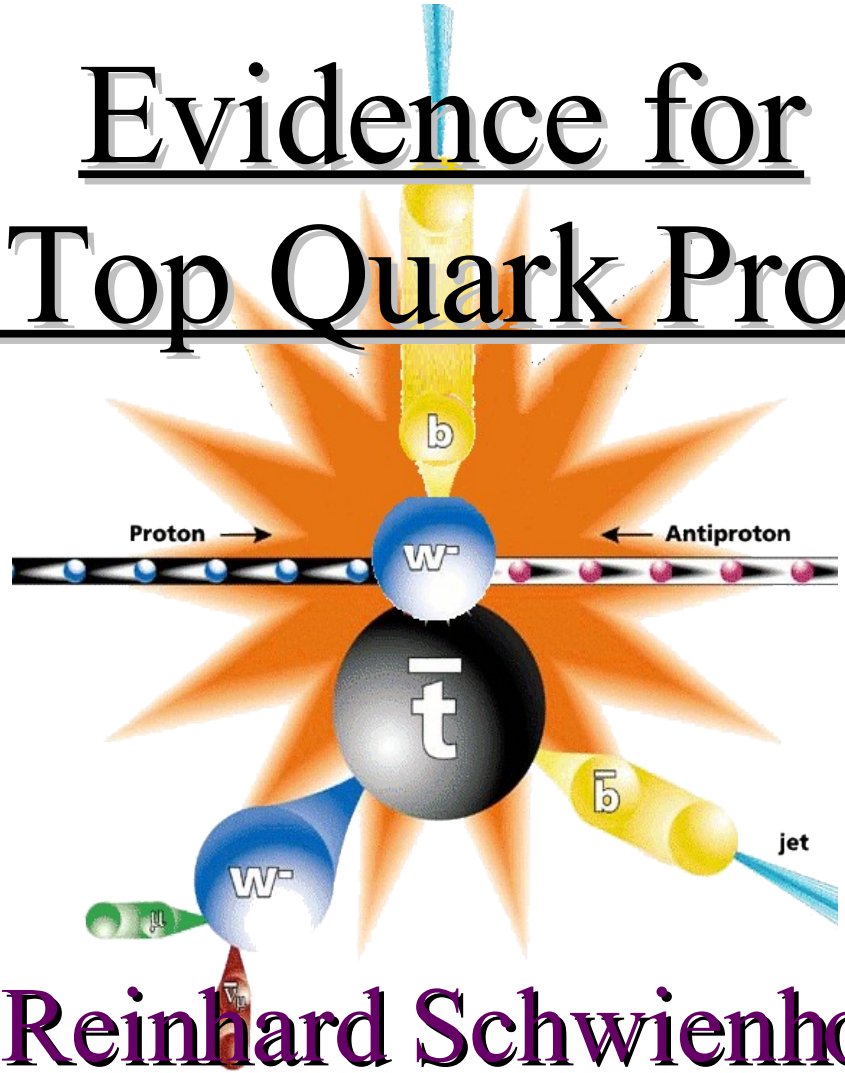
Evidence for Single Top Quark Production



Reinhard Schwienhorst

MSU high energy seminar, 1/9/2007

Outline

- Motivation
- Preparation
- Optimized Event Analysis
- Sensitivity
- Cross section measurement
- $|V_{tb}|$
- Conclusions/Outlook

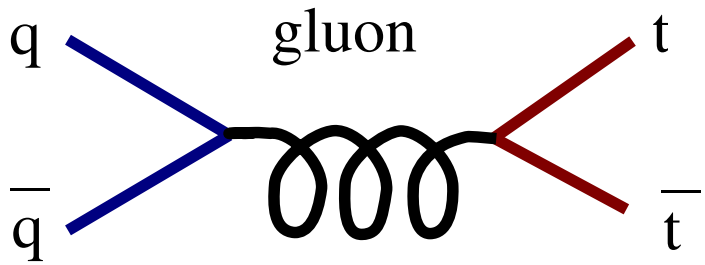
- Emphasis on what's new and different compared to previous analyses

Motivation

What is single top
and
why does it matter?

Top Quark properties:

- Mass, strong coupling



Top Quark properties:

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

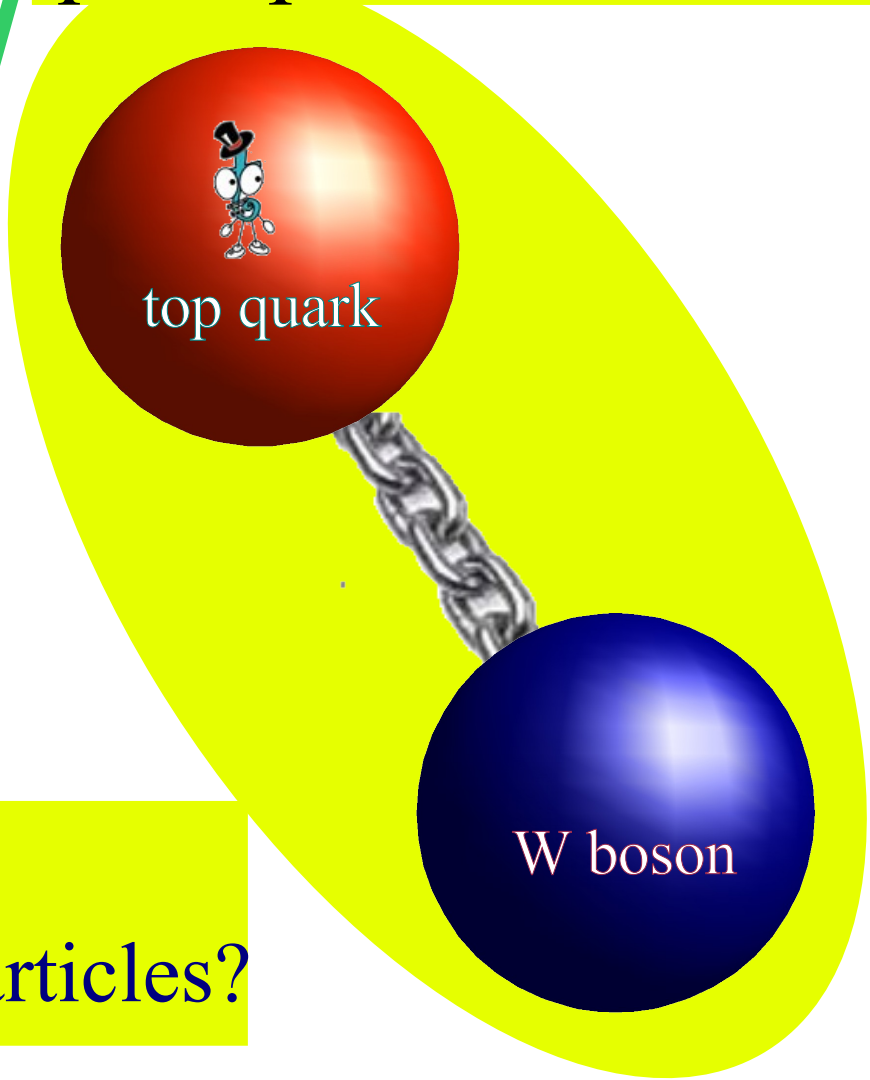
New physics?

- Coupling to Higgs?
- Modified weak coupling?
- SUSY? Coupling to new particles?

Top Quark properties:

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

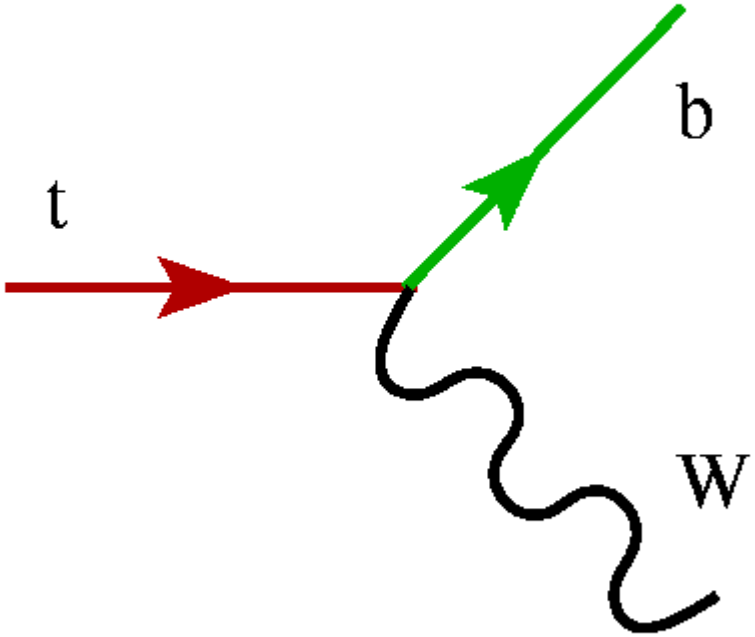
Study in single top quark production



Really don't know:

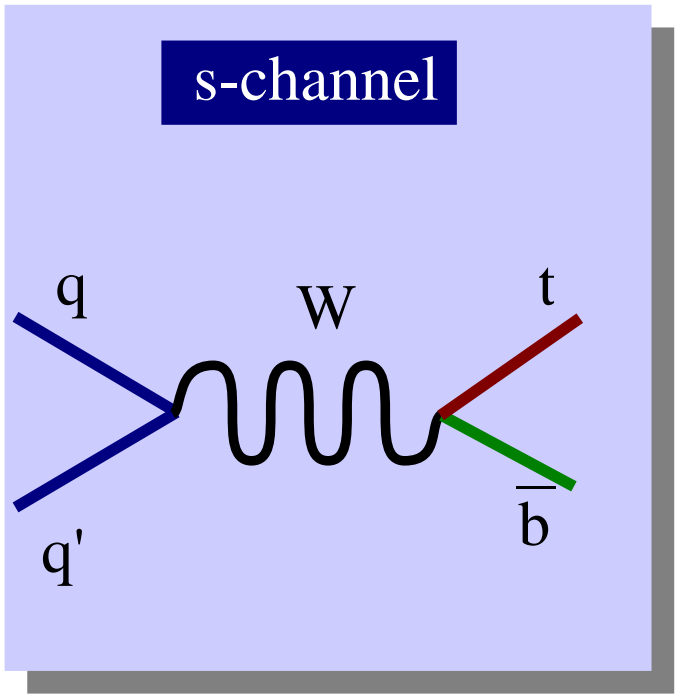
- Coupling to Higgs?
- Modified weak coupling?
- SUSY? Coupling to new particles?

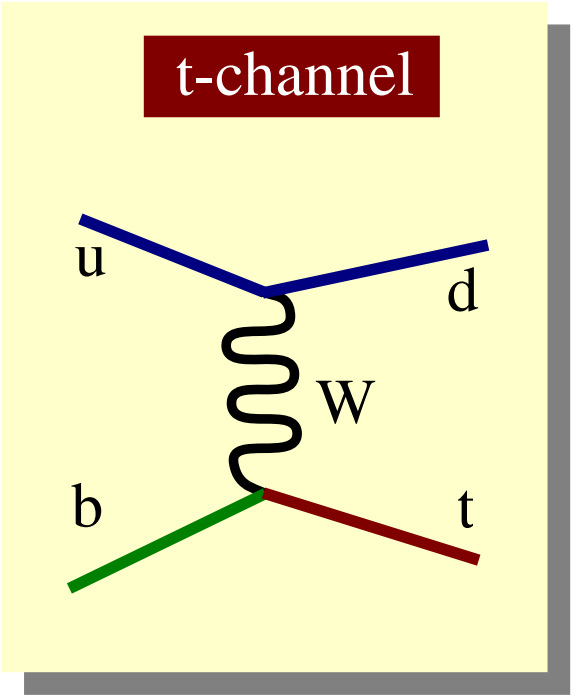
Top quark electroweak charged current interaction

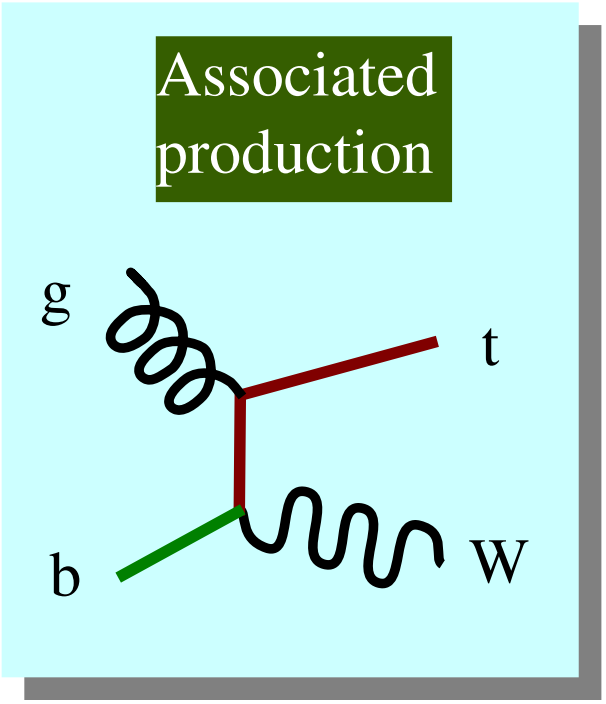


top quark decay

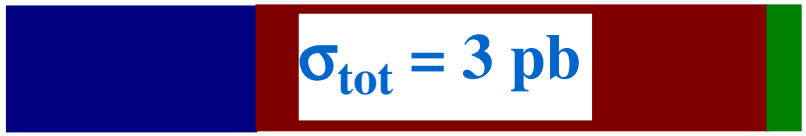
SM single top quark production







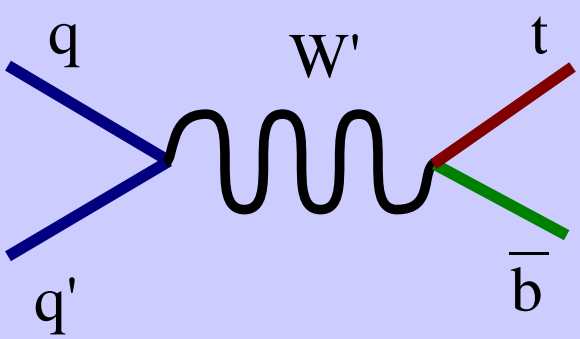
TeV:



LHC:

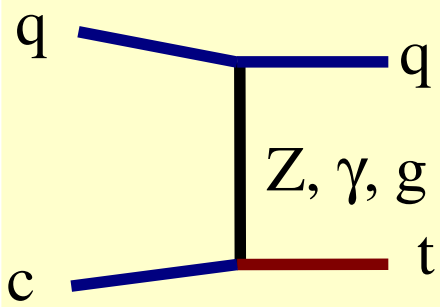
New physics

s-channel



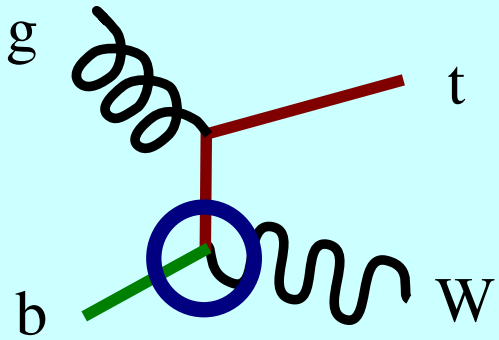
New heavy boson

t-channel



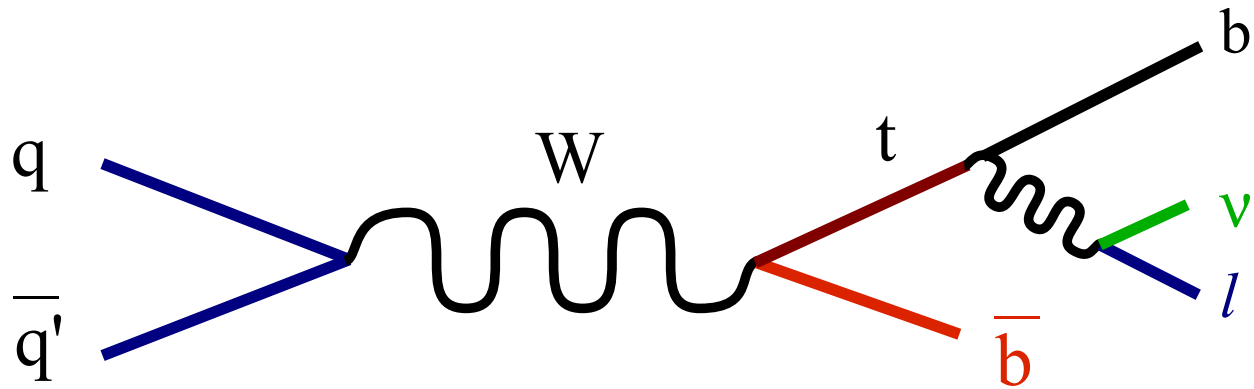
Flavor Changing Neutral Current

Associated production

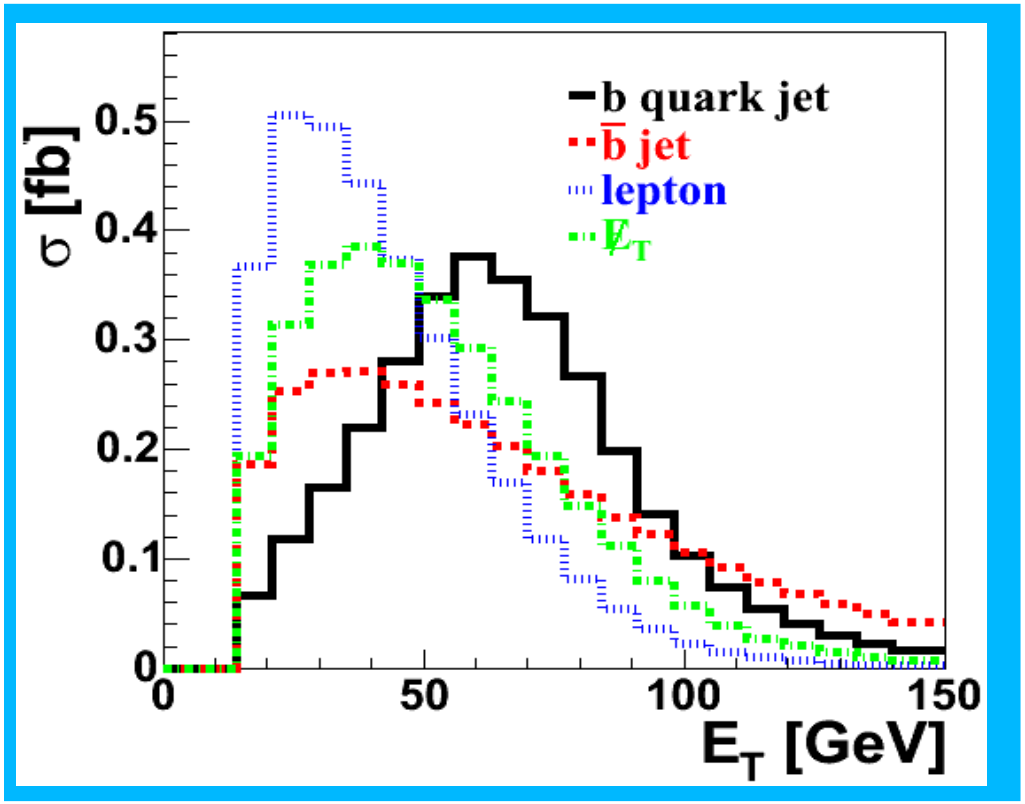


Modified Wtb coupling

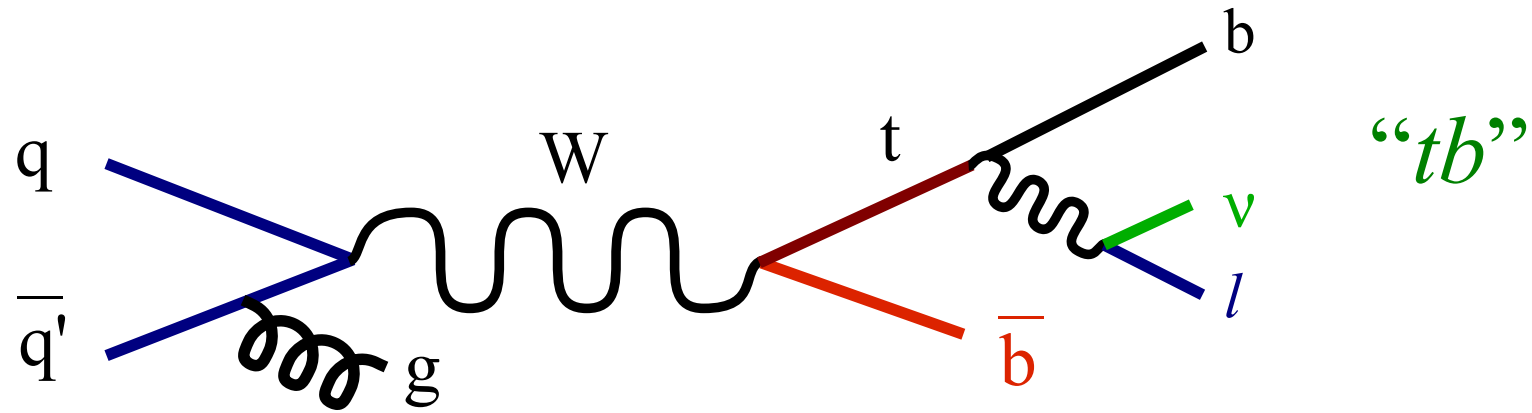
Tevatron s-channel signature

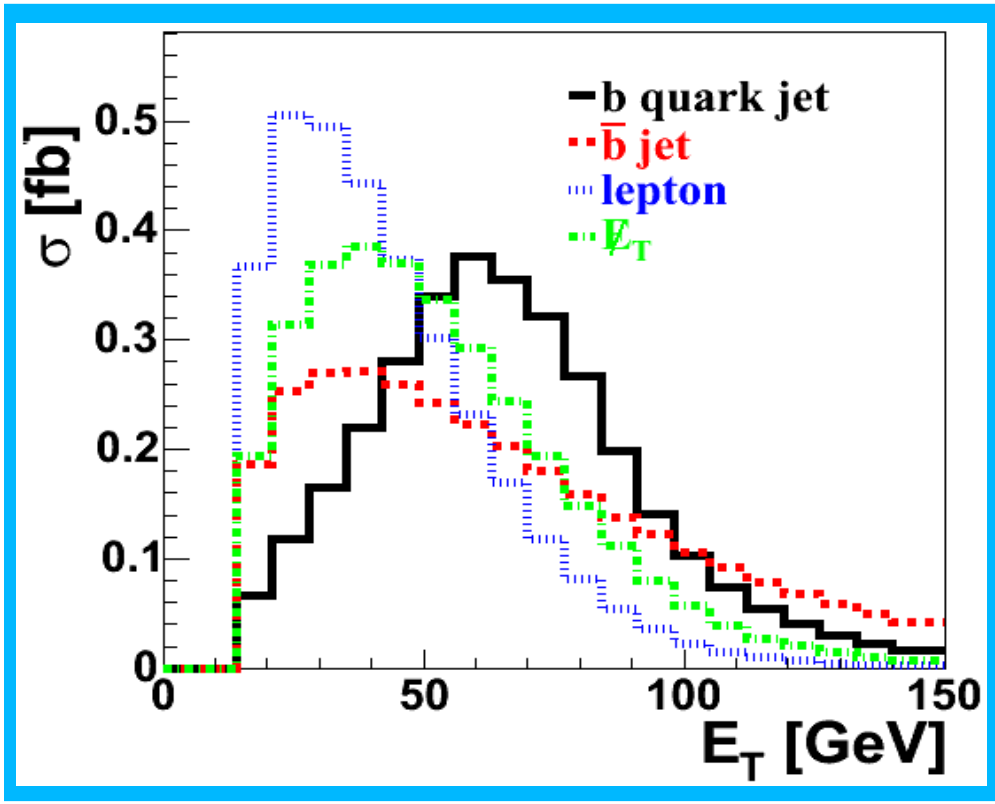


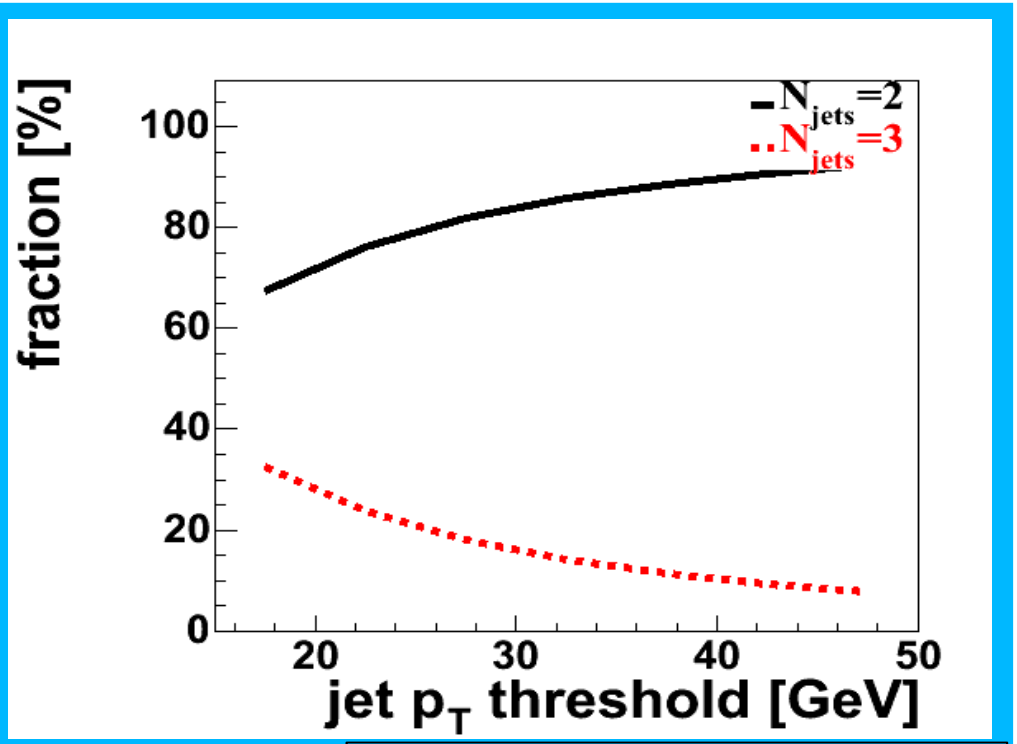
"*tb*"



Tevatron s-channel signature

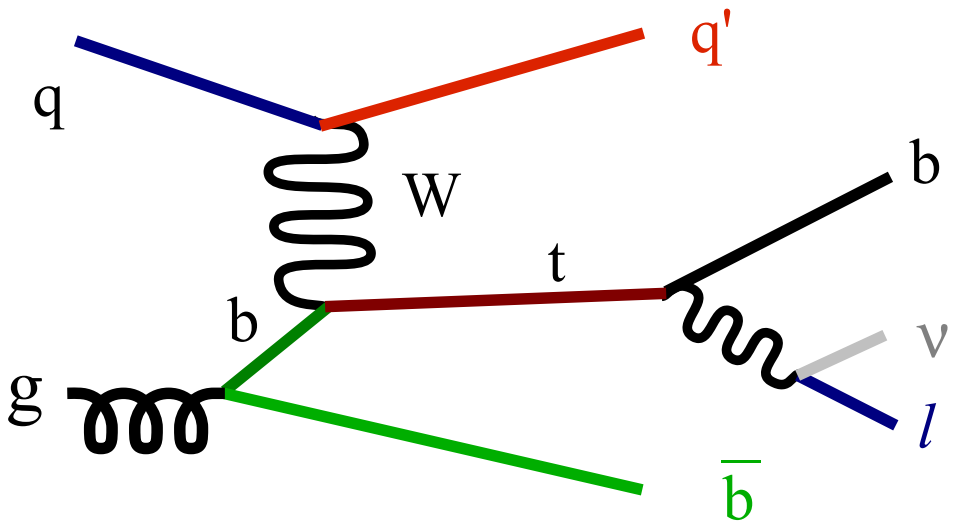




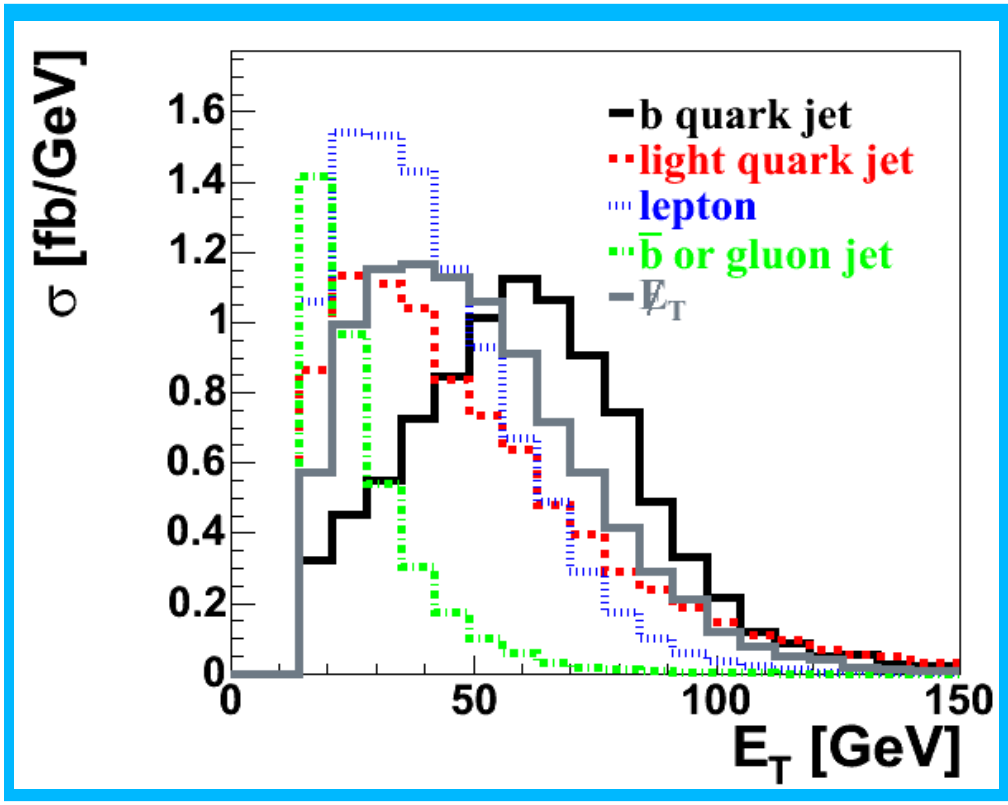


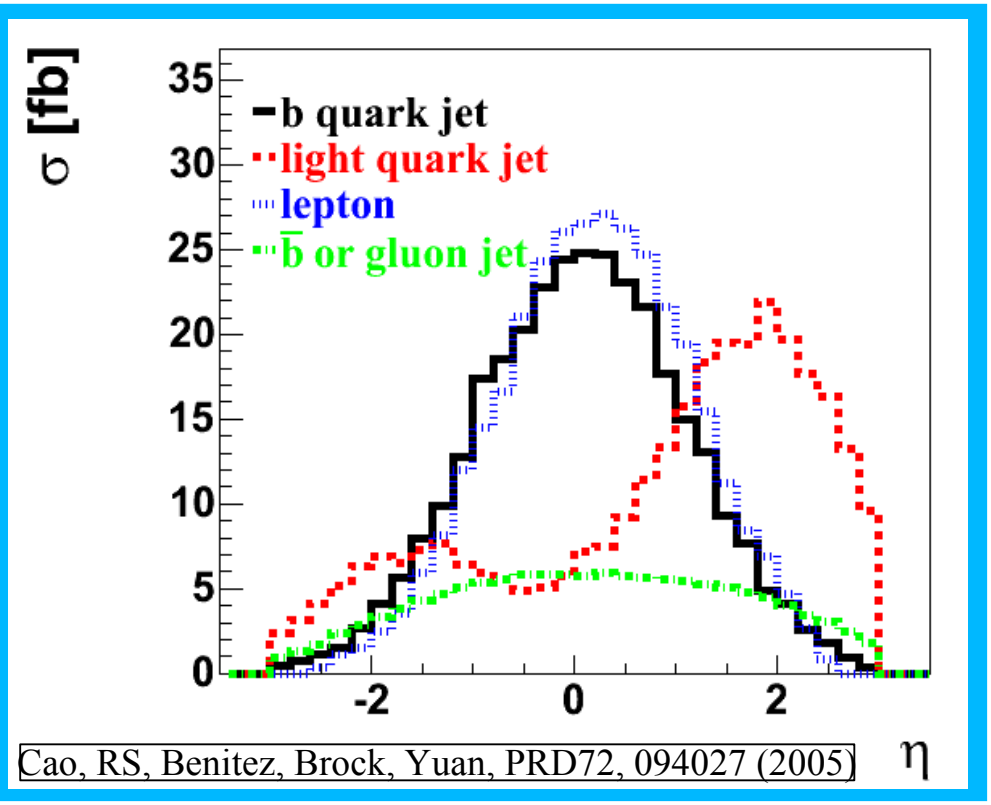
Cao, RS, Yuan PRD71, 054023 (2005)

Tevatron t-channel signature



"*tqb*"





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

Results, Run I and Run II

	tqb 95% upper limit
2001 Search for electroweak production of single top quarks in ppbar collisions" Phys. Rev. D 63, 031101 (2001)	< 58 pb
2001 "Search for Single Top Quark Production at DØ Using Neural Networks," Phys. Lett. **B 517**, 282 (2001).	< 22 pb
2004 "Search for Single Top Quark Production at DØ in Run II," DØ Note 4398 (2004).	< 25 pb
2005 "Improved Search for Single Top Quark Production," DØ Note 4670 (2005).	< 5.0 pb
2005 "Search for Single Top Quark Production in $p\overline{p}$ Collisions at $\sqrt{s} = 1.96$ TeV," Phys. Lett. **B 622**, 265 (2005).	< 5.0 pb
2006 "Multivariate Searches for Single Top Quark Production with the DØ Detector," submitted to Phys. Rev. D, hep-ex/0604020.	< 5.0 pb
2005 "Search for Single Top Quark Production using likelihood discriminants," DØ Note 4825 (2005).	< 4.4 pb

- Plus 7 PhDs so far

Tevatron single top goals

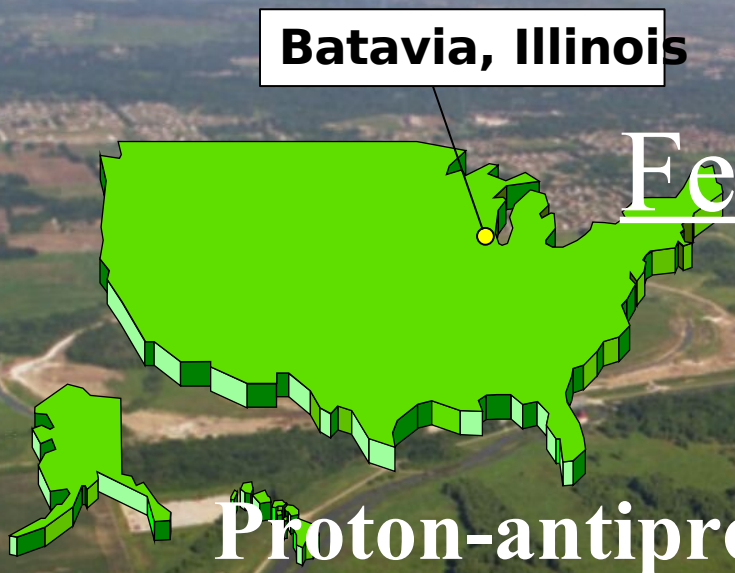
Production cross sections:	*s-channel*	*t-channel*
NLO calculation:	**0.88 pb (±8%)**	**1.98 pb (±11%)**
current 95% CL limits, DØ:	< 5.0 pb	< 4.4 pb
CDF:	< 3.1 pb	< 3.2 pb

- 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 searches

Preparation

How do we collect a sample of candidates?

Experimental setup: Fermilab Tevatron in Run II



Proton-antiproton collider

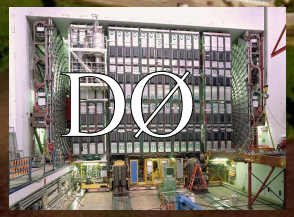
CM energy 1.96TeV

→ *Energy frontier*

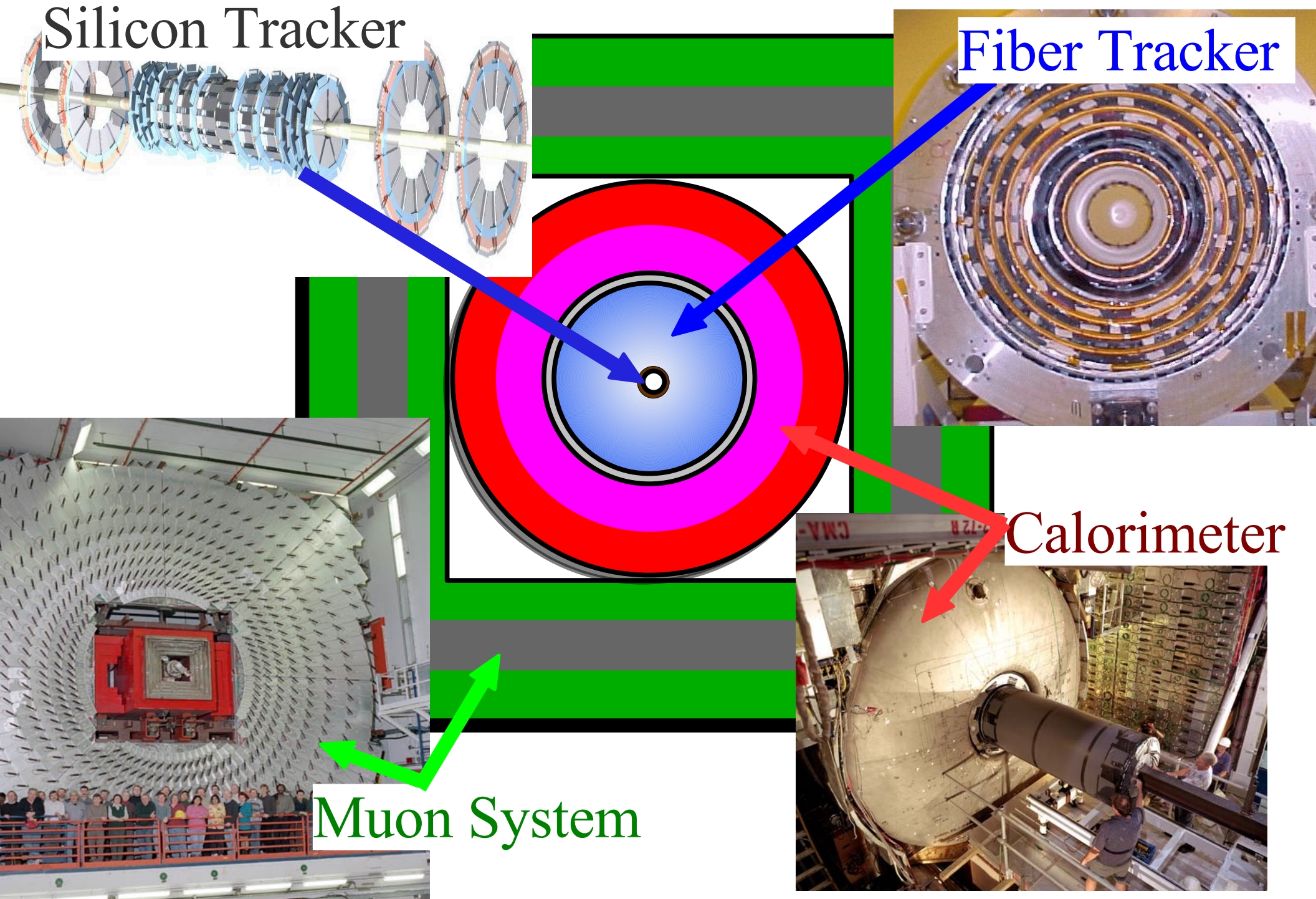
Instantaneous luminosity >250E30cm^{-2}s^{-1}

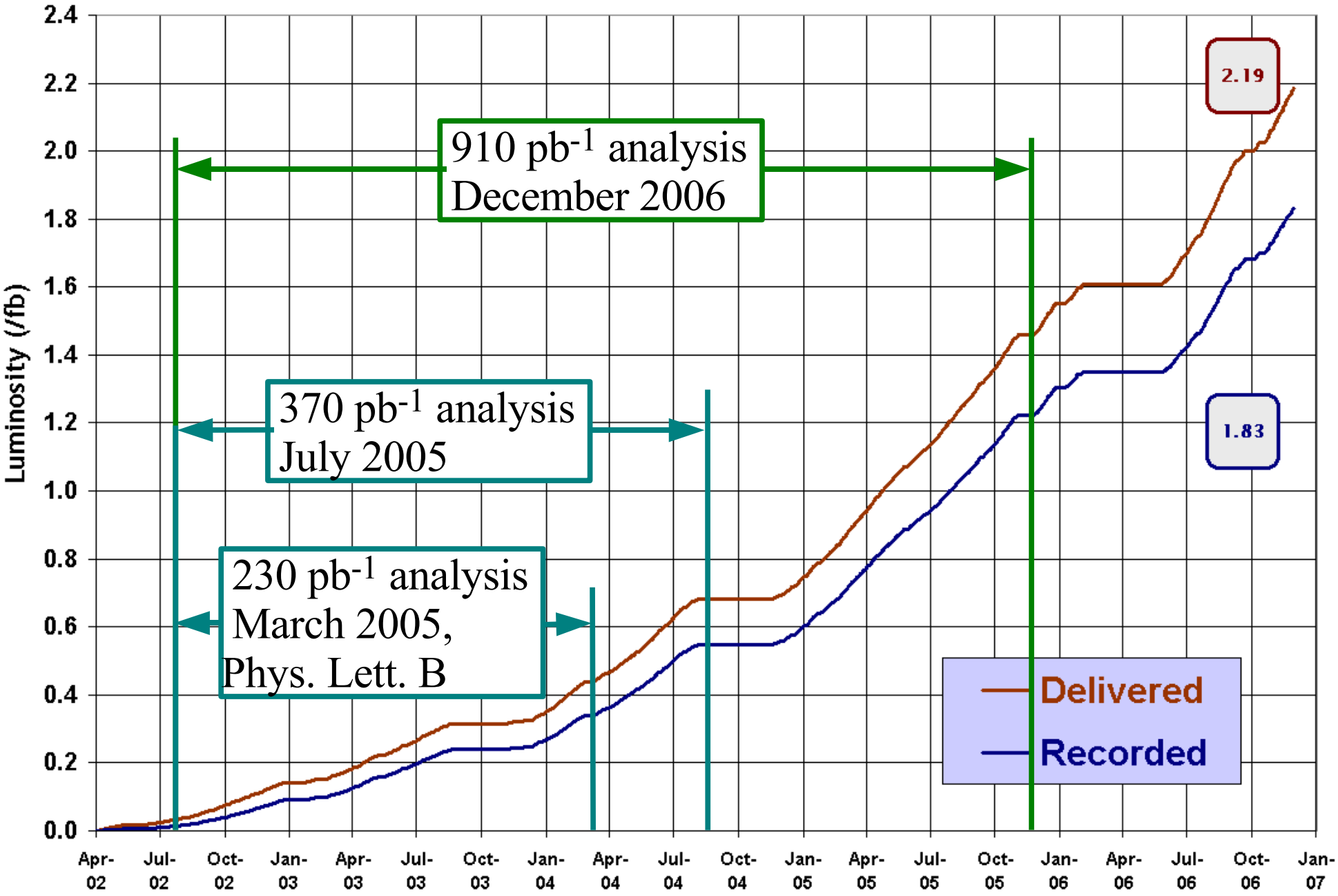
– ~4 interactions per crossing, 1.7M crossing per second

→ *Luminosity frontier*



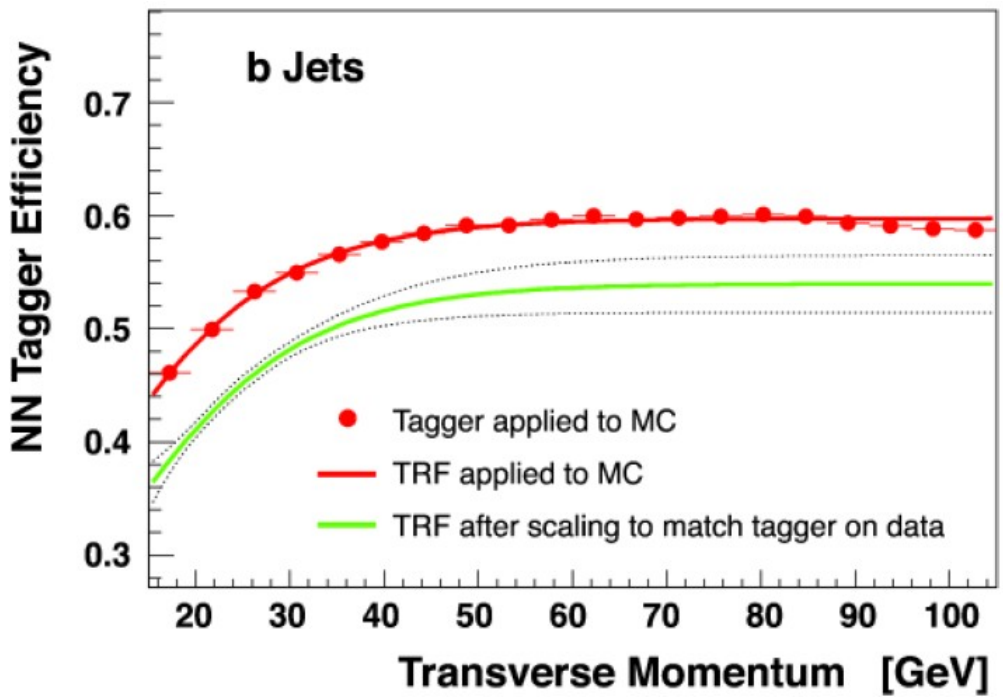
Apparatus: Run II DØ Detector



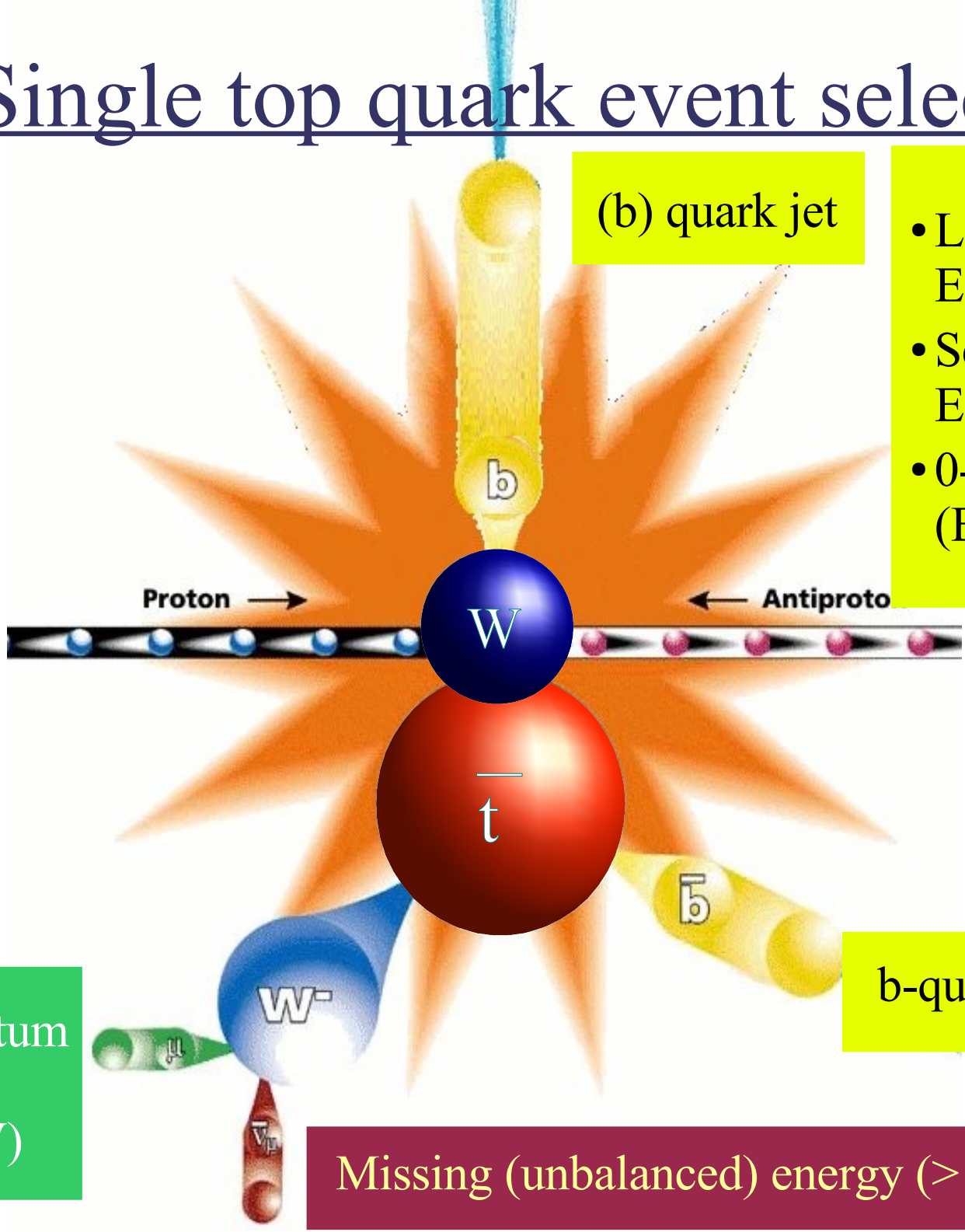

Run II Integrated Luminosity
19 April 2002 - 17 December 2006
Luminosity (/fb)
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Apr-02
Jul-02
Oct-02
Jan-03
Apr-03
Jul-03
Oct-03
Jan-04
Apr-04
Jul-04
Oct-04
Jan-05
Apr-05
Jul-05
Oct-05
Jan-06
Apr-06
Jul-06
Oct-06
Jan-07
910 pb-1 analysis
December 2006
370 pb-1 analysis
July 2005
230 pb-1 analysis
March 2005,
Phys. Lett. B
2.19
1.83
Delivered
Recorded

Improvements

- More than twice as much data
- Improved W+jets background modeling
- Fully reprocessed dataset
  - New calibrations, lower thresholds, ...
- Neural Network b-quark tagging
- Split analysis into 12 separate channels
  - By lepton, jet multiplicity, tag multiplicity
- Combined s+t search
  - Assuming SM ratio of cross sections



Single top quark event selection



(b) quark jet

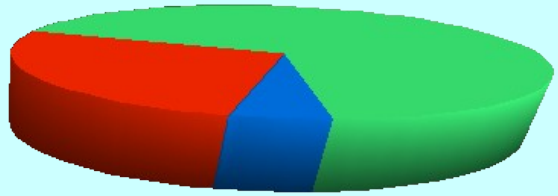
- Leading jet: $E_T > 25$ GeV
- Second jet: $E_T > 20$ GeV
- 0-2 additional jets (ET > 15 GeV)

b-quark jet

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

Missing (unbalanced) energy (> 15 GeV)

Event Sample Composition

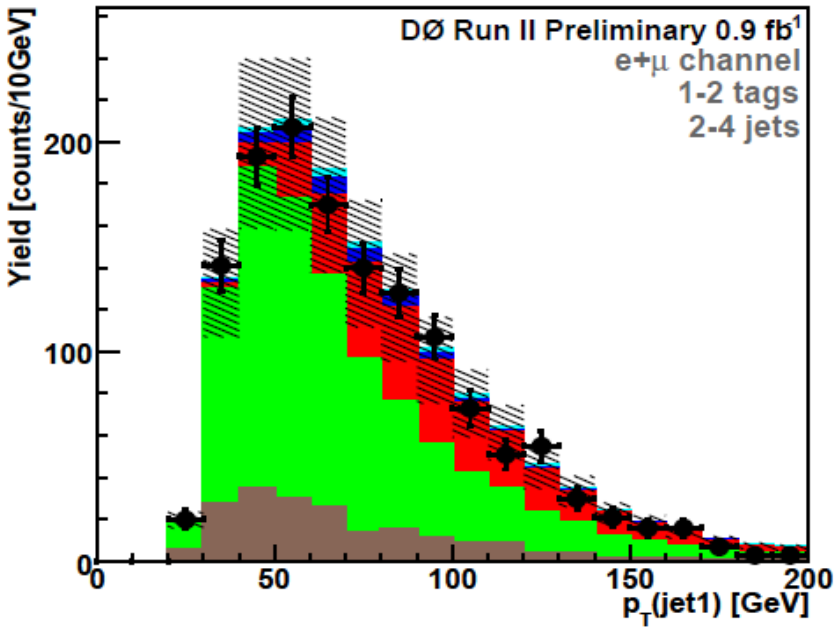


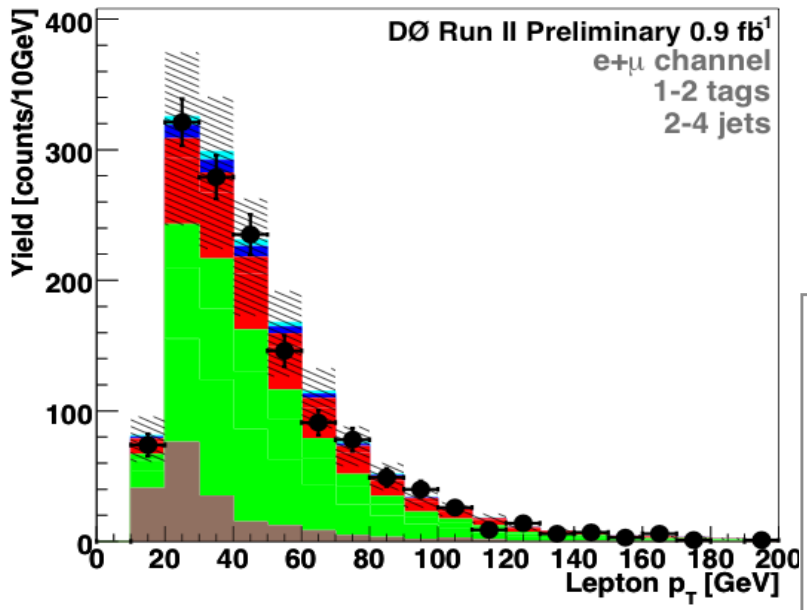
(~ 1 ev pb)

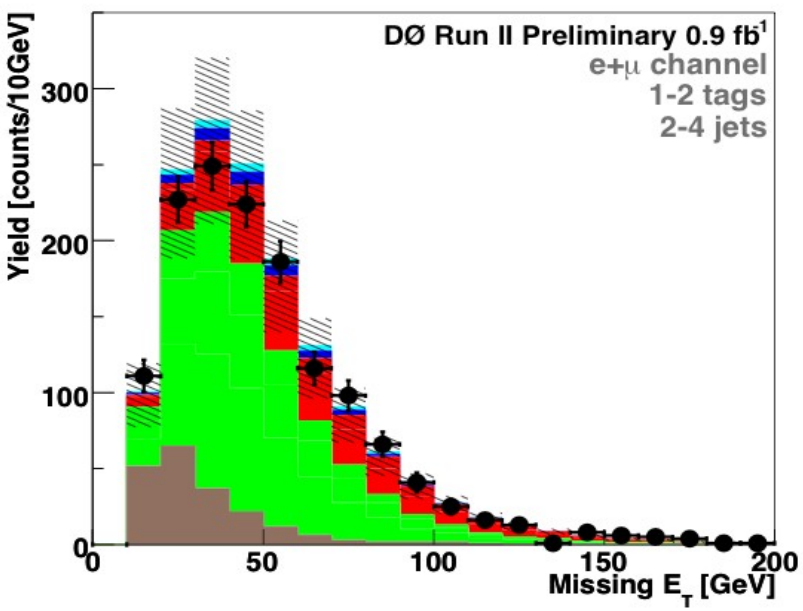
Percentage of single top *tb+tqb* selected events and S:B ratio (white squares = no plans to analyze)

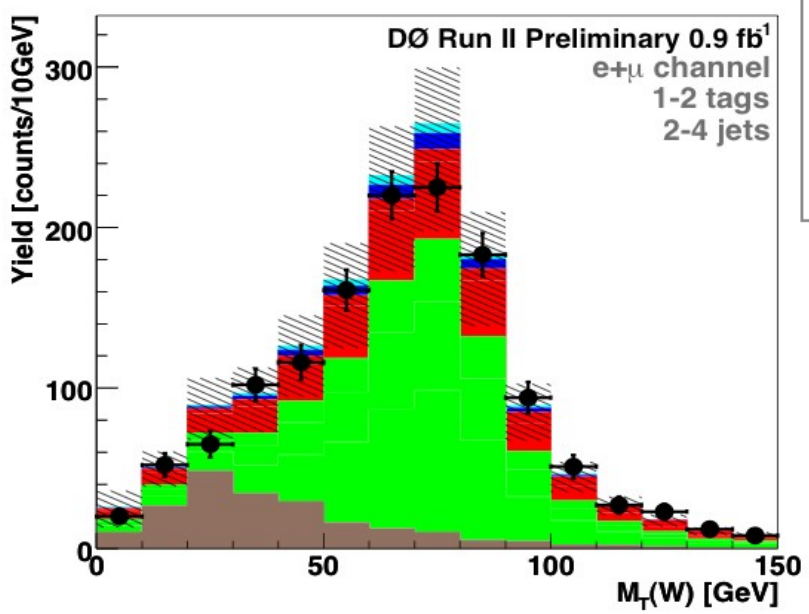
Electron + Muon	1 jet	2 jets	3 jets	4 jets	≥ 5 jets
0 tags	10% 1 : 3,200	25% 1 : 390	12% 1 : 300	3% 1 : 270	1% 1 : 230
1 tag	6% 1 : 100	21% 1 : 20	11% 1 : 25	3% 1 : 40	1% 1 : 53
2 tags		3% 1 : 11	2% 1 : 15	1% 1 : 38	0% 1 : 43

Data-background comparison









Key for Plots

- Data
- tb
- tqb
- $t\bar{t}$
- W + jets
- Multijets
- ±1σ uncertainty on background

Optimized Event Analysis

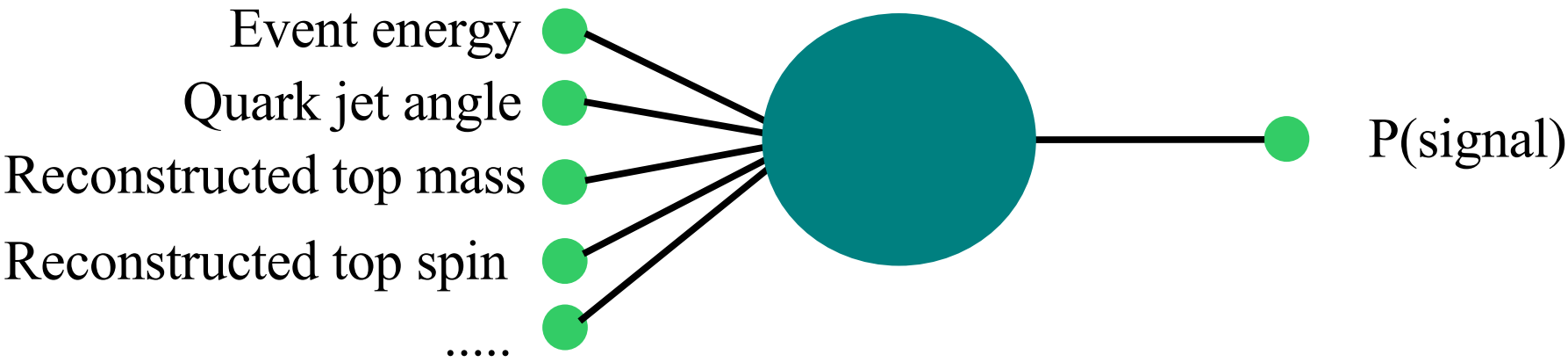
How do we find the needle in the haystack?

Multivariate Methods

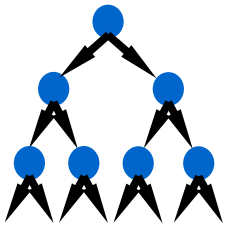
Input:
discriminating variables

Method:
multivariate analysis

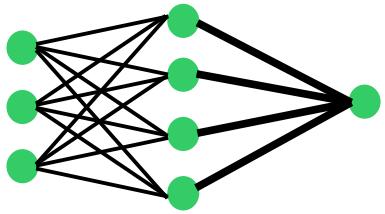
Output:
signal probability



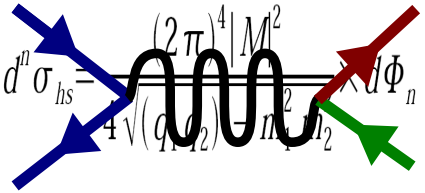
Boosted Decision Trees



Bayesian Neural Networks



Matrix Elements

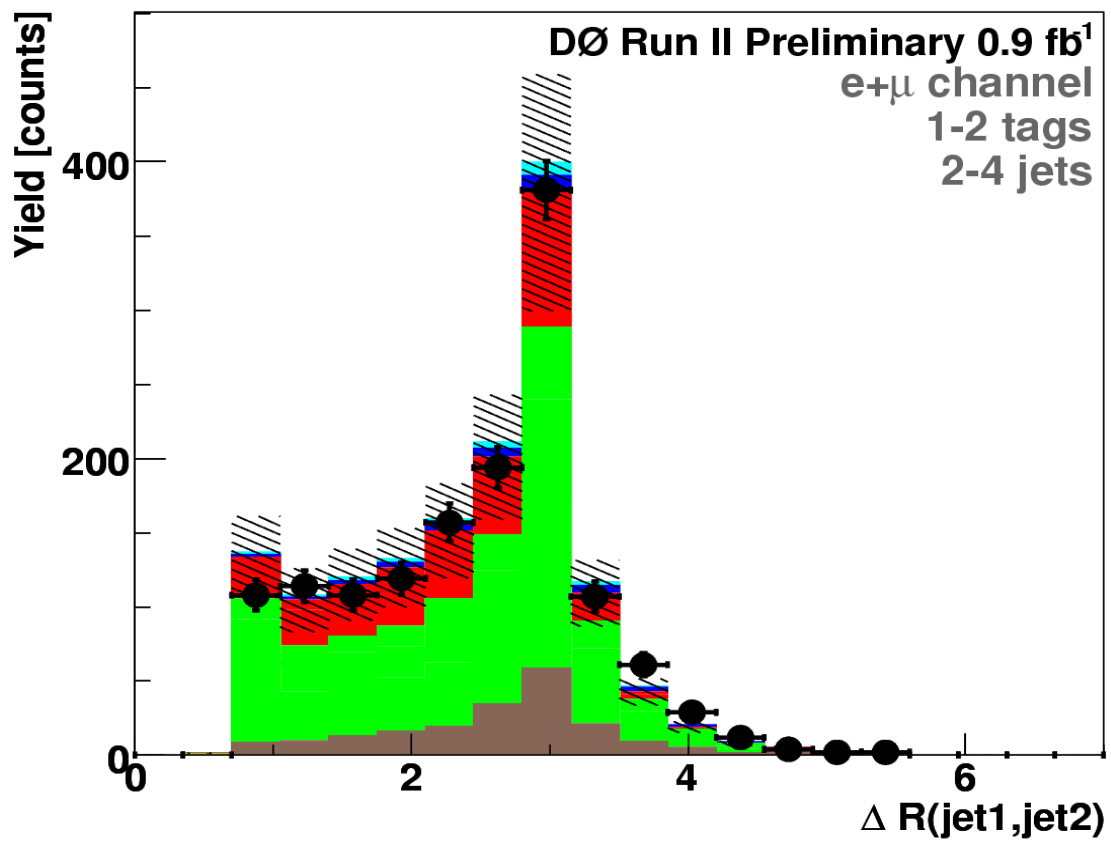


Discriminating Variables

- 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

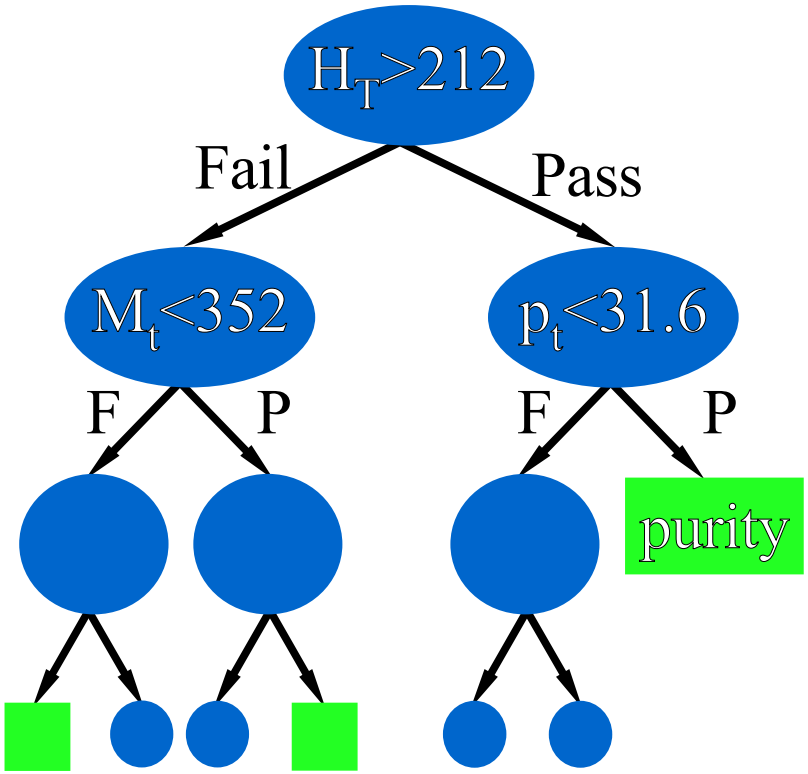
Object kinematics

Jet p_T for different jets

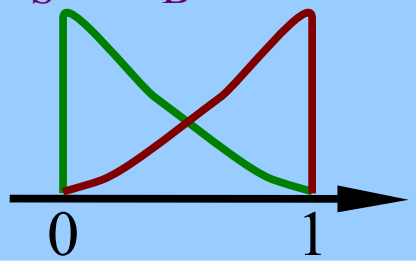


49 variables total

Decision Trees



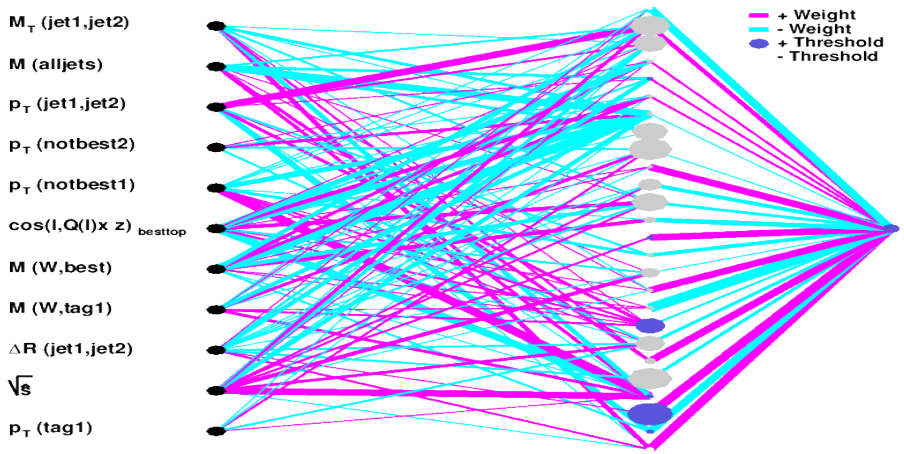
- Send each event down the tree
- Each node corresponds to a cut
  - Divide sample in two: Pass↔Fail
- A leaf corresponds to a node without branches
  - Defines purity = $N_S/(N_S+N_B)$ from MC sample
- Training: optimize Gini improvement
  - Gini = $2\, N_S\, N_B\, /(N_S + N_B)$
- Output: purity for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



- Bayesian Idea:
  explore all possible weights
- Average over 100 individual neural networks
  - Each network gets a weight based on training performance

Matrix Elements

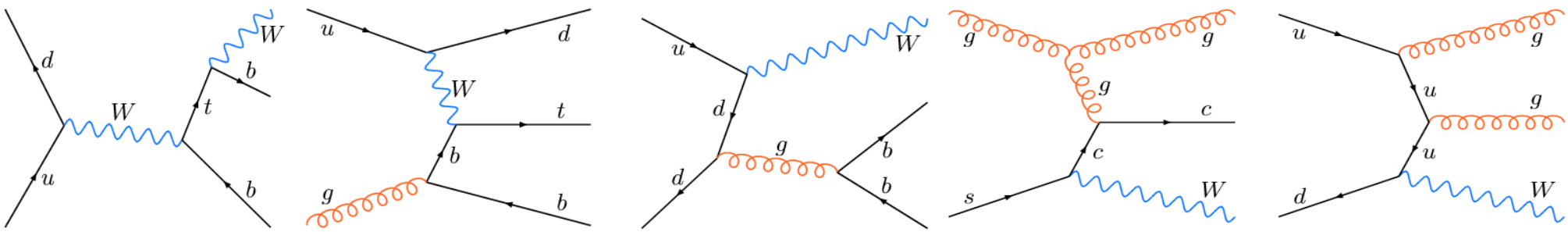
- Calculate signal discriminant directly for each event

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

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

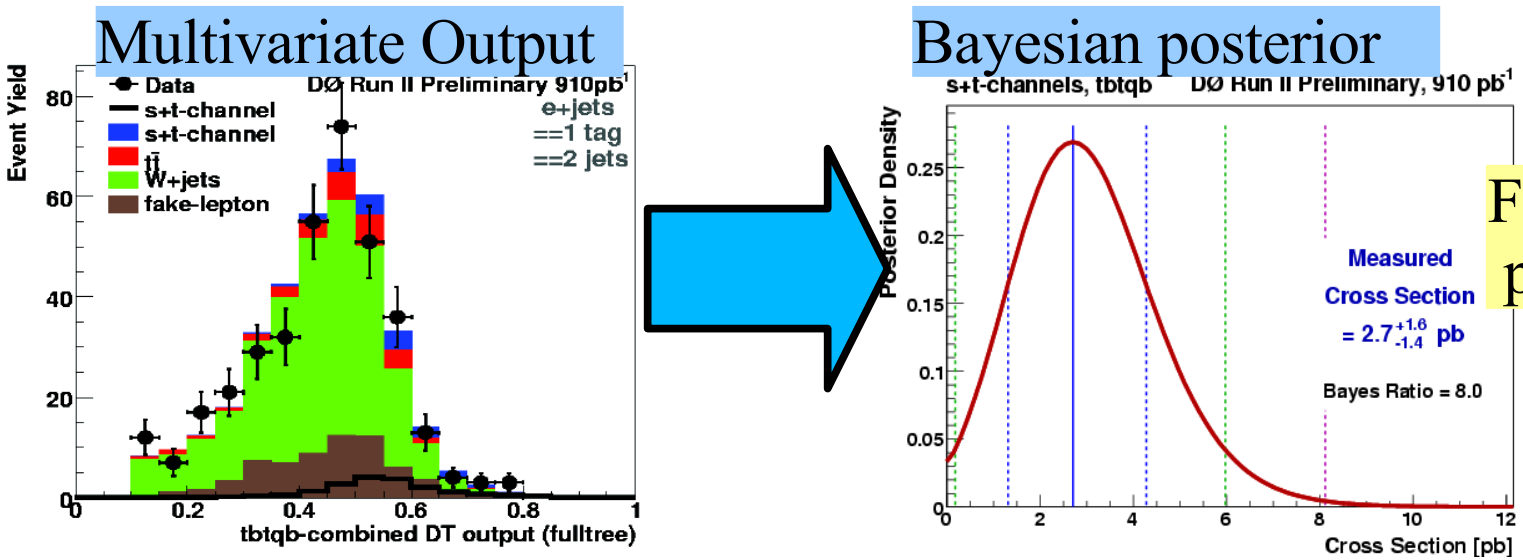
$$P_{Signal}(\vec{x}) = \frac{1}{\sigma_S} d\sigma_S(\vec{x}) \quad \sigma_S = \int d\sigma_S(\vec{x})$$

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



- Integrate over ME and measured momenta

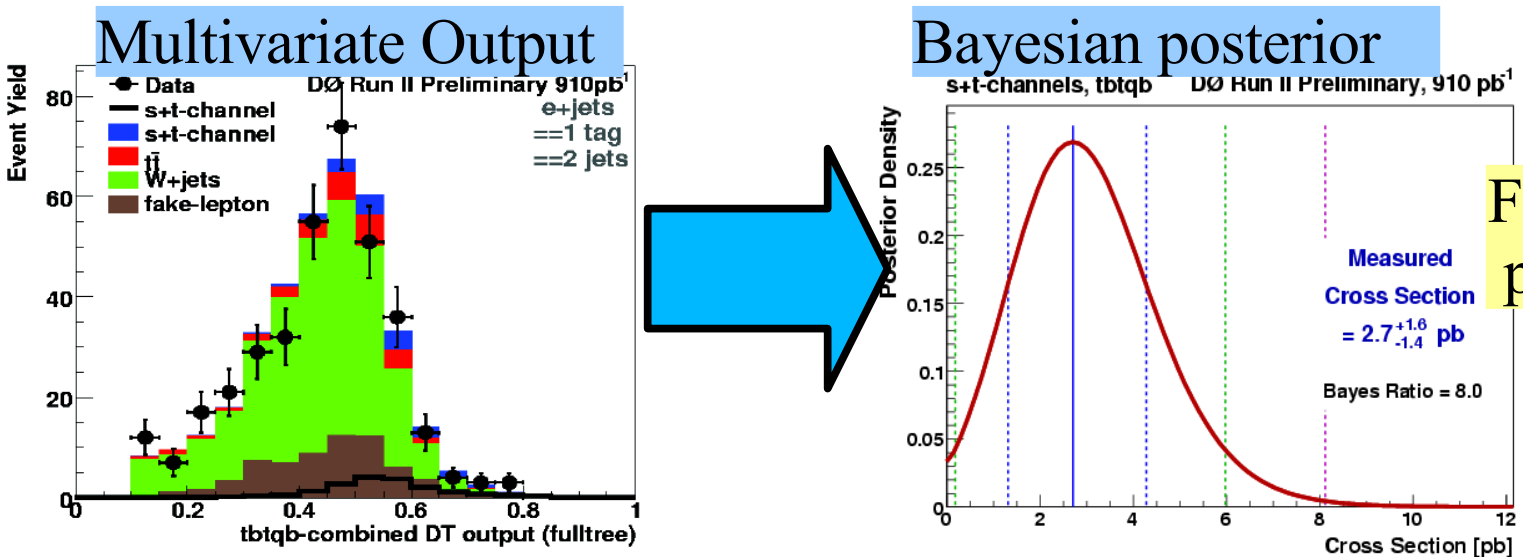
Measurement Procedure



For each, measure peak position σ

- Separate optimization for each process
  - s-channel, t-channel
    - Different processes, sensitivity to new physics
  - s+t combined
    - Assuming ratio of SM XS
      - Maximize sensitivity to SM single top

Measurement Procedure



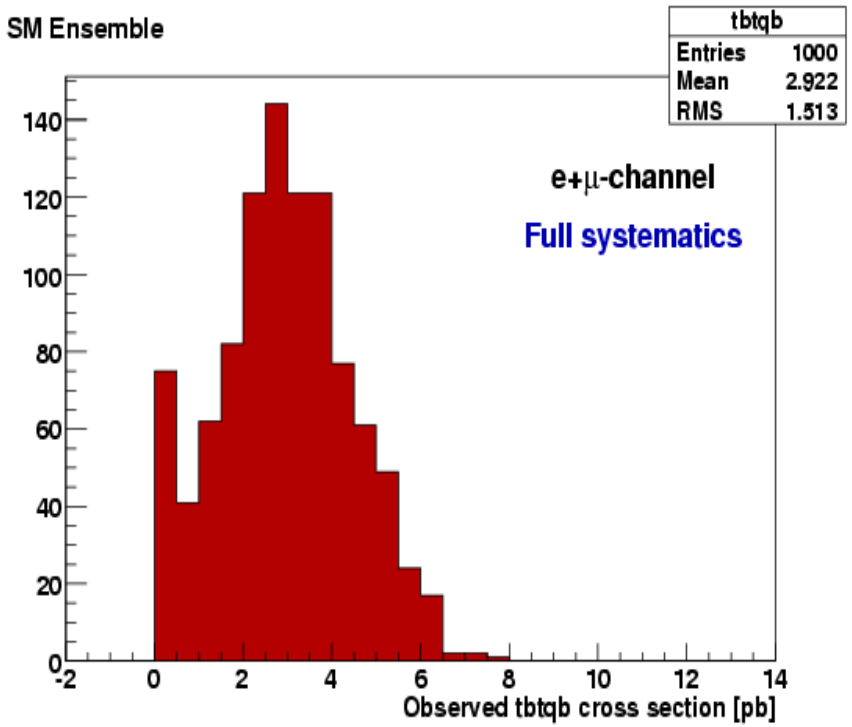
For each, measure peak position σ

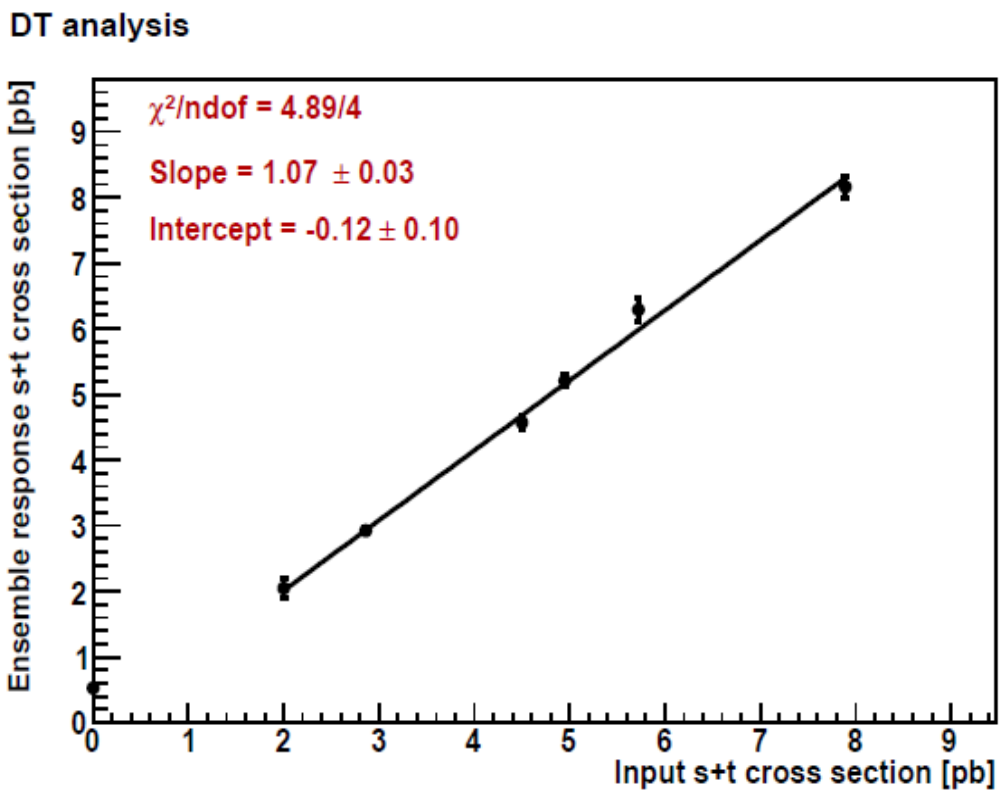
- Separate optimization for each process
  - s-channel, t-channel
    - Different processes, sensitivity to new physics
  - s+t combined
    - Assuming ratio of SM XS
      - Maximize sensitivity to SM single top

Focus on this for the remainder of the talk!

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

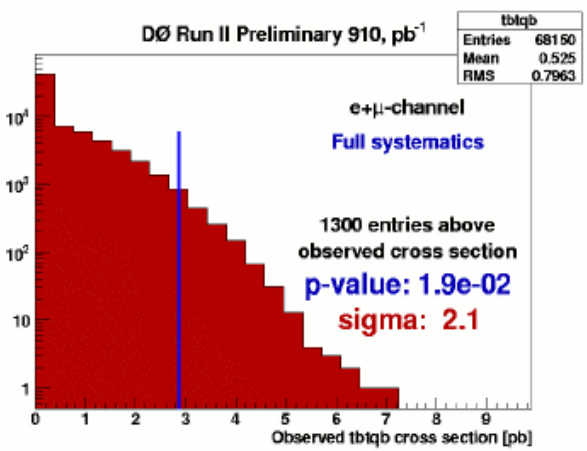




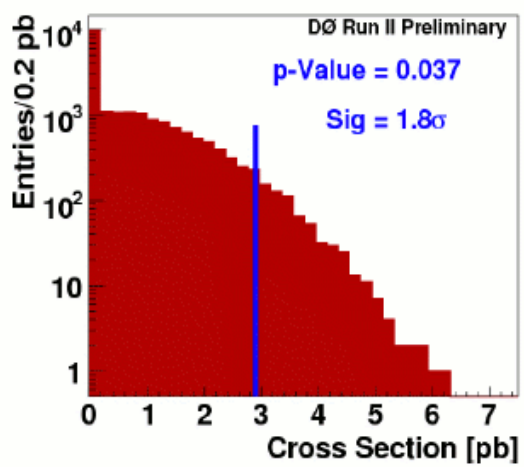
Sensitivity, p-value

- P-value: fraction of 0-signal ensembles measuring σ above observed value
- Expected p-value: fraction of 0-signal ensembles measuring σ above SM value
- Expected p-values:

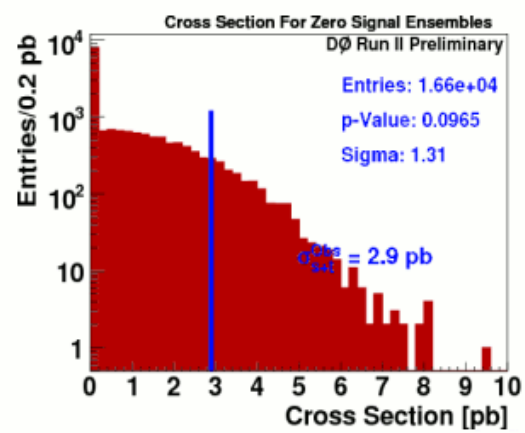
Decision Trees
p-value **1.9%**



Matrix Elements
p-value **3.7%**



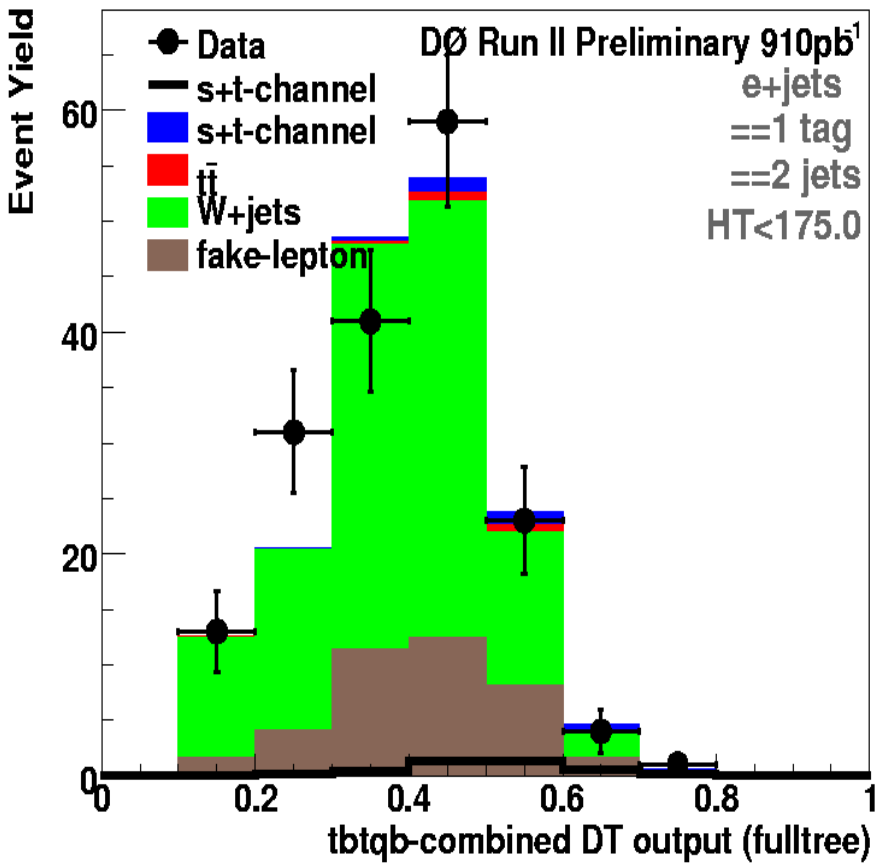
Bayesian NN
p-value **9.7%**

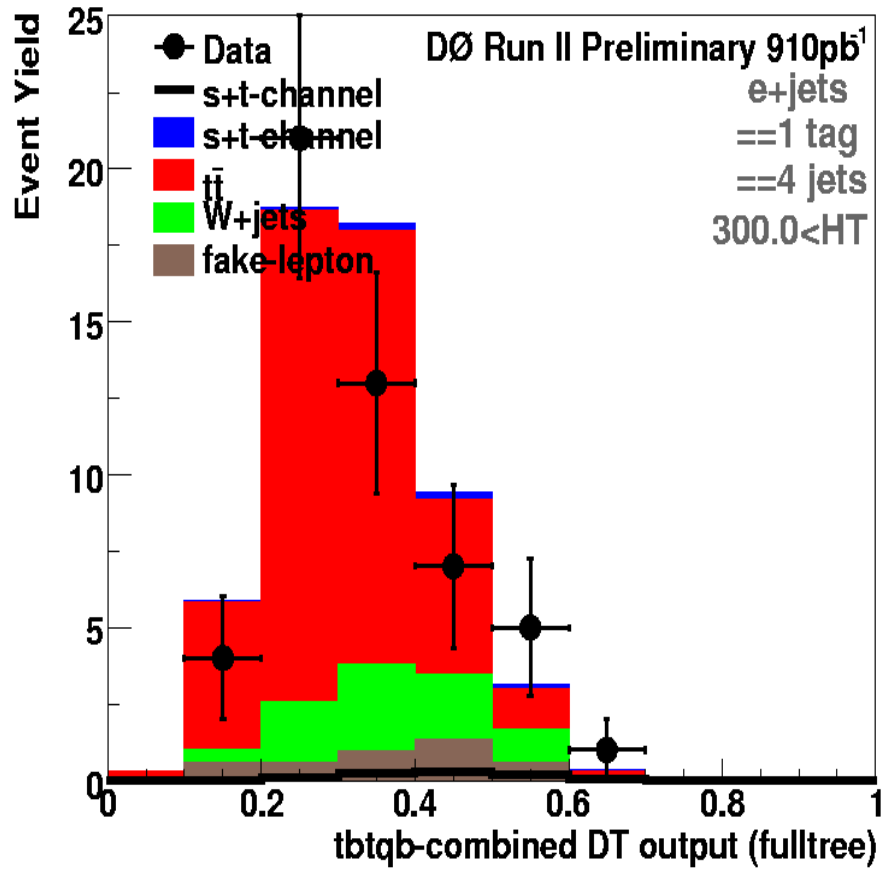


Test model on data

- W+jets sample
  = 2 jets, low event energy (H_T (l,j) < 175 GeV)

Top quark pairs
= 4 jets, high event energy (H_T (l,j) > 300 GeV)

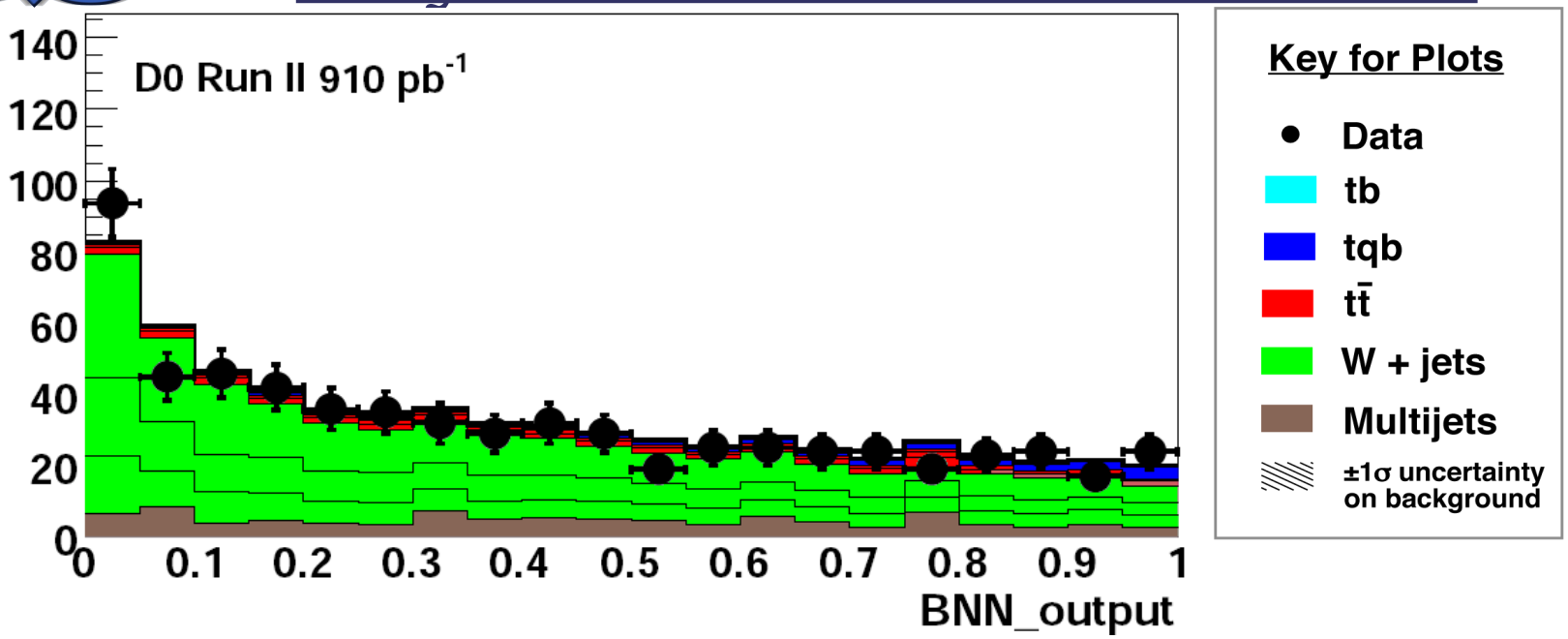


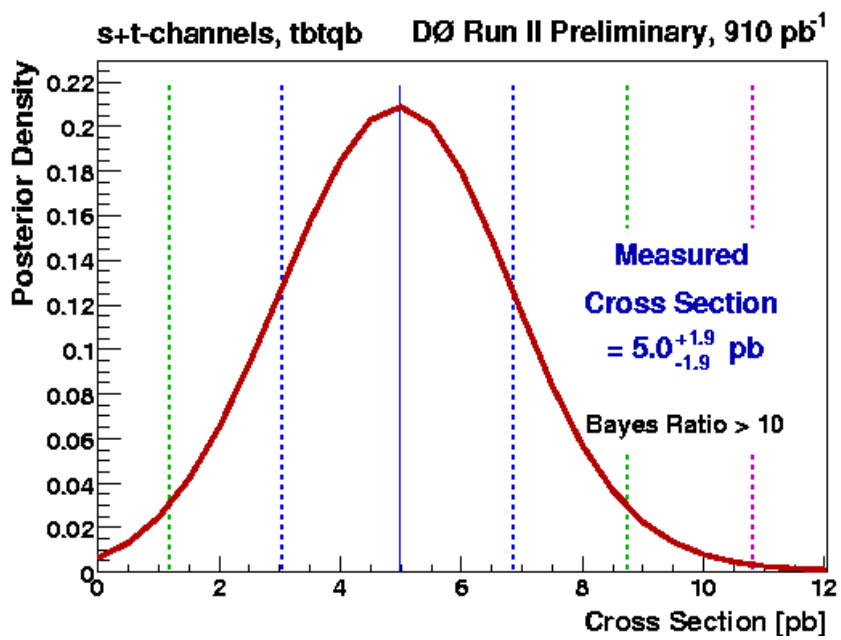


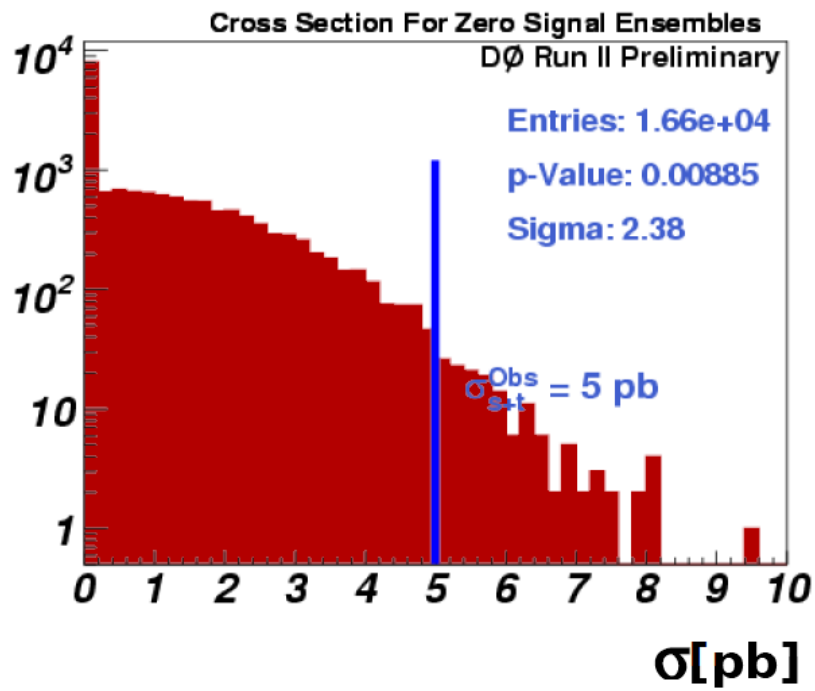
Results

Let Data speak!

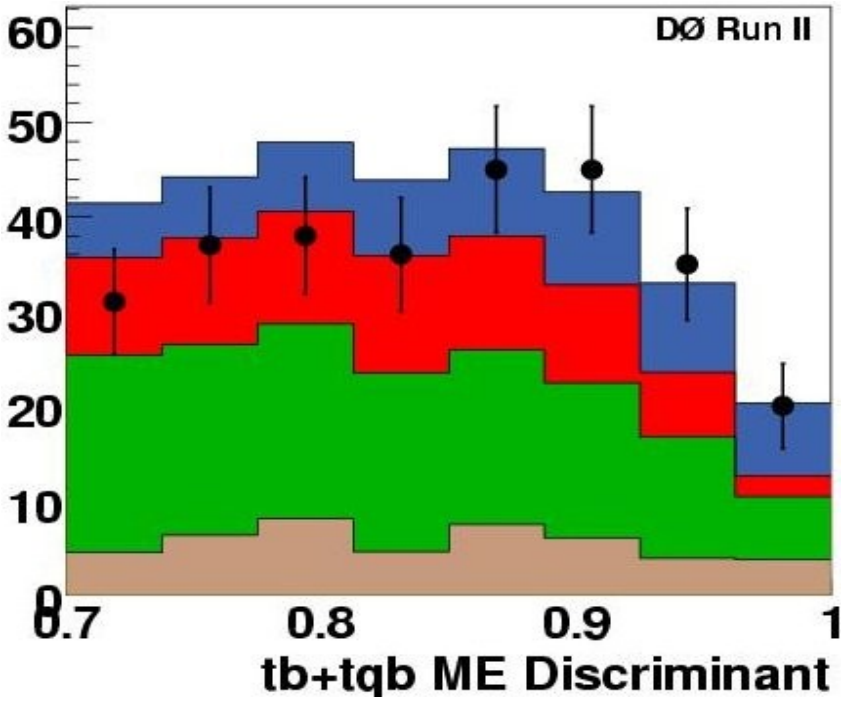
Bayesian Neural Network

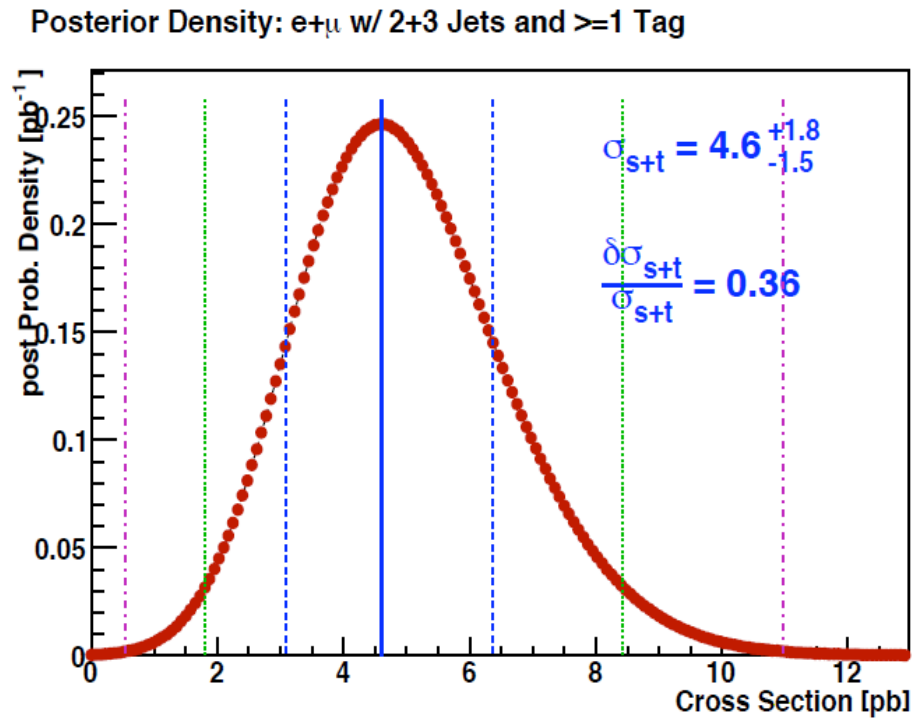


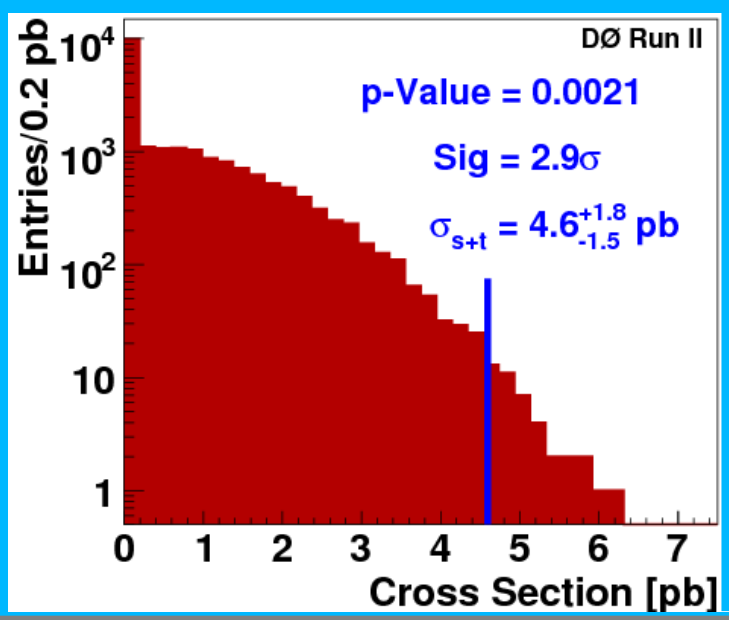


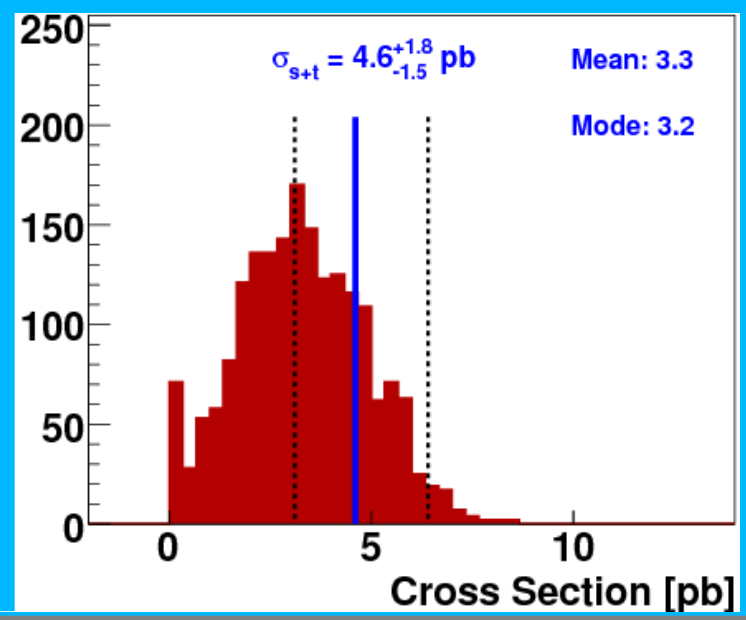


Matrix Element

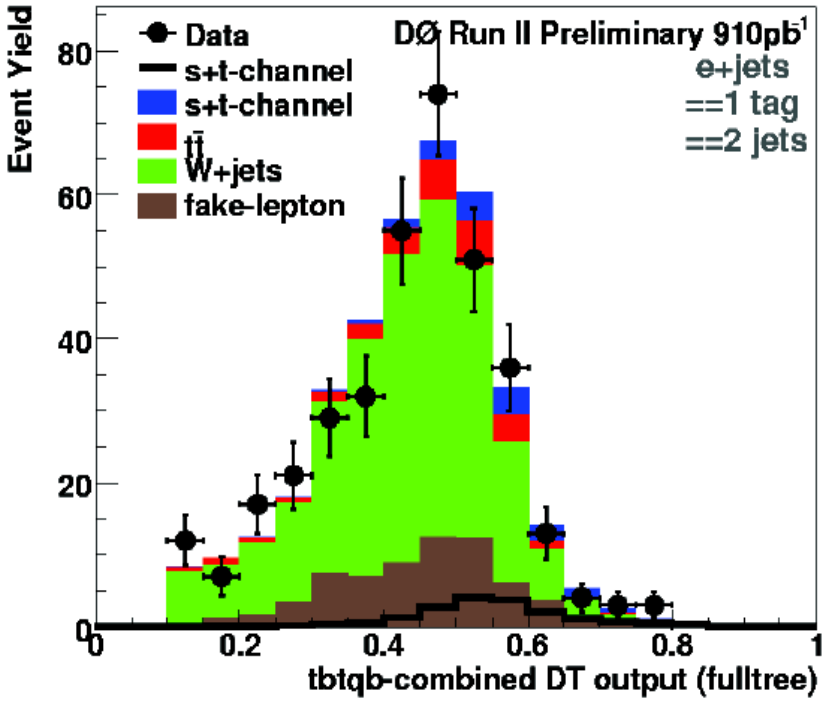


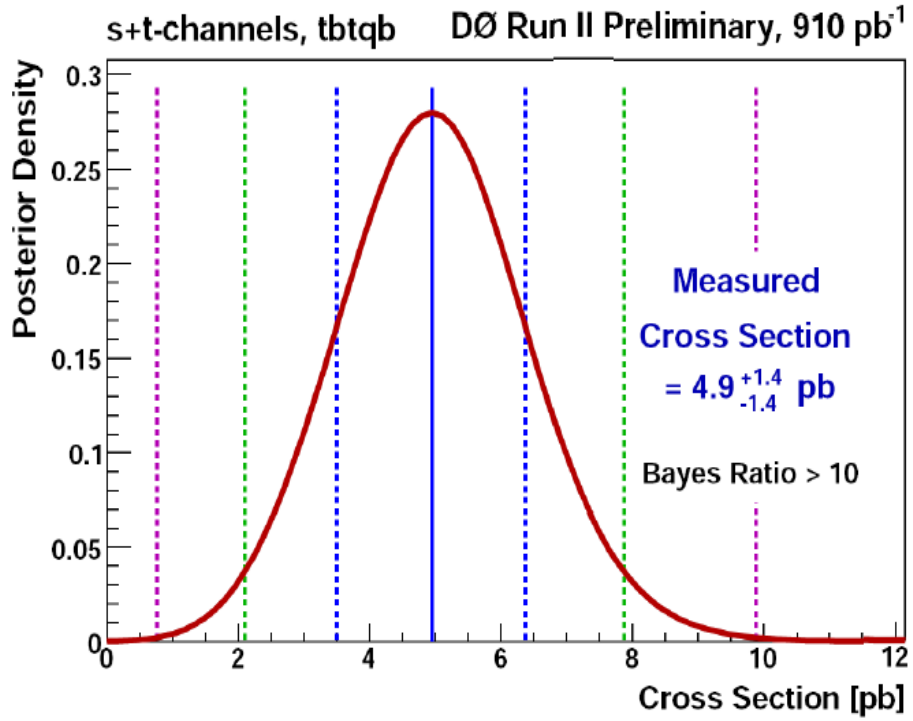


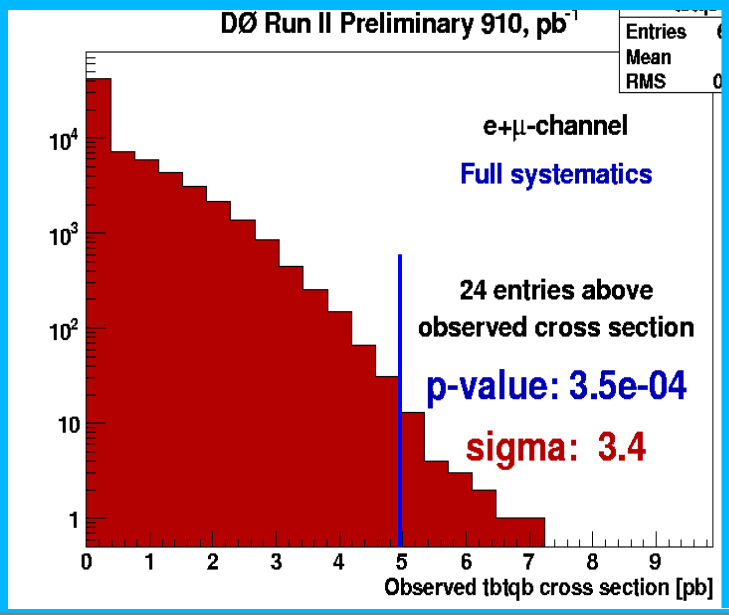


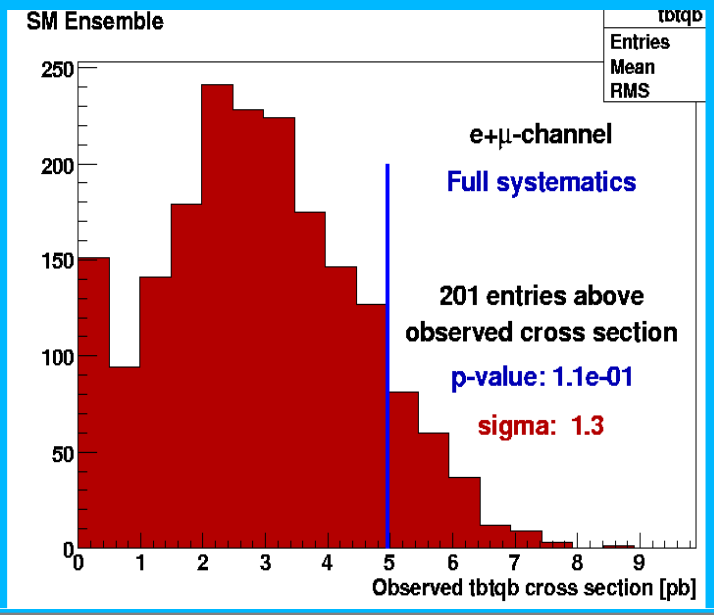


Boosted Decision Trees

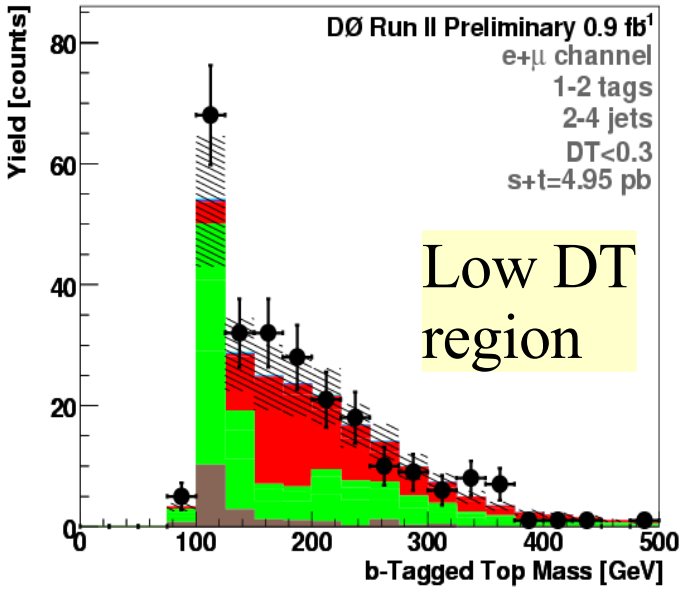


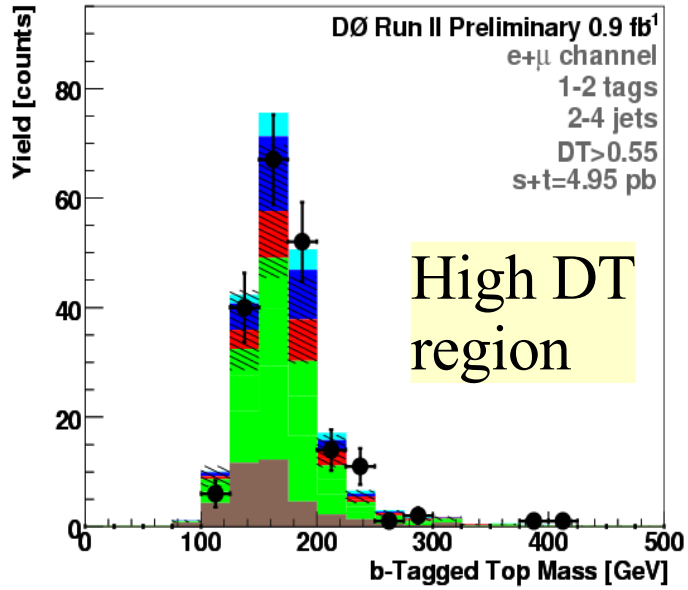


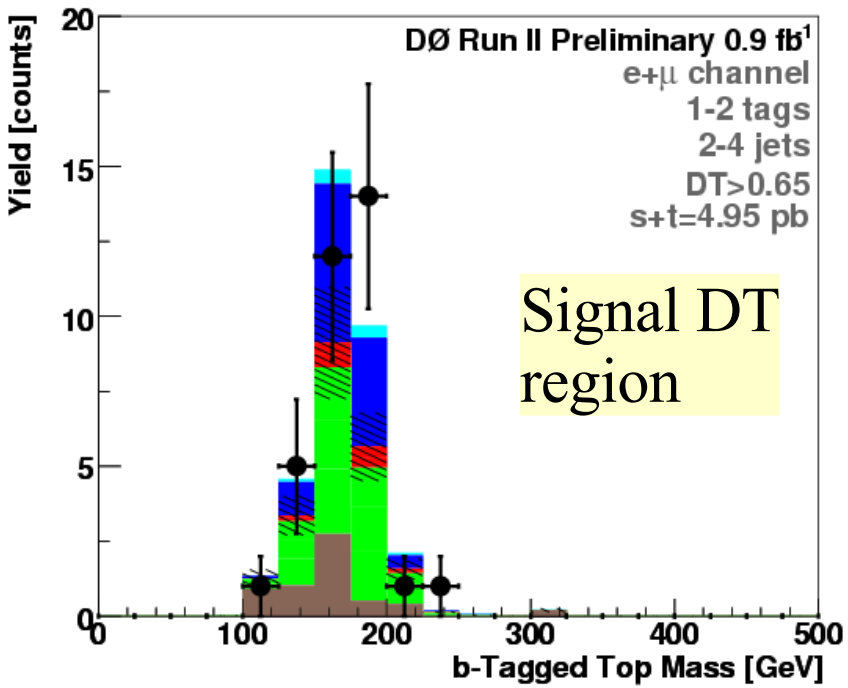




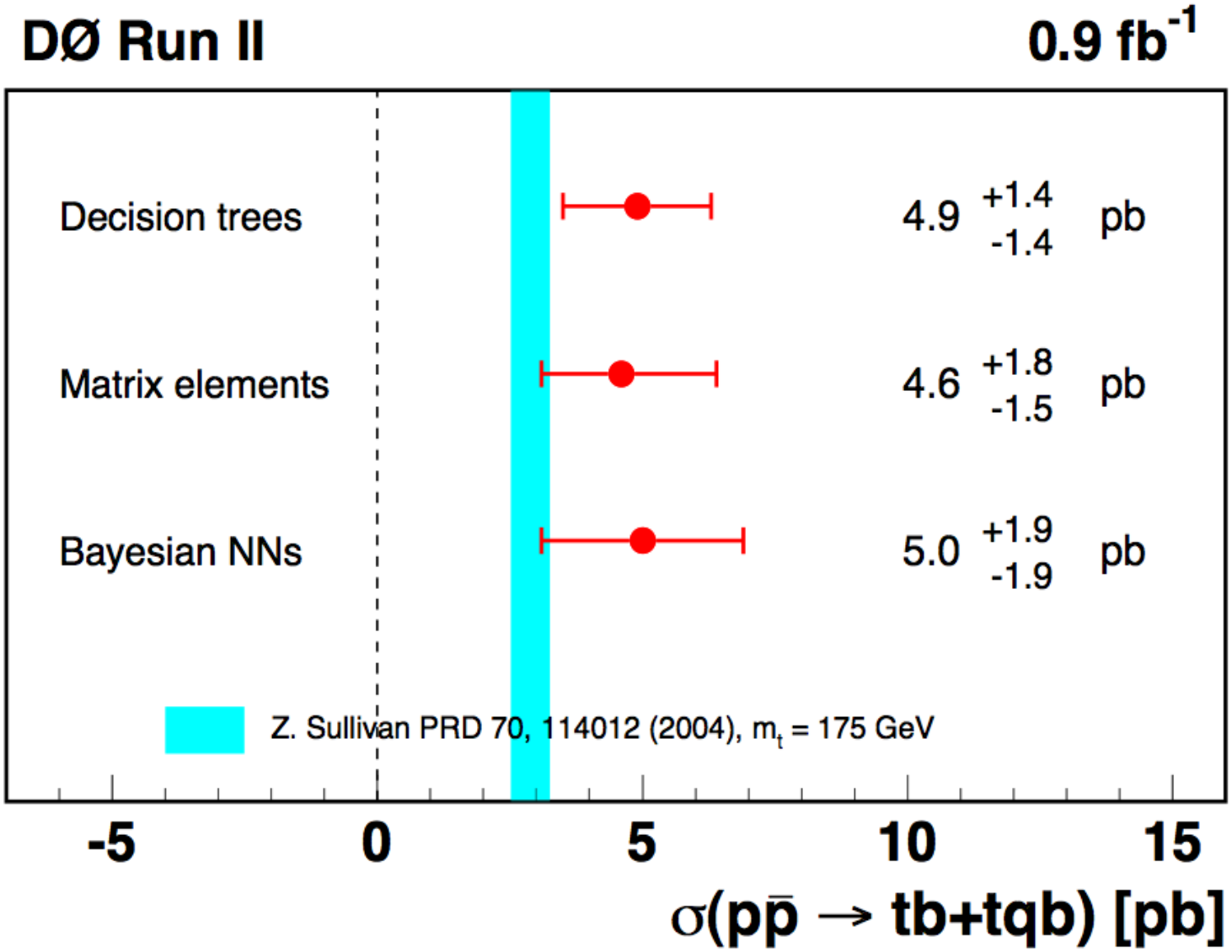
Reconstructed top quark mass





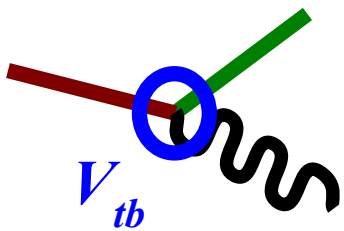


Summary



Submitted to PRL

V_{tb}



CKM Matrix

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

- Weak interaction eigenstates are not mass eigenstates
  Top quark must decay to a W plus a d, s, or b quark

$$V_{td}^{\ 2} + V_{ts}^{\ 2} + V_{tb}^{\ 2} = 1 \qquad \rightarrow \qquad V_{tb} > 0.999$$

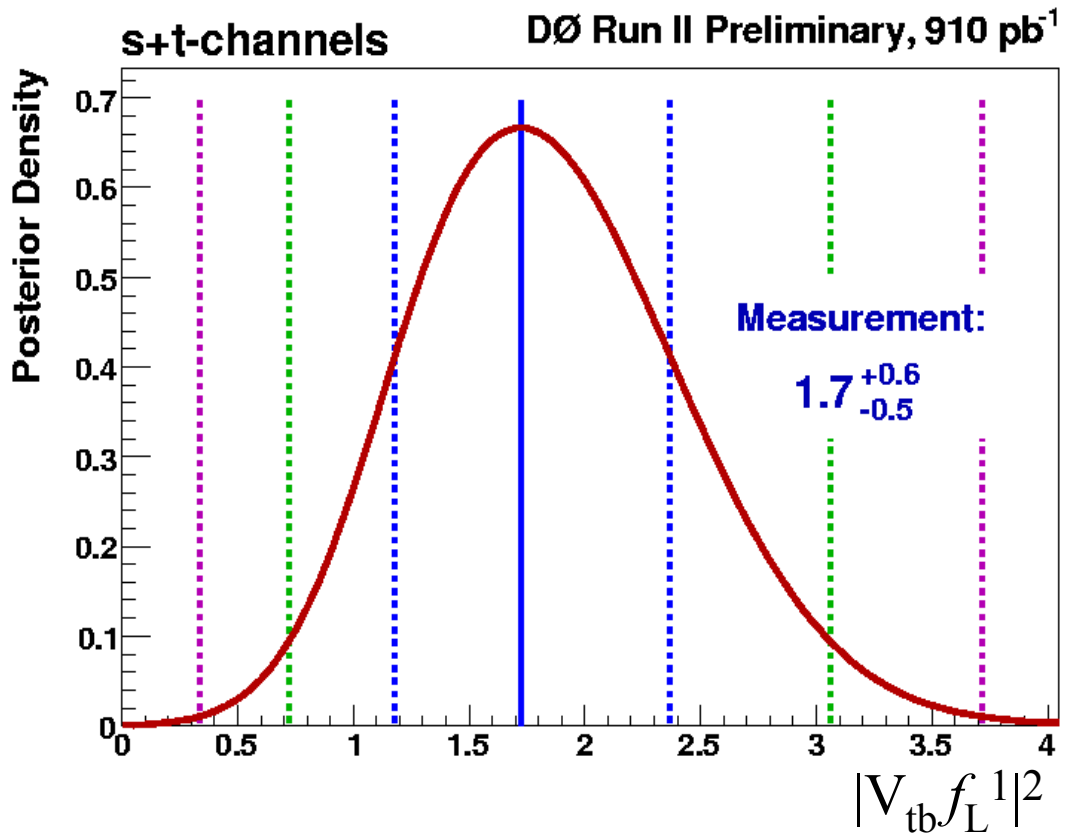
  New physics that couples to the top quark:

$$V_{td}^{\ 2} + V_{ts}^{\ 2} + V_{tb}^{\ 2} + V_{tx}^{\ 2} = 1$$

  Only weak constraints on V_{tb}

- Measurement: $|V_{tb} \times f_L^{\ 1}|$
  - Add uncertainties for M_{top}, scale, PDF
  - Assume SM top quark decay

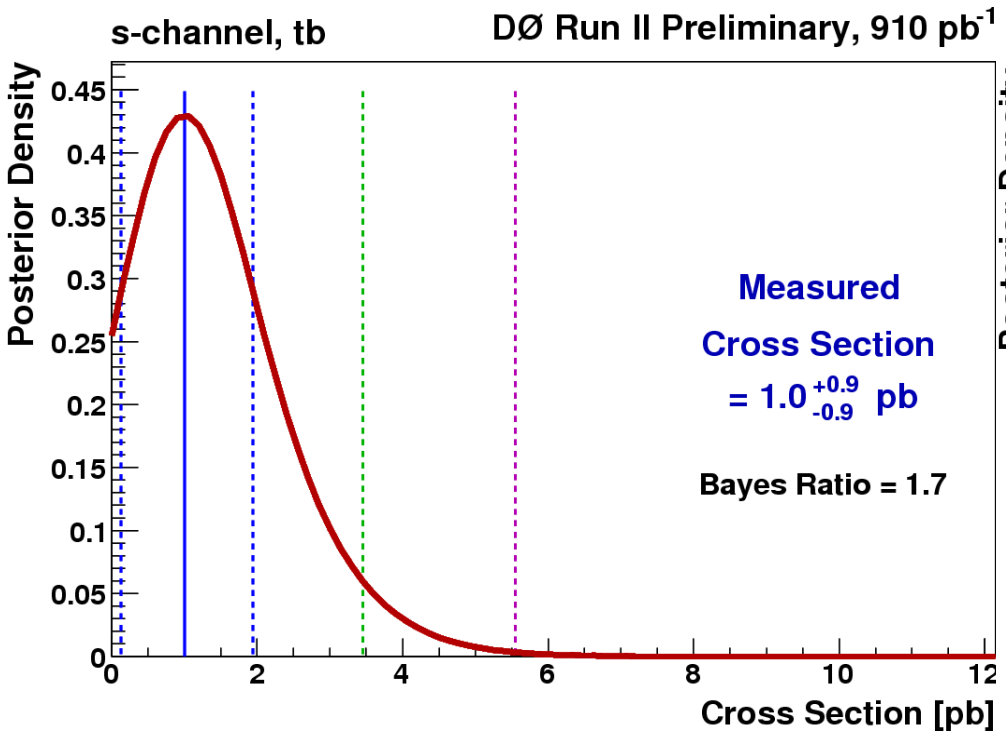
Probability density for $|V_{tb} f_L{}^1|^2$

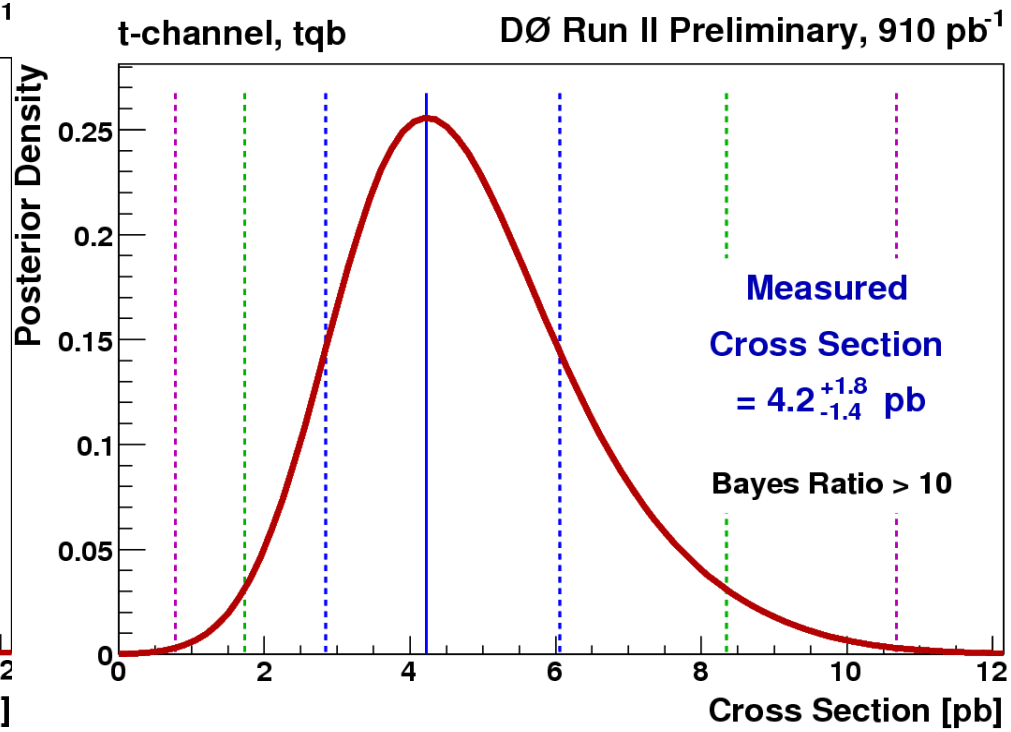


- SM: coupling $f_L{}^1 = 1$
  - Modified, additional couplings beyond SM
- Assume SM coupling: $|Vtb| > 0.68$ at 95 % C.L.

Separate s-channel and t-channel analyses

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





Conclusions/Outlook

- We have 3.4 σ evidence for single top quark production
  - $|V_{tb}| > 0.68$ at the 95 % C.L.
- Outlook:
  - Further analysis improvements
  - 5σ discovery
  - Separate s-channel from t-channel
  - Tevatron dataset will increase ×5 in next 2 years