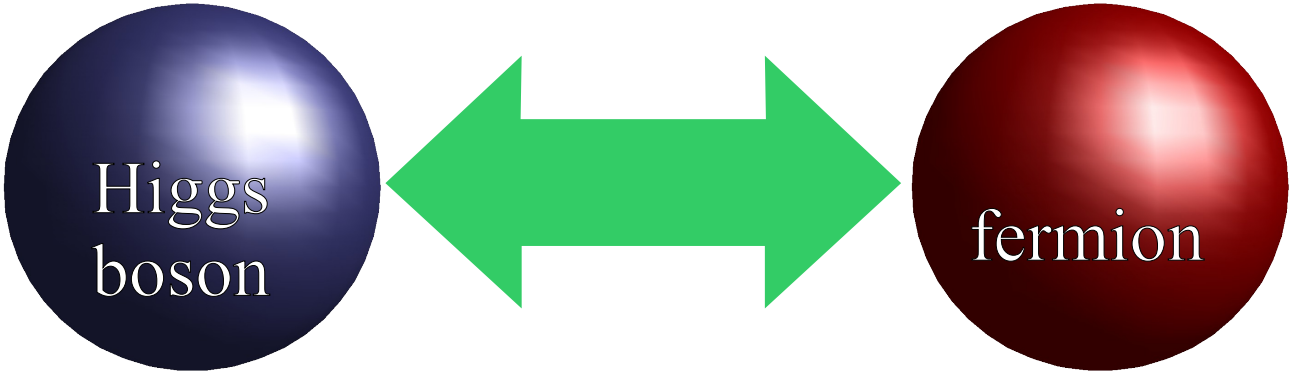
- Many details not covered

Electroweak symmetry breaking

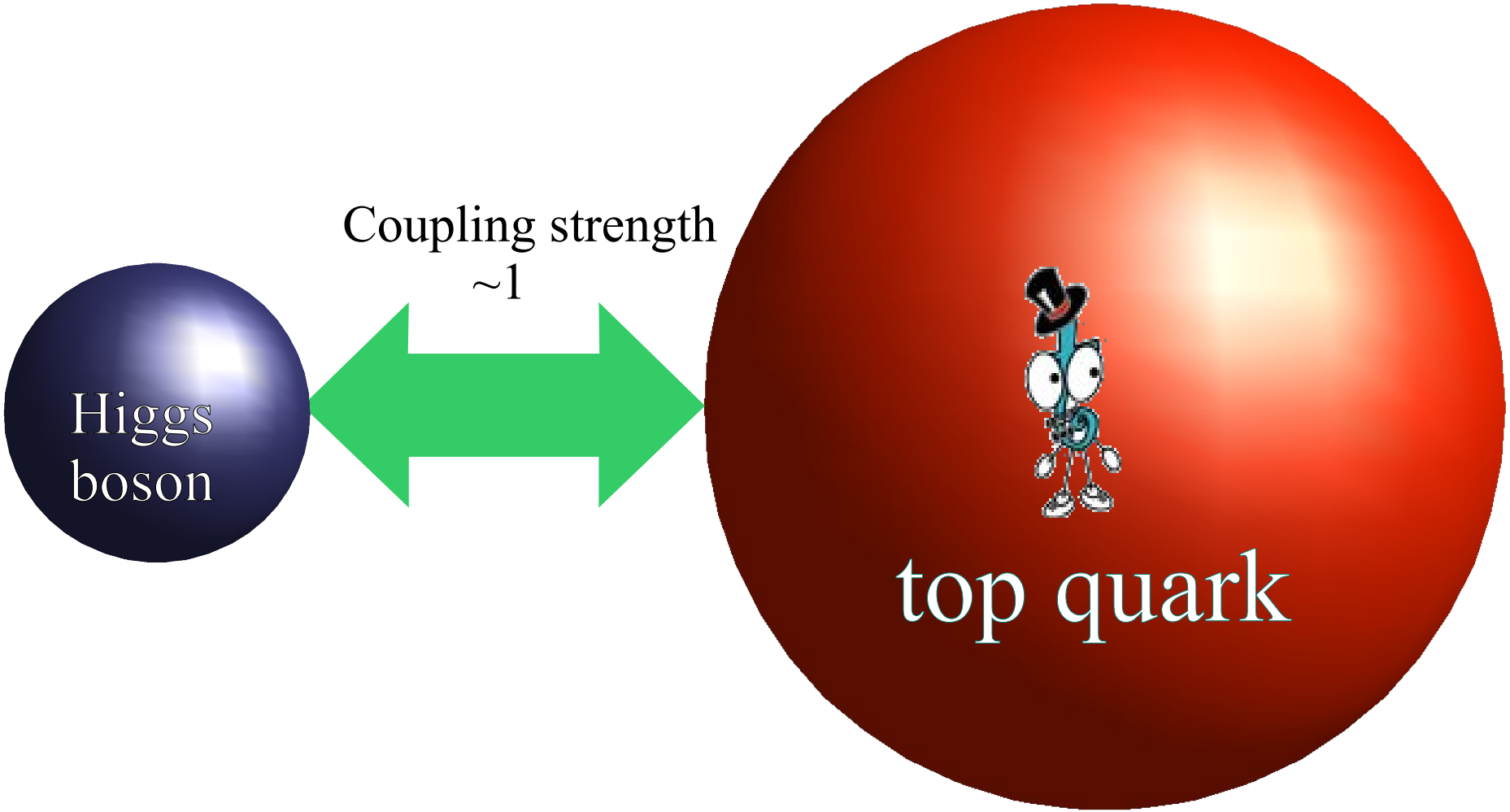
Gauge boson coupling to Higgs field



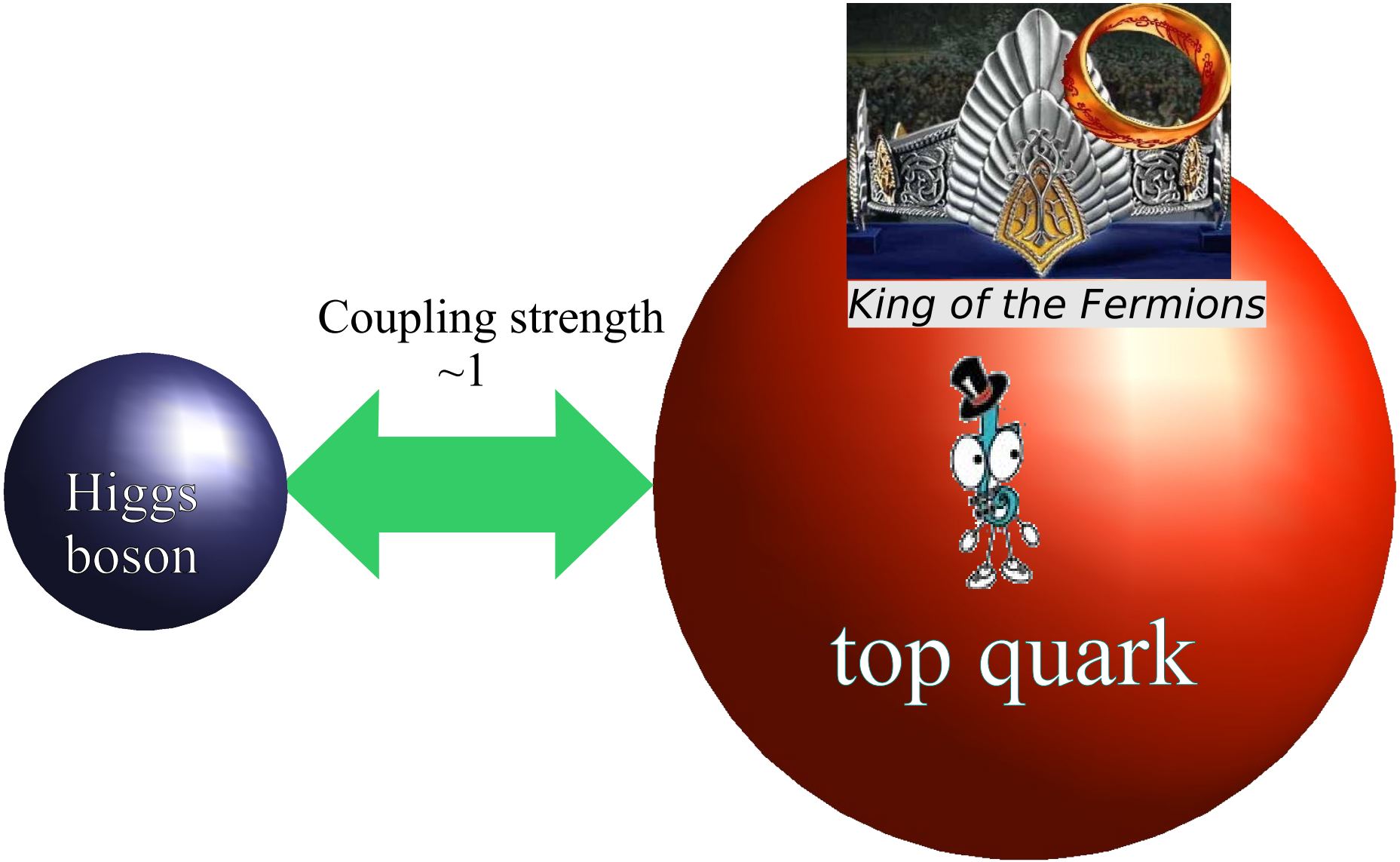
Fermions acquire mass through Higgs coupling



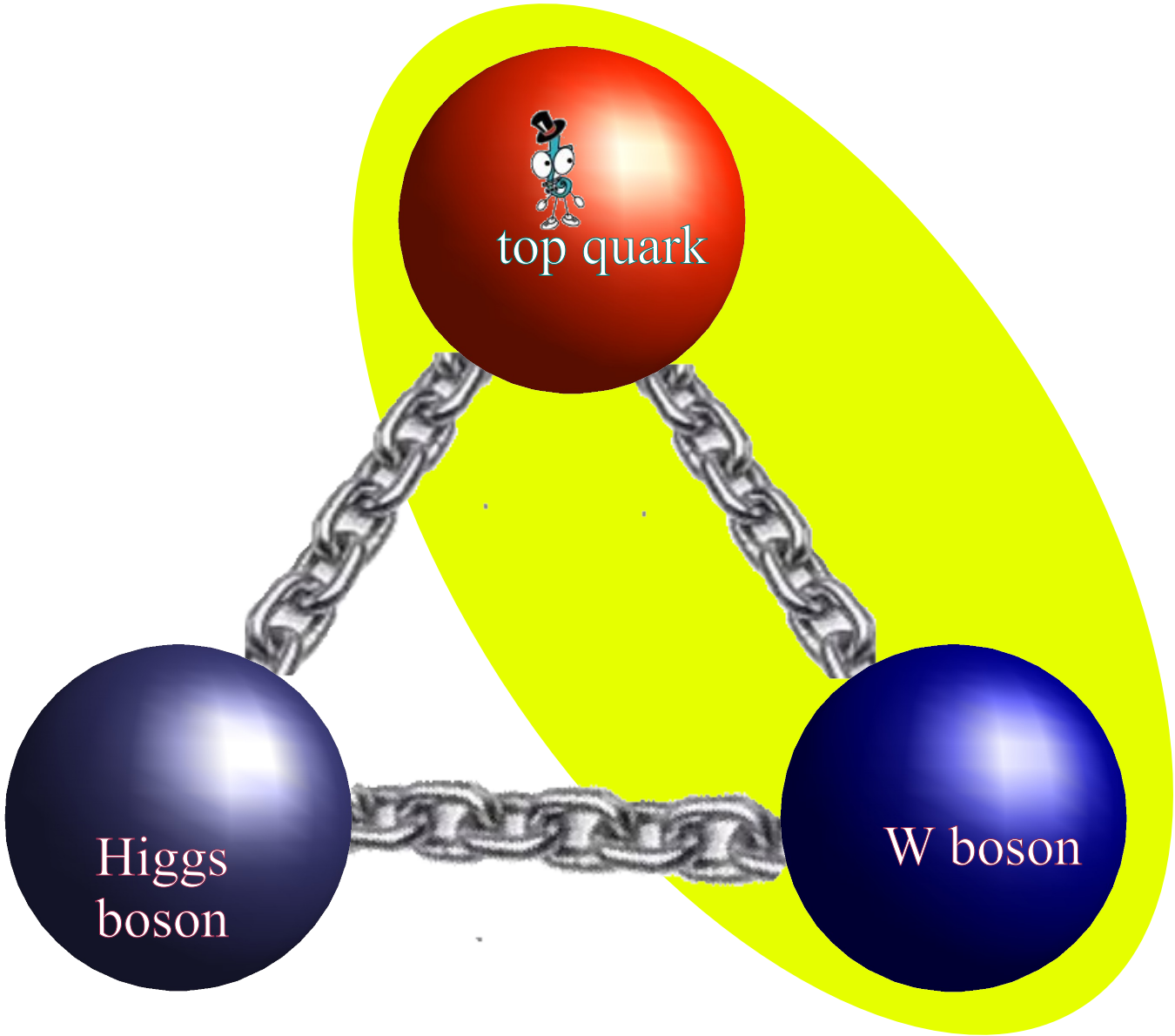
Top quark



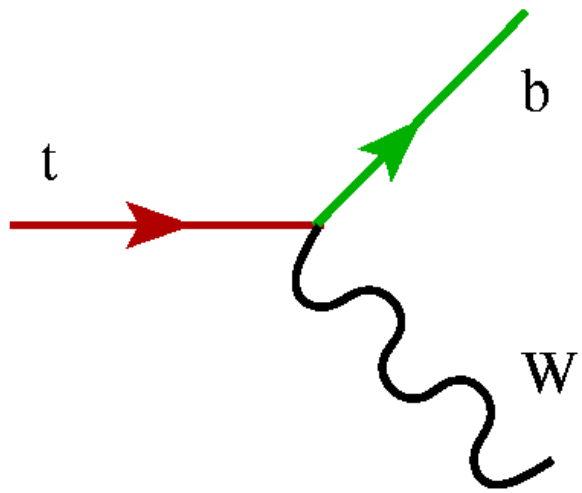
Top quark


King of the Fermions
Coupling strength
~1
Higgs
boson
top quark

Key to electroweak symmetry breaking

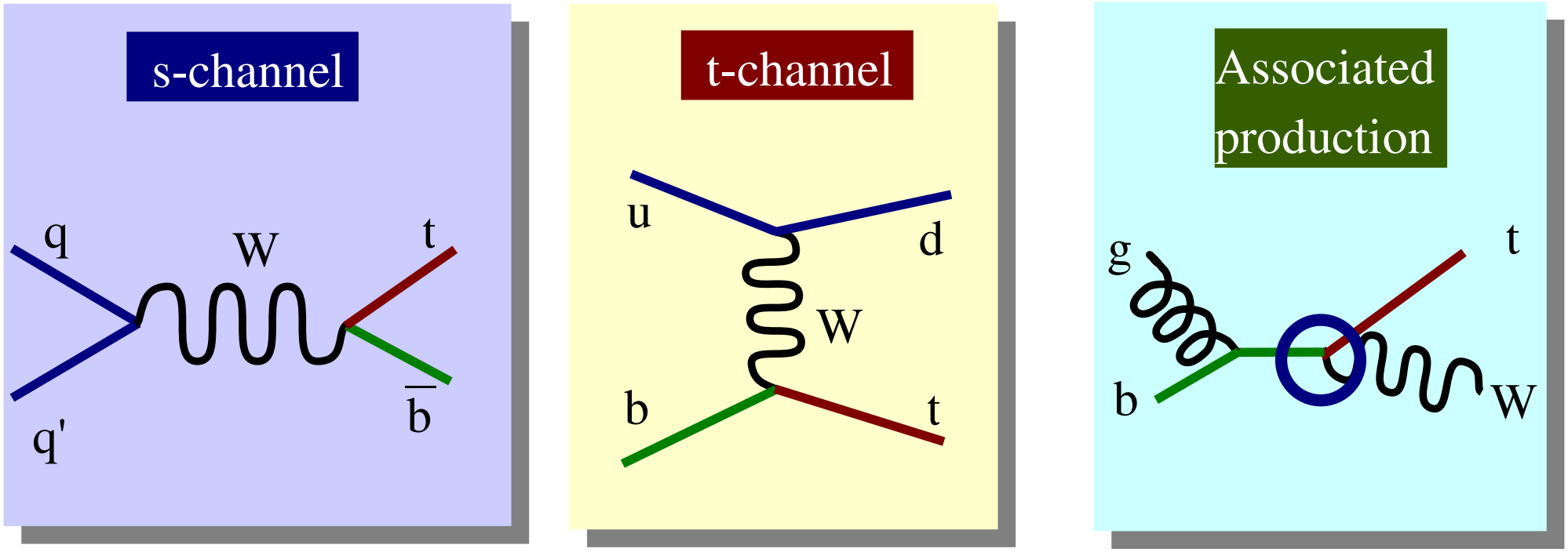


Top quark electroweak charged current interaction

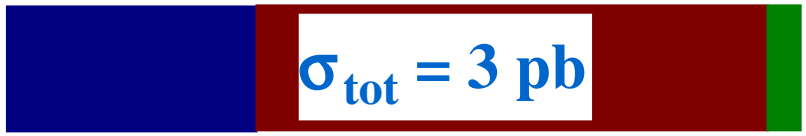


top quark decay

SM single top quark production



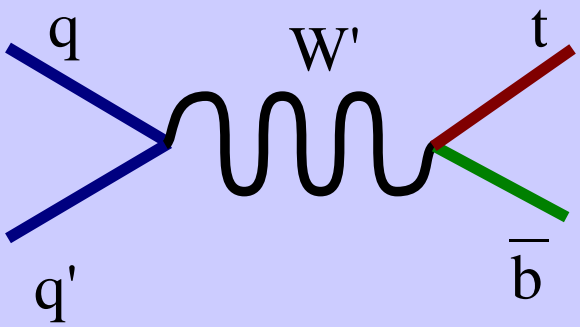
TeV:



LHC:

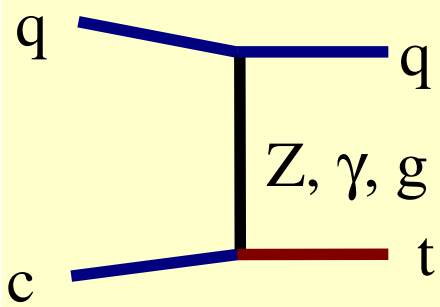
New physics

s-channel



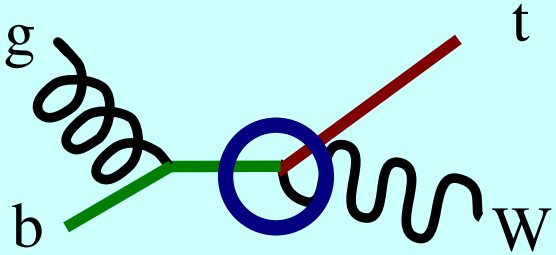
New heavy boson

t-channel



Flavor Changing Neutral Current

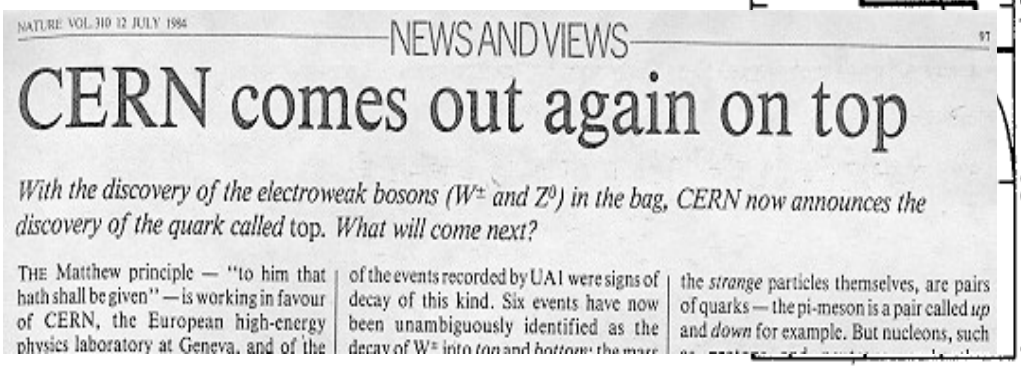
Associated production



Modified Wtb coupling

Discovery of single top?

- Excess of lepton+MET+2jet events at UA1 in 1984
  - Consistent with production of single top quark and bottom quark
  - SPS: $\sqrt{s} = 540$ GeV
- $M_{top} \approx 40$ GeV



NATURE VOL. 310 12 JULY 1984 — NEWS AND VIEWS

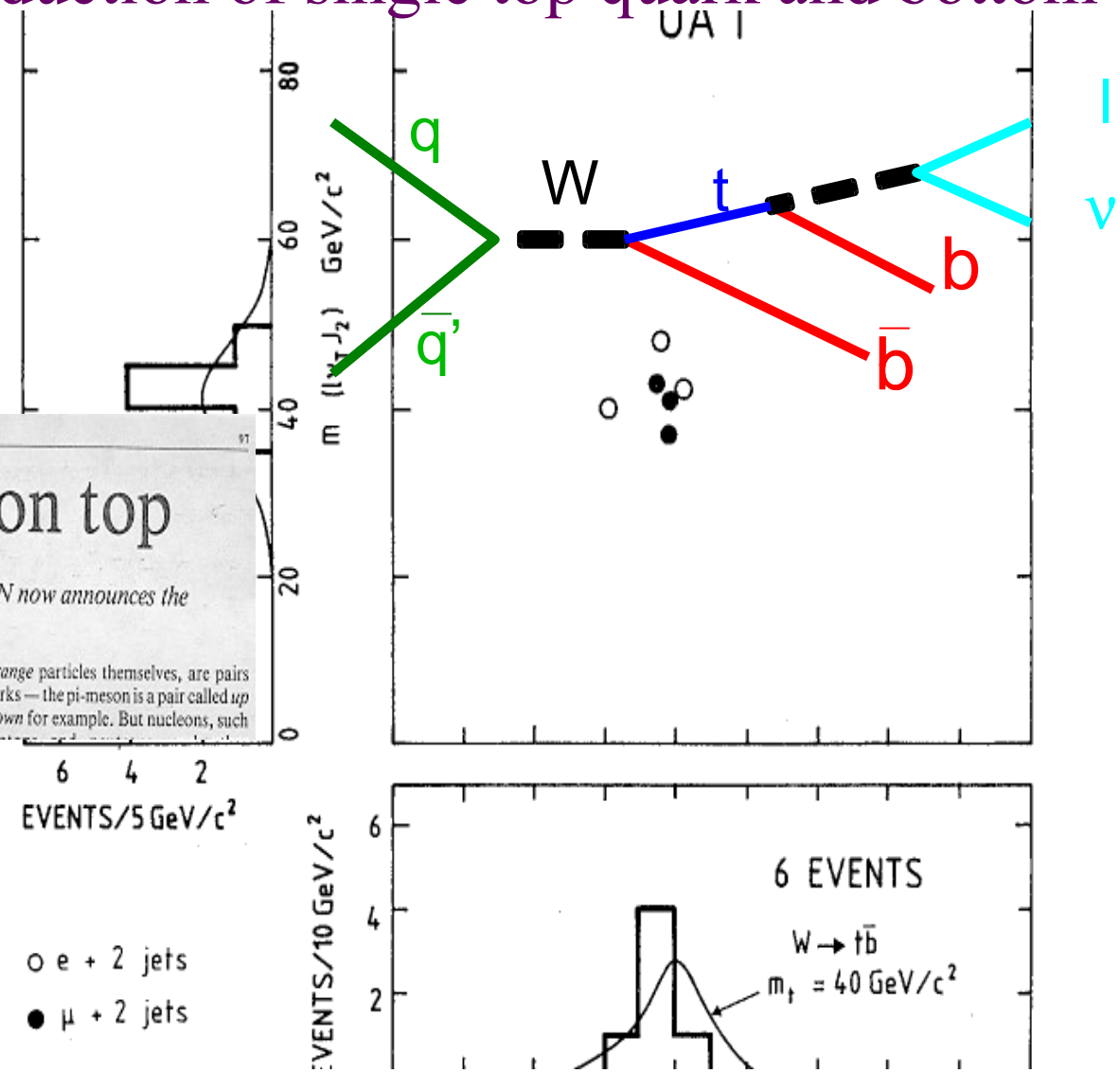
CERN comes out again on top

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?*

THE Matthew principle — "to him that hath shall be given" — is working in favour of CERN, the European high-energy physics laboratory at Geneva, and of the

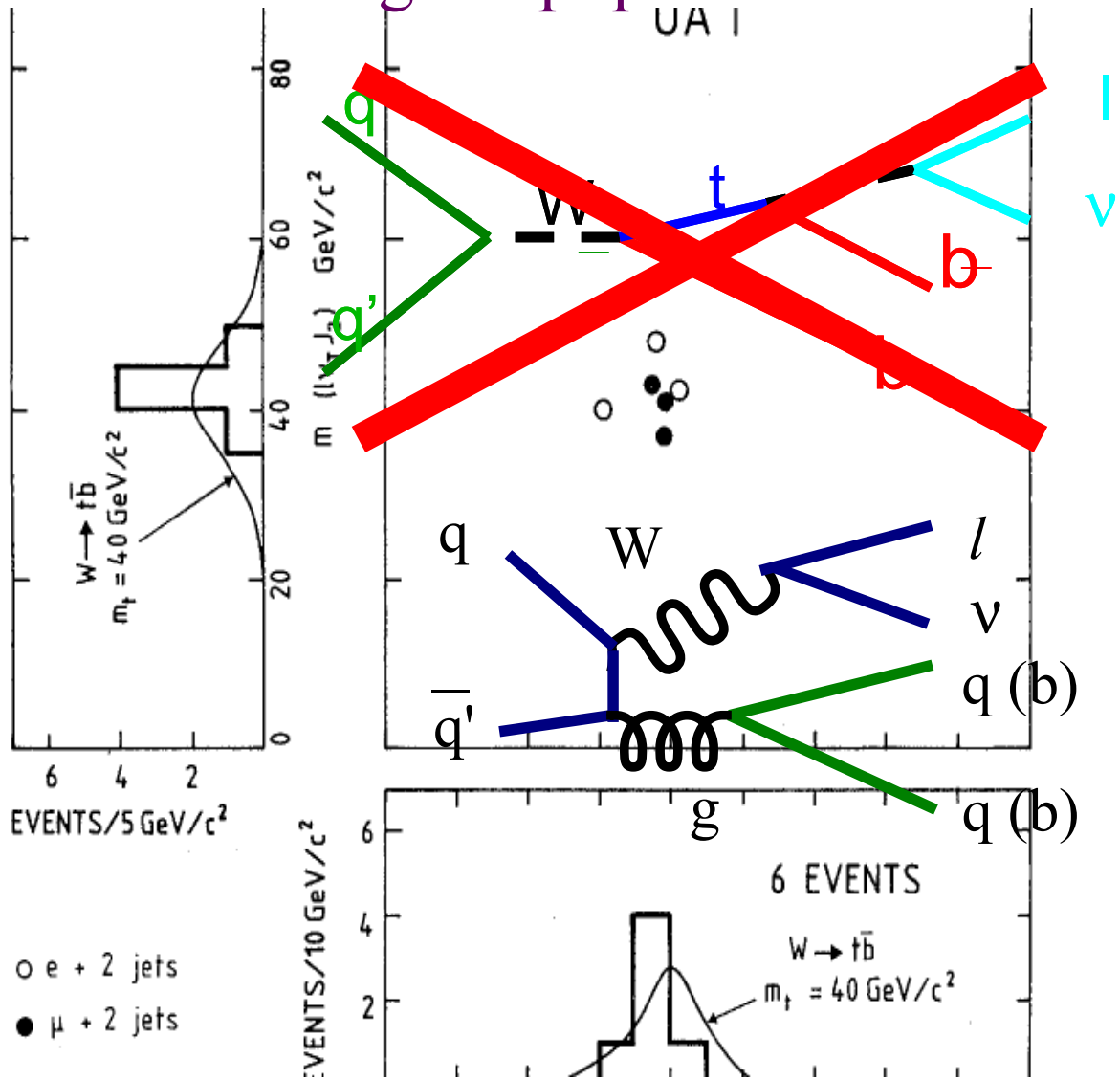
of the events recorded by UA1 were signs of decay of this kind. Six events have now been unambiguously identified as the decay of $W^{\pm}$ into *top* and *bottom*; the mass

the *strange* particles themselves, are pairs of quarks — the pi-meson is a pair called *up* and *down* for example. But nucleons, such



Discovery of single top?

- Excess of lepton+MET+2jet events at UA1 in 1984
  - Consistent with production of single top quark and bottom quark
    - $M_{top} \approx 40$ GeV
  - Not confirmed after more data and better background estimation
    - W+jets production!



Tevatron single top goals

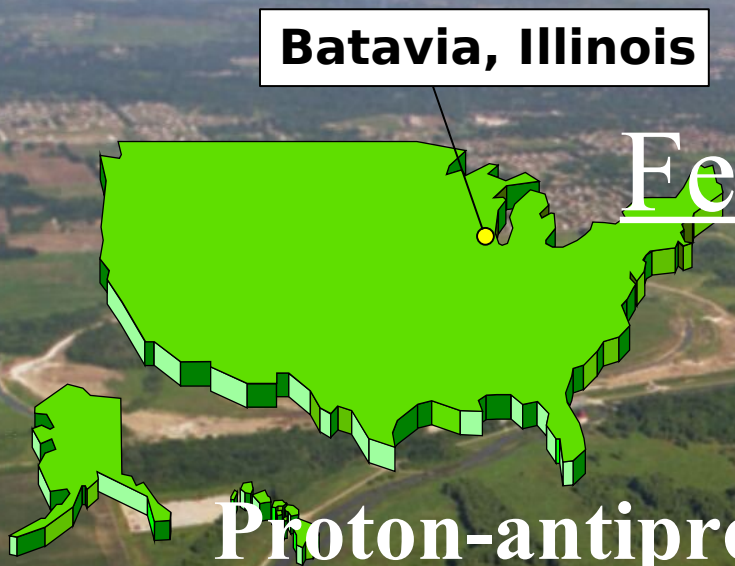
Production cross sections:	*s-channel*	*t-channel*
NLO calculation:	**0.88 pb (±8%)**	**1.98 pb (±11%)**
current 95% CL limits, DØ:	< 5.0 pb	< 4.4 pb
CDF:	< 3.1 pb	< 3.2 pb

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

Preparation

How do we collect a sample of candidates?

Experimental setup: Fermilab Tevatron in Run II



Proton-antiproton collider

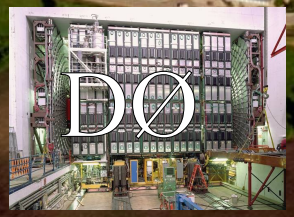
CM energy 1.96TeV

→ ***Energy frontier***

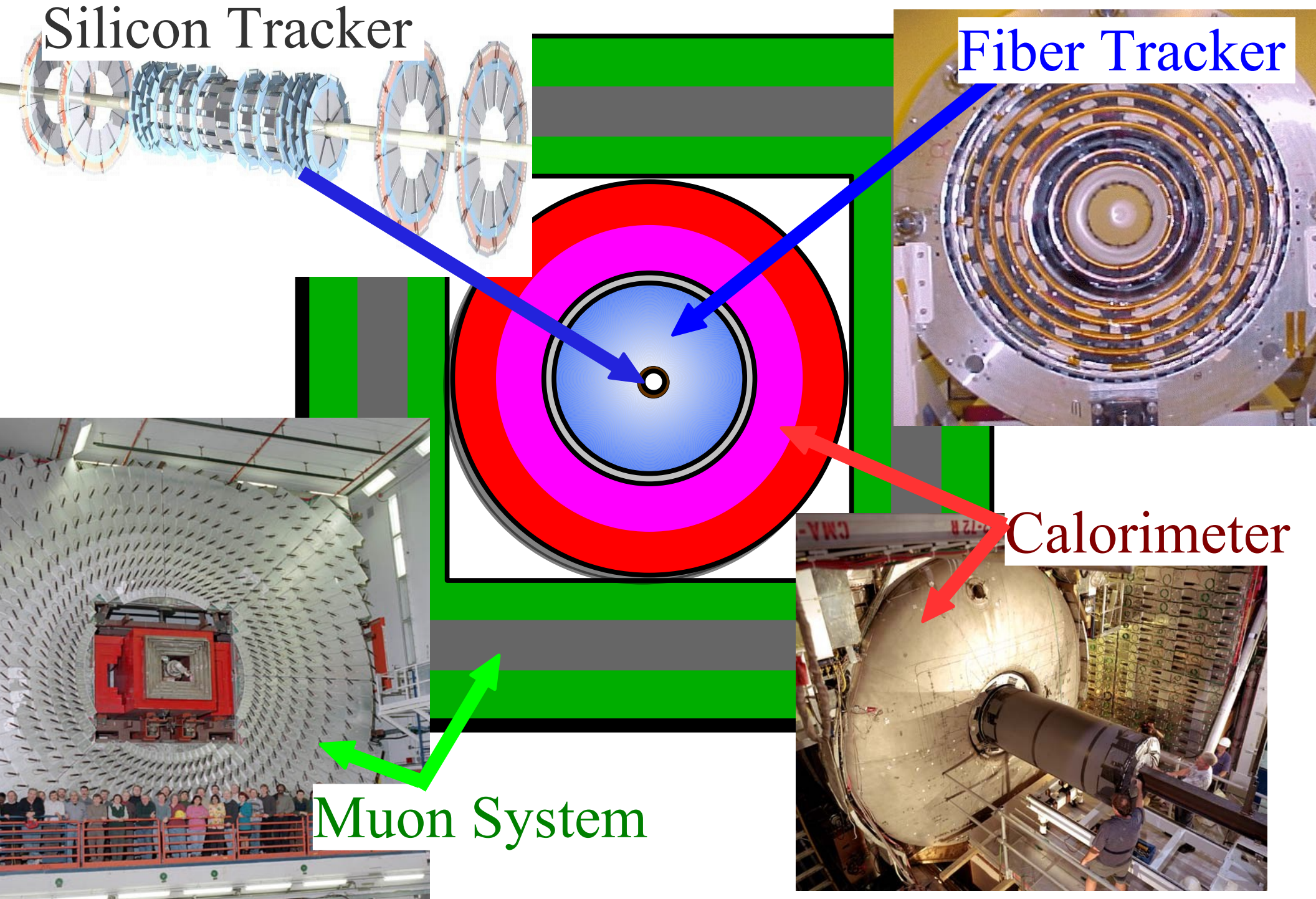
Instantaneous luminosity >250E30cm^{-2}s^{-1}

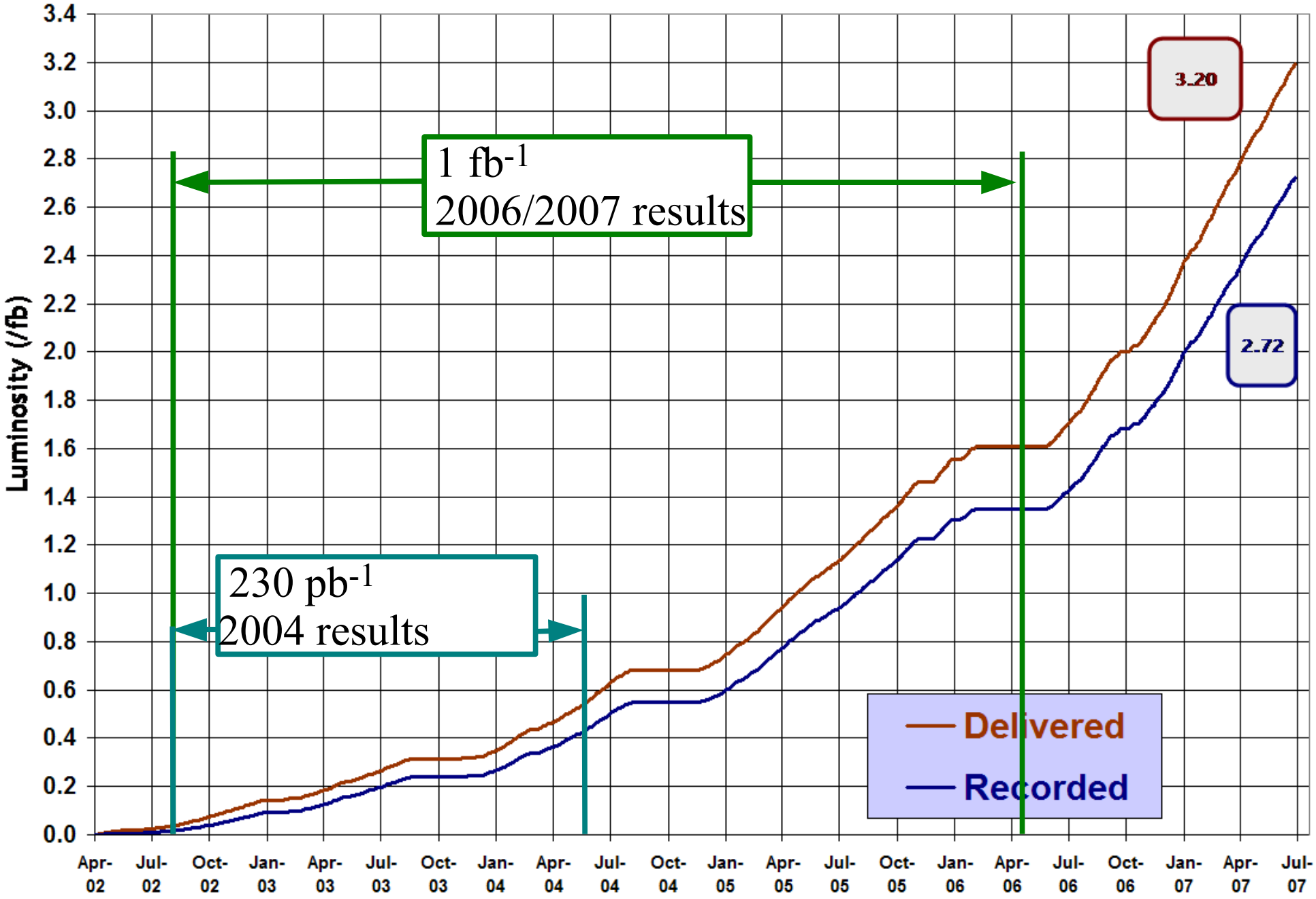
– ~4 interactions per crossing, 1.7M crossing per second

→ ***Luminosity frontier***



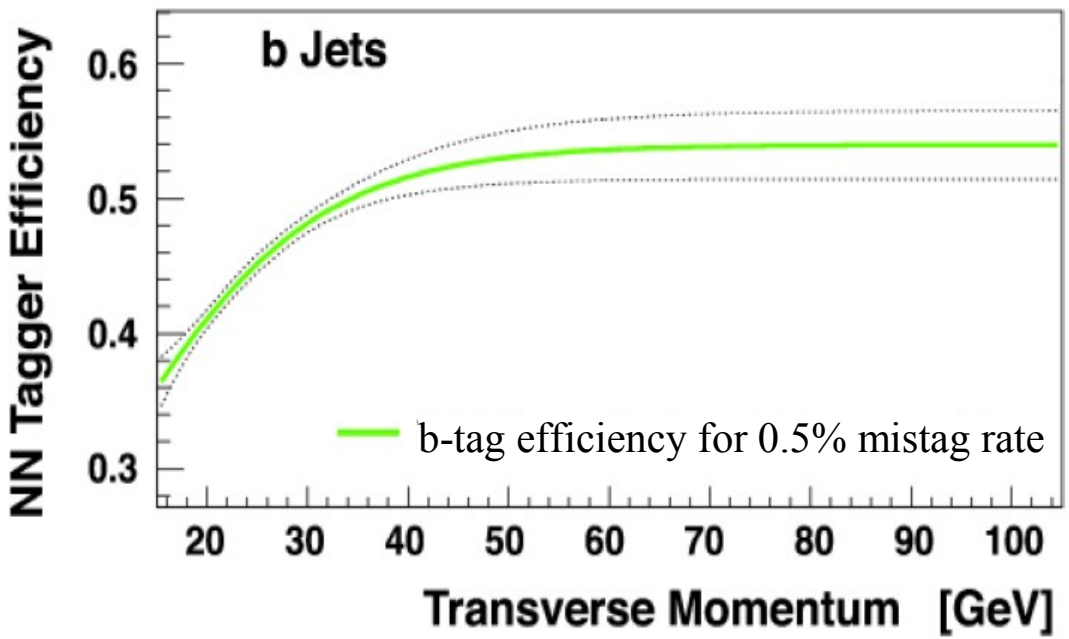
Apparatus: Run II DØ Detector




Run II Integrated Luminosity
19 April 2002 - 15 July 2007
Luminosity (/fb)
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
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
Oct-06
Jan-07
Apr-07
Jul-07
1 fb-1
2006/2007 results
230 pb-1
2004 results
3.20
2.72
Delivered
Recorded

Recent improvements

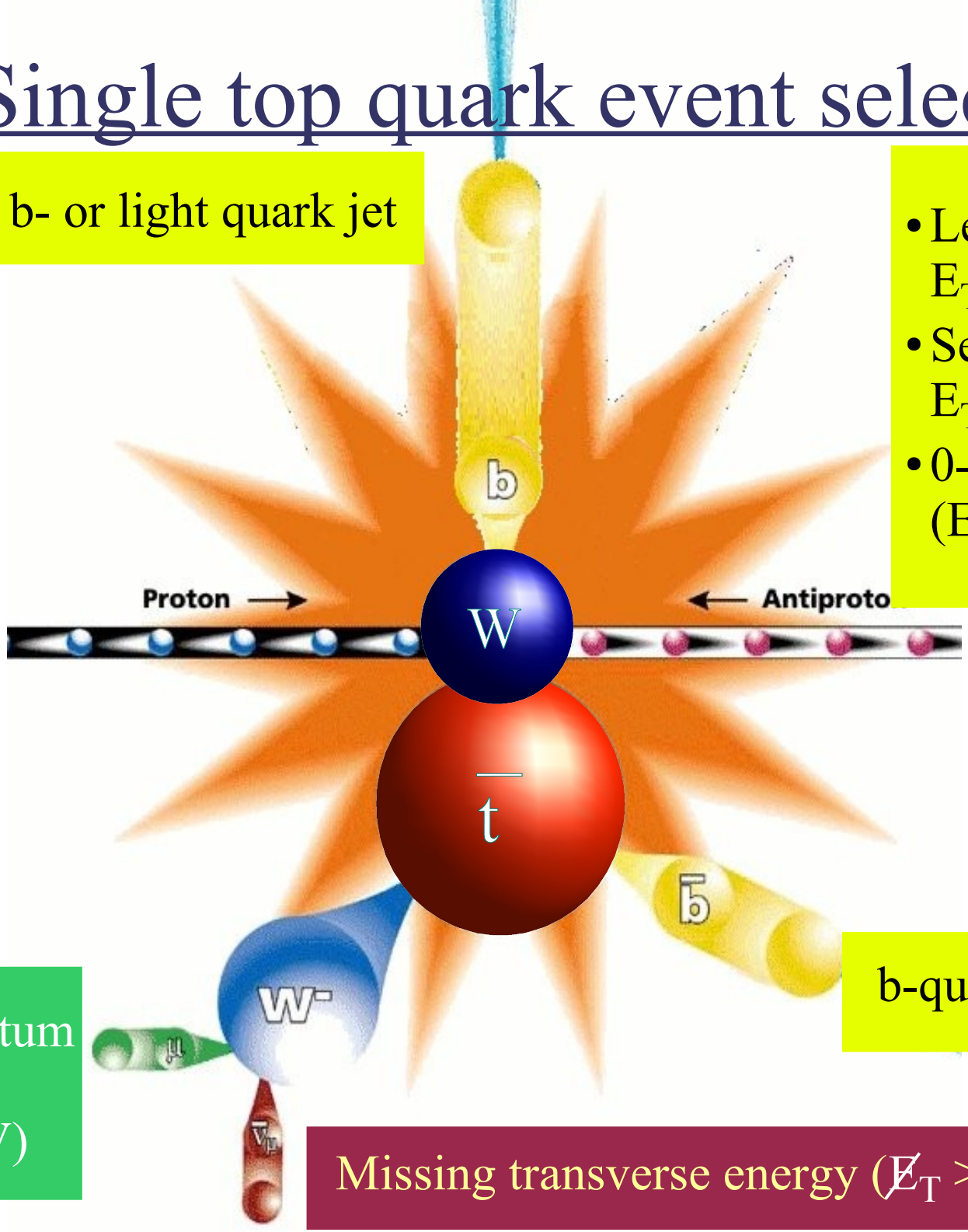
- Improved W+jets modeling
  - Important background for top pairs and single top
  - Alpgen+Pythia with MLM matching
  - Normalize total count and HF fraction to data
- Fully reprocessed dataset
  - New calibrations, lower thresholds, ...
- Neural network b-quark tagging



Single top quark event selection

b- or light quark jet

- Leading jet: $E_T > 25$ GeV
- Second jet: $E_T > 20$ GeV
- 0-2 additional jets ($E_T > 15$ GeV)



b-quark jet

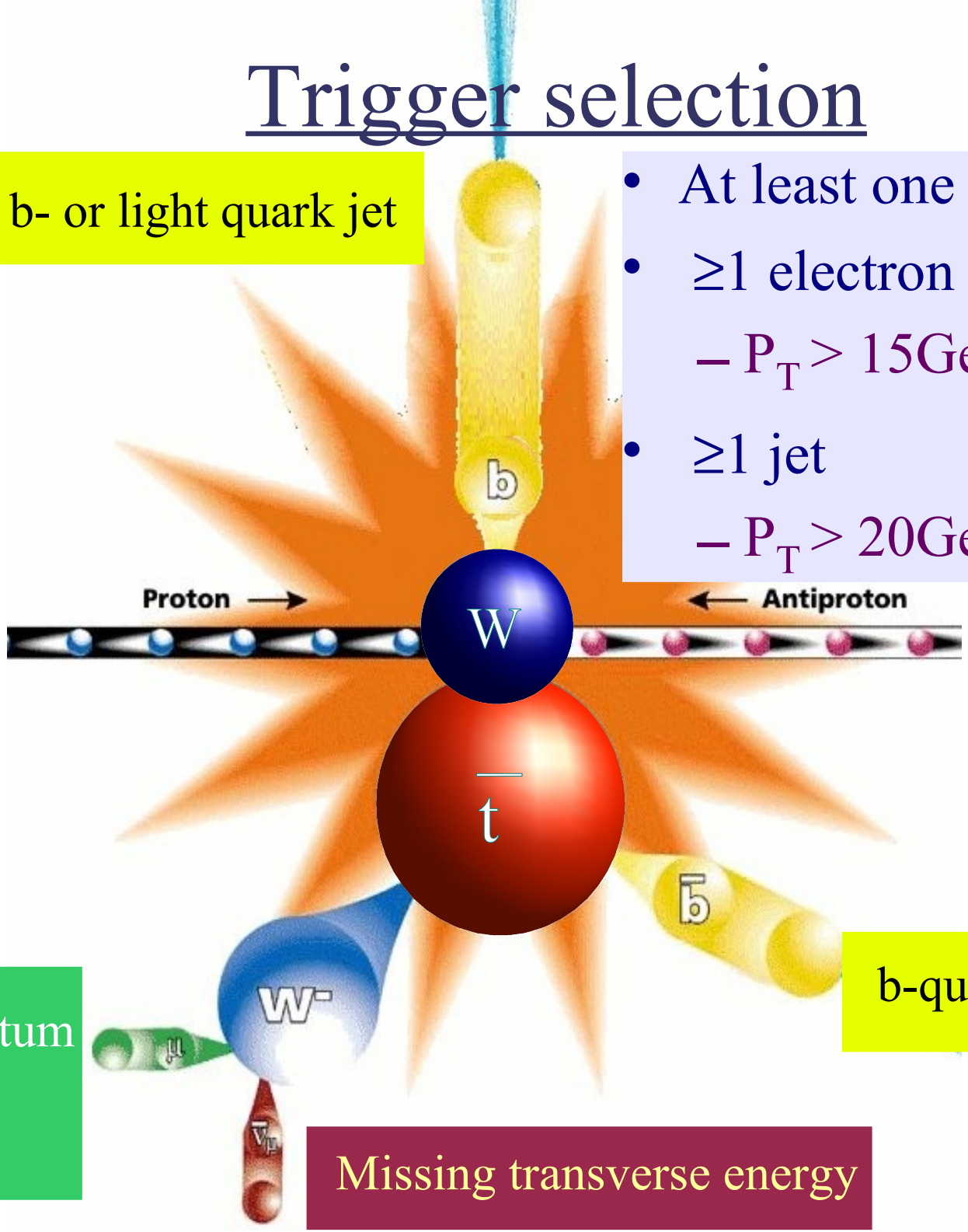
High-momentum lepton ($E_T > 15$ GeV)

Missing transverse energy ($\not{E}_T > 15$ GeV)

Trigger selection

b- or light quark jet

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

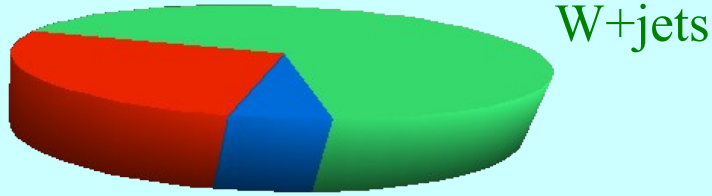


b-quark jet

High-momentum lepton

Missing transverse energy

Event Sample Composition

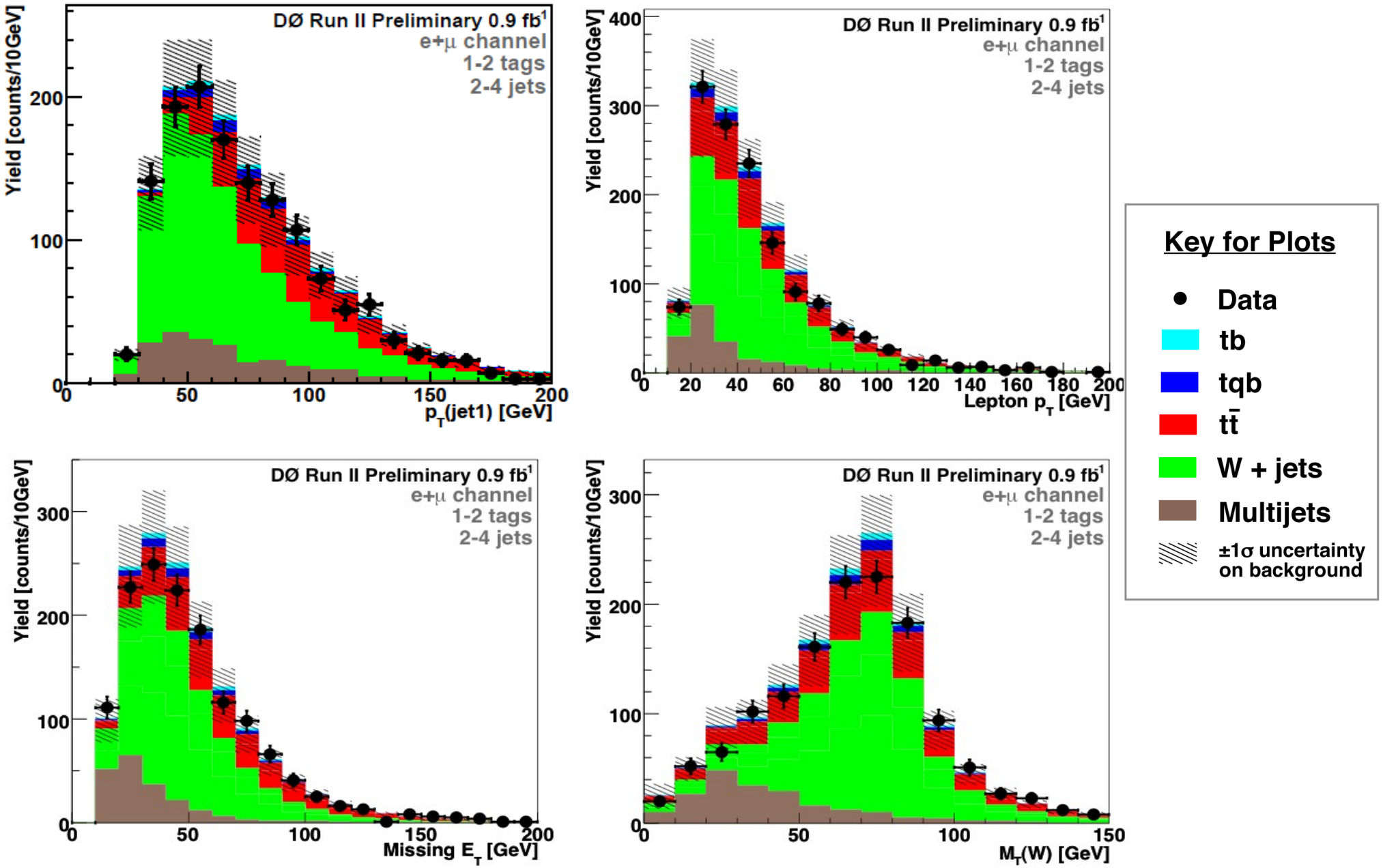


(total ~ 1 ev pb)

Percentage of single top *tb+tqb* selected events and S:B ratio (white squares = no plans to analyze)

Electron + Muon	1 jet	2 jets	3 jets	4 jets	≥ 5 jets
0 tags	10% 1 : 3,200	25% 1 : 390	12% 1 : 300	3% 1 : 270	1% 1 : 230
1 tag	6% 1 : 100	21% 1 : 20	11% 1 : 25	3% 1 : 40	1% 1 : 53
2 tags		3% 1 : 11	2% 1 : 15	1% 1 : 38	0% 1 : 43

Data-background comparison



Optimized Event Analysis

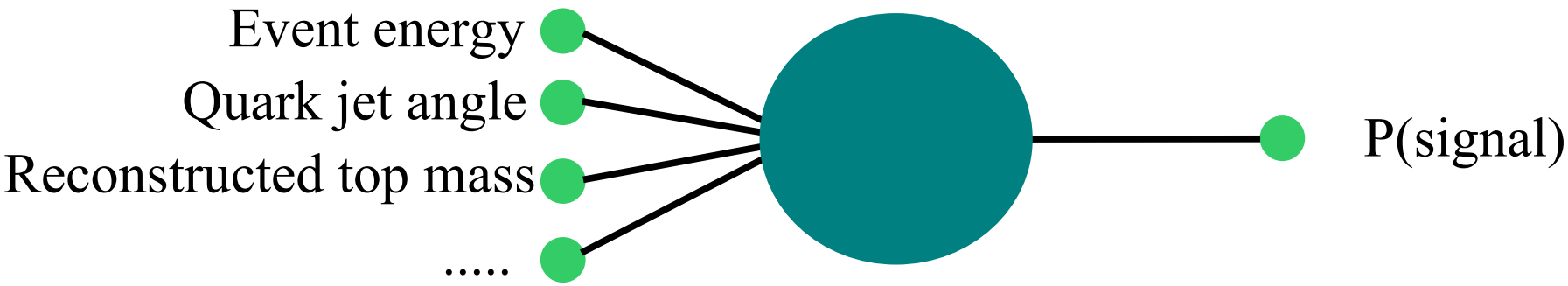
How do we find the needle in the haystack?

Multivariate methods

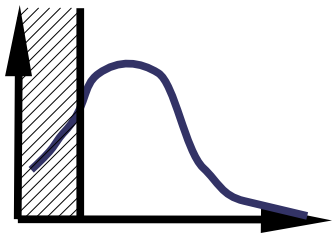
Input:
discriminating variables

Method:
multivariate analysis

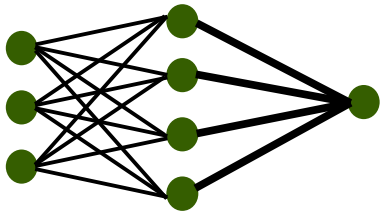
Output:
signal likelihood



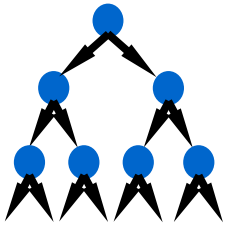
Cut-Based



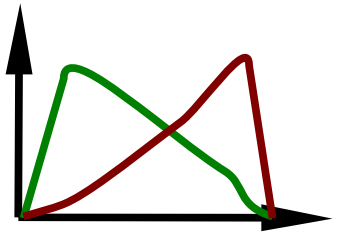
Neural networks



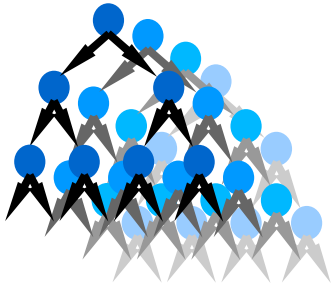
Decision trees



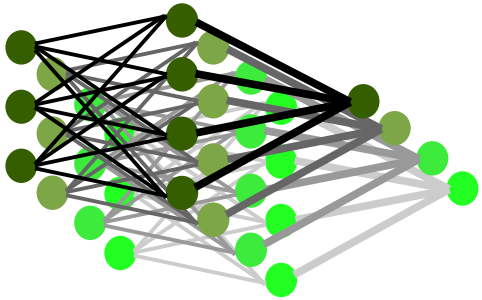
Likelihood



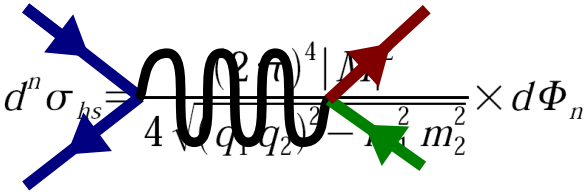
Boosted decision trees



Bayesian neural networks



Matrix Elements

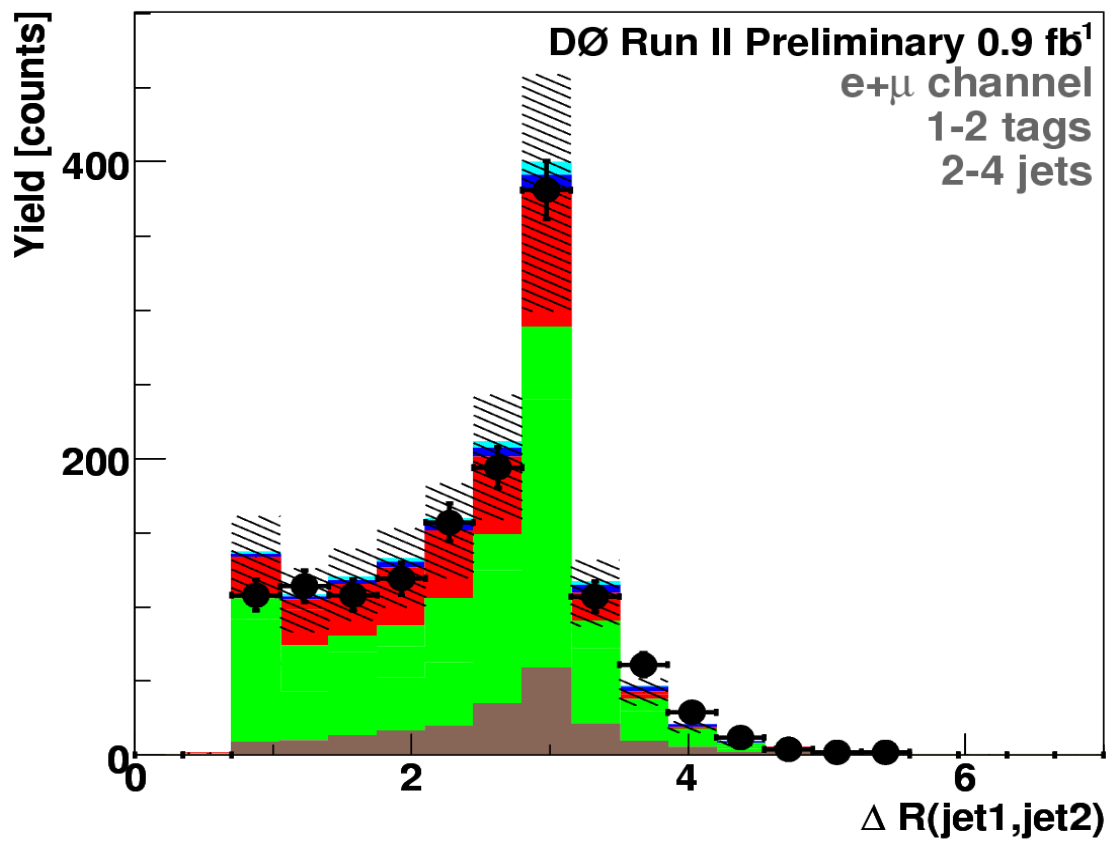


Discriminating Variables

- 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

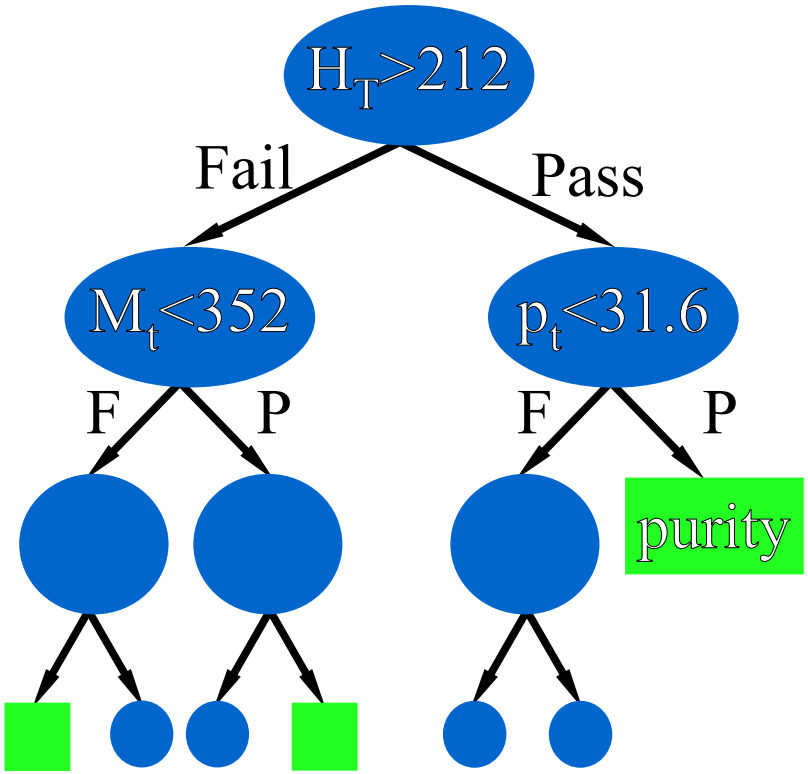
Object kinematics

Jet p_T for different jets

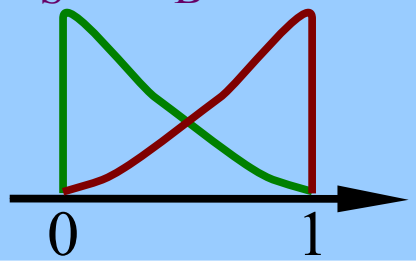


49 variables total

Decision Trees



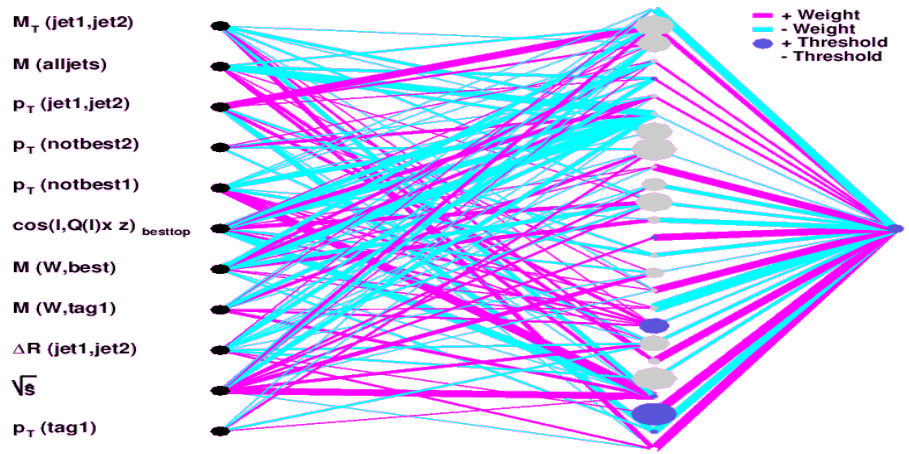
- Send each event down the tree
- Each node corresponds to a cut
  - Divide sample in two: Pass↔Fail
- A leaf corresponds to a node without branches
  - Defines purity = $N_S/(N_S+N_B)$ from MC sample
- Training: optimize Gini improvement
  - Gini = $2\, N_S\, N_B\, /(N_S + N_B)$
- Output: purity for each event



- Boosting: average over many trees (~100)
  - Iterative tree building: train each new tree focusing more and more on misclassified events

Bayesian neural networks

- NN with three layers
  - 24 in put nodes (variables)
  - 40 hidden nodes
  - Each node and each connection has a weight



- Bayesian Idea:
  - Rather than finding one value for each weight, use many values
  - Determine the posterior probability for each weight
  - Sample from the posterior
- In this case, 100 individual neural networks
  - Each network gets a weight based on training performance

Matrix Elements

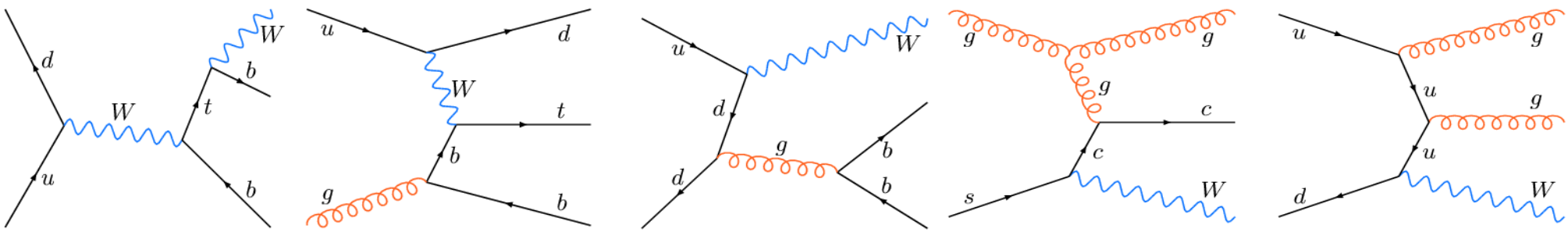
- Calculate signal discriminant directly for each event

$$D_s(\vec{x}) = P(S|\vec{x}) = \frac{P_{Signal}(\vec{x})}{P_{Signal}(\vec{x}) + P_{Background}(\vec{x})}$$

- Signal/Background probabilities are calculated from the differential cross section

$$P_{Signal}(\vec{x}) = \frac{1}{\sigma_S} d\sigma_S(\vec{x}) \quad \sigma_S = \int d\sigma_S(\vec{x})$$

- Calculate differential cross section for each event based on Feynman diagram and event kinematics



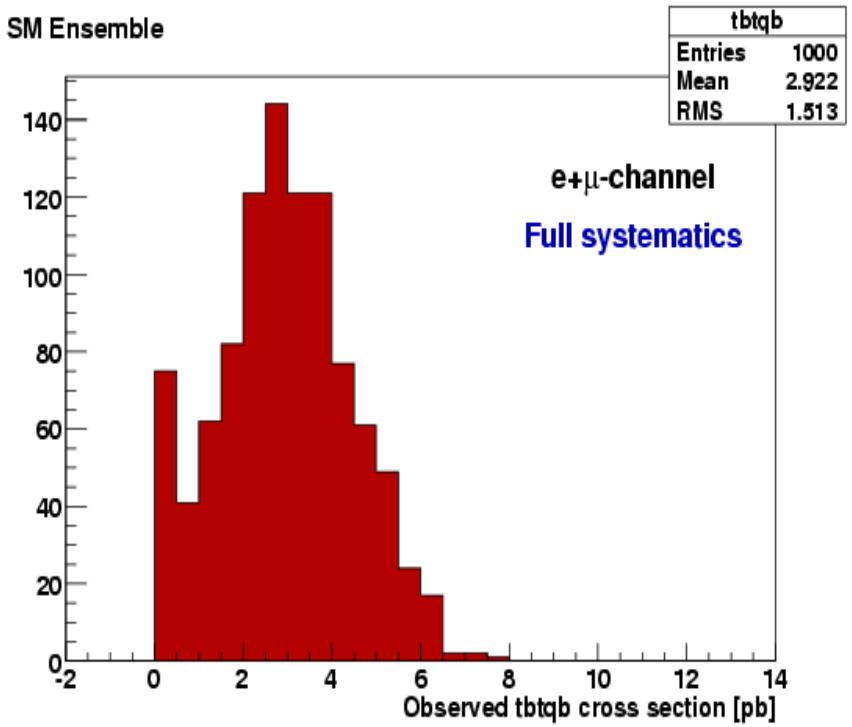
- Integrate over ME and measured momenta

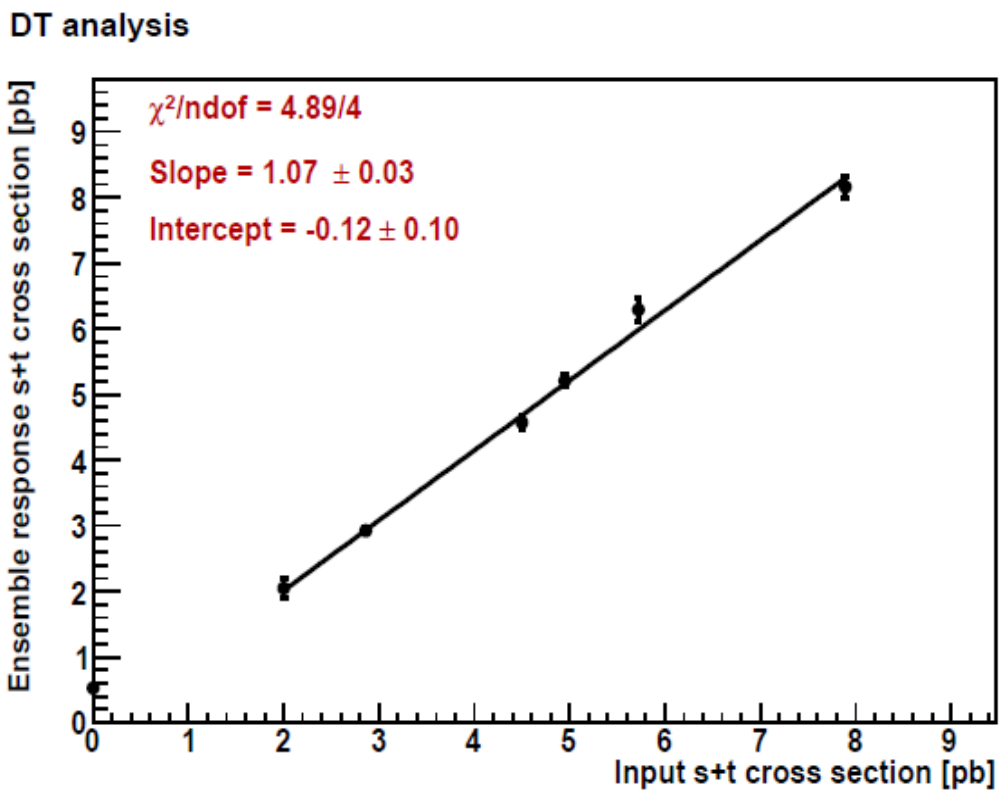
Results

Let Data speak!

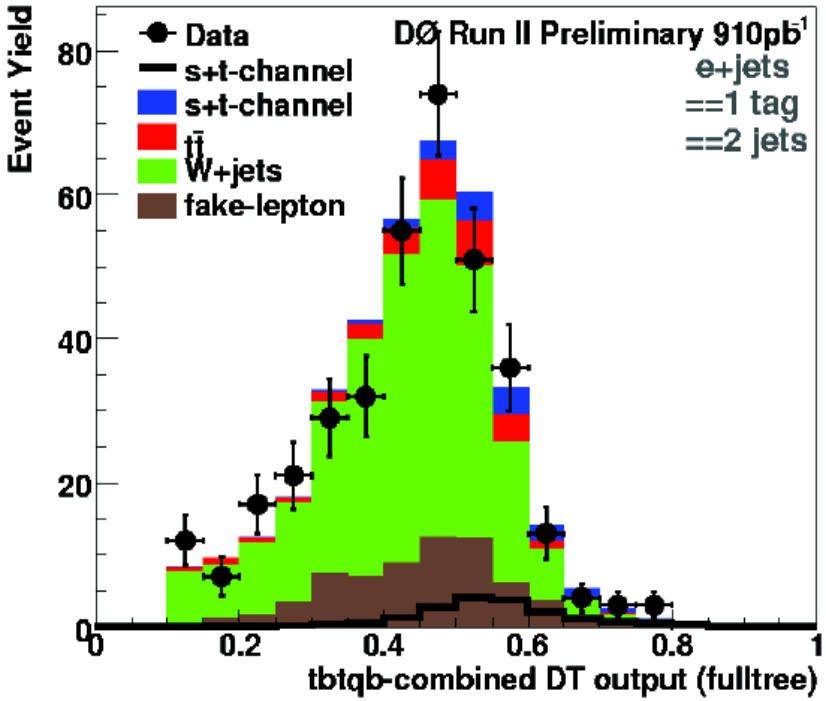
Ensemble Tests

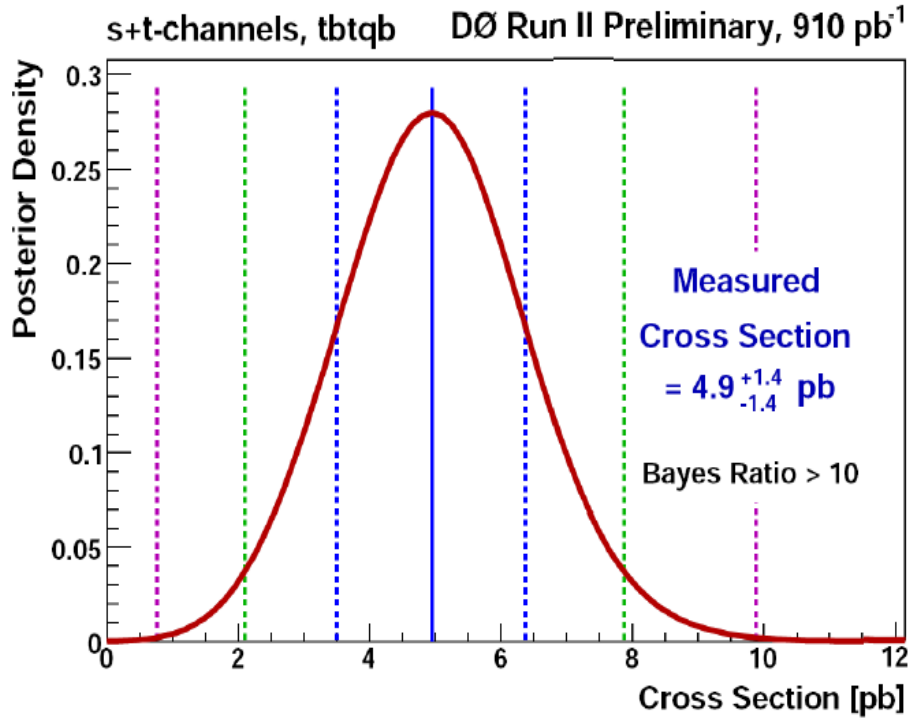
- Draw ~1,000,000 "pseudo-data" sets of events from the signal+background MC
  - Bootstrap with replacement
  - Several different signal XS values
- Repeat full statistical analysis and measure σ for each

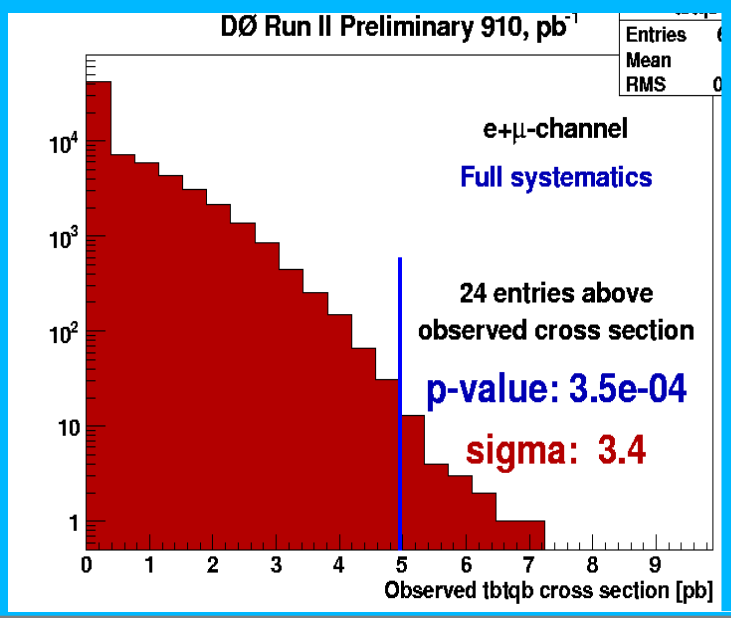


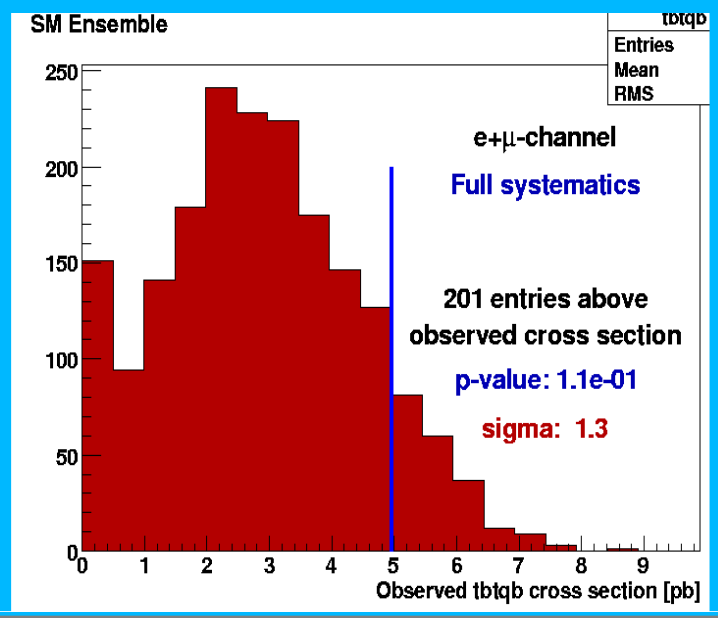


Boosted Decision Trees

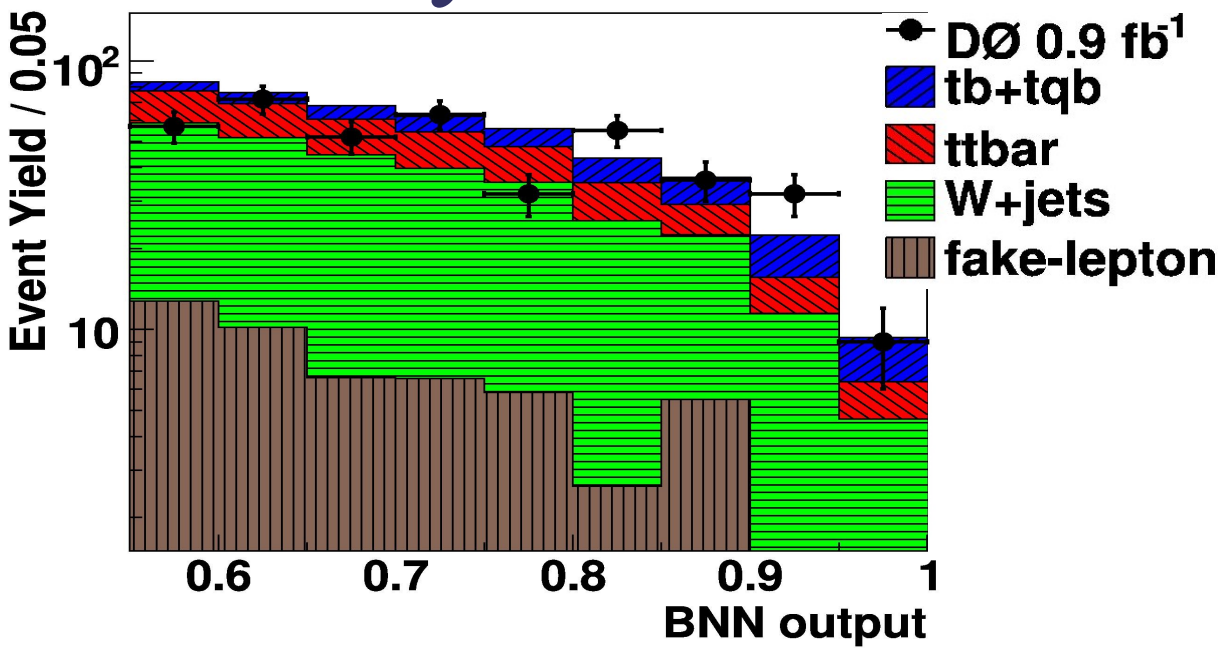


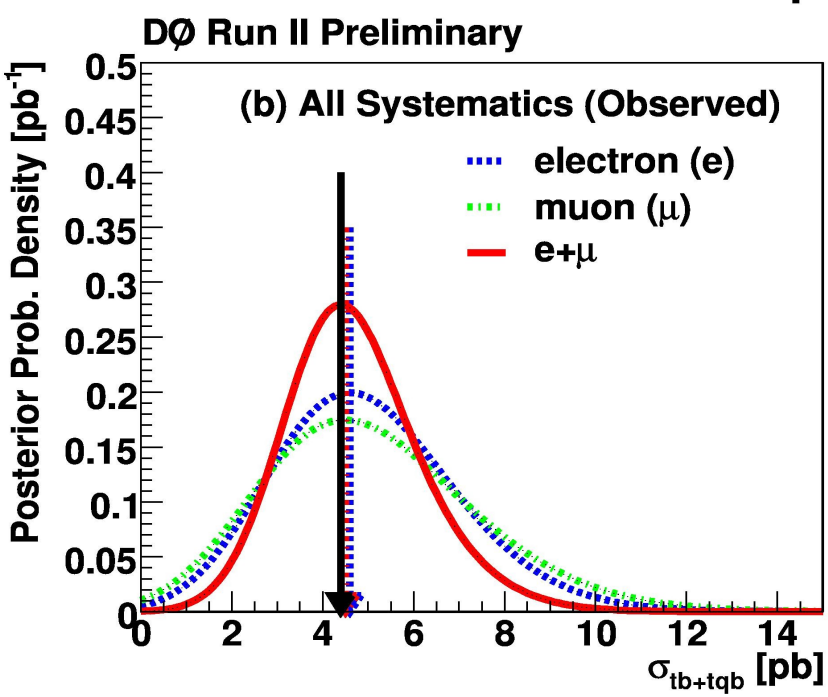


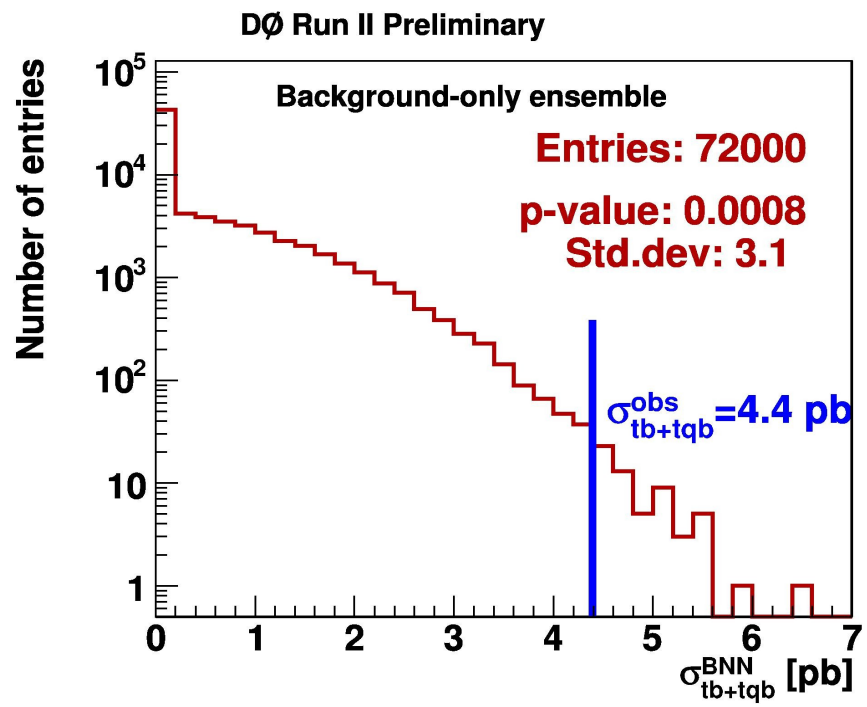




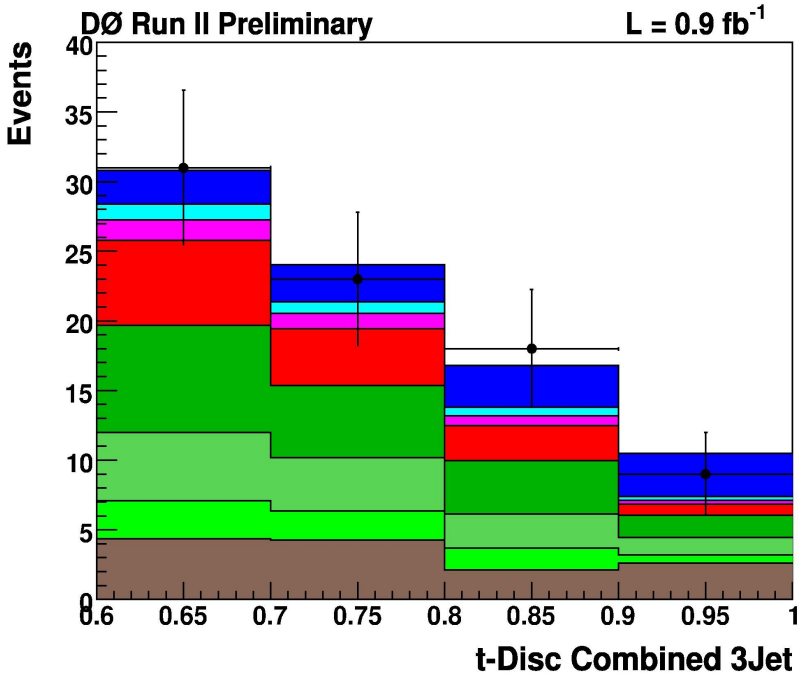
Bayesian Neural Network

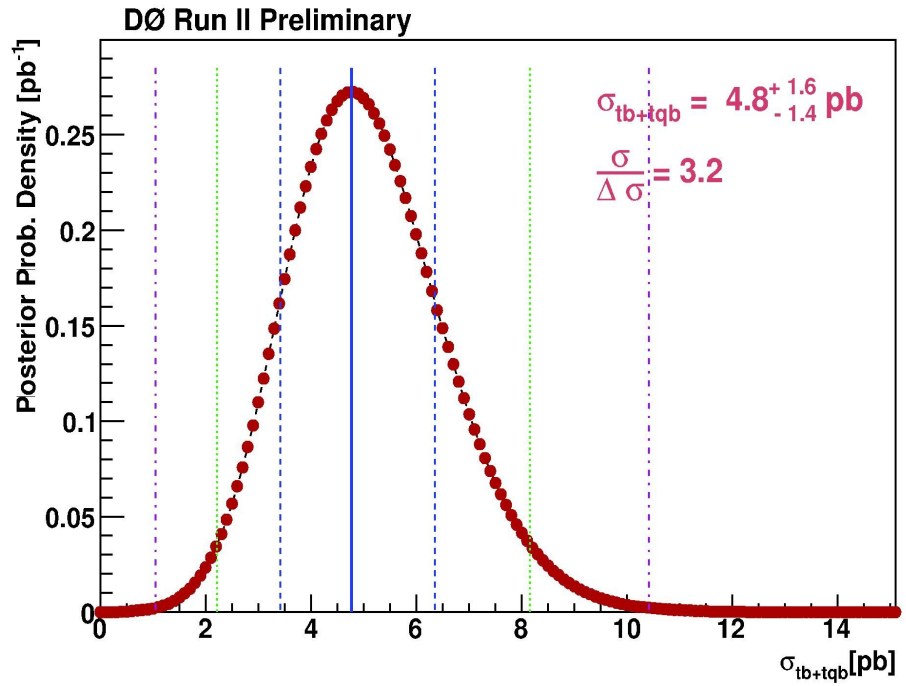


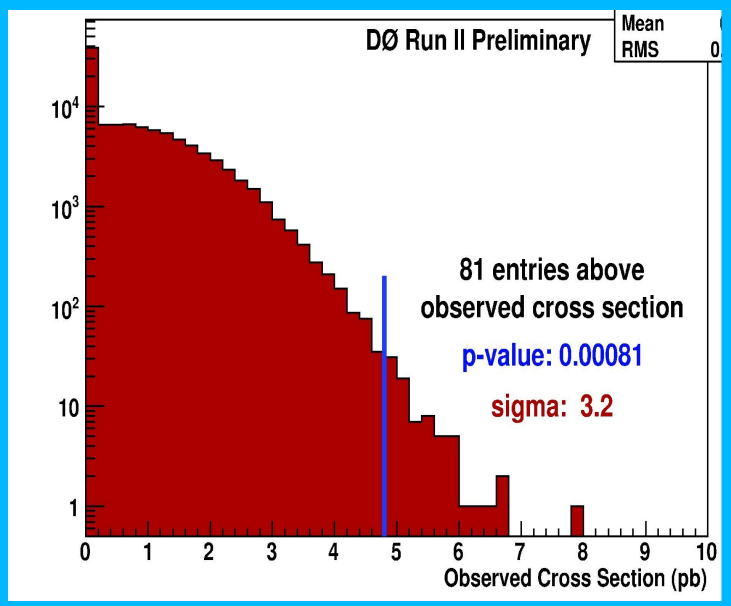


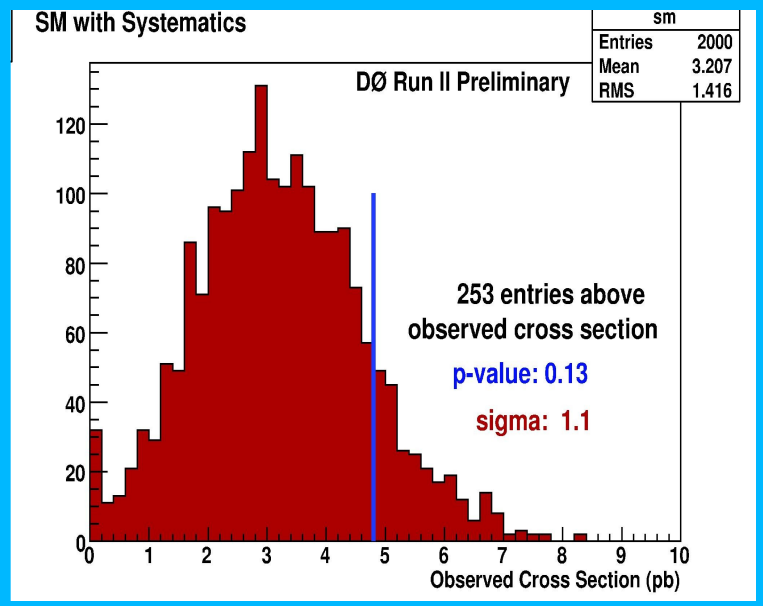


Matrix Element

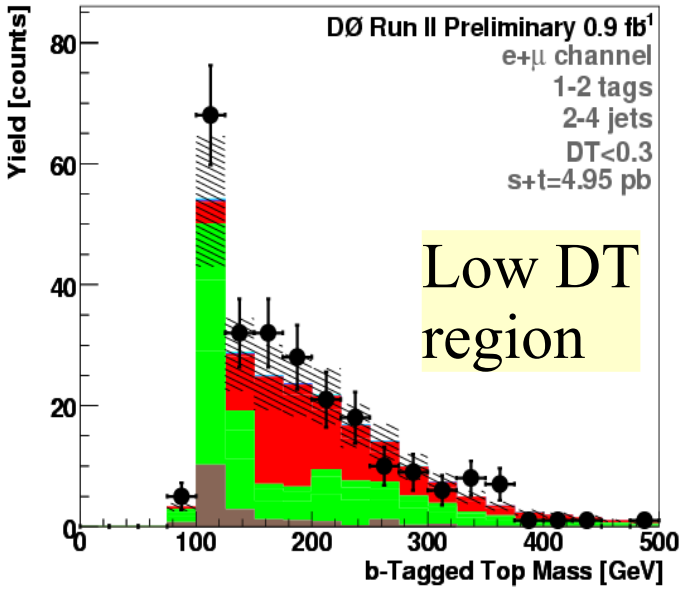


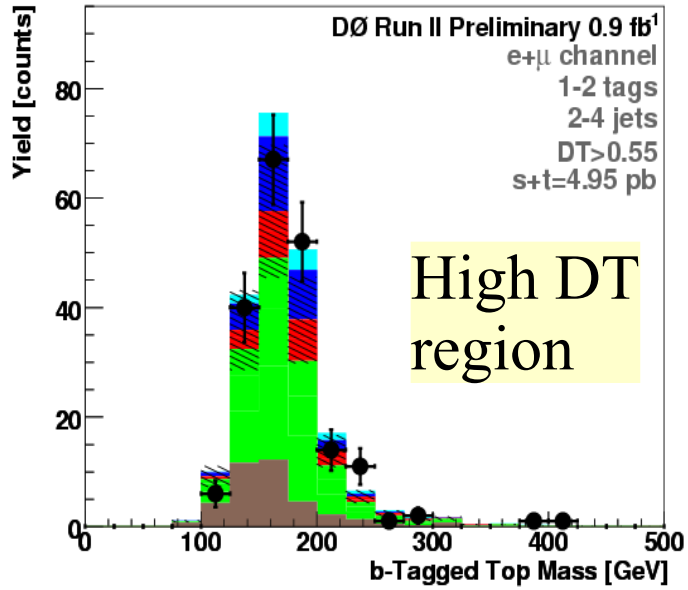


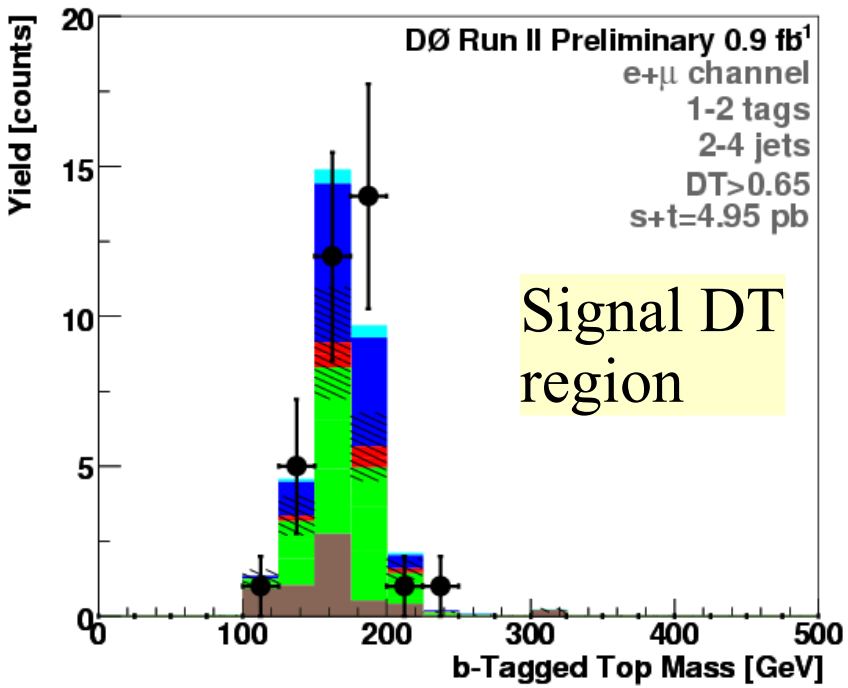




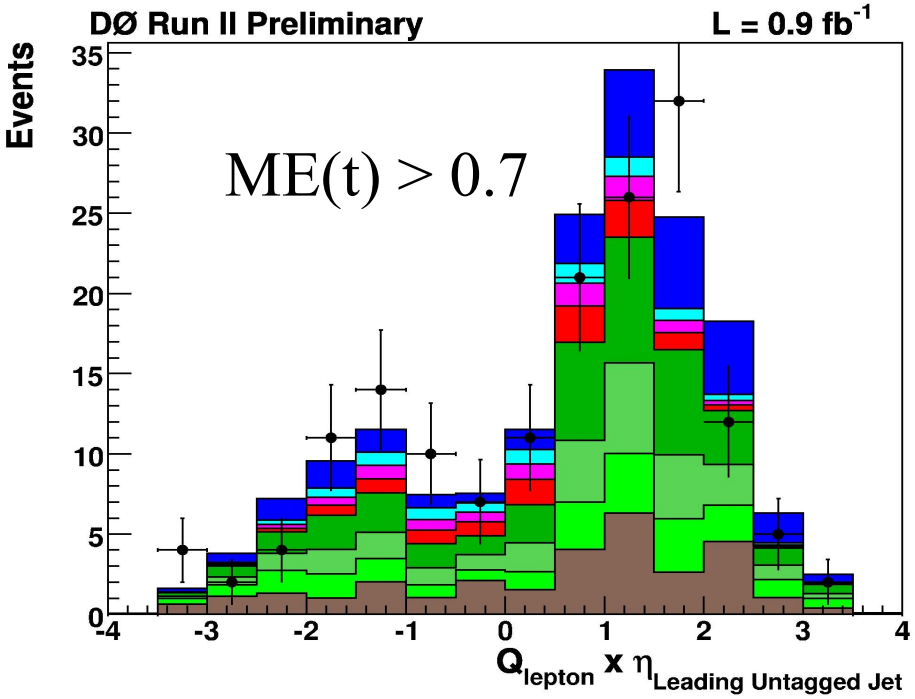
Reconstructed top quark mass

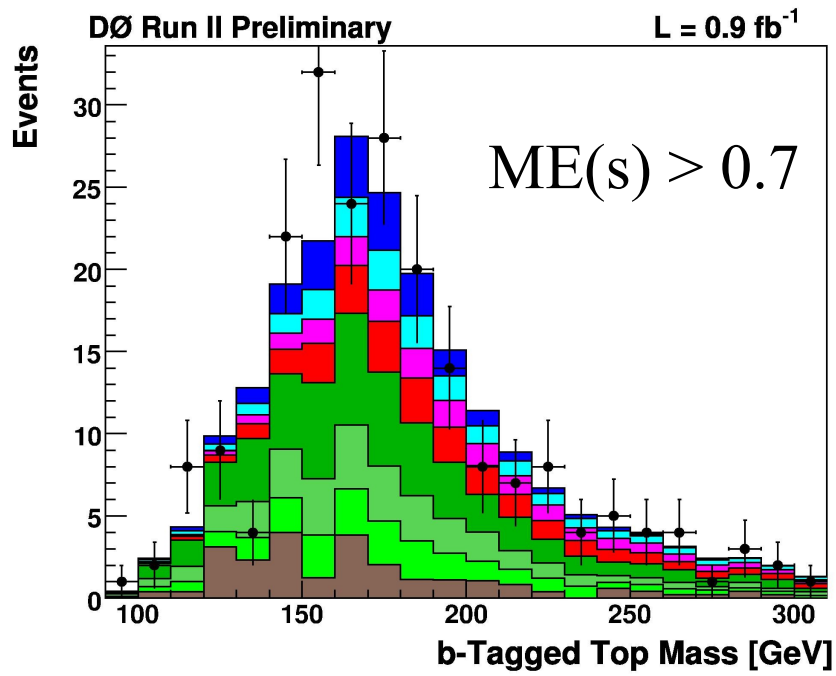


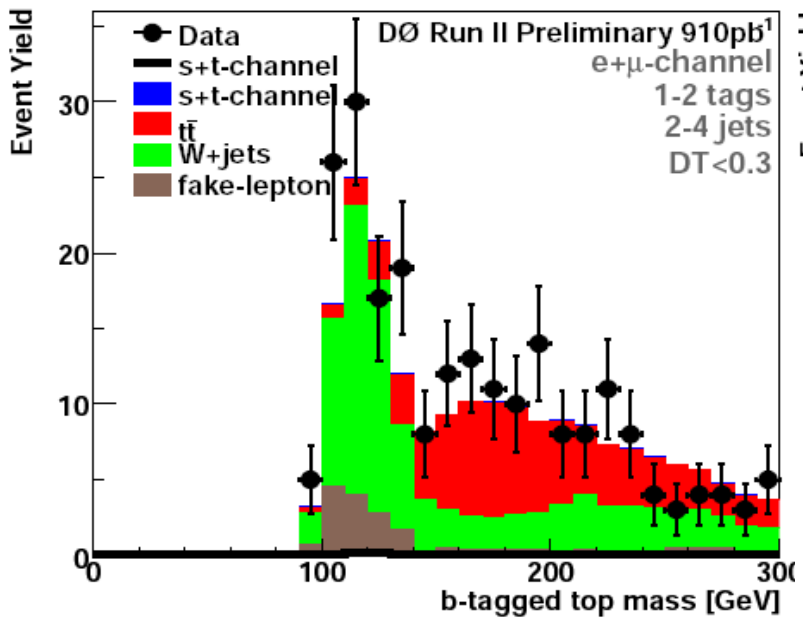


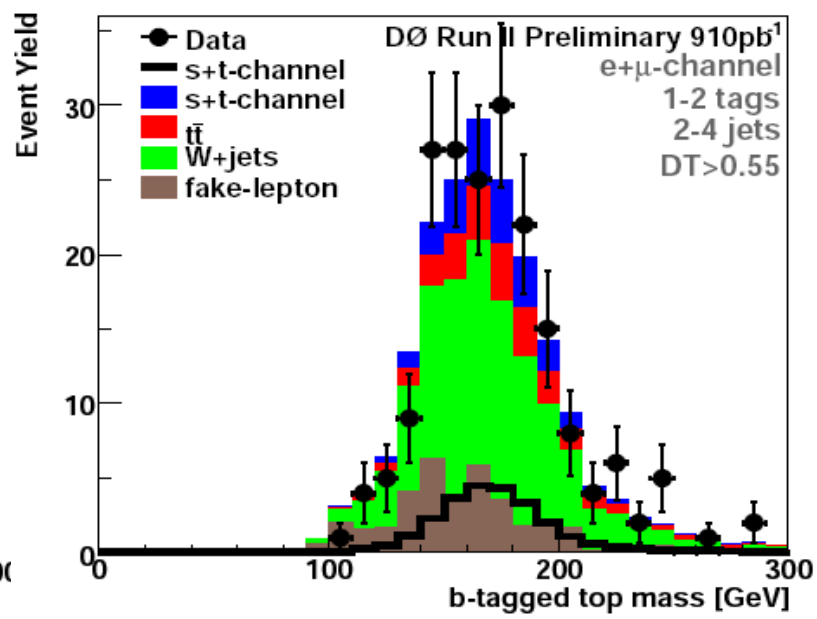


Variables after cut on likelihood

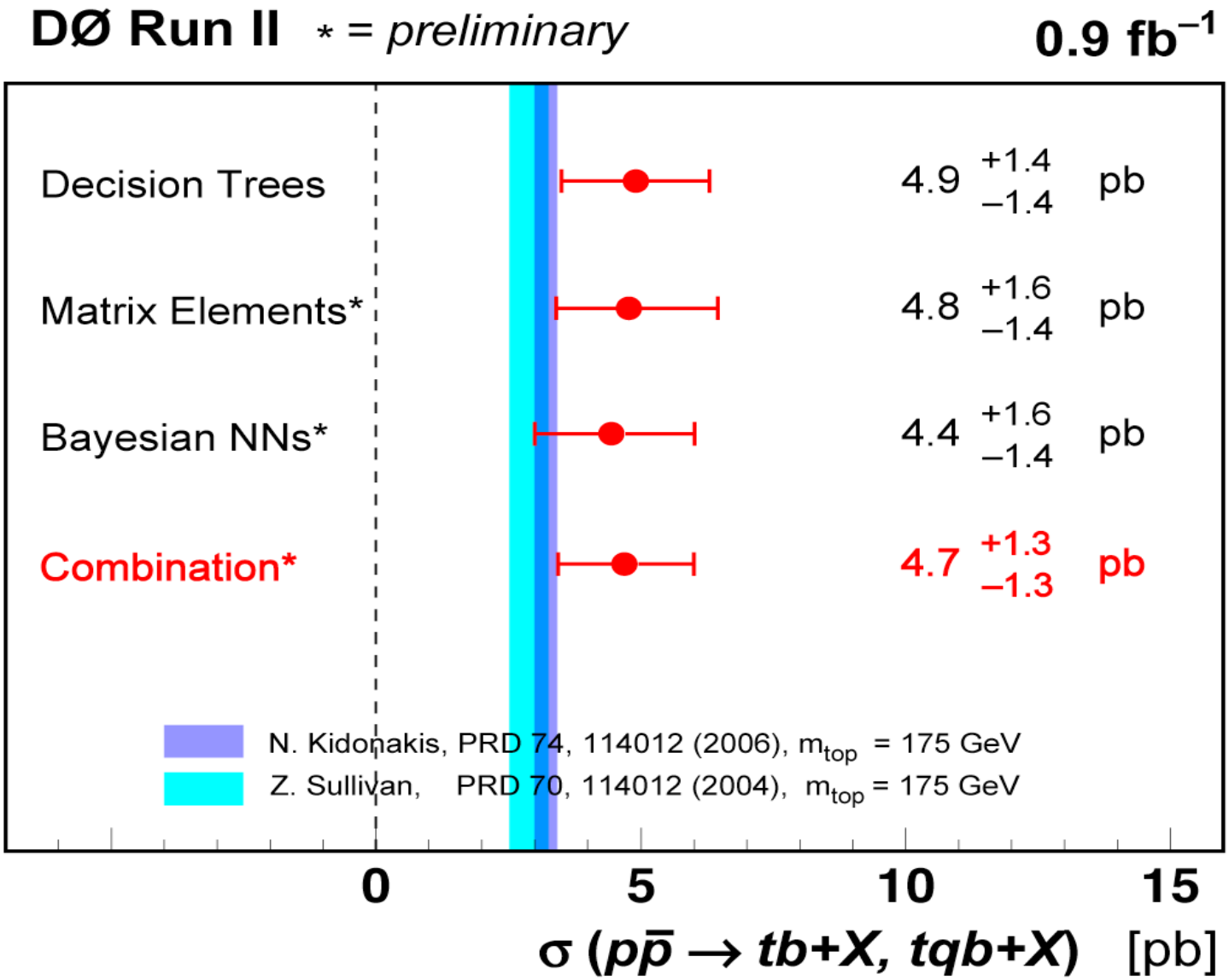




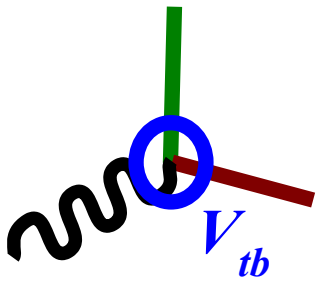




Single top summary



CKM matrix element $|V_{tb}|$

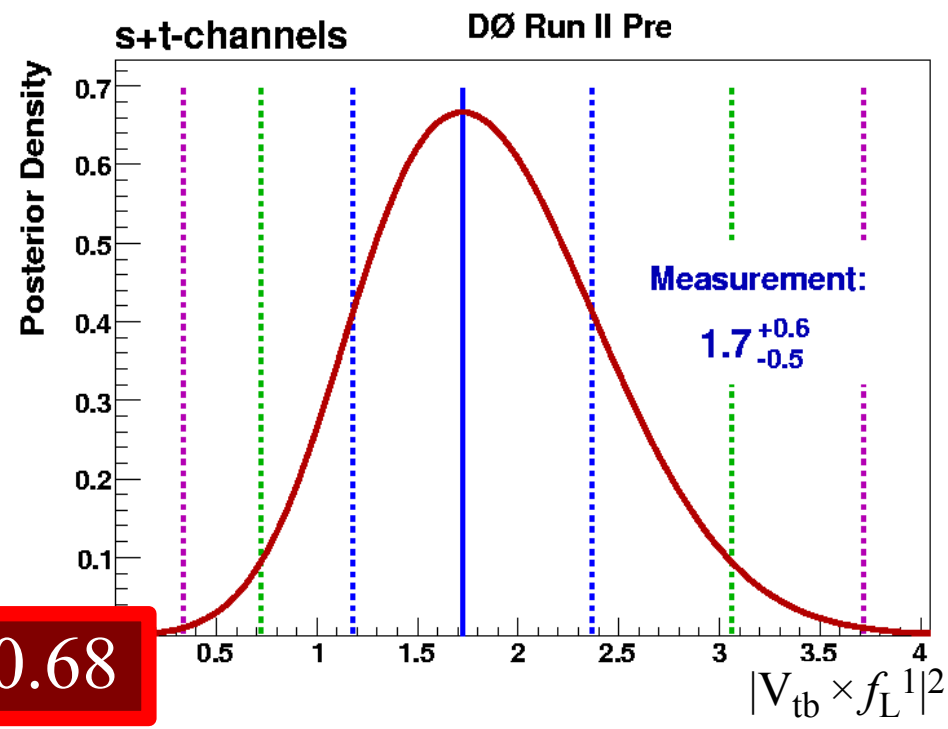


CKM Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

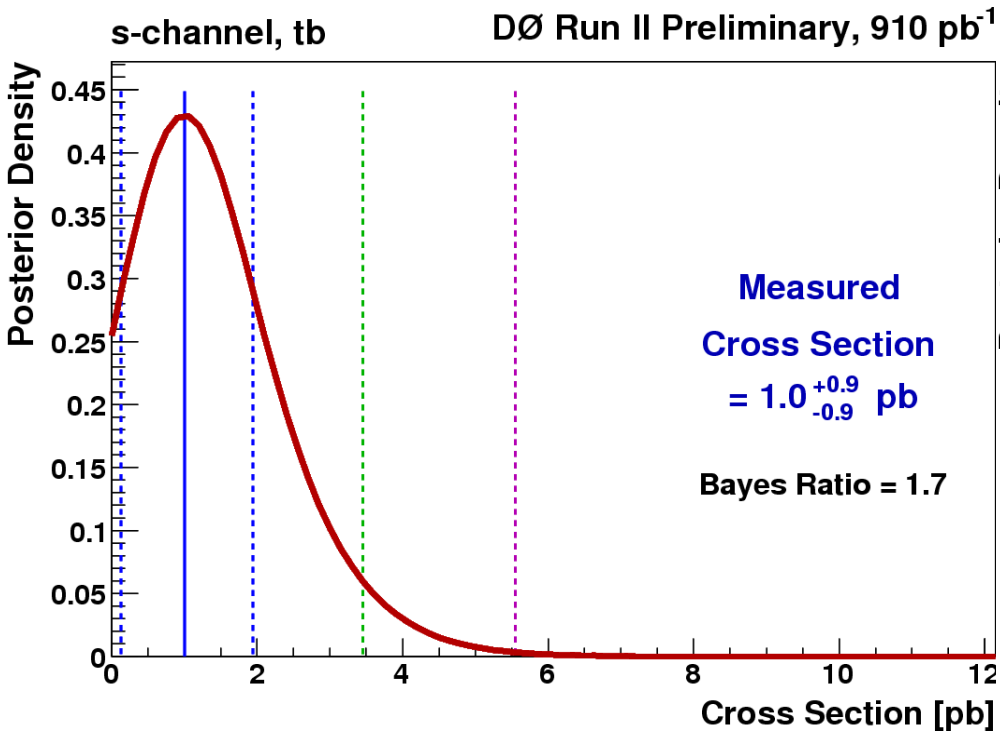
- Measurement: $|V_{tb} \times f_L^1|$
  - Based on DT result
  - Include XS uncertainties
  - Assume SM top quark decay
- No constraint on # of generations
- Assume $f_L^1 = 1$

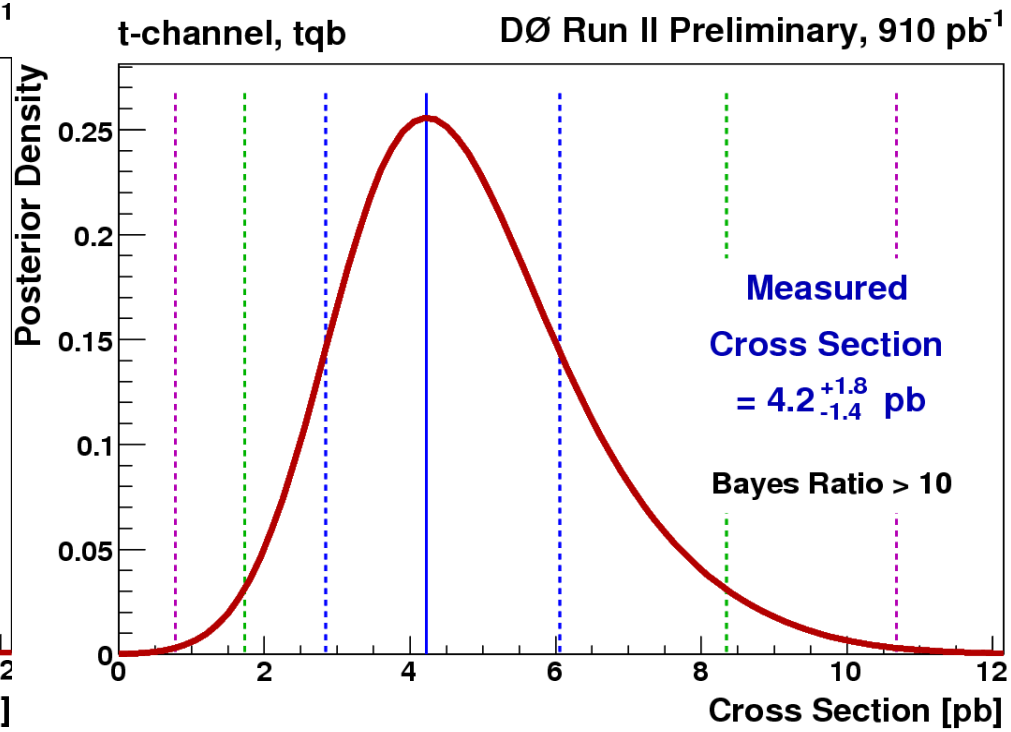
  $\rightarrow$ lower limit on V_{tb}
- At the 95% C.L.: $|Vtb| > 0.68$



Separate s-channel and t-channel analyses

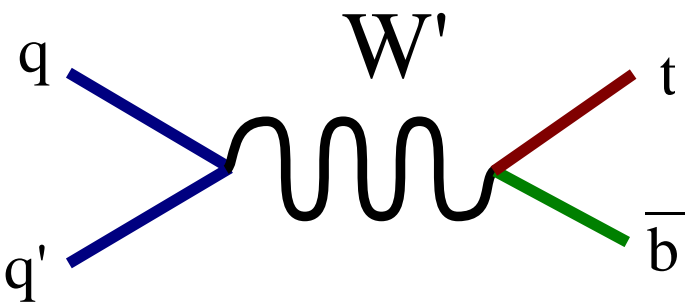
- Train filters individually for s-channel and t-channel
- Repeat statistical analysis
- DT result:

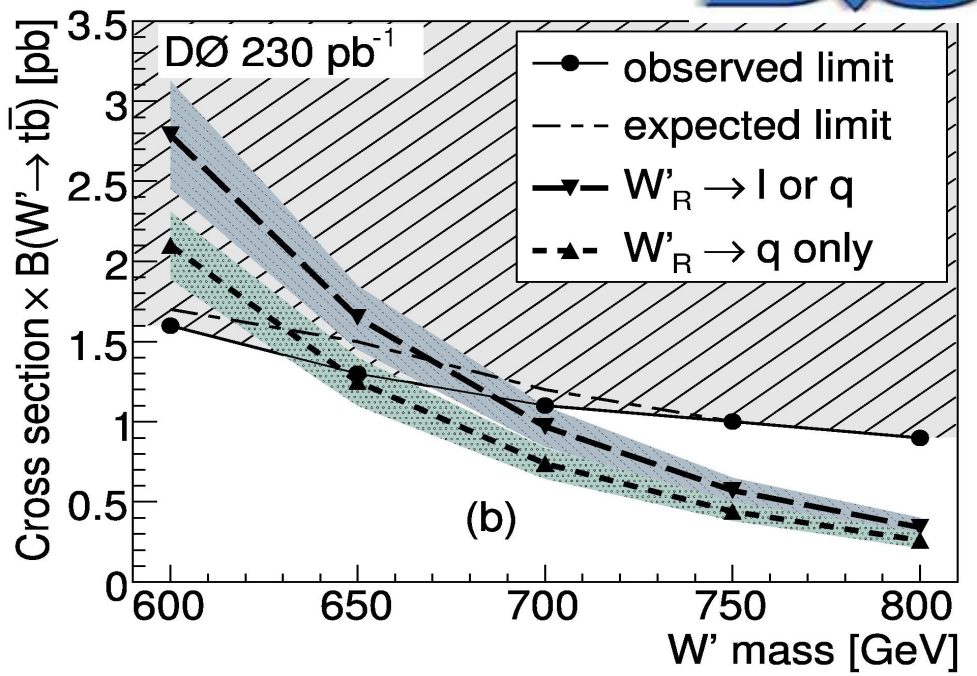




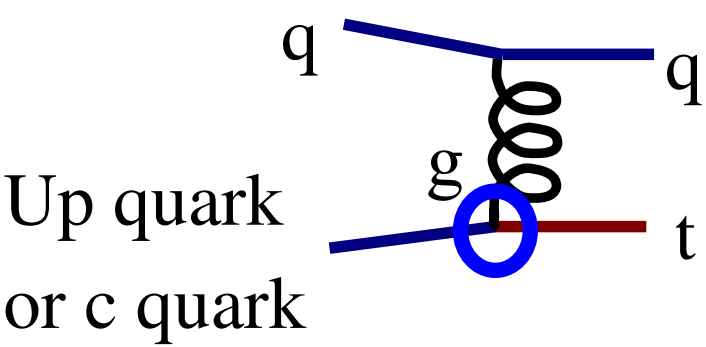
Searches for new physics in single top

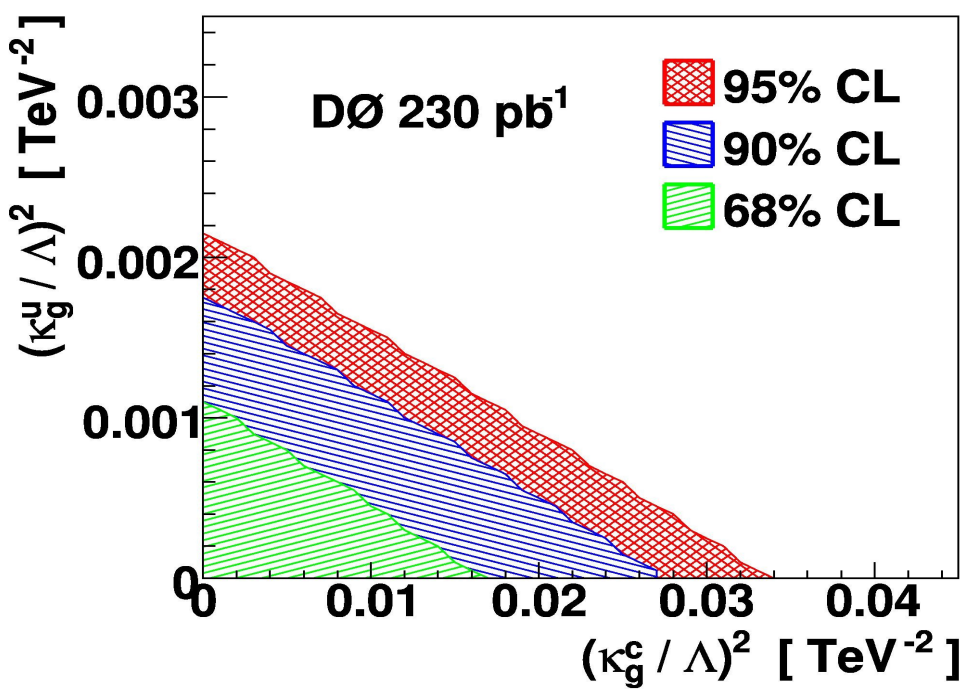
- Searches for new heavy boson W'



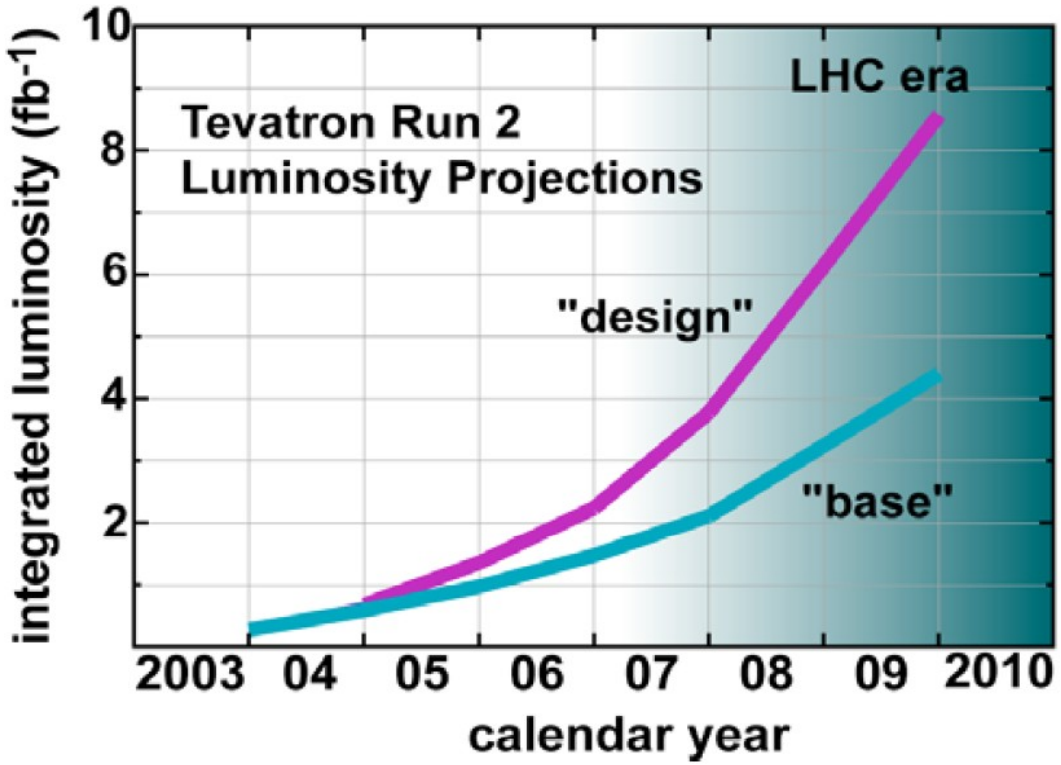


- Flavor-changing neutral currents





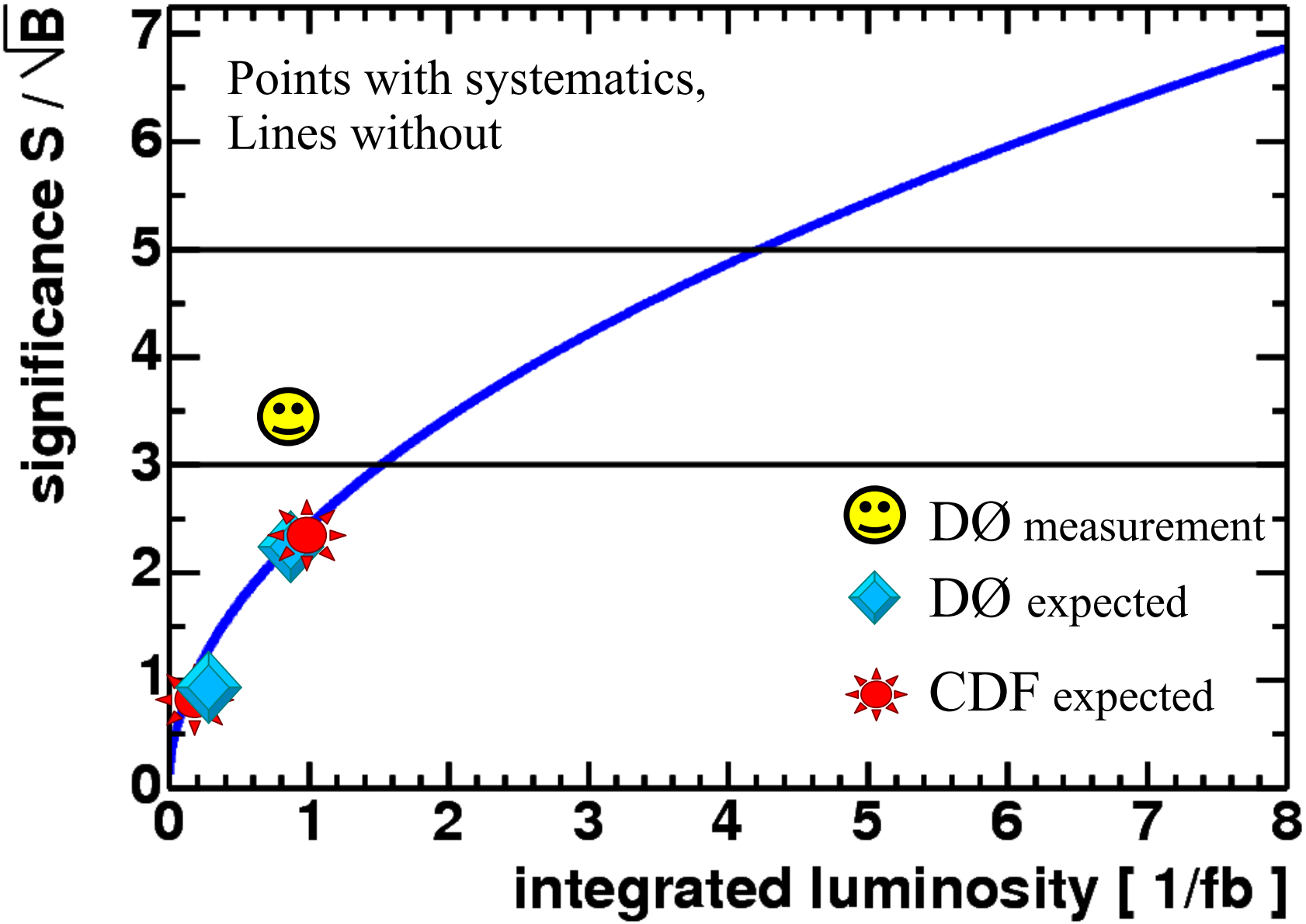
The future



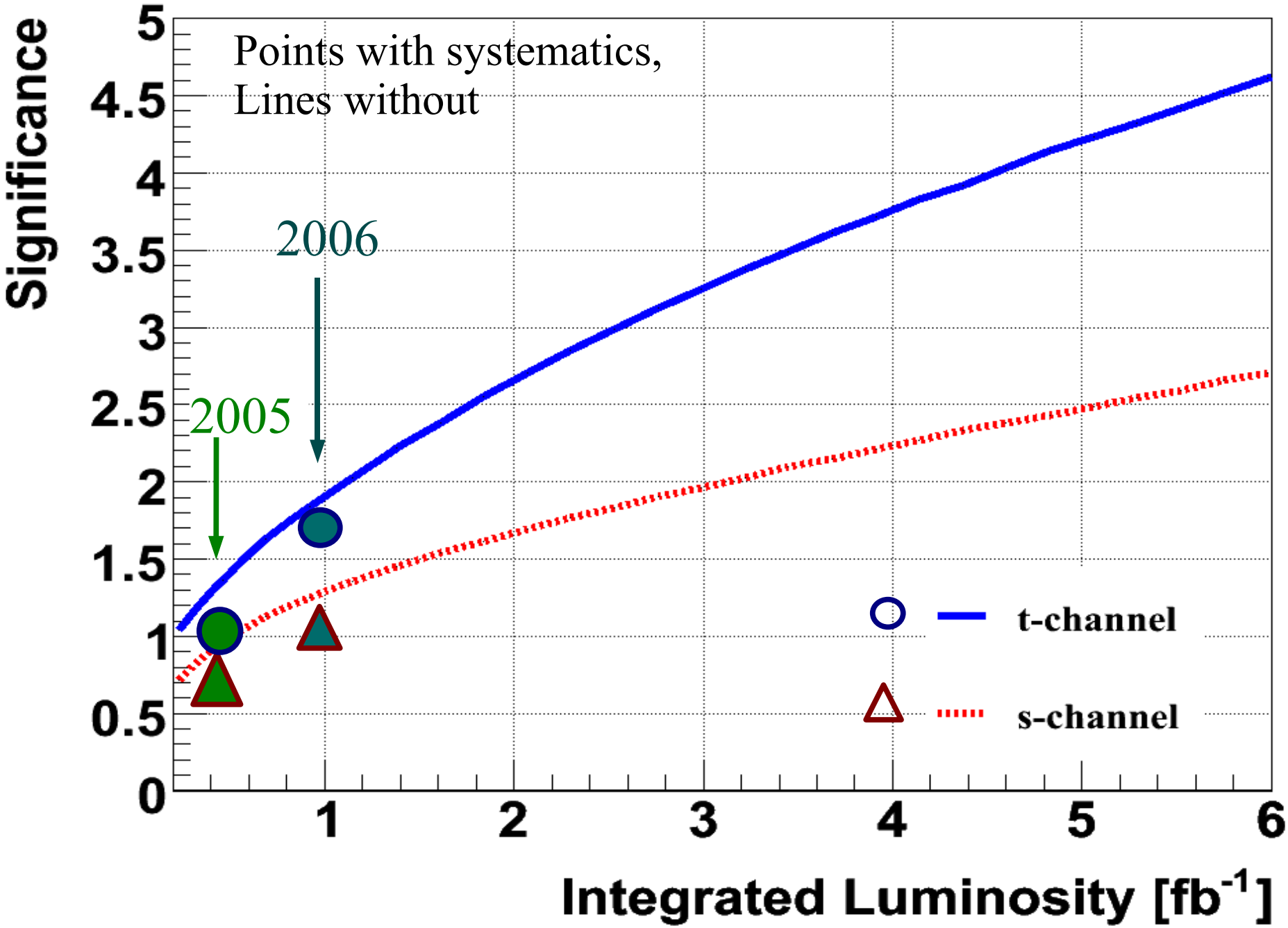
- We will likely be analyzing 4 fb^{-1} in 2009
  - Possibly already in 2008

Prospects for s+t

Projection by CDF for P5 in 2005



Prospects for s and t separately



Conclusions/Outlook

- The Tevatron experiments are getting to know the top quark very well
- We have 3.4 σ evidence for single top quark production
  - $|V_{tb}| > 0.68$ at the 95 % C.L.
- Outlook:
  - Tevatron dataset will increase ×5 in next 2 years
  - Single top goals:
    - 5 sigma observation
    - Separate s-channel from t-channel
    - Measure top quark spin correlation