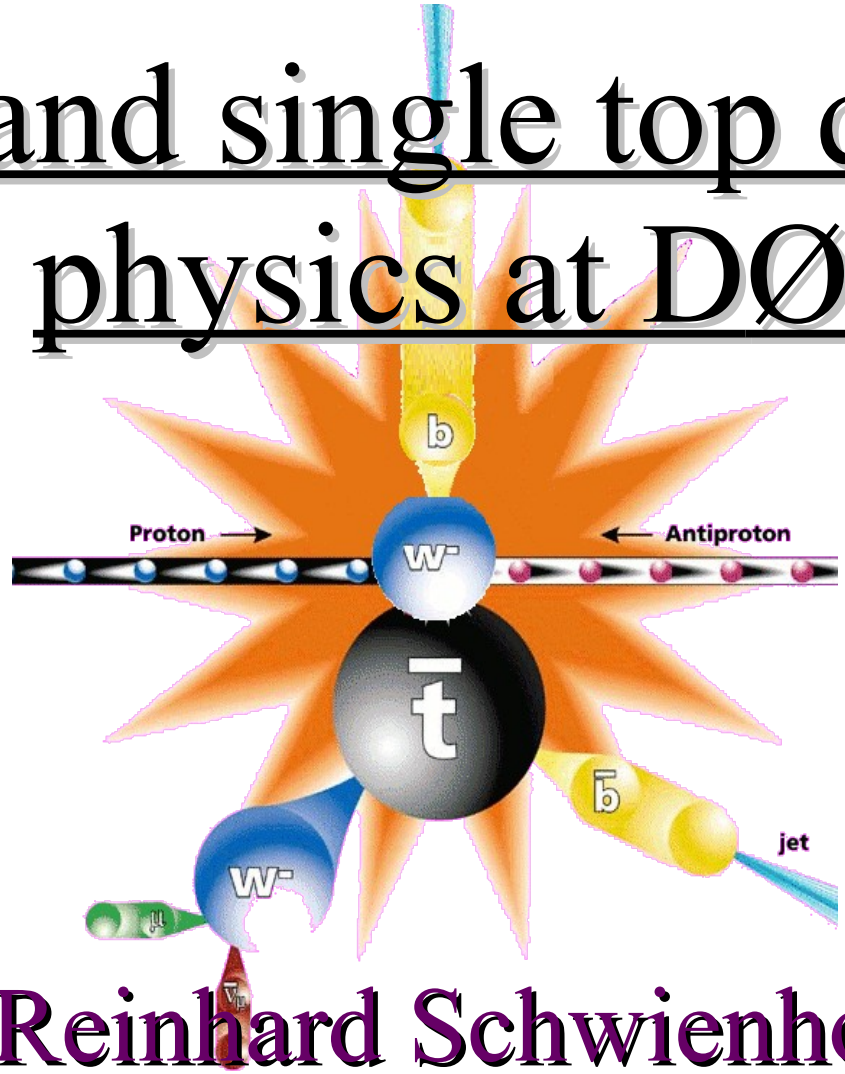
Top and single top quark physics at DØ



Reinhard Schwienhorst

MICHIGAN STATE UNIVERSITY

LPSC seminar, July 3, 2007

Outline

- Introduction
- Tevatron and DØ
- Top quark pair production
- Single top quark production
  - Optimized event analysis
- Conclusions

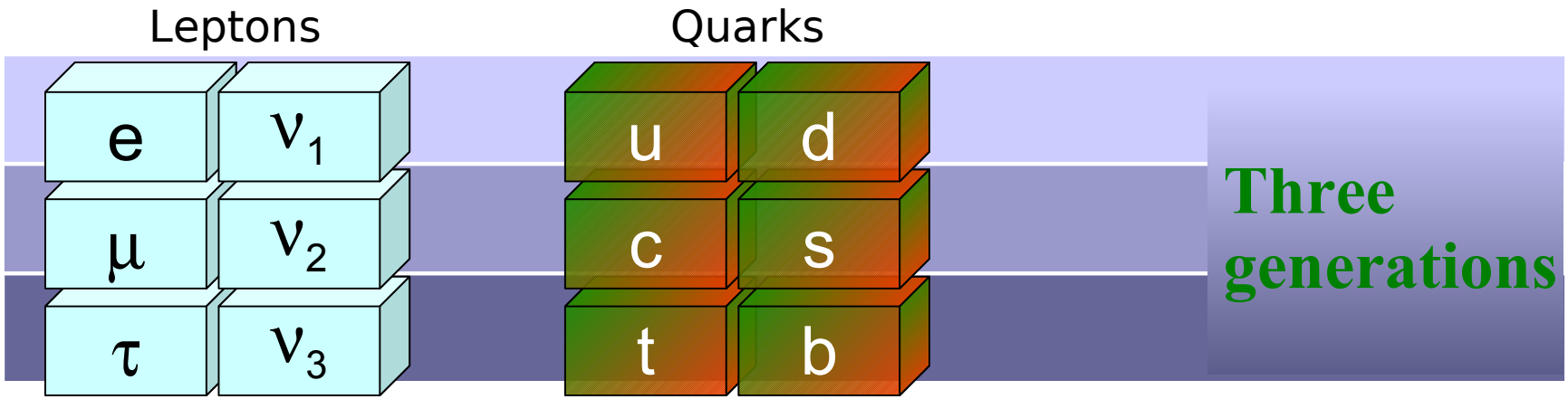
- Emphasis on what's new and what's special

State of the art

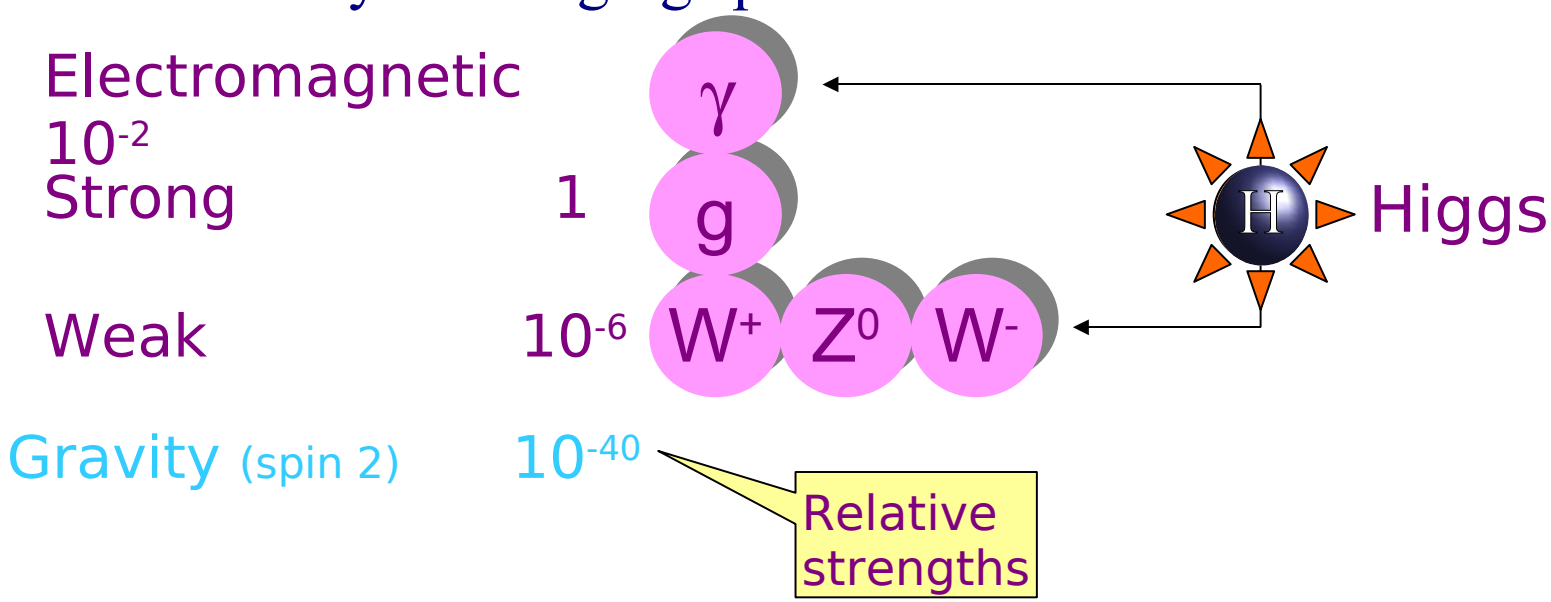
What do we know already?

Standard model of particles and forces

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



- Which interact by exchanging spin-1 vector bosons

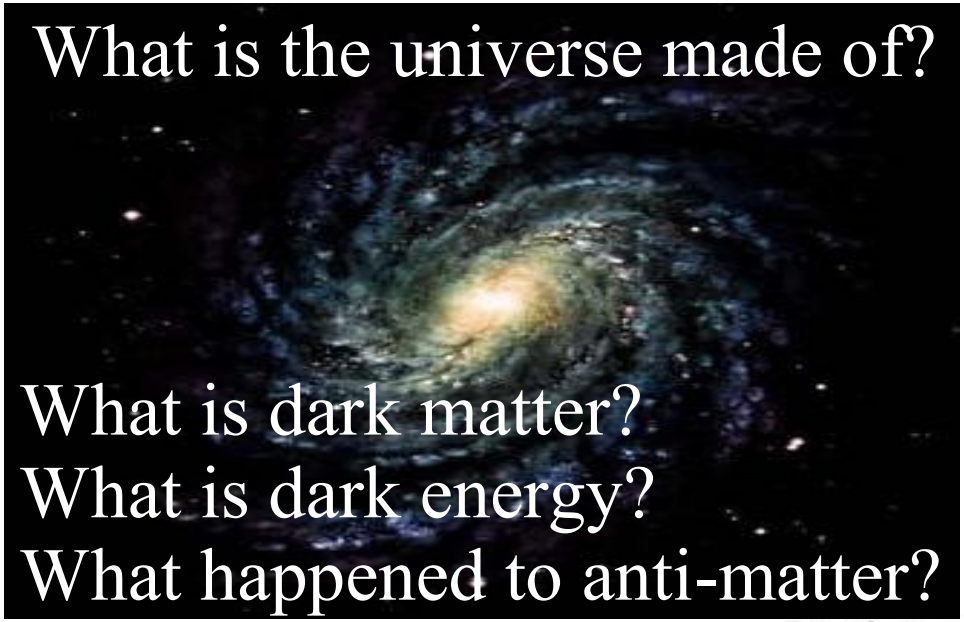


A fundamental question

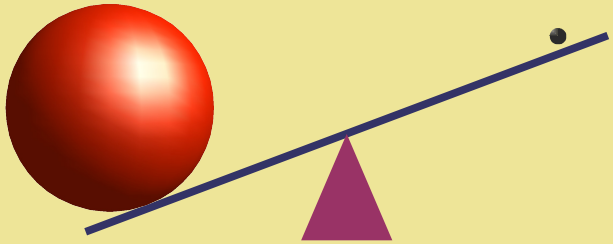
What is the origin of matter?

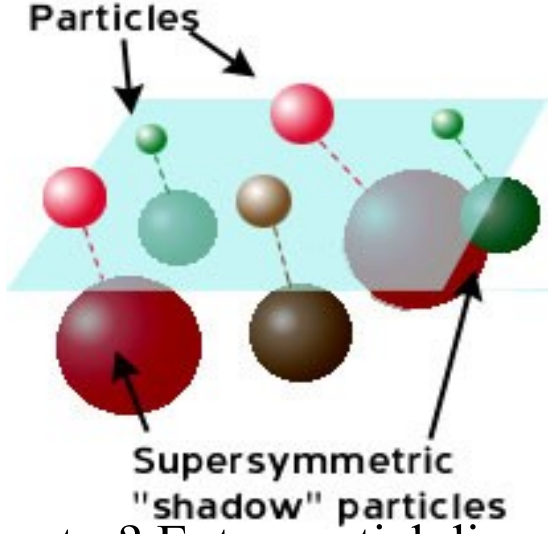
What is the origin of matter?

What gives mass to elementary particles?



What makes quarks so heavy and neutrinos so light?





Supersymmetry? Extra spatial dimensions? ...

Experimental 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.

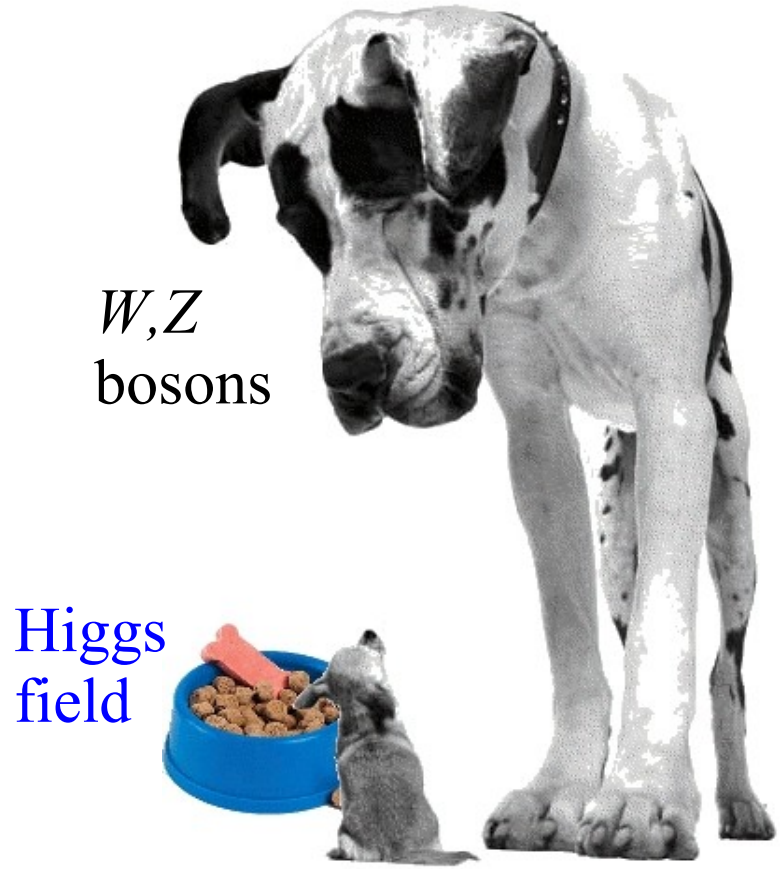
Galileo

Gauge boson masses in the SM

Gauge bosons

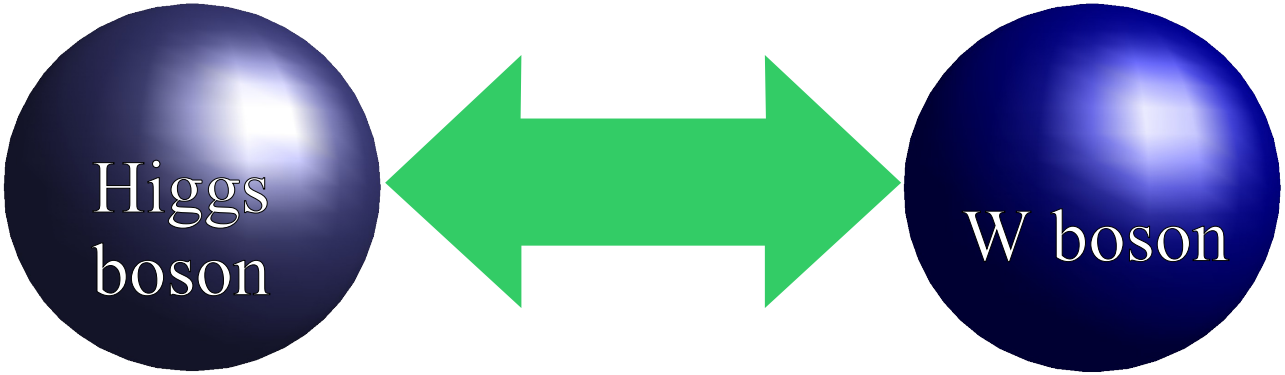
Higgs field

Electroweak symmetry breaking



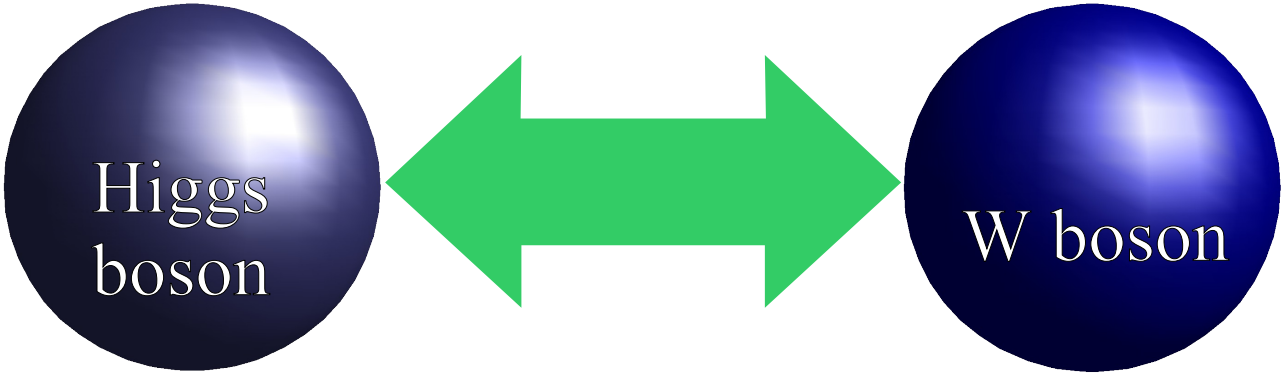
Electroweak symmetry breaking

Gauge boson coupling to Higgs field

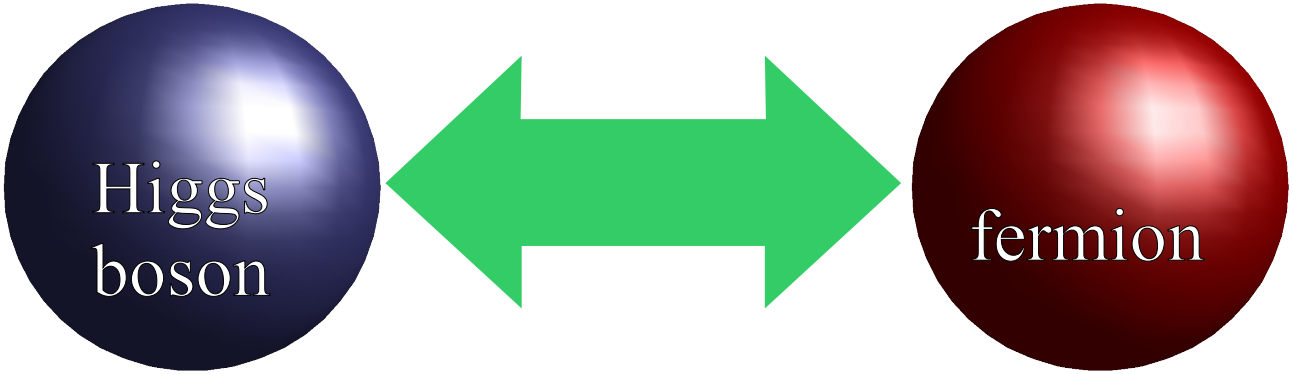


Electroweak symmetry breaking

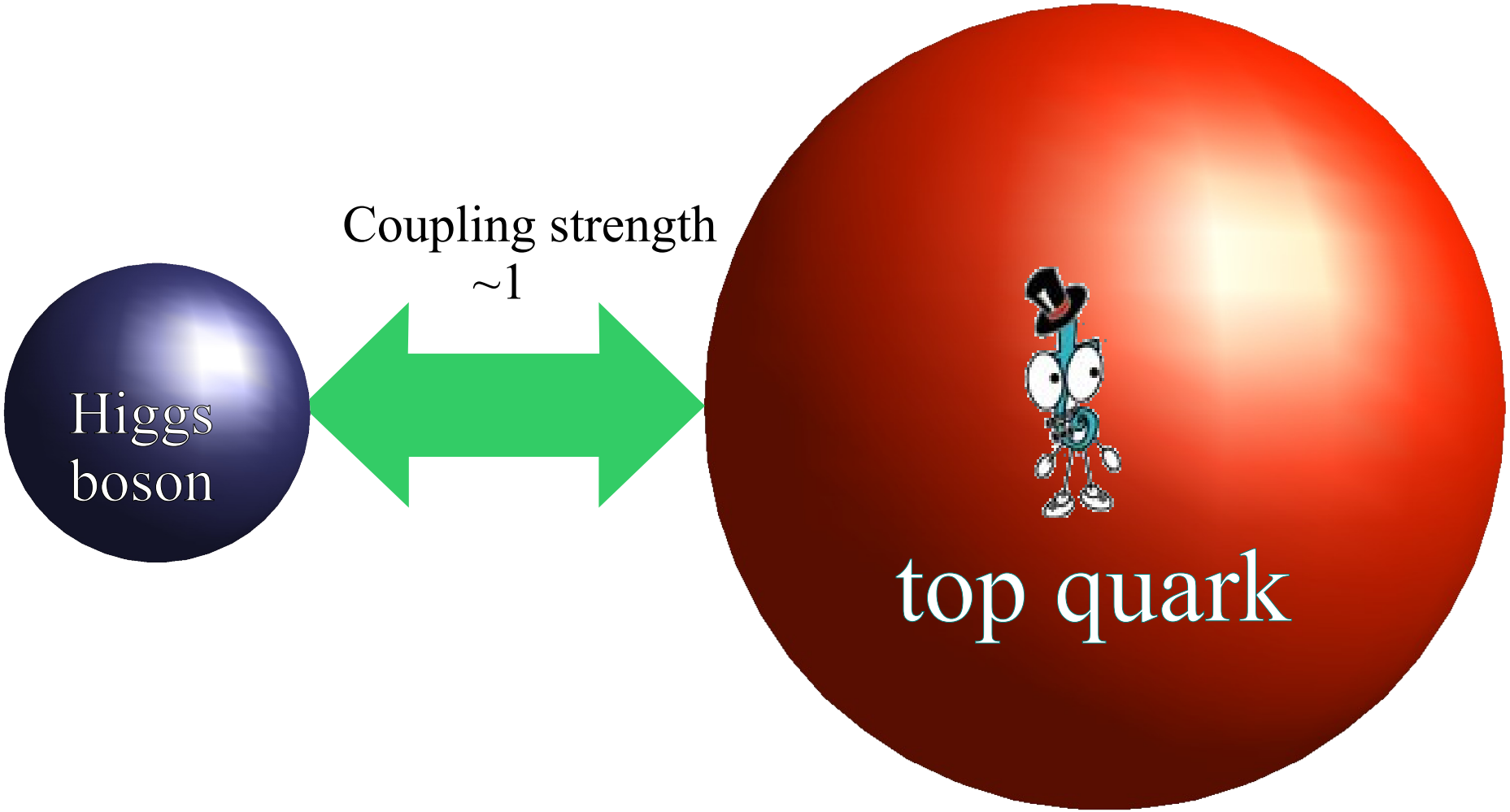
Gauge boson coupling to Higgs field



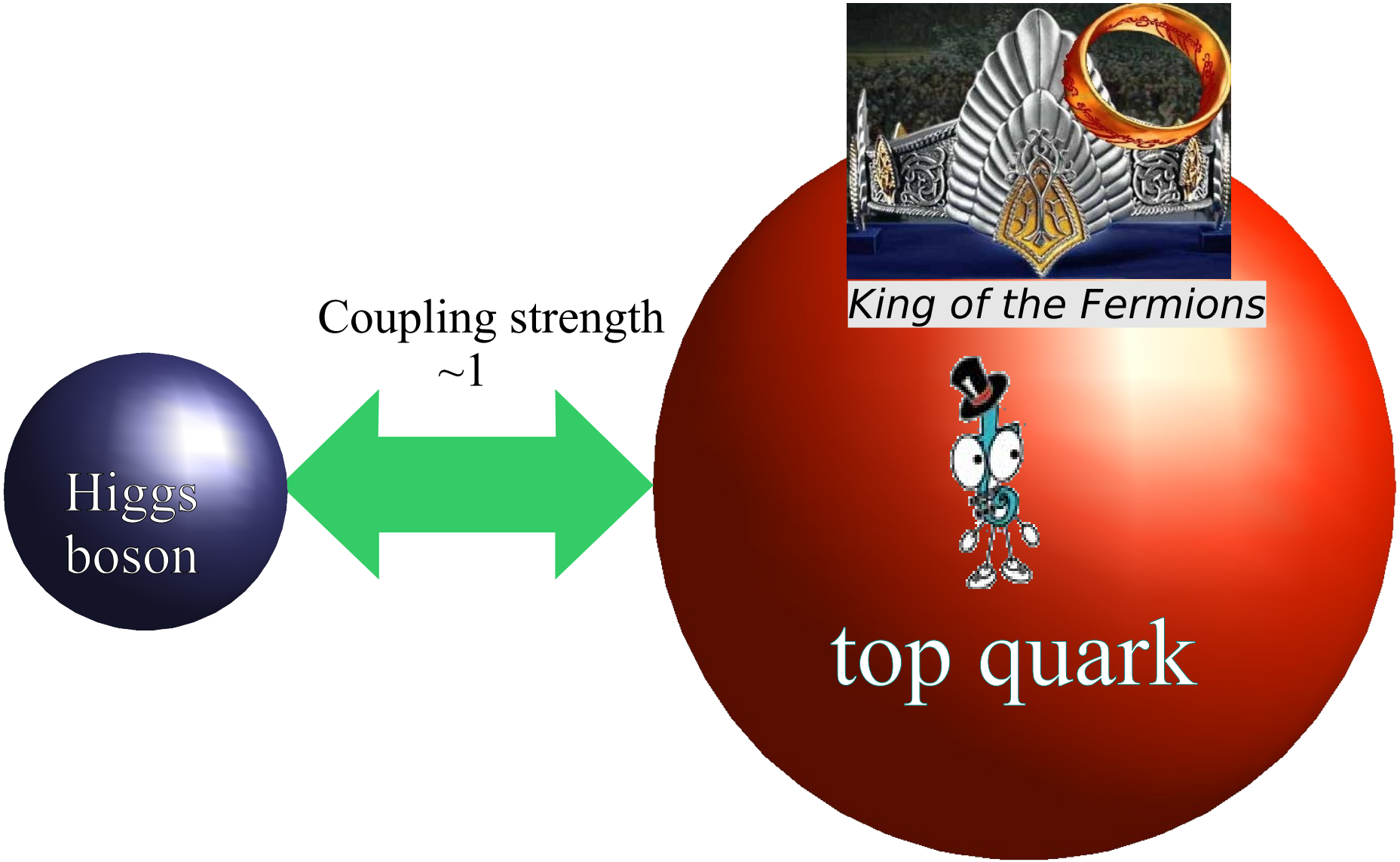
Fermions acquire mass through Higgs coupling



Top quark mass



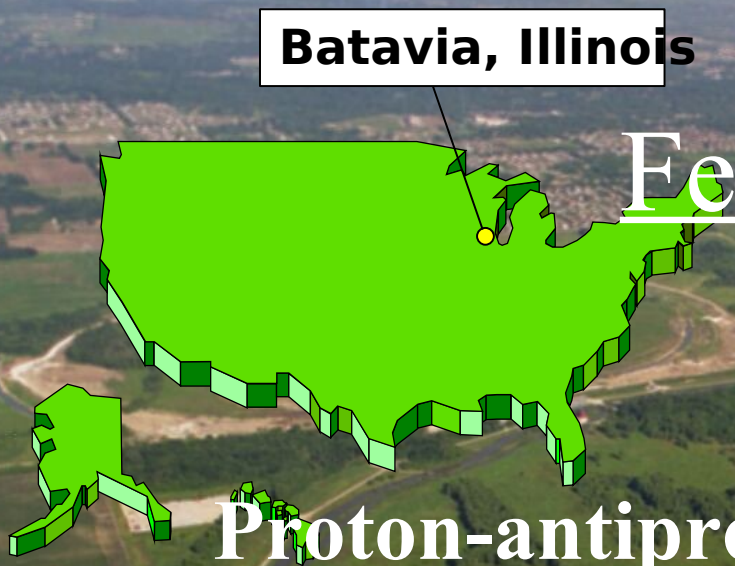
Top quark mass



Preparation

How do we collect a sample of candidates?

Experimental setup: Fermilab Tevatron in Run II



Proton-antiproton collider

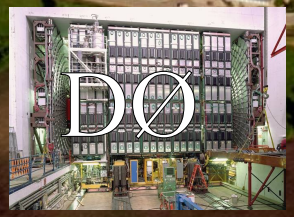
CM energy 1.96TeV

→ ***Energy frontier***

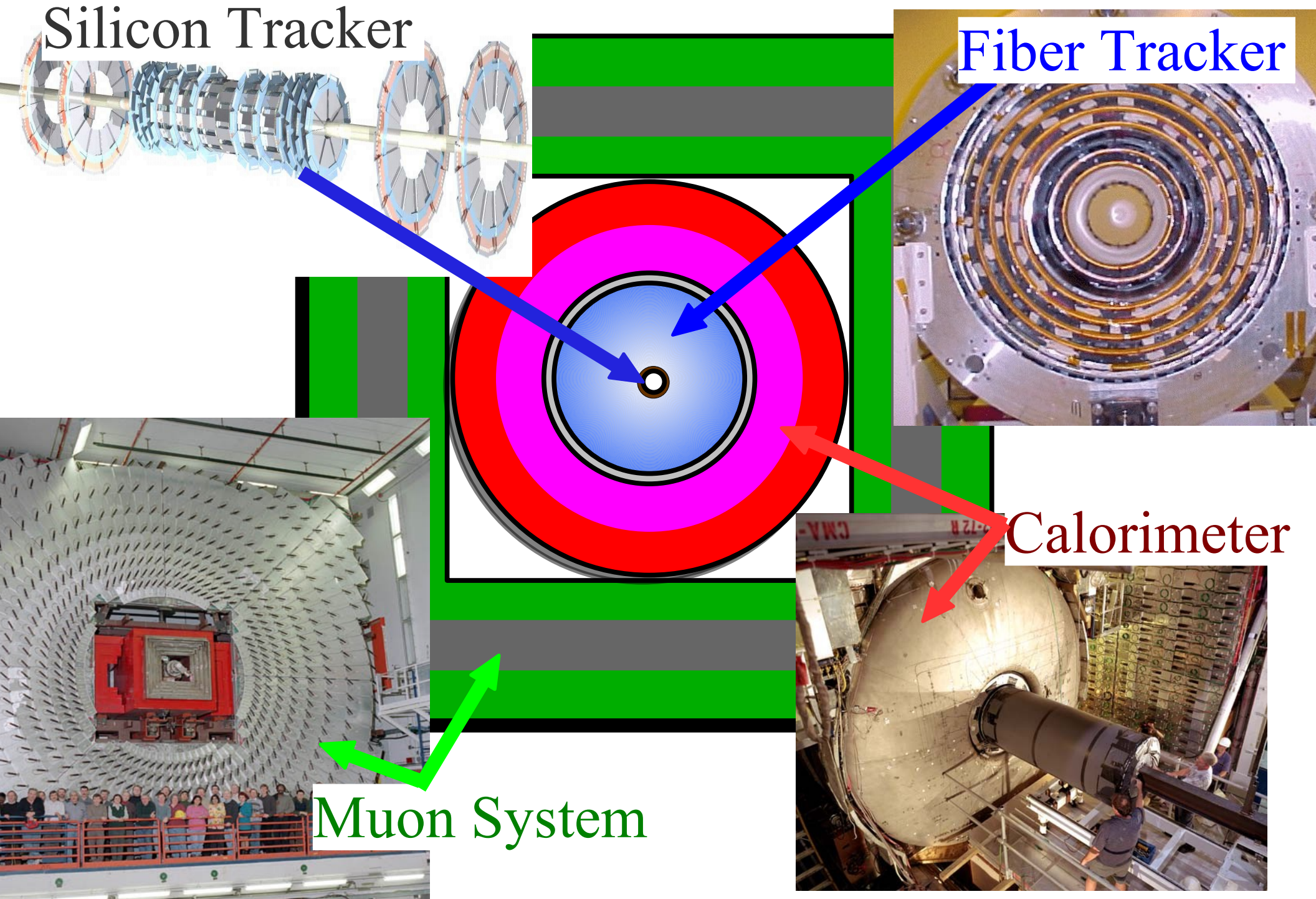
Instantaneous luminosity >250E30cm^{-2}s^{-1}

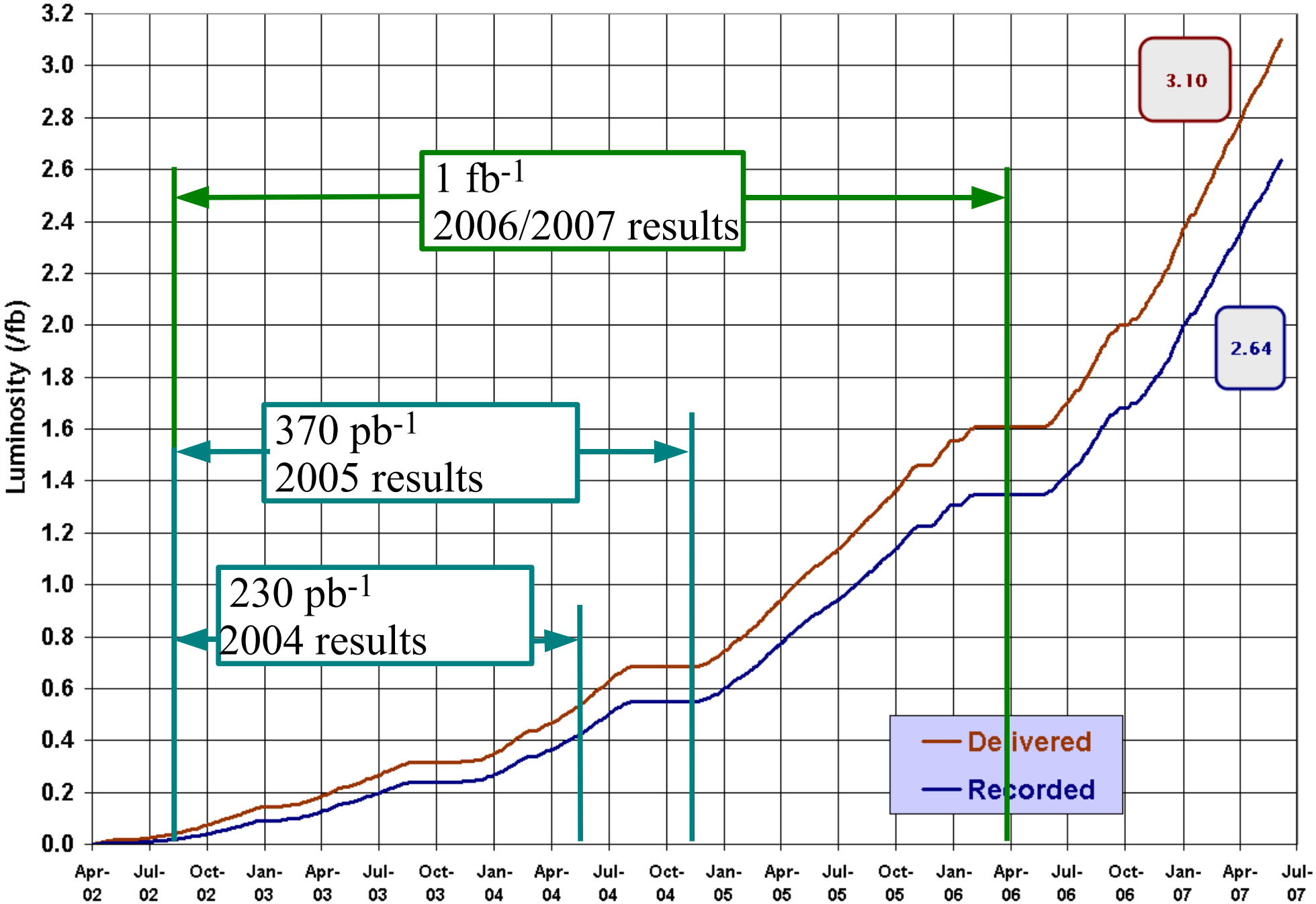
– ~4 interactions per crossing, 1.7M crossing per second

→ ***Luminosity frontier***



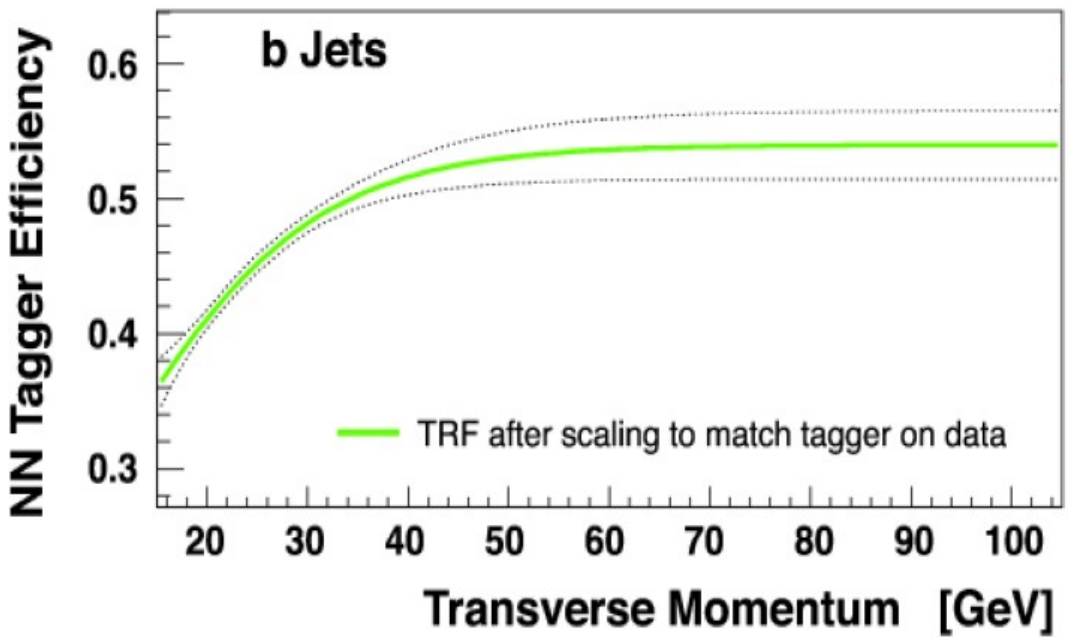
Apparatus: Run II DØ Detector




Run II Integrated Luminosity
19 April 2002 - 24 June 2007
Luminosity (/fb)
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
1 fb-1
2006/2007 results
370 pb-1
2005 results
230 pb-1
2004 results
3.10
2.64
Delivered
Recorded
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

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

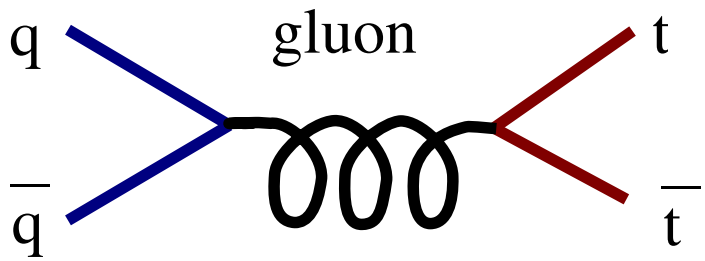


Measurements

What do we know about the top quark?

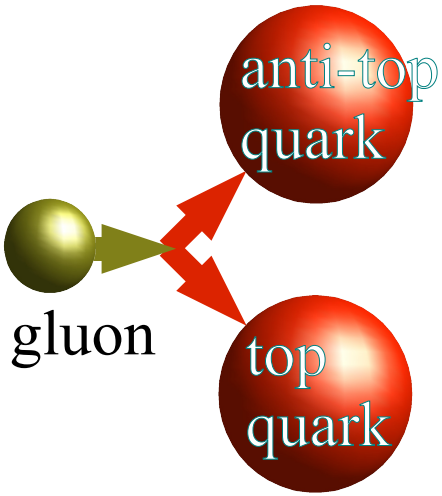
Top Quark properties:

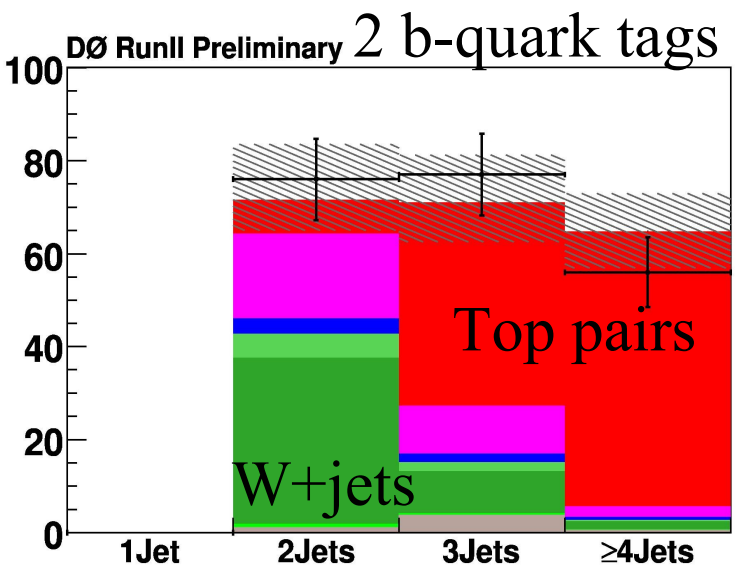
- Strong coupling
- Top quark mass

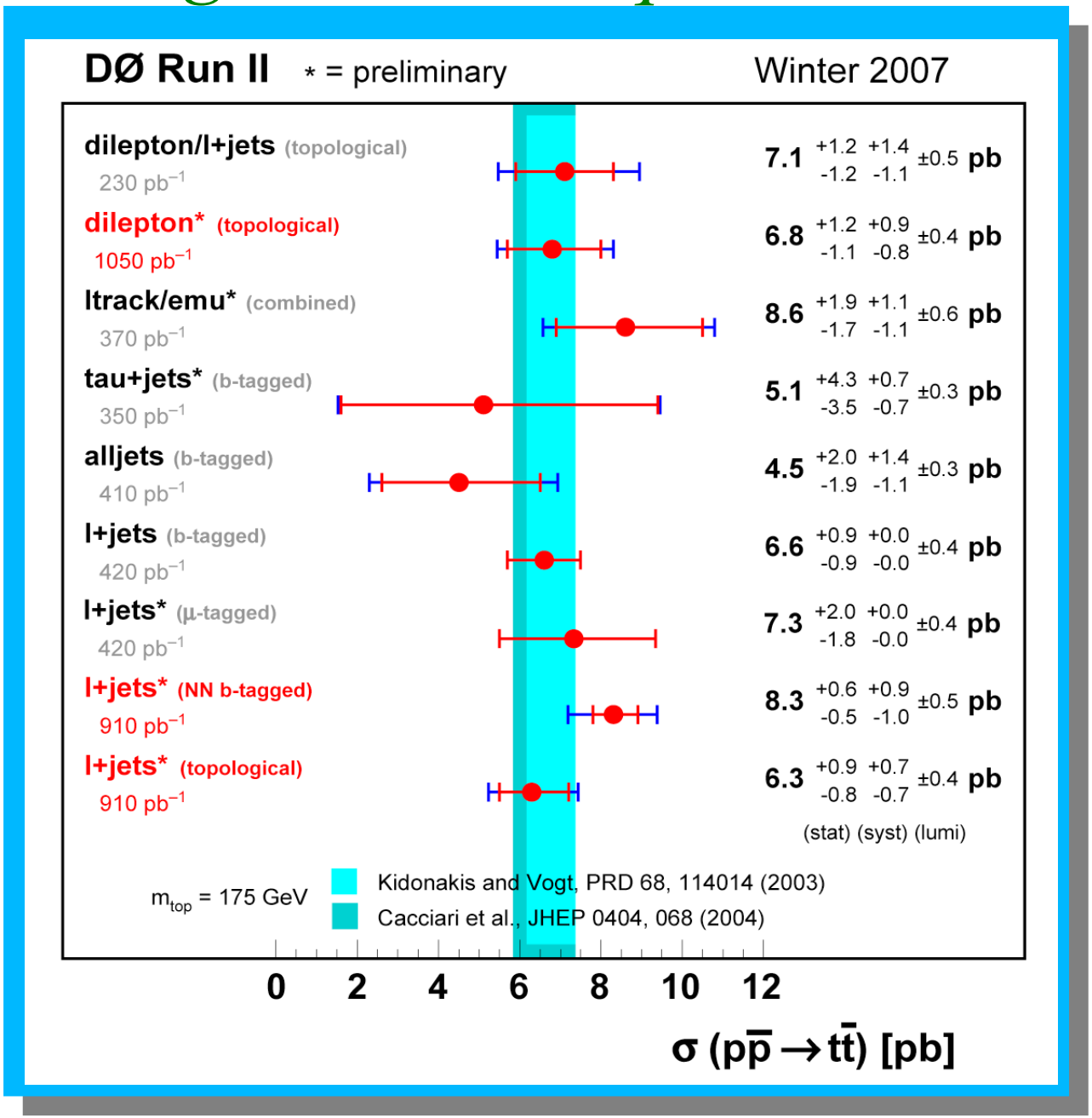


Top quark strong interaction –

Does it couple to gluons like a quark?



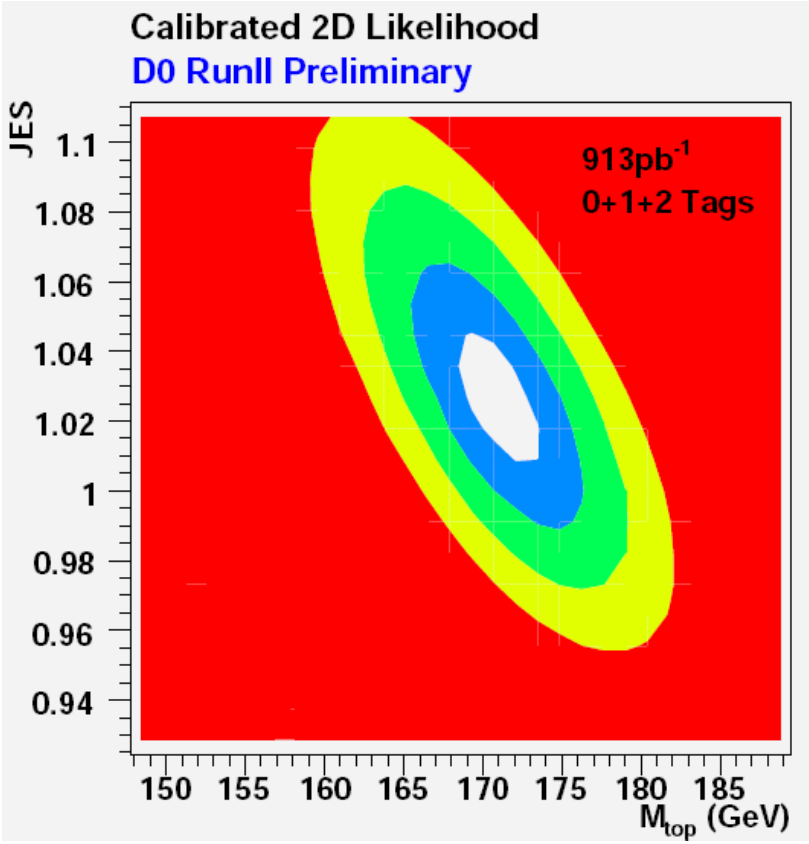


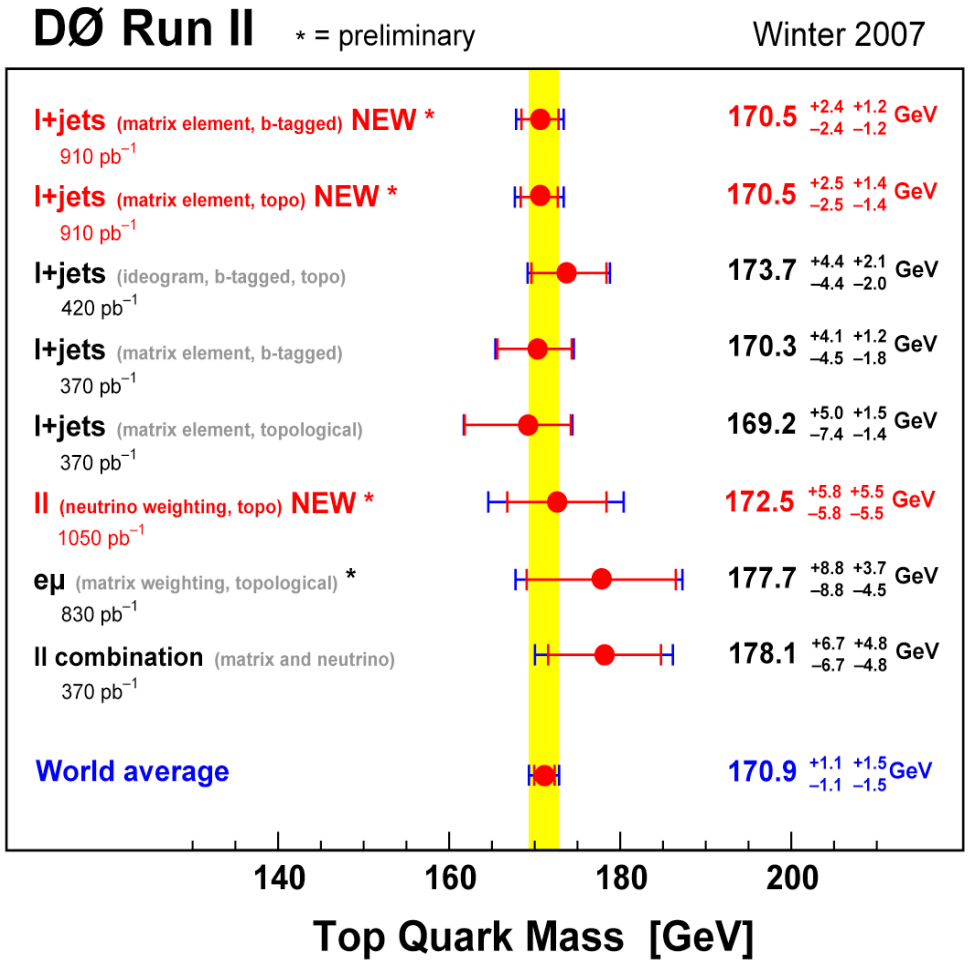


Top quark mass determination

- Large sample of top quarks
  - ➔ Measurement uncertainty dominated by systematic effects
  - – Fit mass and jet energy scale systematic simultaneously

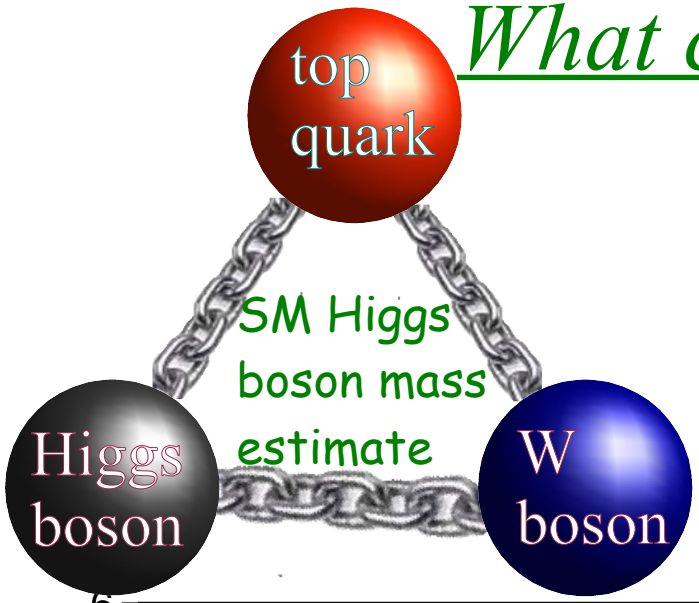
lepton+jets mass, matrix element method

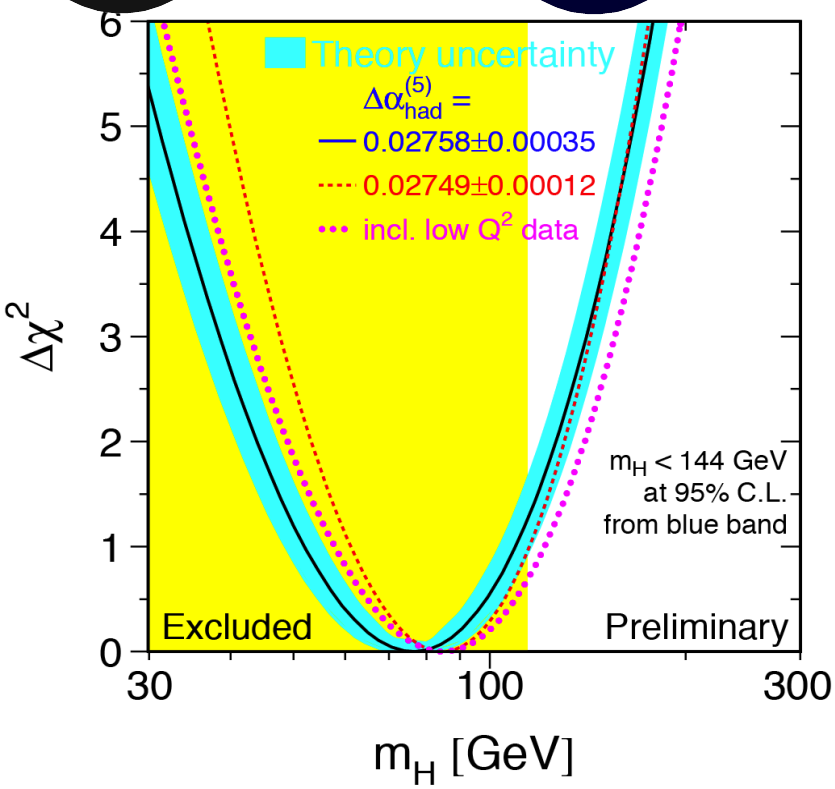


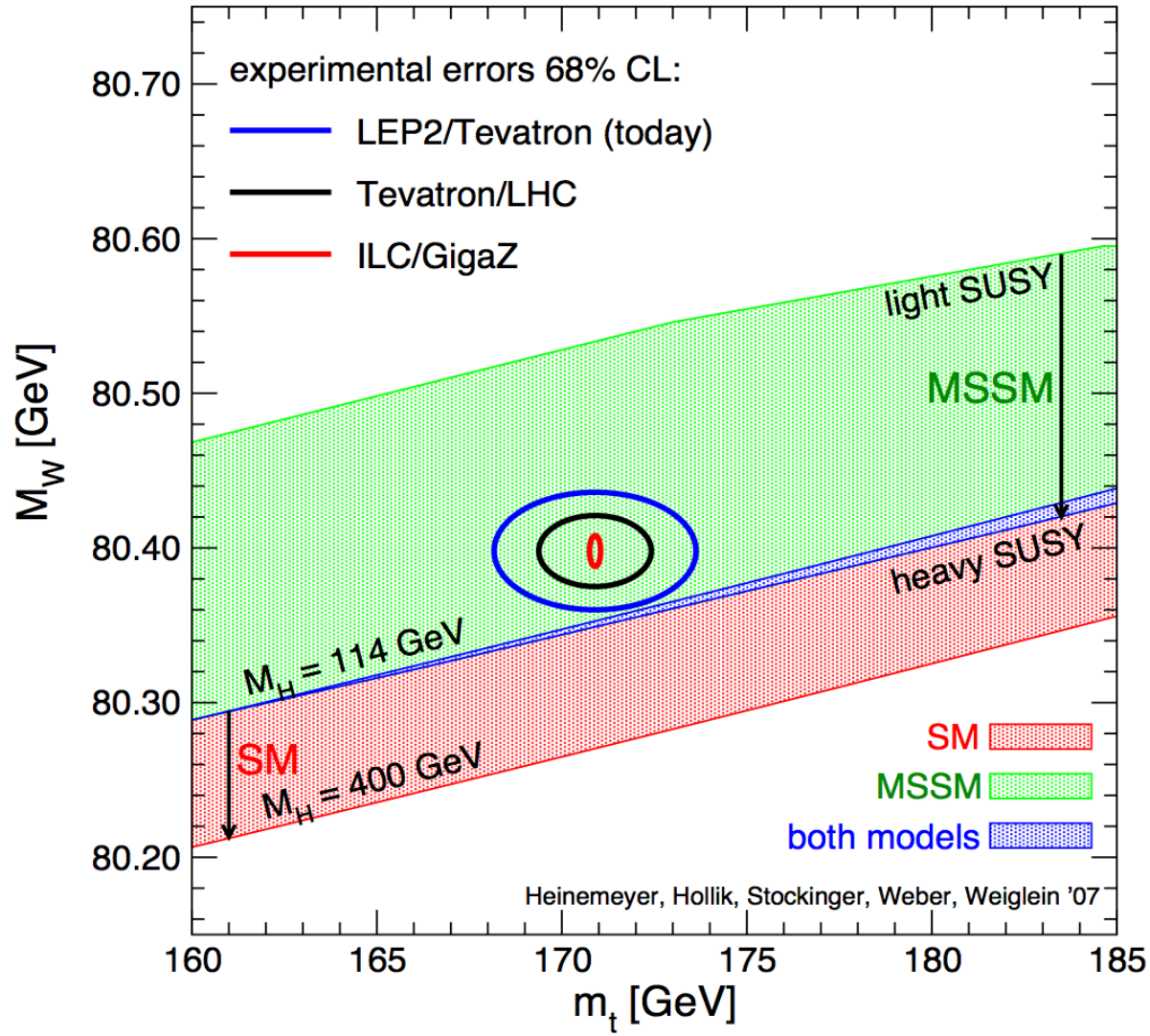


Top quark mass implications –

What can Top tell us about Higgs?







Top Quark properties:

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

Unknow:

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

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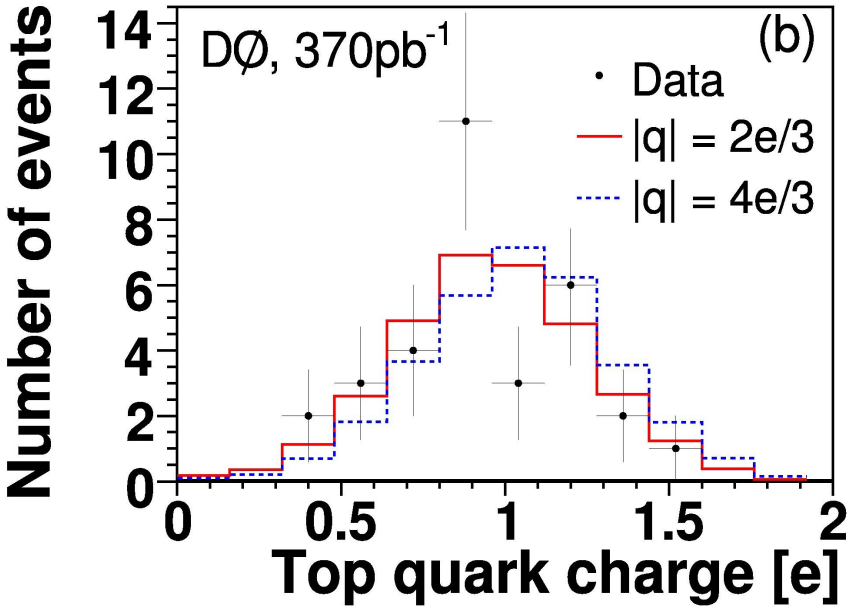
Exclude charge +4/3 with p-value of 7.8%



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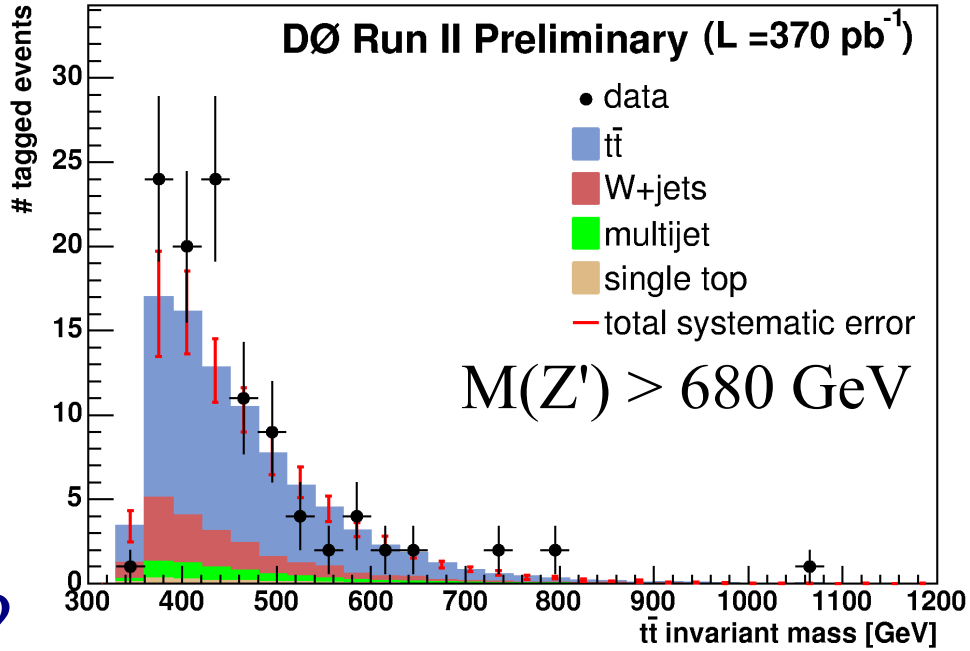

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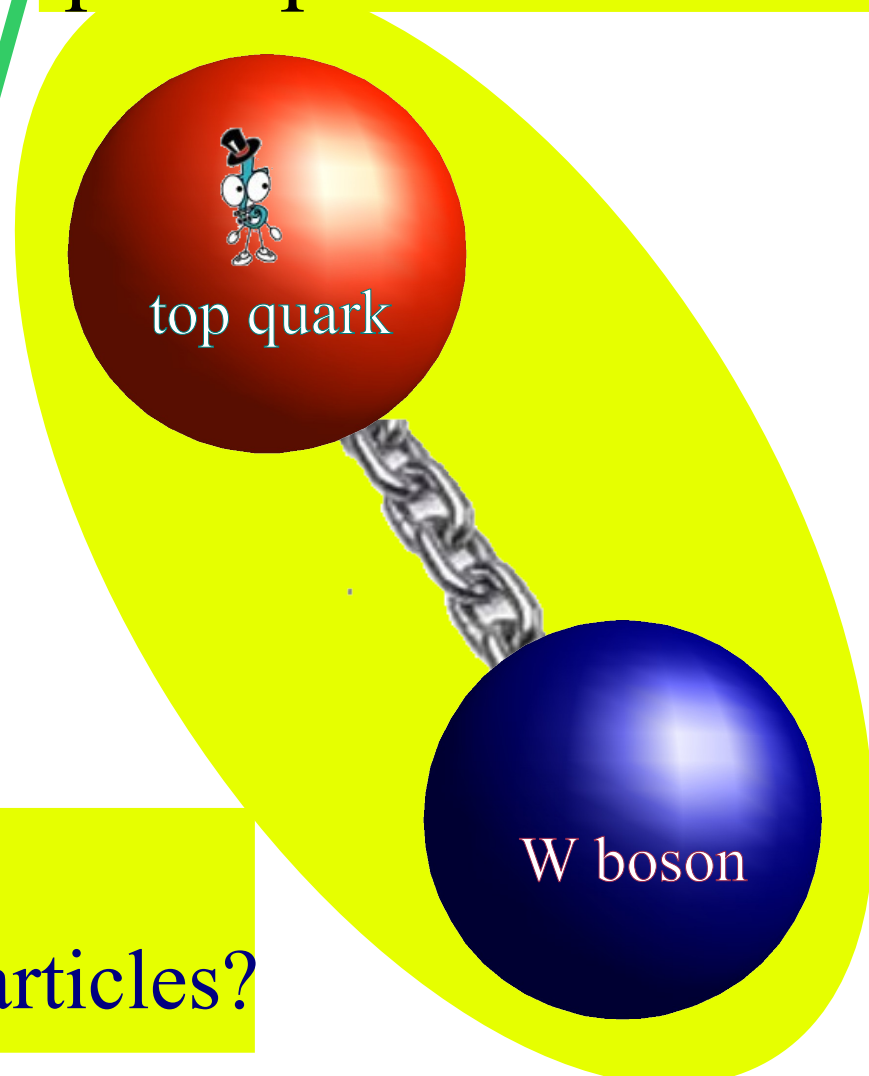
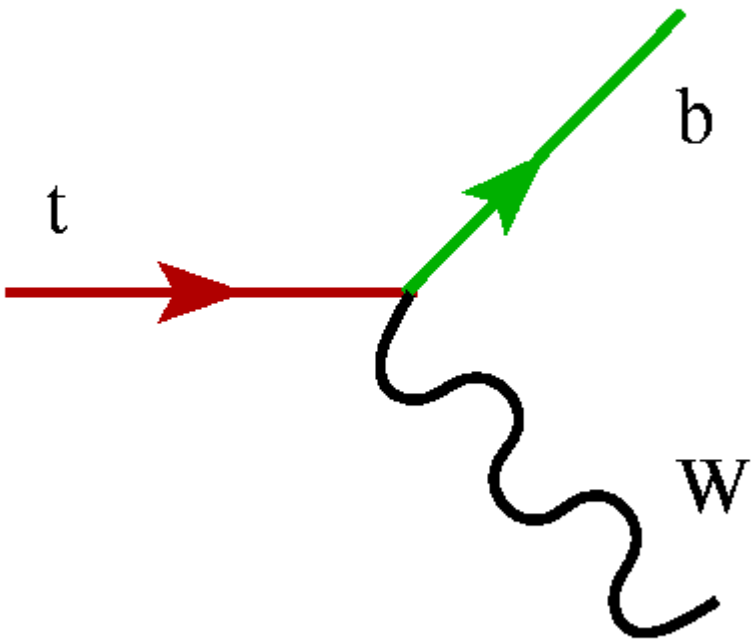
Study in single top quark production



Really don't know:

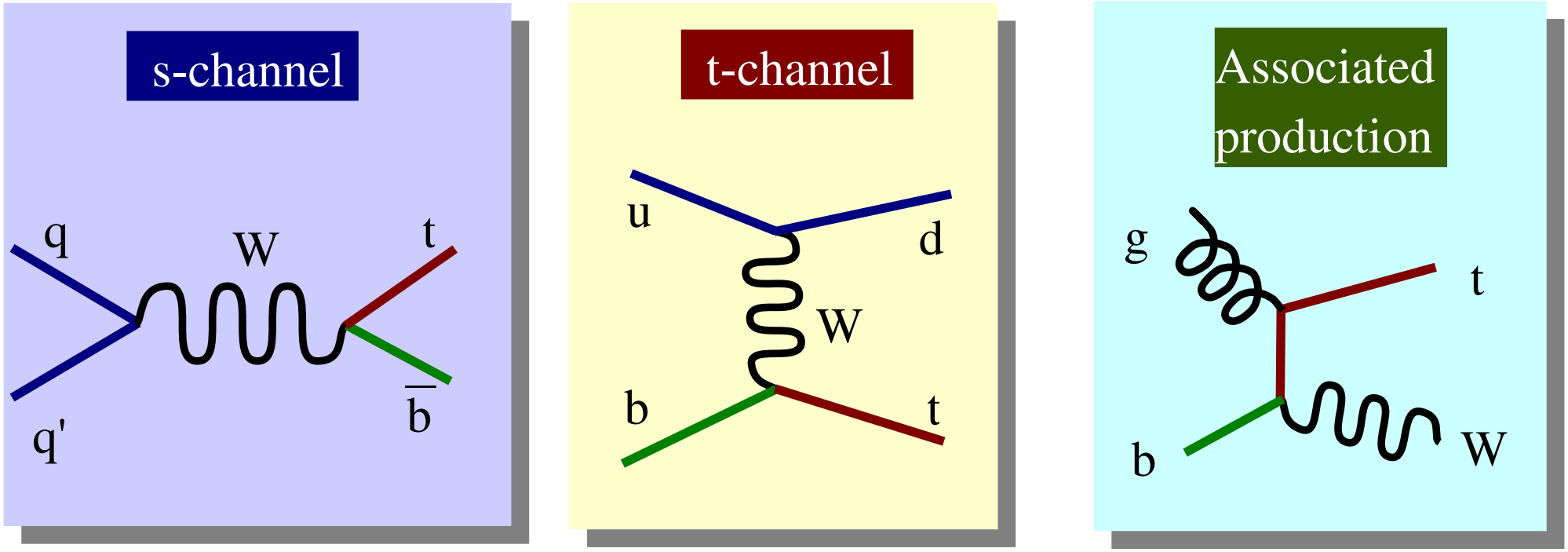
- Coupling to Higgs?
- Modified weak coupling?
- SUSY? Coupling to new particles?

Top quark electroweak charged current interaction

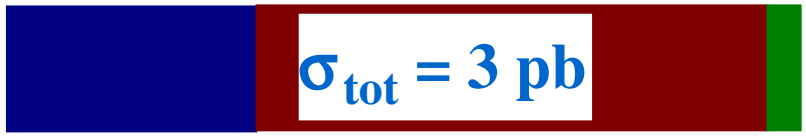


top quark decay

SM single top quark production



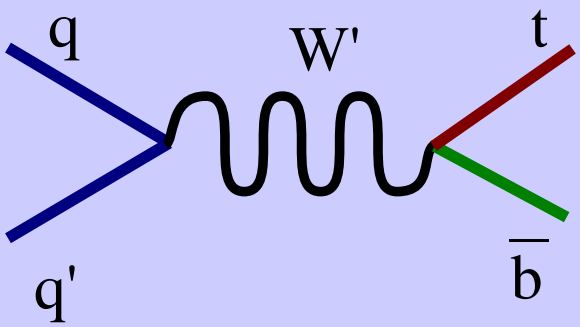
TeV:



LHC:

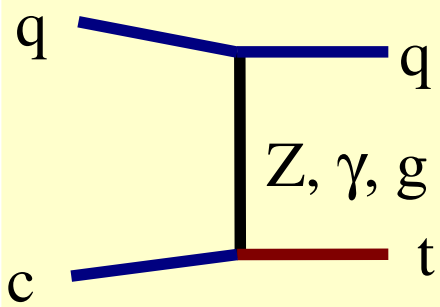
New physics

s-channel



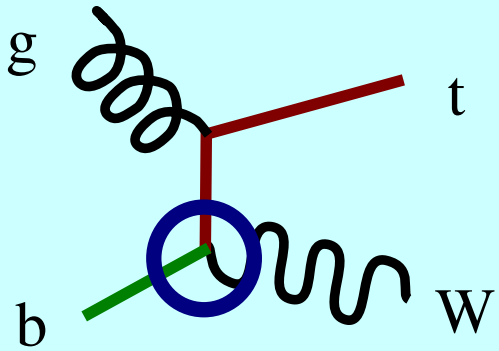
New heavy boson

t-channel



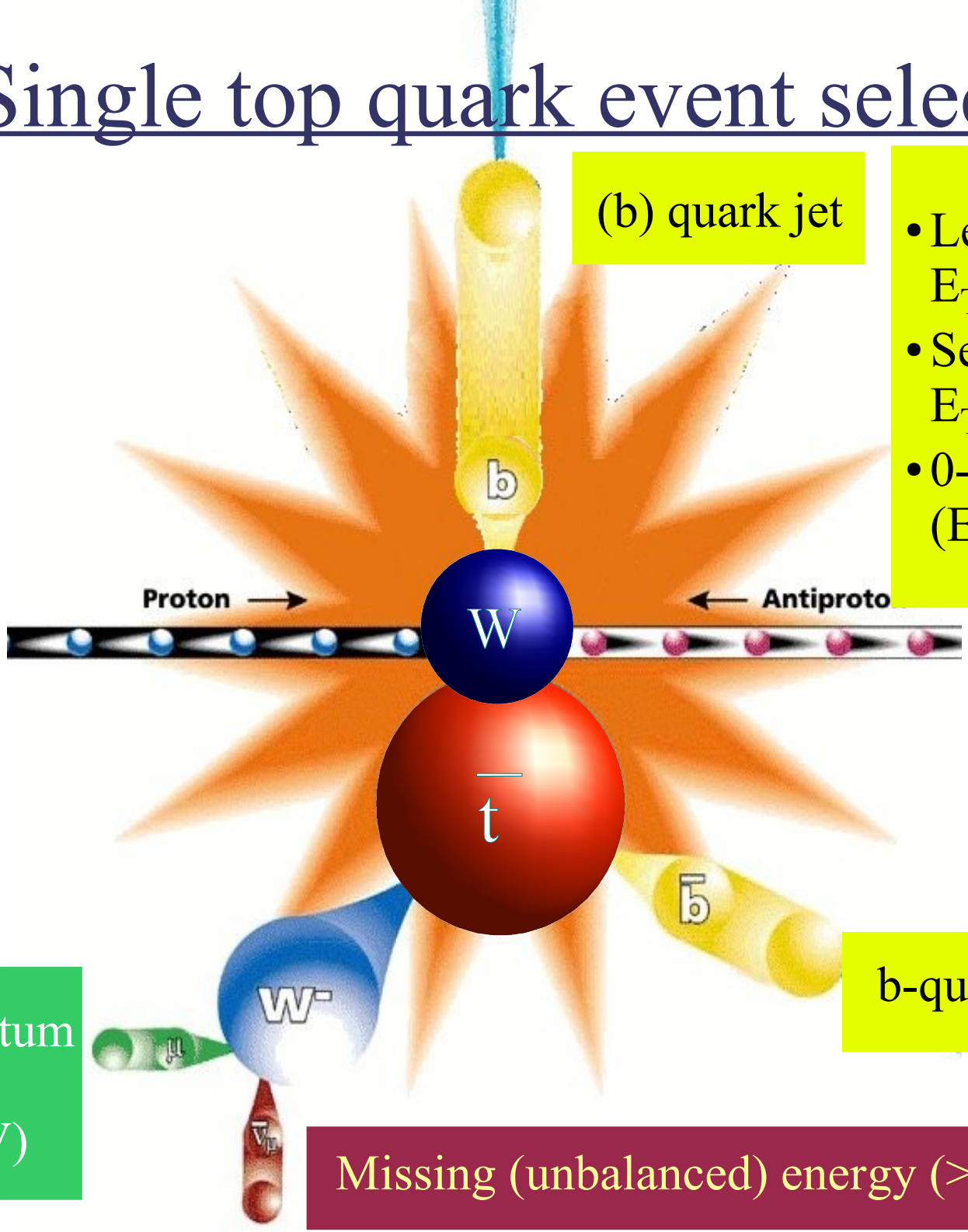
Flavor Changing Neutral Current

Associated production



Modified Wtb coupling

Single top quark event selection



(b) quark jet

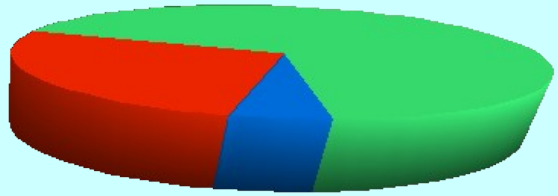
- Leading jet: $E_T > 25$ GeV
- Second jet: $E_T > 20$ GeV
- 0-2 additional jets (ET > 15 GeV)

b-quark jet

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

Missing (unbalanced) energy (> 15 GeV)

Event Sample Composition



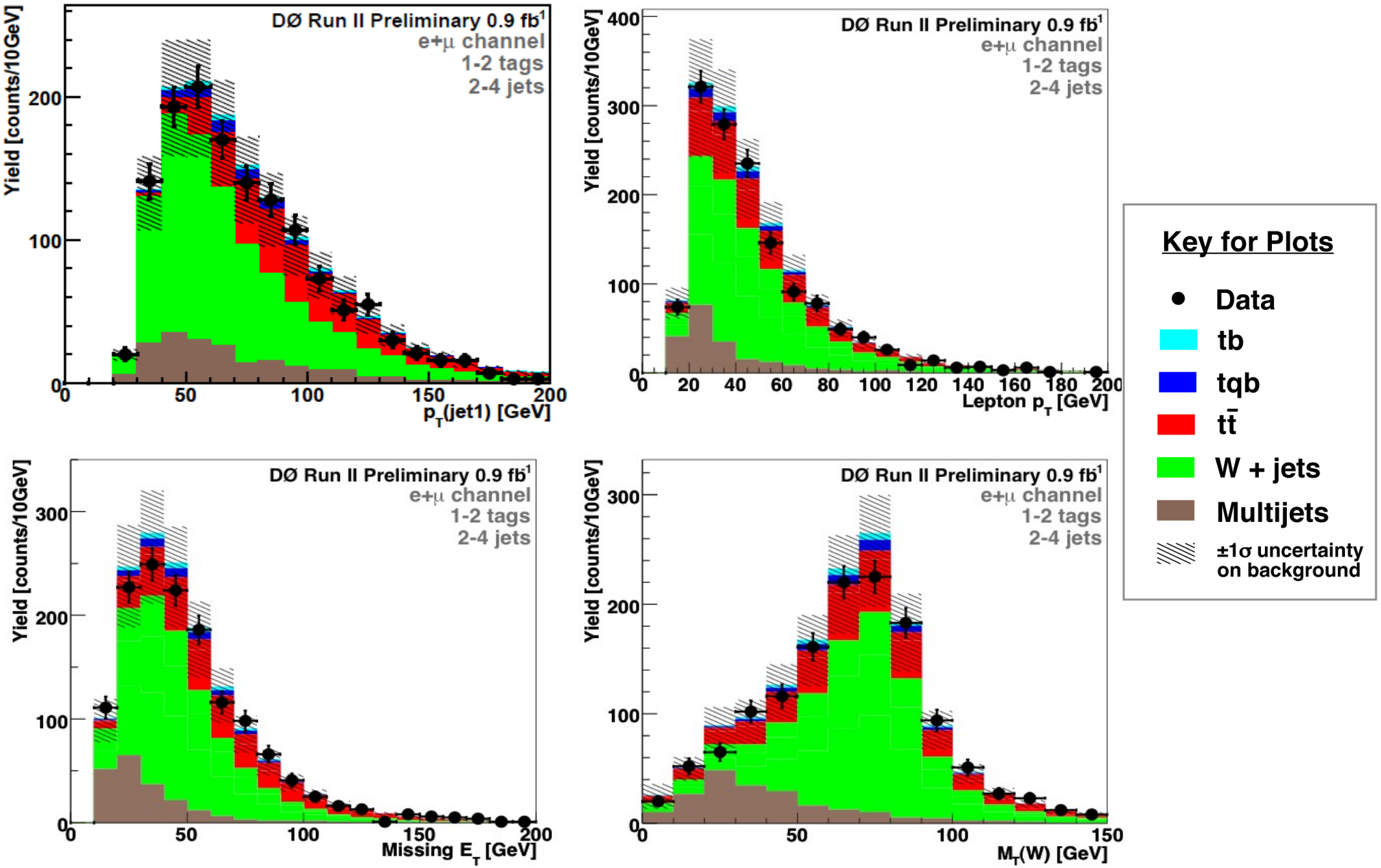
(~ 1 ev pb)

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



Optimized Event Analysis

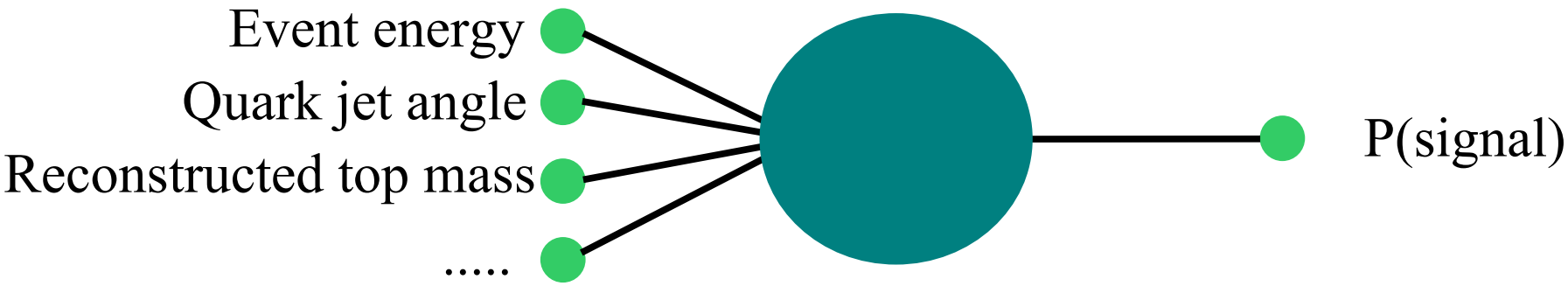
How do we find the needle in the haystack?

Multivariate methods

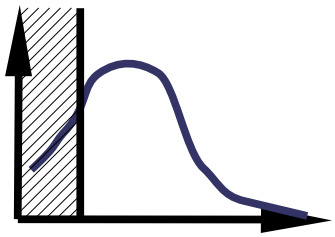
Input:
discriminating variables

Method:
multivariate analysis

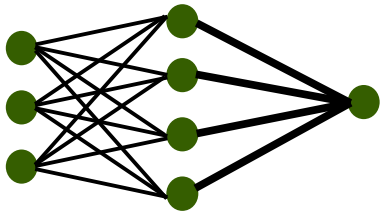
Output:
signal likelihood



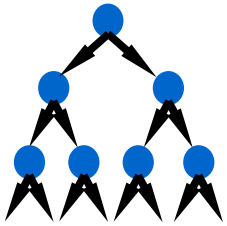
Cut-Based



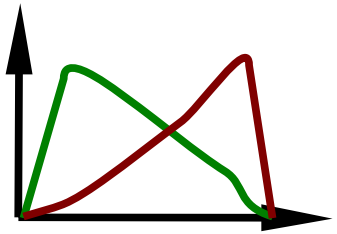
Neural networks



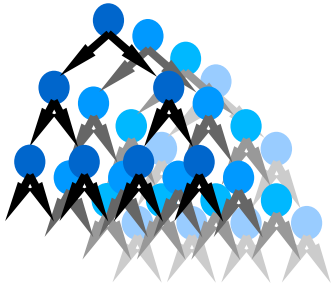
Decision trees



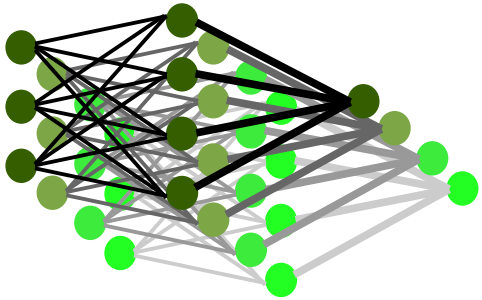
Likelihood



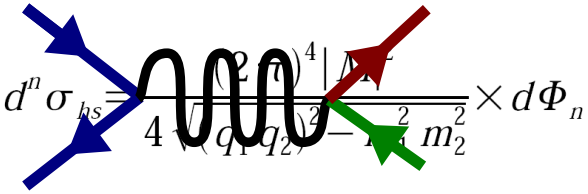
Boosted decision trees



Bayesian neural networks



Matrix Elements

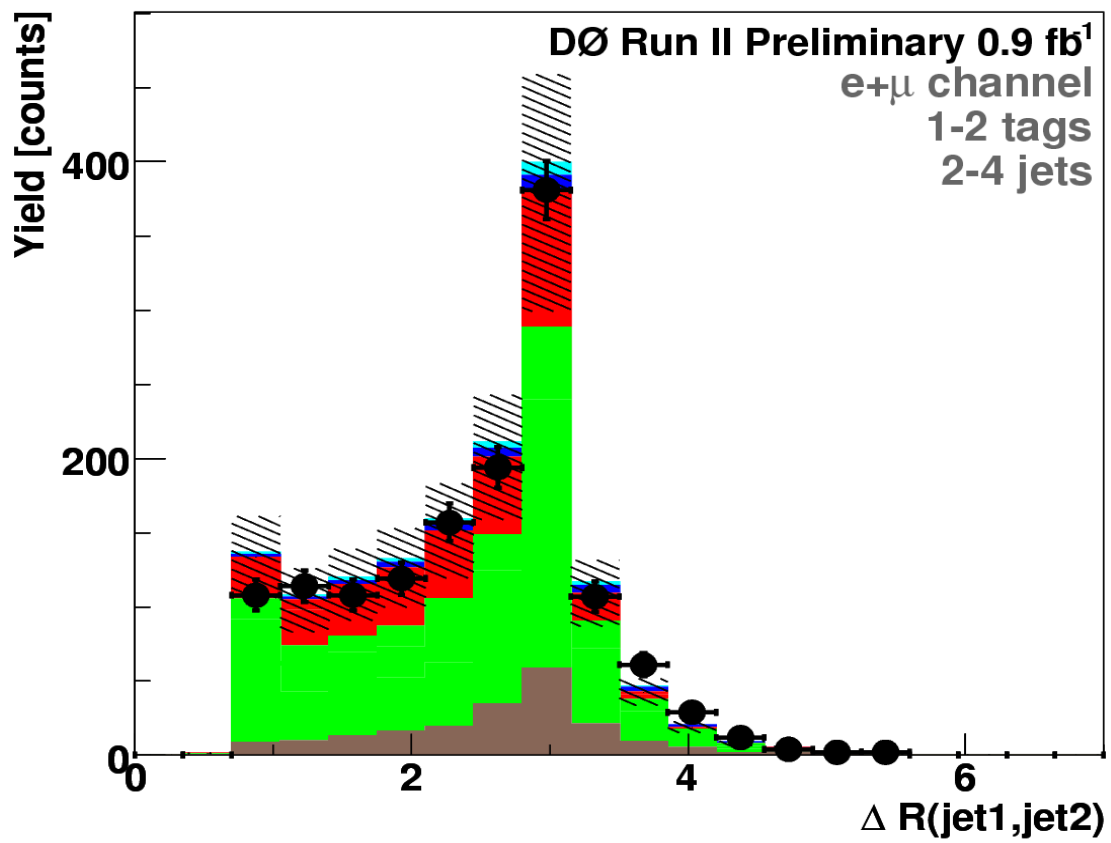


Discriminating Variables

- 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

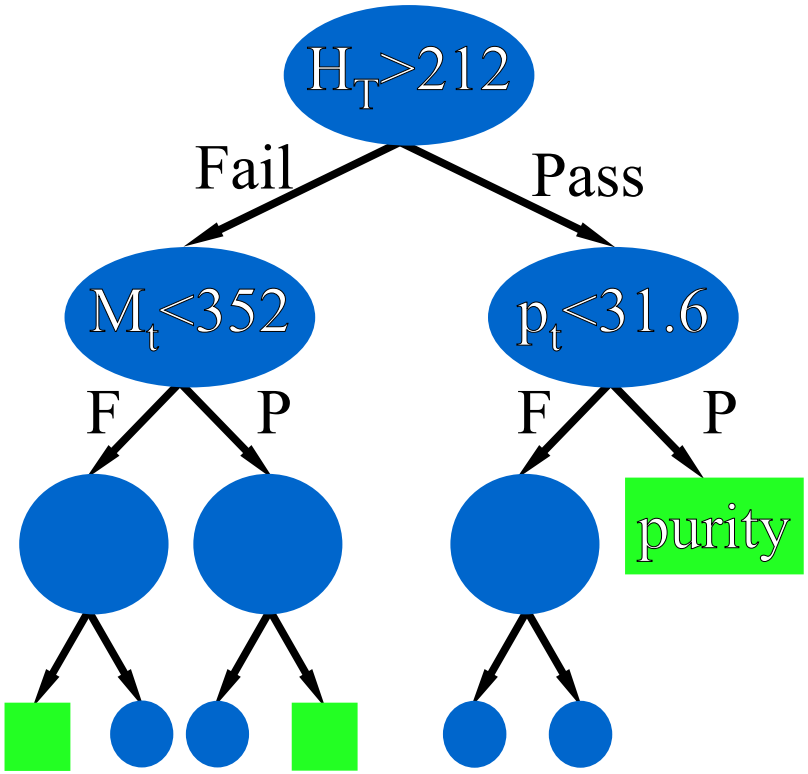
Object kinematics

Jet p_T for different jets

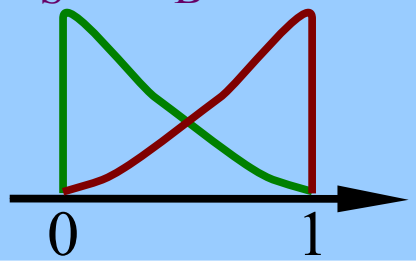


49 variables total

Decision Trees



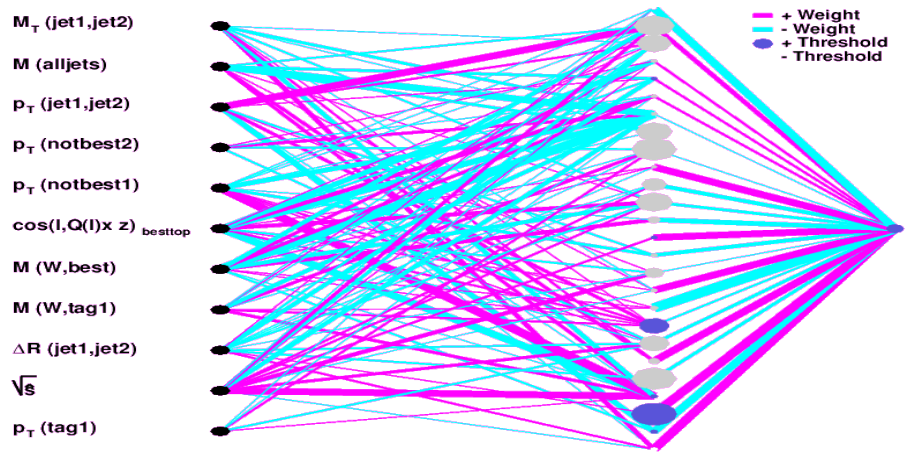
- Send each event down the tree
- Each node corresponds to a cut
  - Divide sample in two: Pass↔Fail
- A leaf corresponds to a node without branches
  - Defines purity = $N_S/(N_S+N_B)$ from MC sample
- Training: optimize Gini improvement
  - Gini = $2\, N_S\, N_B\, /(N_S + N_B)$
- Output: purity for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

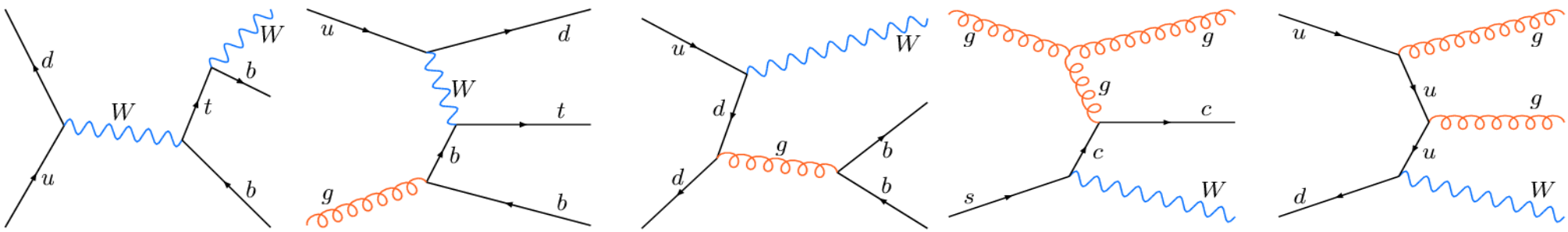
- Calculate signal discriminant directly for each event

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

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

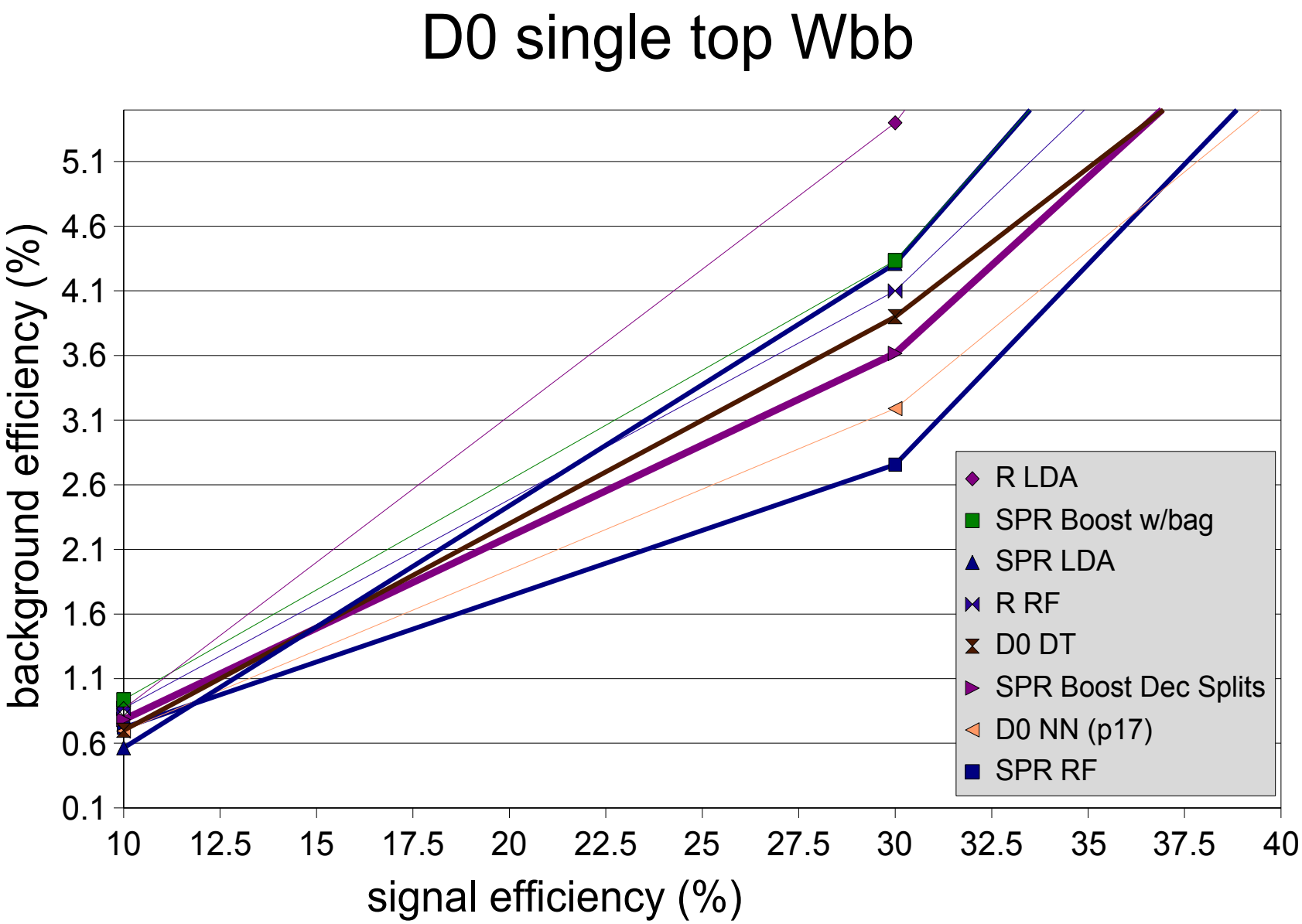
$$P_{Signal}(\vec{x}) = \frac{1}{\sigma_S} d\sigma_S(\vec{x}) \quad \sigma_S = \int d\sigma_S(\vec{x})$$

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



- Integrate over ME and measured momenta

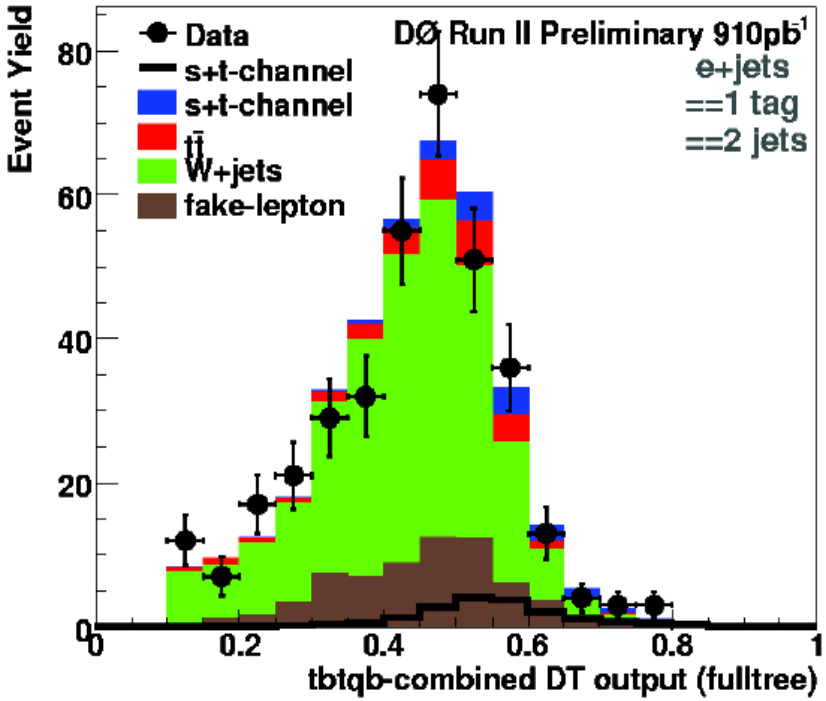
Classifier comparison

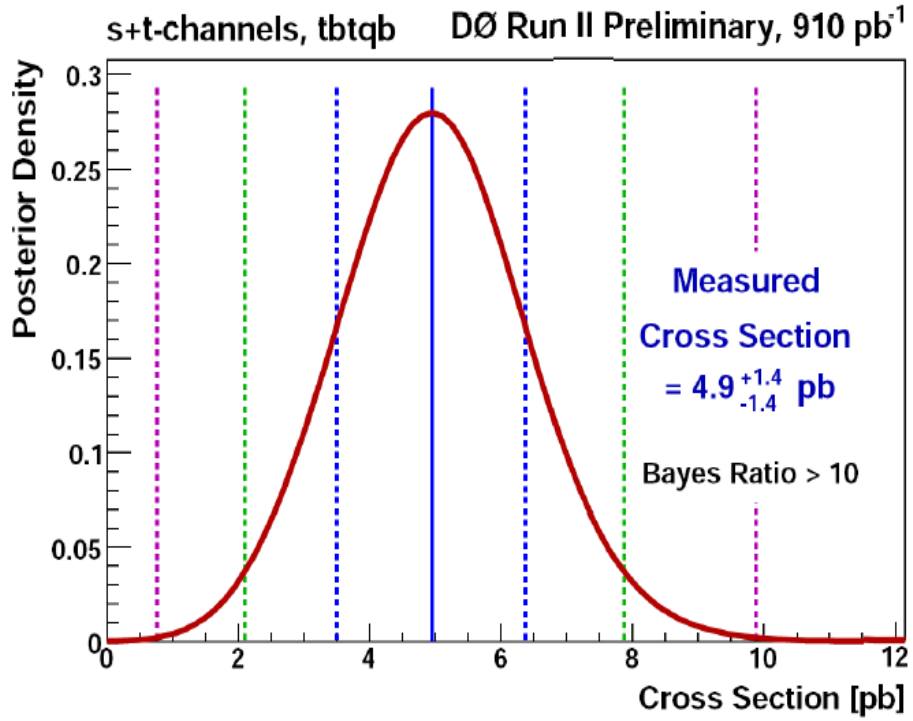


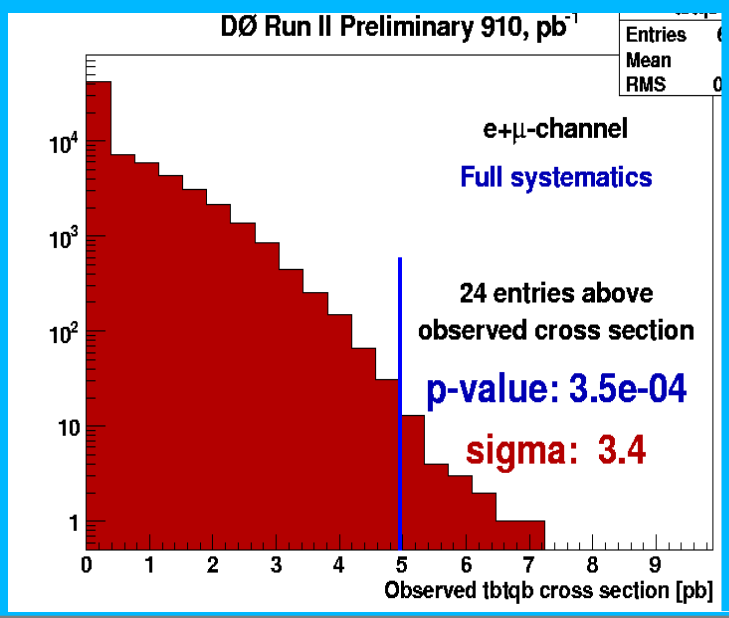
Results

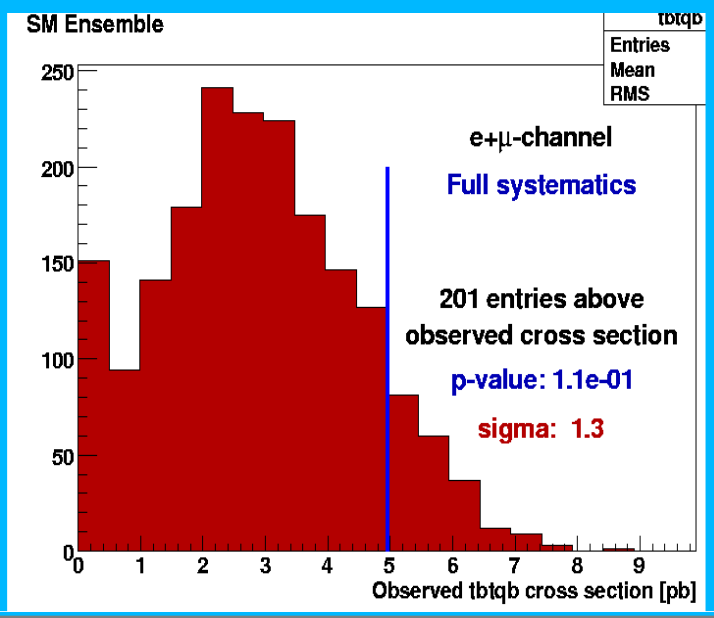
Let Data speak!

Boosted Decision Trees

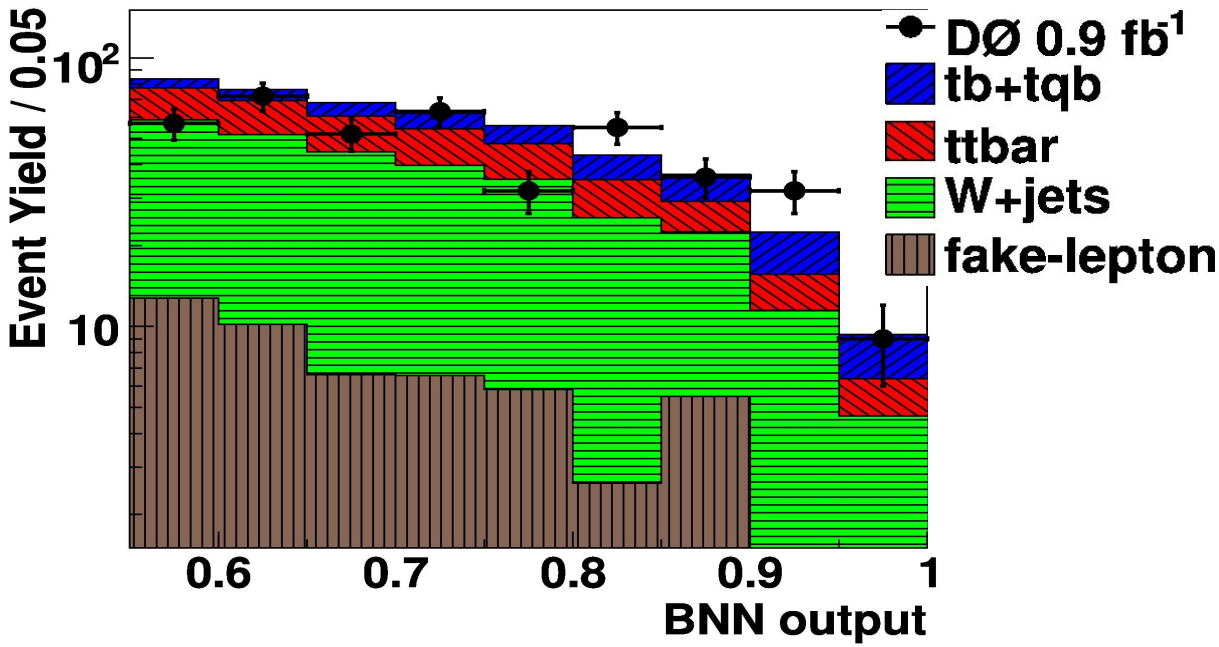


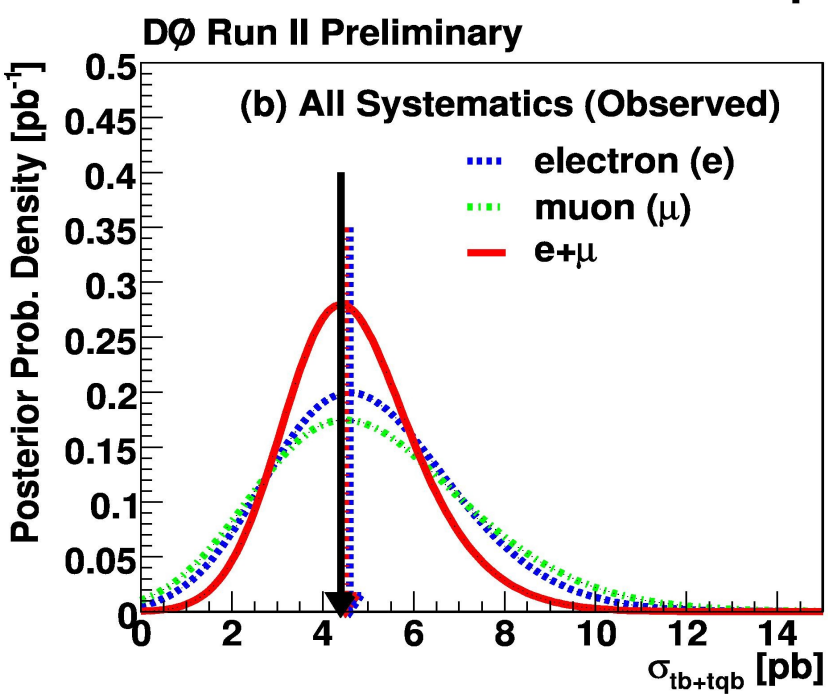


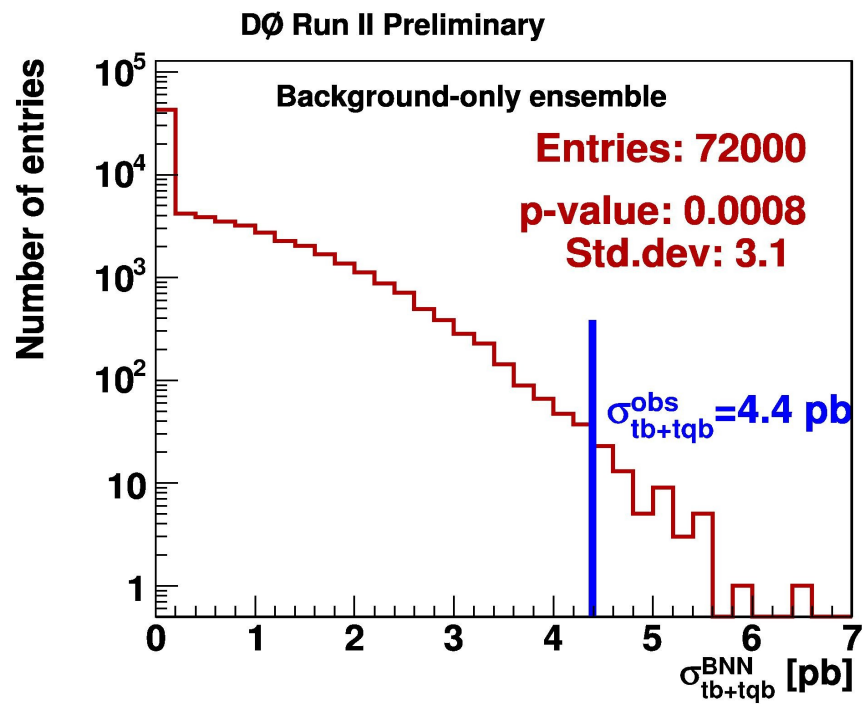




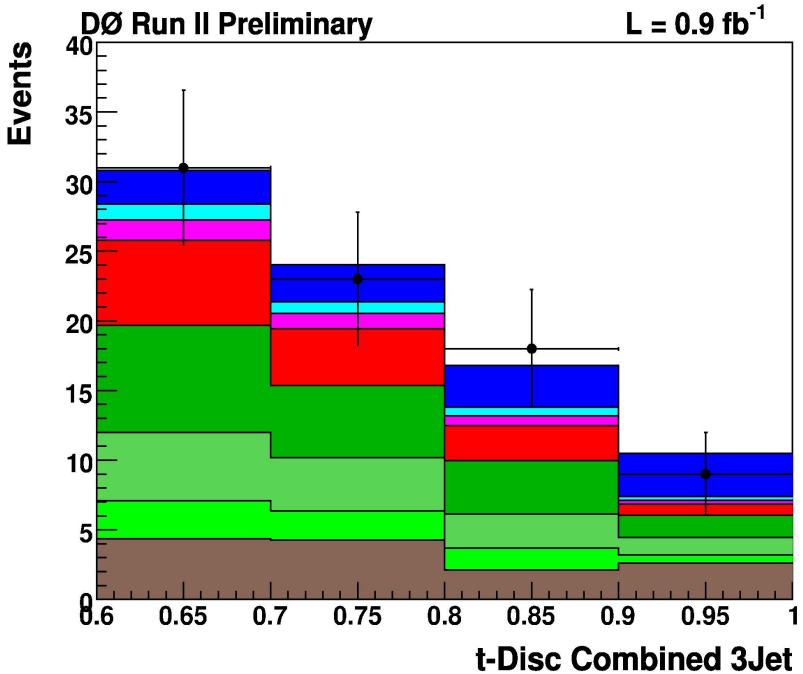
Bayesian Neural Network

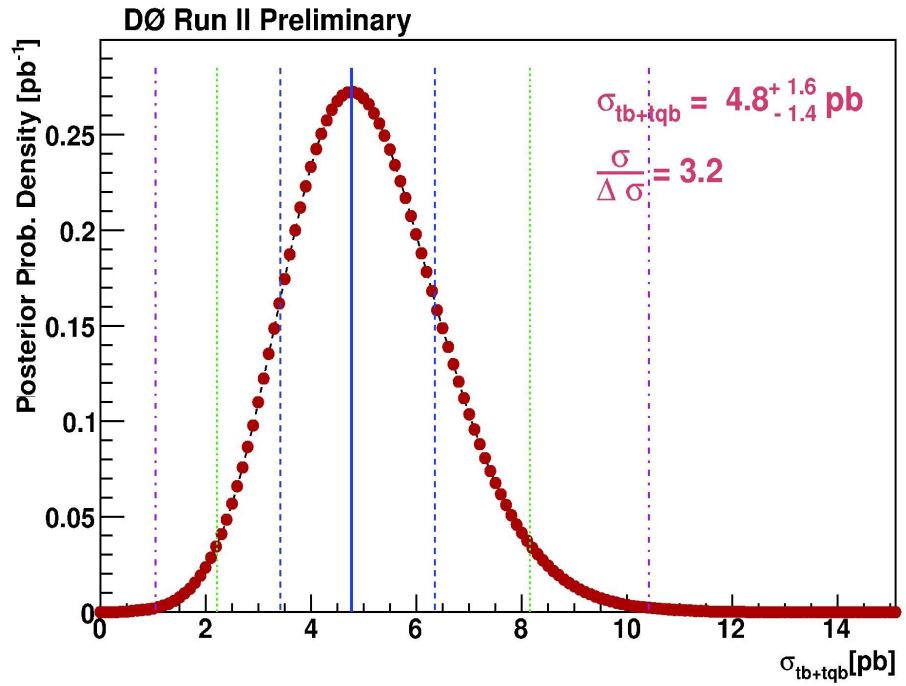


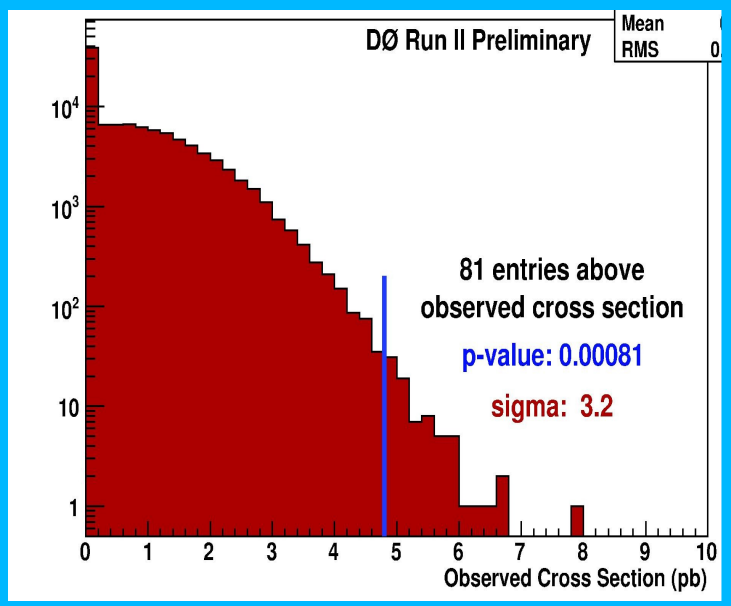


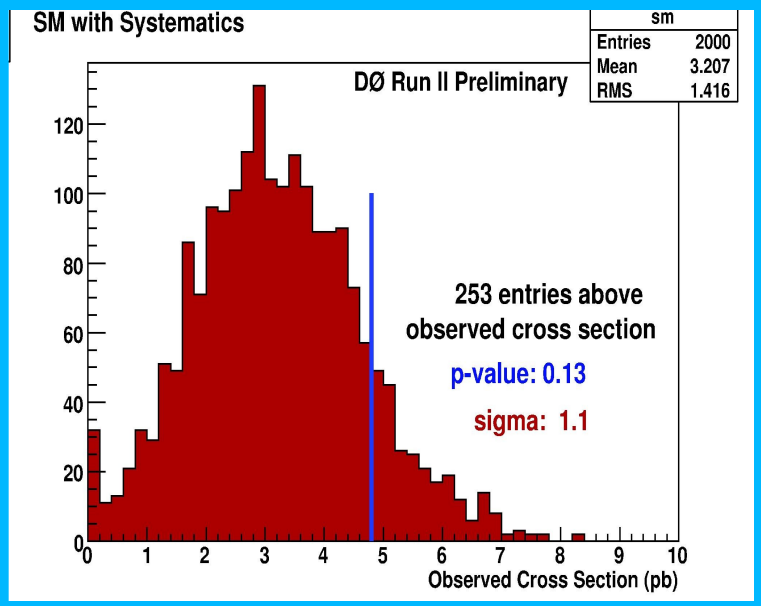


Matrix Element

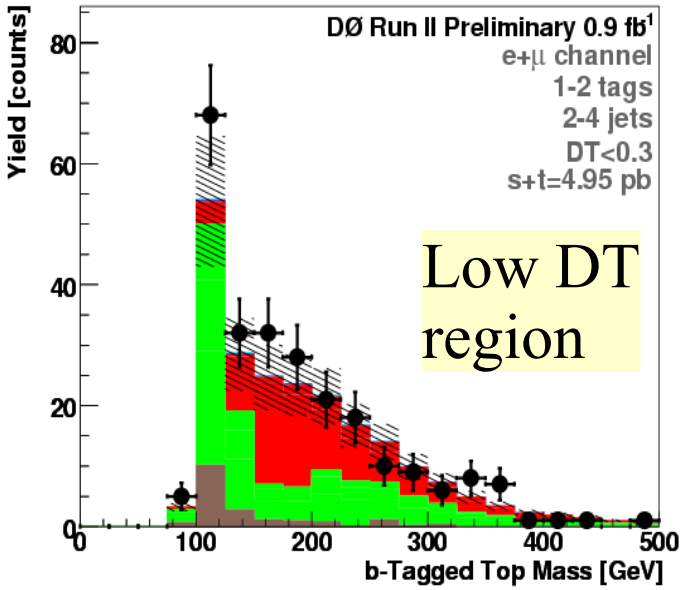


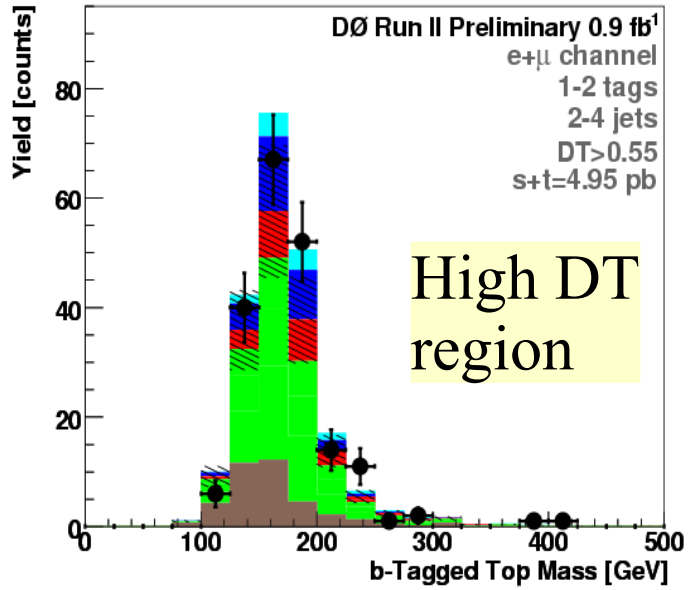


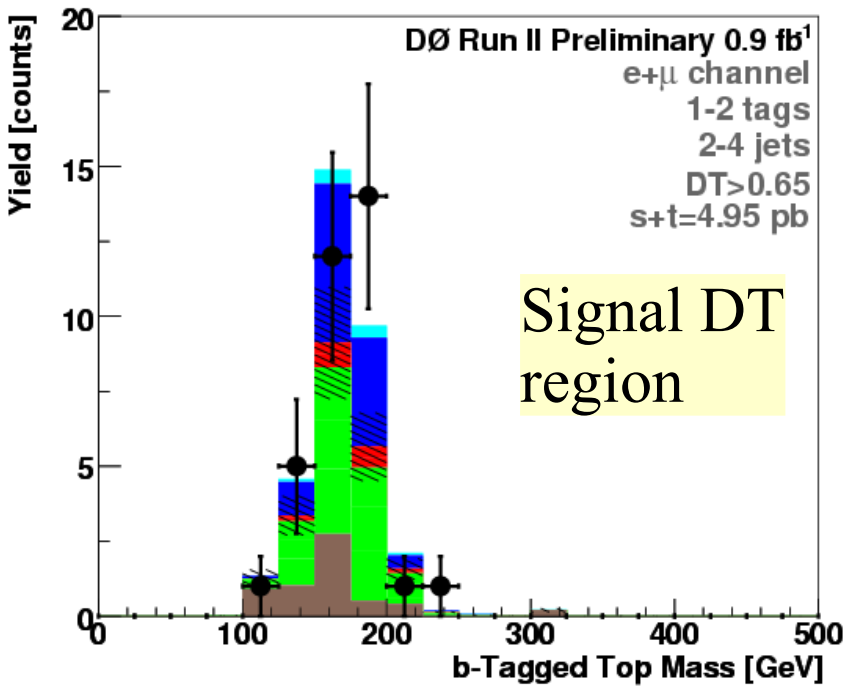




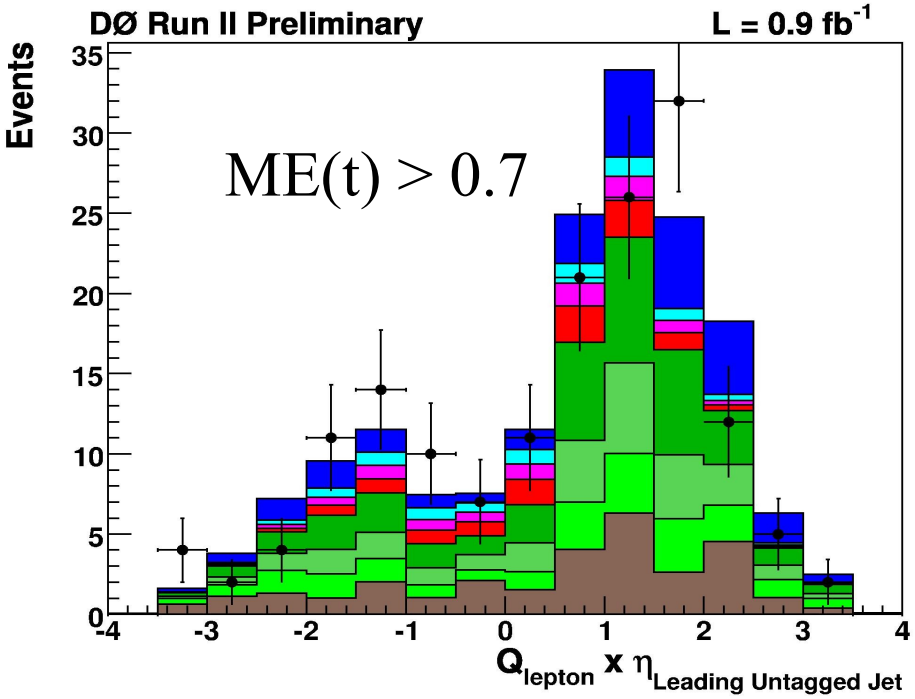
Reconstructed top quark mass

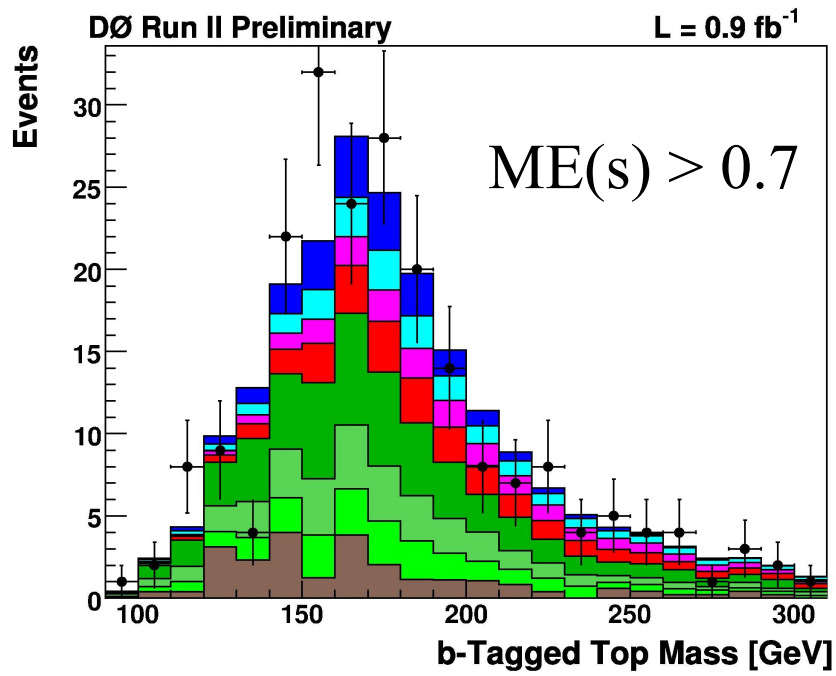


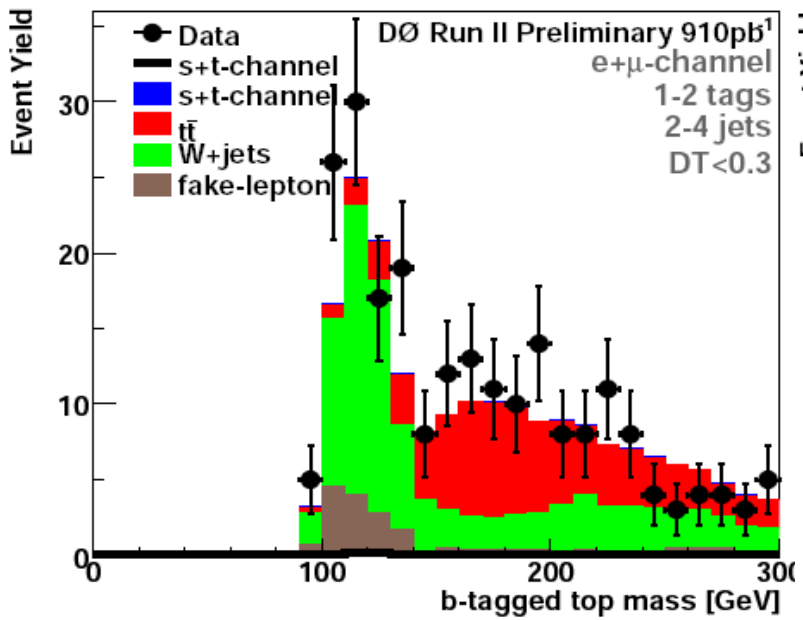


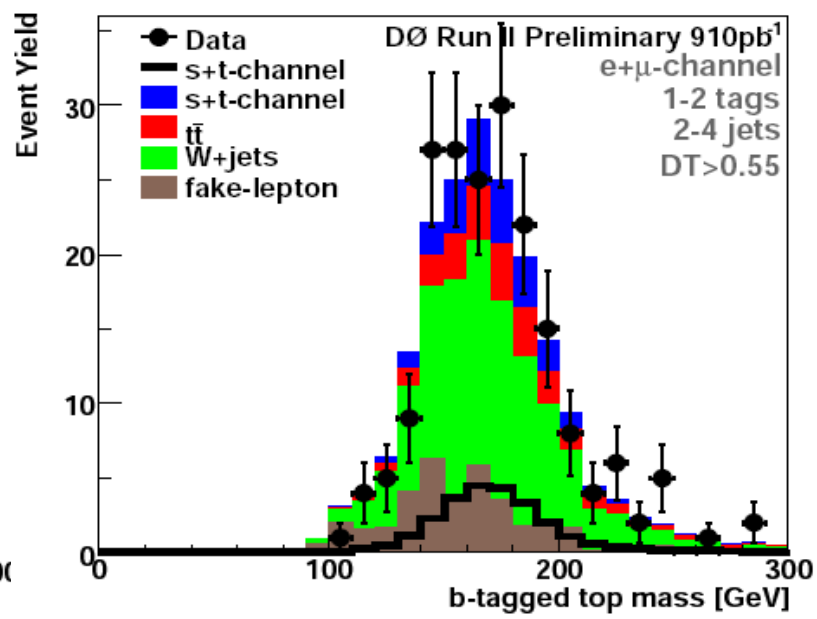


Variables after cut on likelihood

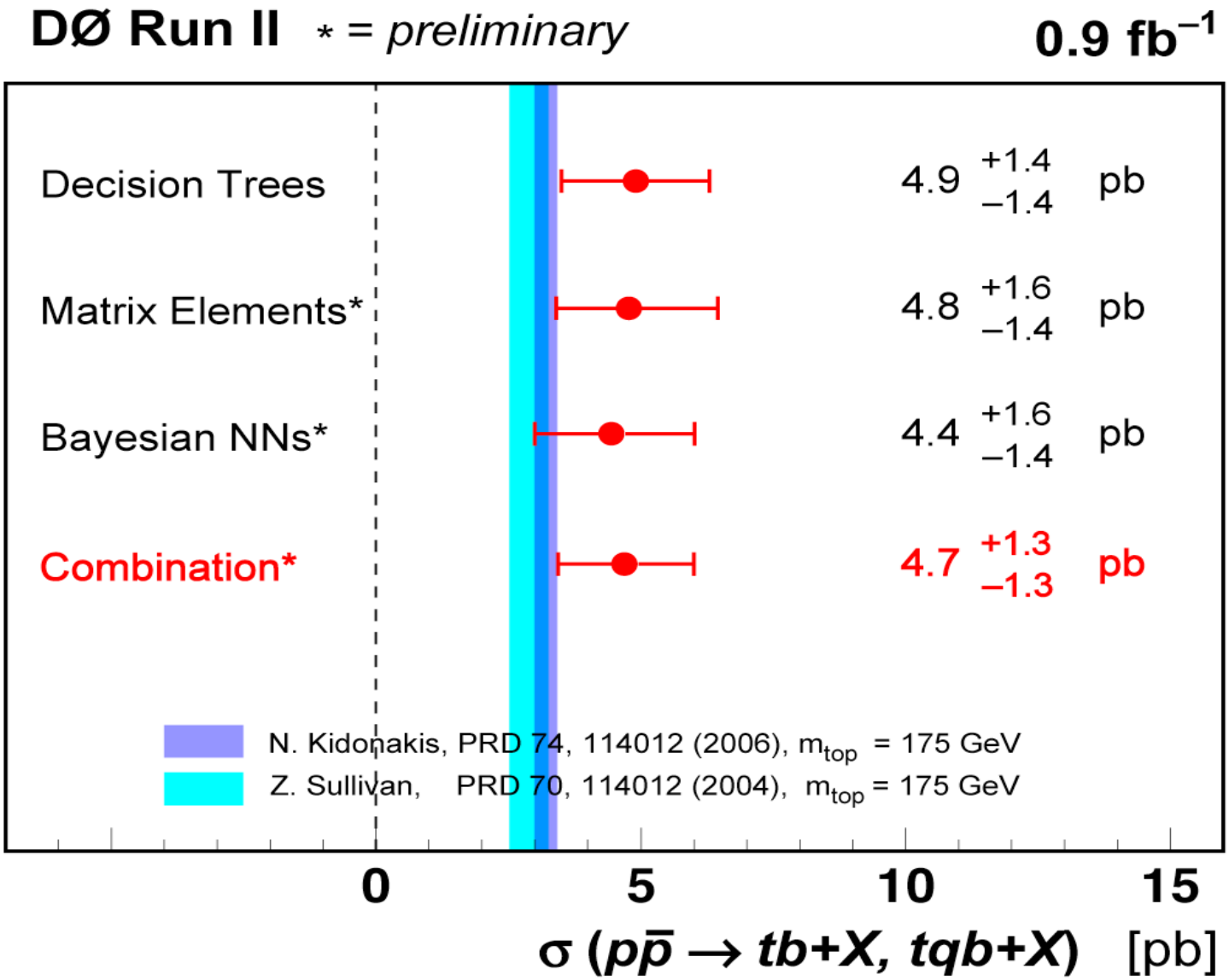




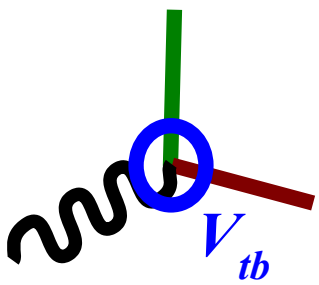




Single top summary



CKM matrix element $|V_{tb}|$

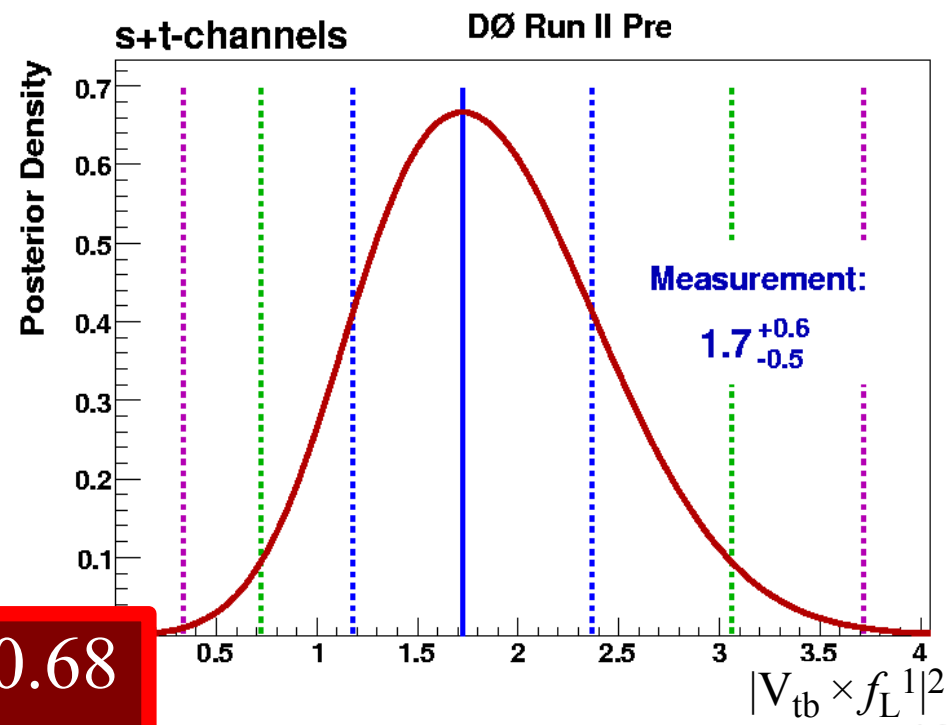


CKM Matrix

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

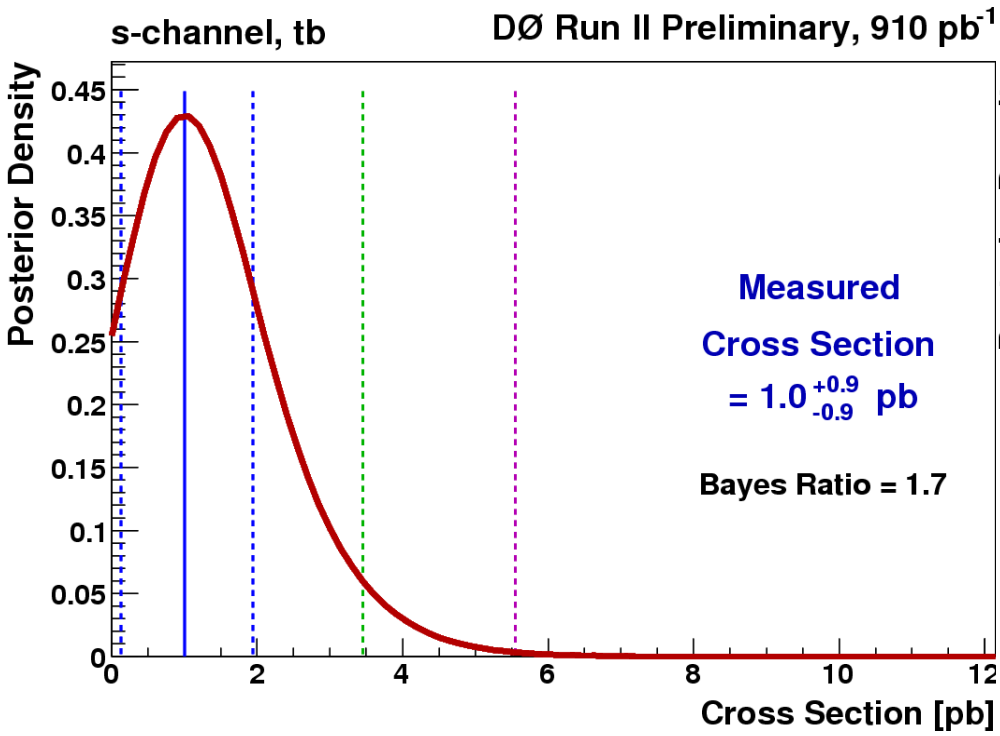
- Measurement: $|V_{tb} \times f_L^1|$
  - Based on DT result
  - Include XS uncertainties
  - Assume SM top quark decay
- No constraint on # of generations
- Assume $f_L^1 = 1$

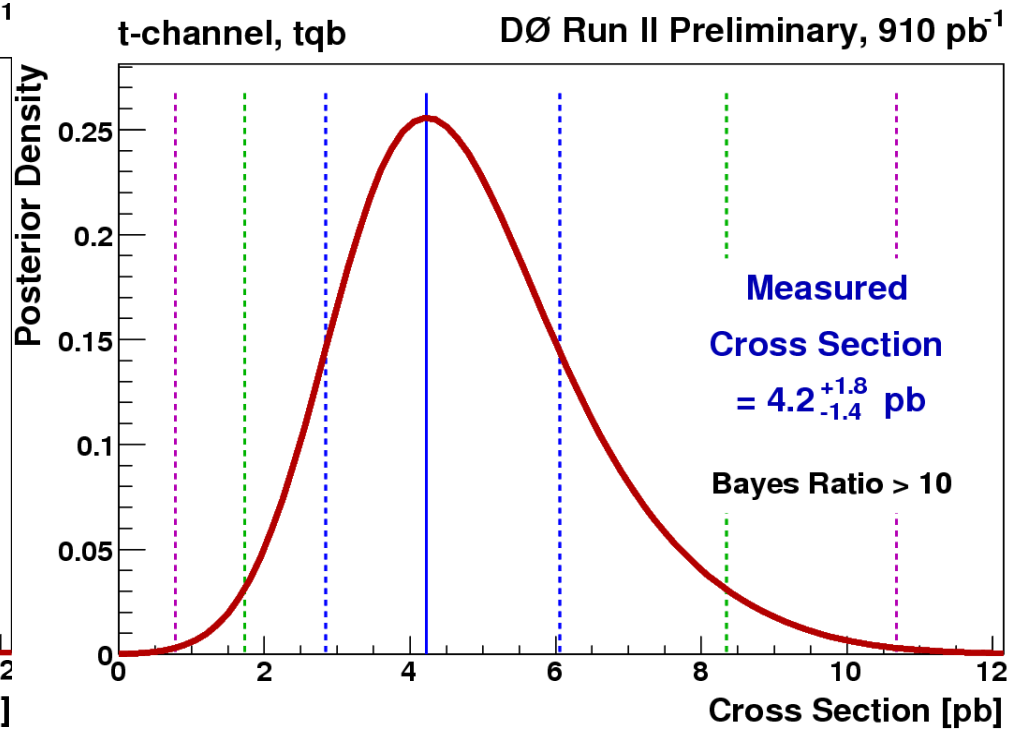
  $\rightarrow$ lower limit on V_{tb}
- At the 95% C.L.: $|Vtb| > 0.68$



Separate s-channel and t-channel analyses

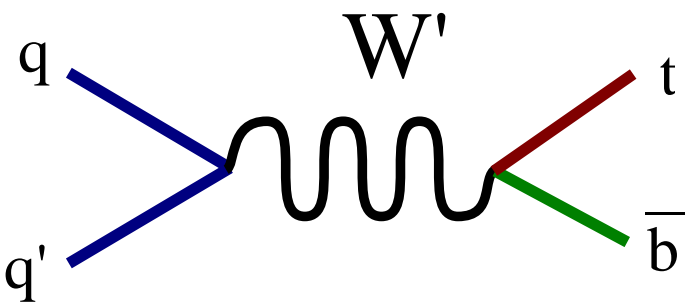
- Train filters individually for s-channel and t-channel
- Repeat statistical analysis
- DT result:

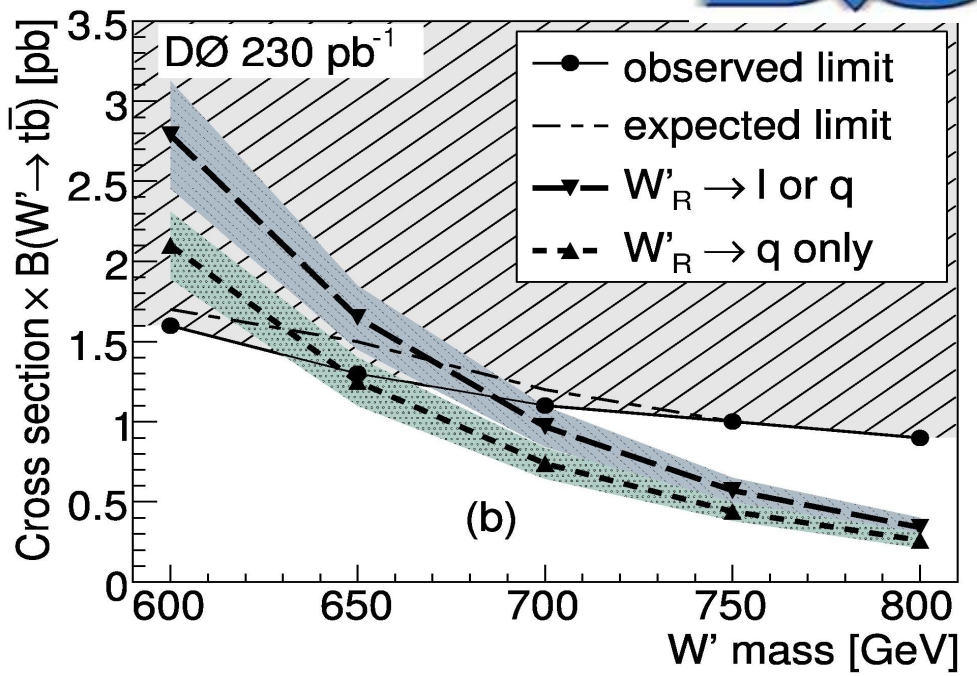




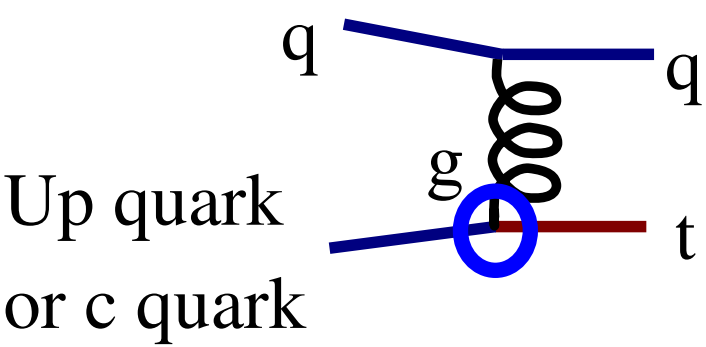
Searches for new physics in single top

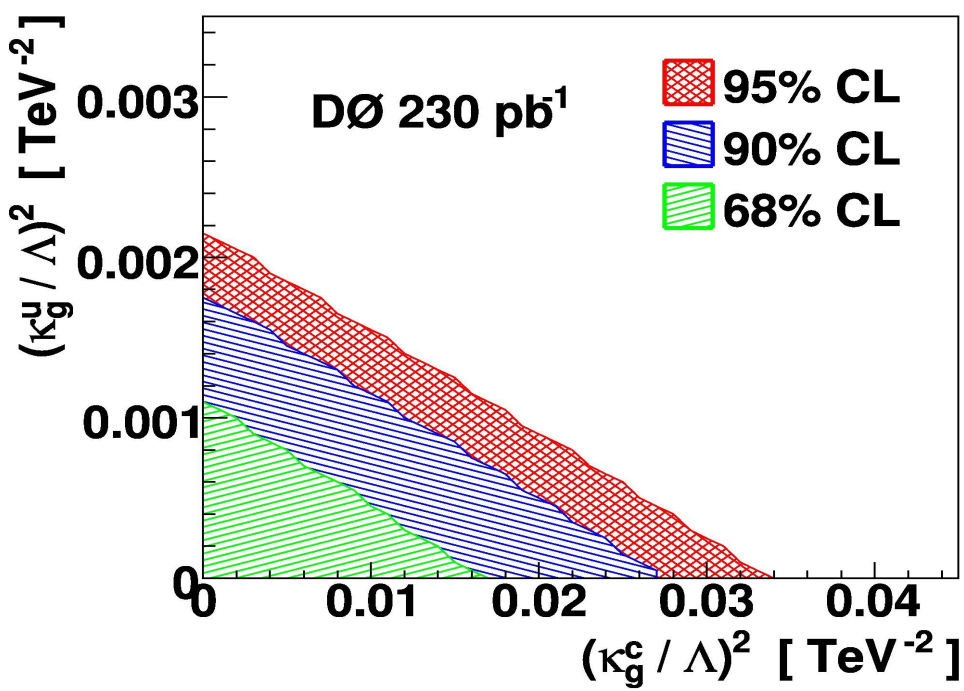
- Searches for new heavy boson W'



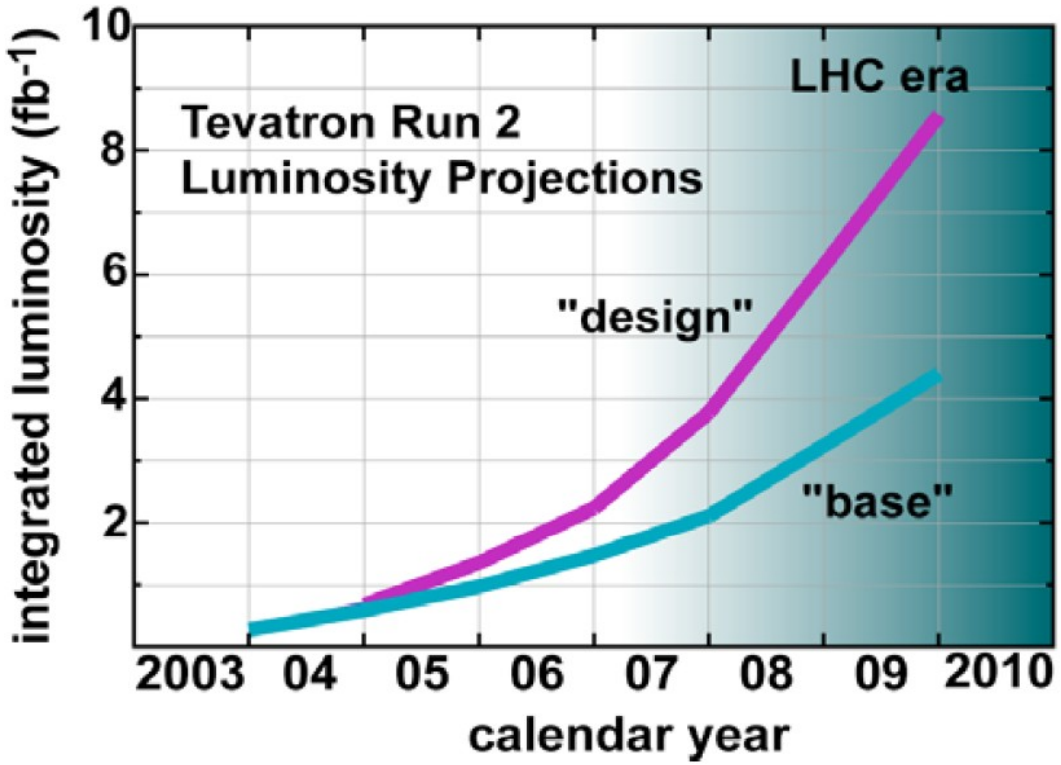


- Flavor-changing neutral currents





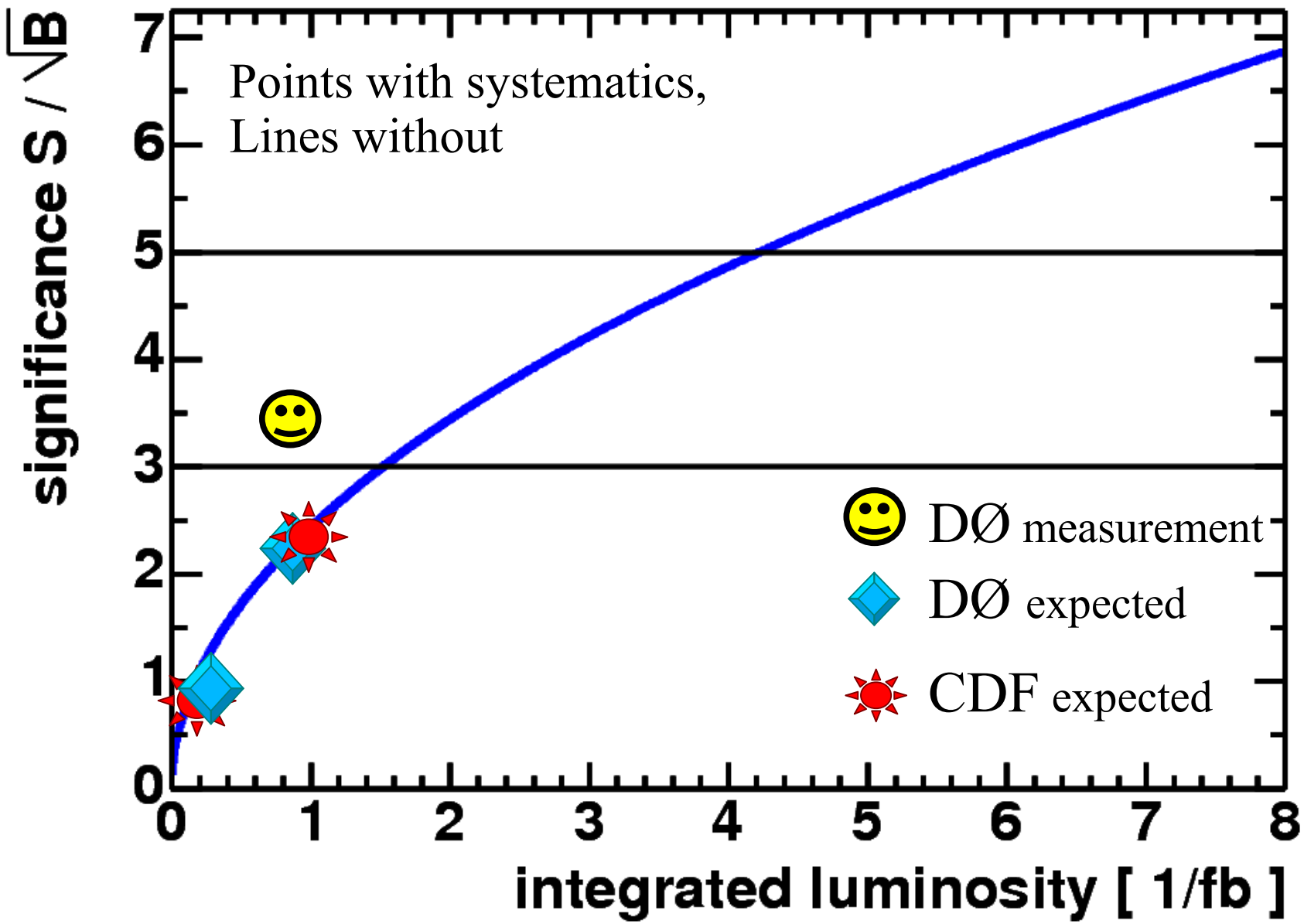
The future



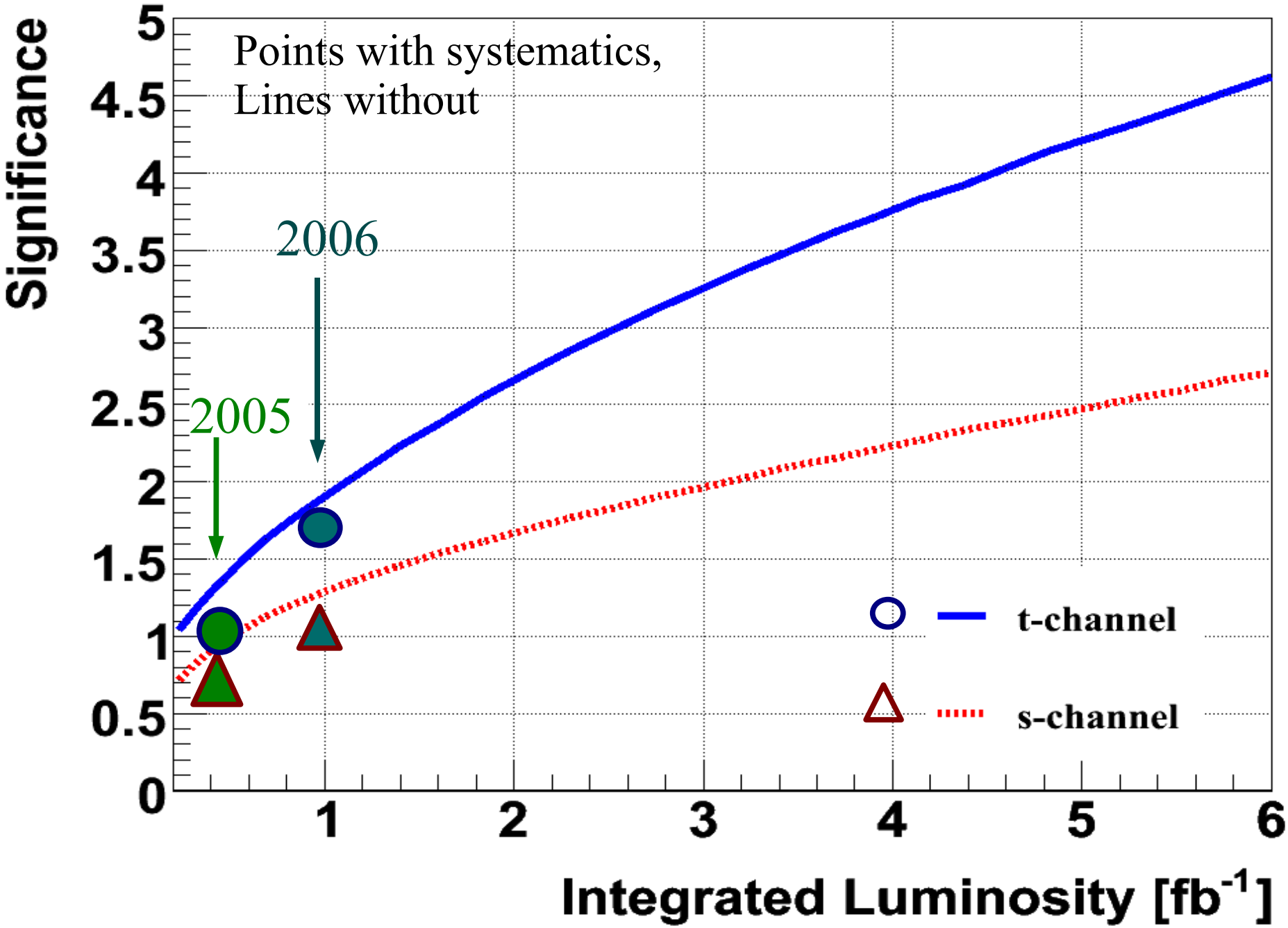
- We will likely be analyzing 4 fb^{-1} in 2009
  - Possibly already in 2008

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
  - Mass measured to ~2 GeV
  - Cross section measured to ~12%
- 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:
    - 5 sigma observation
    - Separate s-channel from t-channel