Top Quark Pair and Single Top Quark Production at the Tevatron

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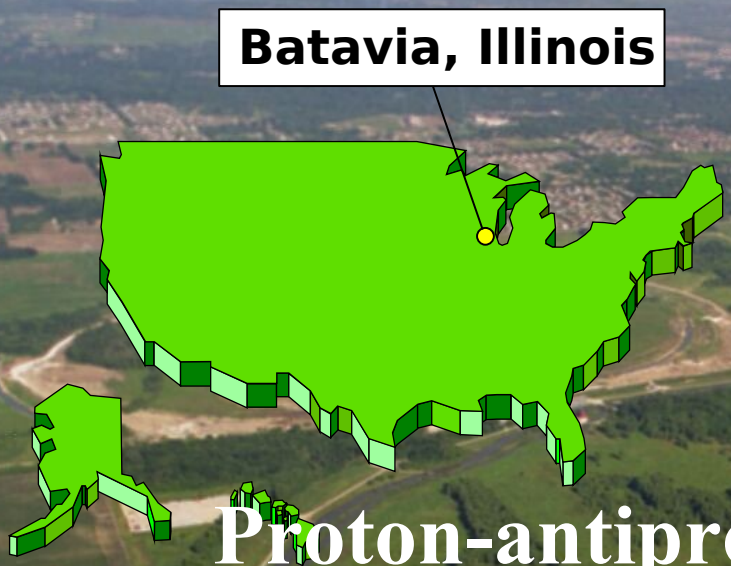
CTEQ LHC Workshop, 5/15/2007

Outline

- The Tevatron
- Top quark pair production
- Single top quark production
- Conclusions/Outlook

Fermilab Tevatron



Proton-antiproton collider

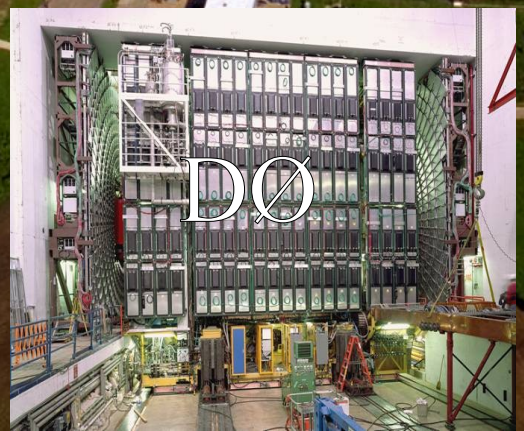
CM energy 1.96TeV

→ ***Energy frontier***

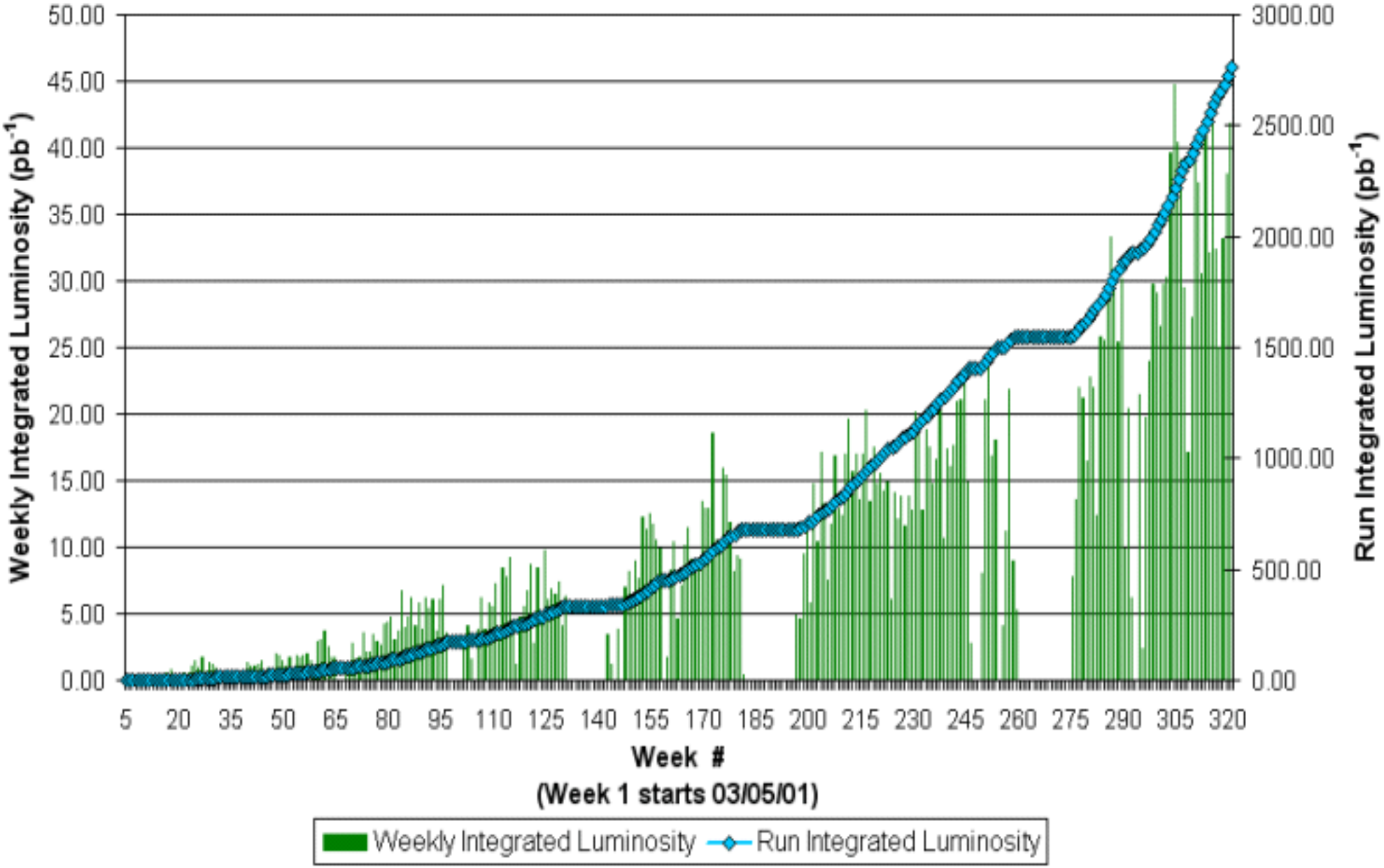
Instantaneous luminosity >280E30cm^{-2}s^{-1}

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

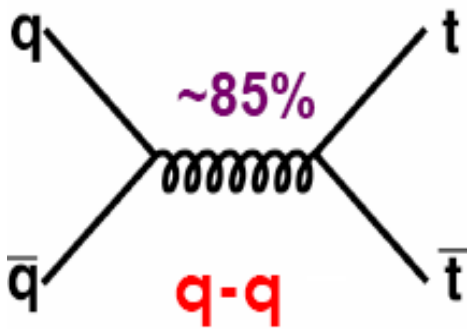
→ ***Luminosity frontier***

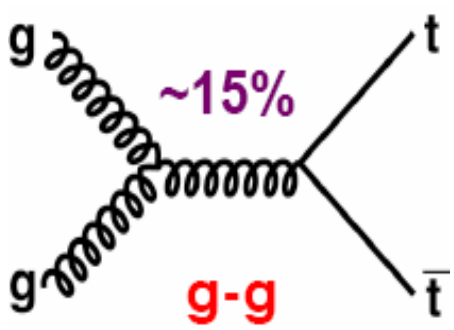


Tevatron Run II Integrated Luminosity



Top quark pair production





Production cross section measurement

$$\sigma(p\bar{p} \to t\bar{t}) = \frac{N_{observed} - N_{background}}{A_{tot} \int L dt}$$

Estimated from MC Simulation and/or Data

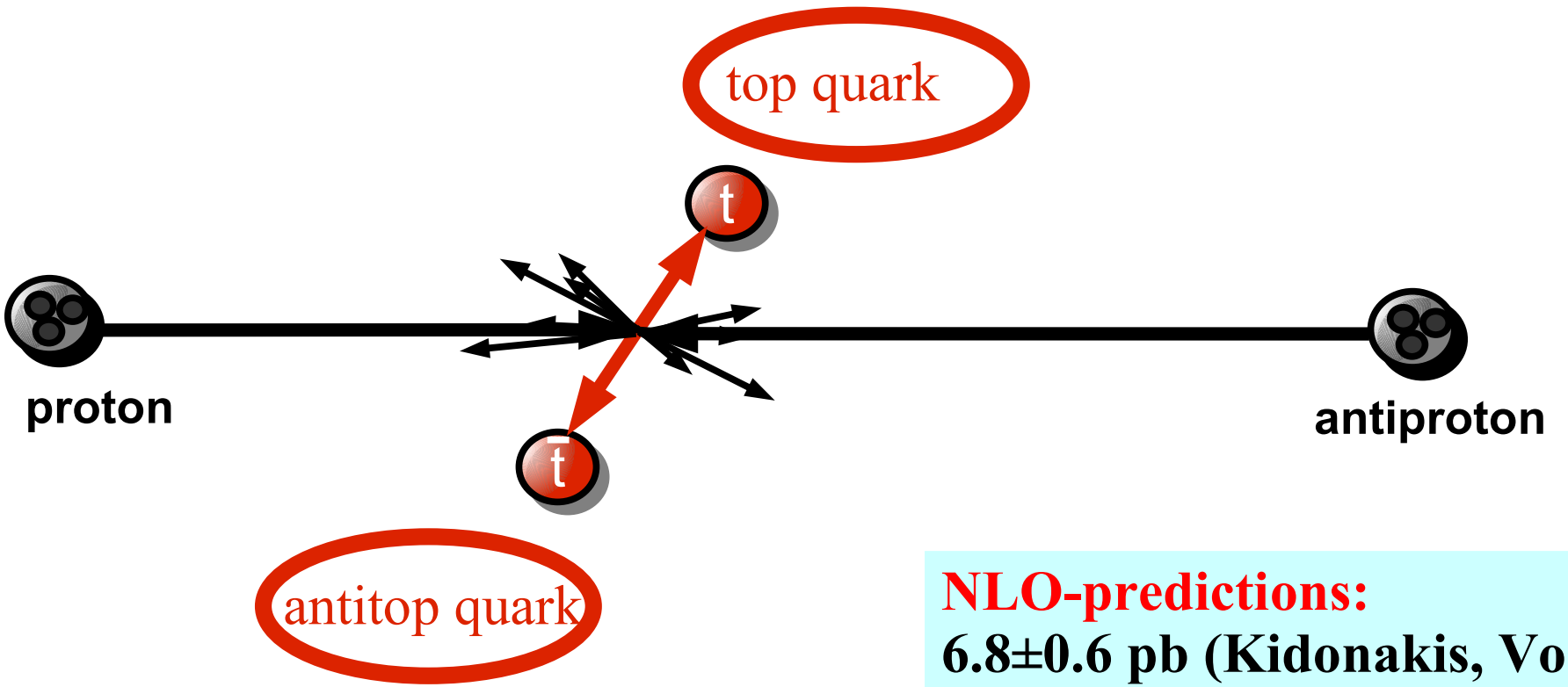
Slight mass dependence: m_{top}=175 GeV

- **Important test of QCD at high p_T**
  - ⇒ higher x-section if resonant top production or non-SM production
- **Measurements of different decay channels**
  - exotic top decays ($t \to H^+$ or stop) modify contributions to different channels
  - di-lepton/l+jets ratio probes non-W top decays
- **Measurements with different methods:**
  - b-jet tagging method assumes BR($t \to Wb$)= 1, kinematic methods are free of this assumption

Top quark pair production

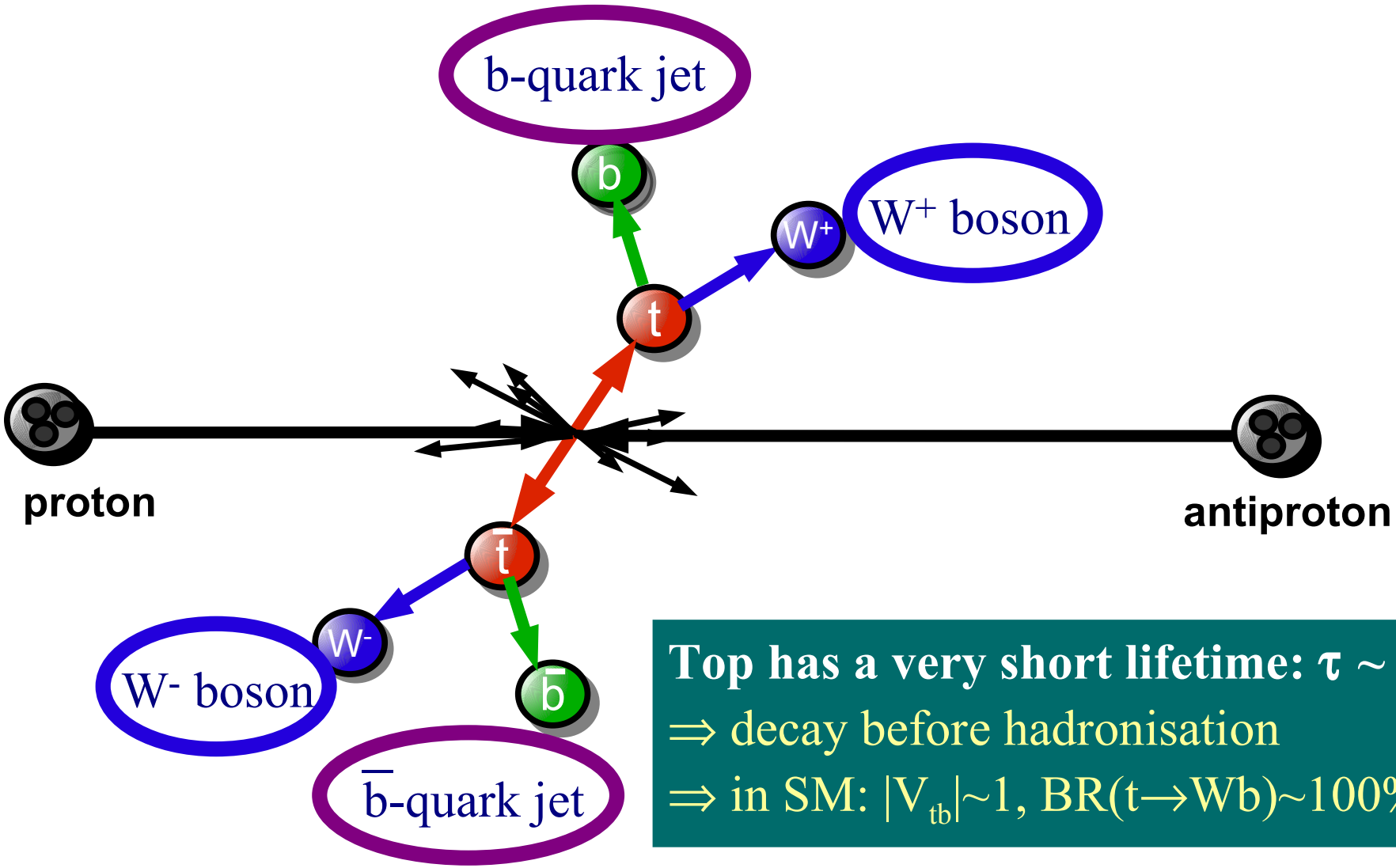
Run I : $\sqrt{s}$ = 1.8TeV with L~100pb^{-1}:
CDF: $6.5^{+1.7}_{-1.4}$ DØ: 5.7± 1.6 ➡ $\delta\sigma$~25%

Run II: $\sqrt{s}$ = 1.96TeV
➡ increase of σ_{tt} by 30%
L=1fb^{-1} analyzed ➡ decrease $\delta\sigma$~10%



NLO-predictions:
6.8±0.6 pb (Kidonakis, Vogt)
$6.7^{+0.7}_{-0.9}$pb (Cacciari et al.)
➡ $\delta\sigma$ ~ 10%

Top quark decay products

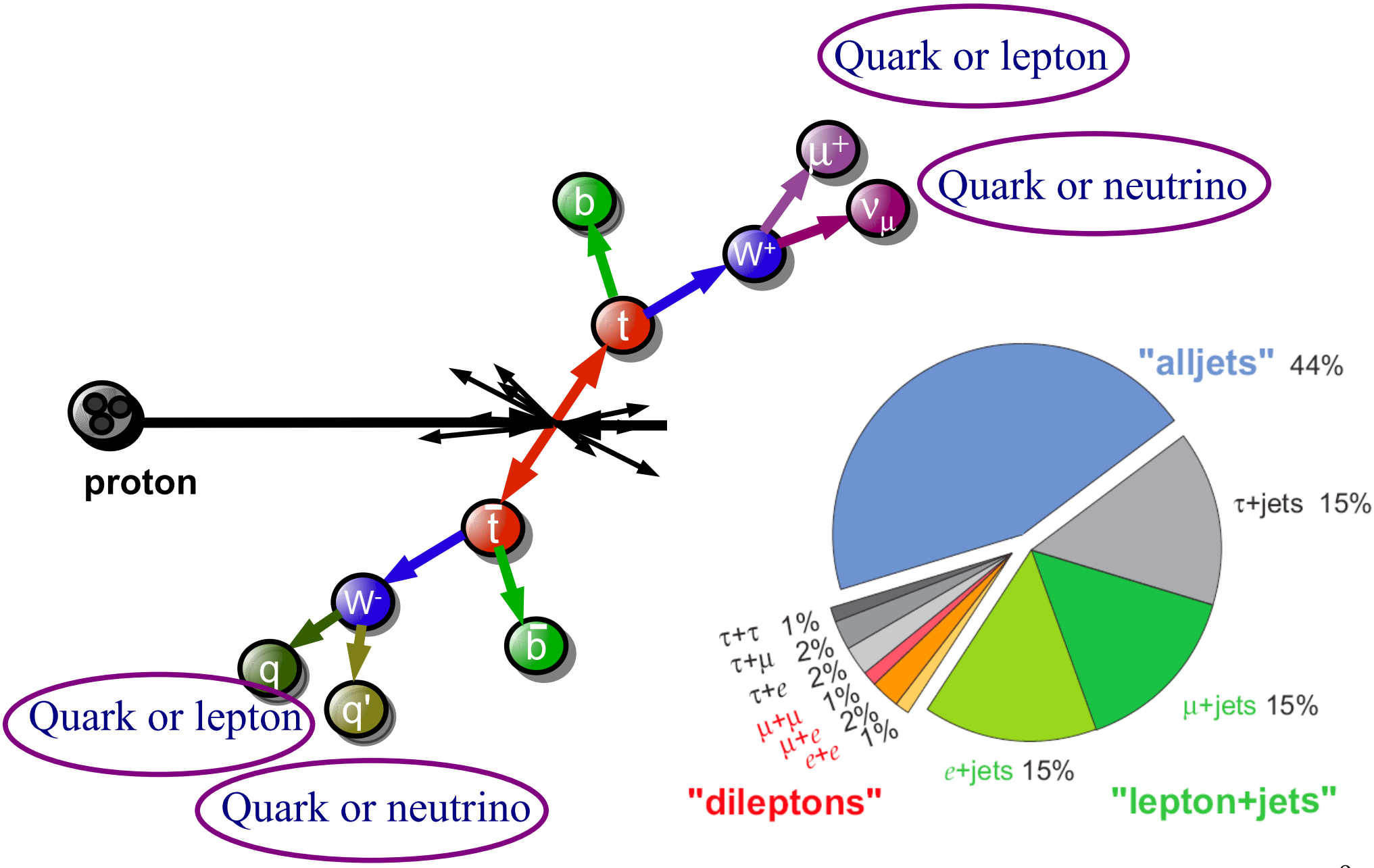


Top has a very short lifetime: $\tau \sim 10^{-25}$s

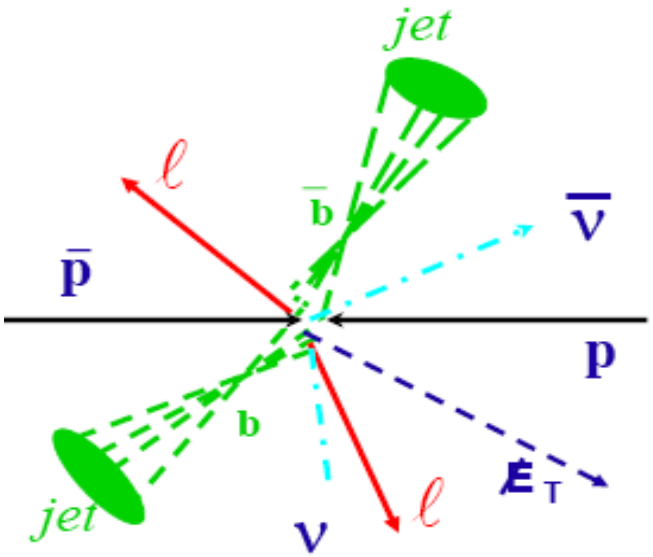
$\Rightarrow$ decay before hadronisation

$\Rightarrow$ in SM: $|V_{tb}|\sim 1$, BR($t \rightarrow Wb$)~100%

Top quark pair final state



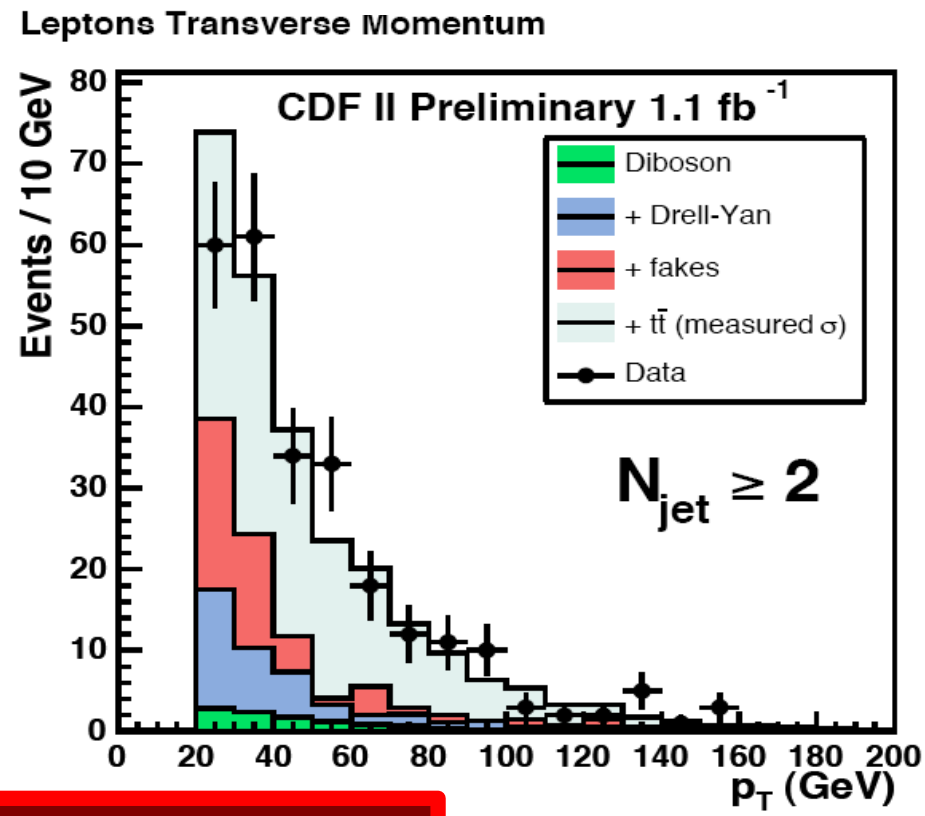
Di-lepton results



- Using lepton+track events
  - 1 isolated lepton
  - 1 isolated track

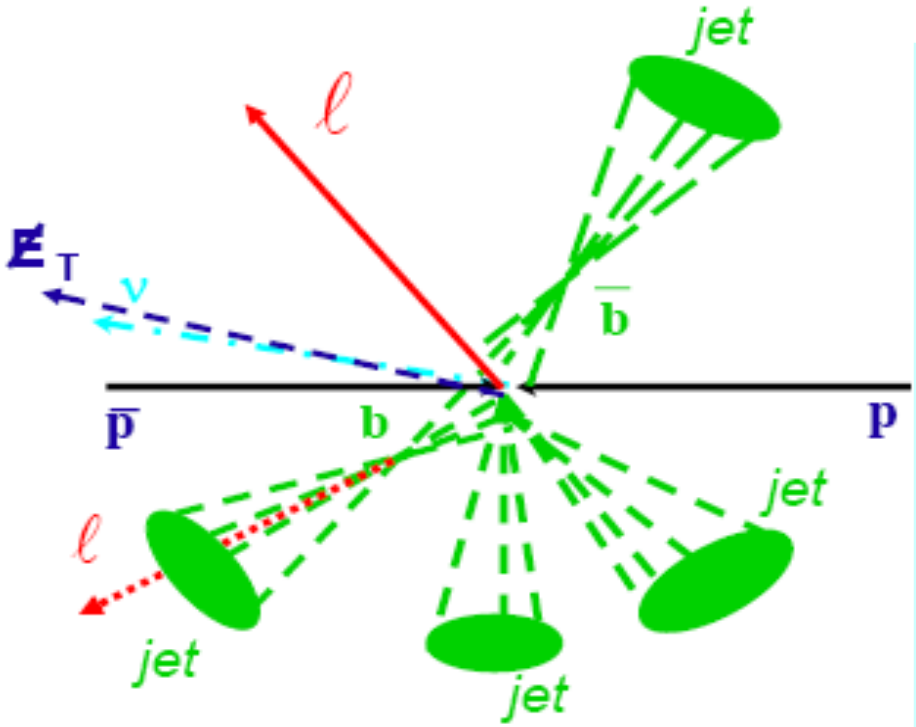
Acceptance: 14% (inclusive)
129 evts observed
Expected S/B 60.5 (tt)/48.2(bckg) ~1.3
➡ Higher acceptance, lower S/B than "classic" method

Improvement on error:
$\delta\sigma/\sigma$ = 15%



$$\sigma_{tt} = 9.0 \pm 1.3(\text{stat}) \pm 0.5(\text{sys}) \pm 0.5(\text{lumi})\ \text{pb}$$

Lepton+jets



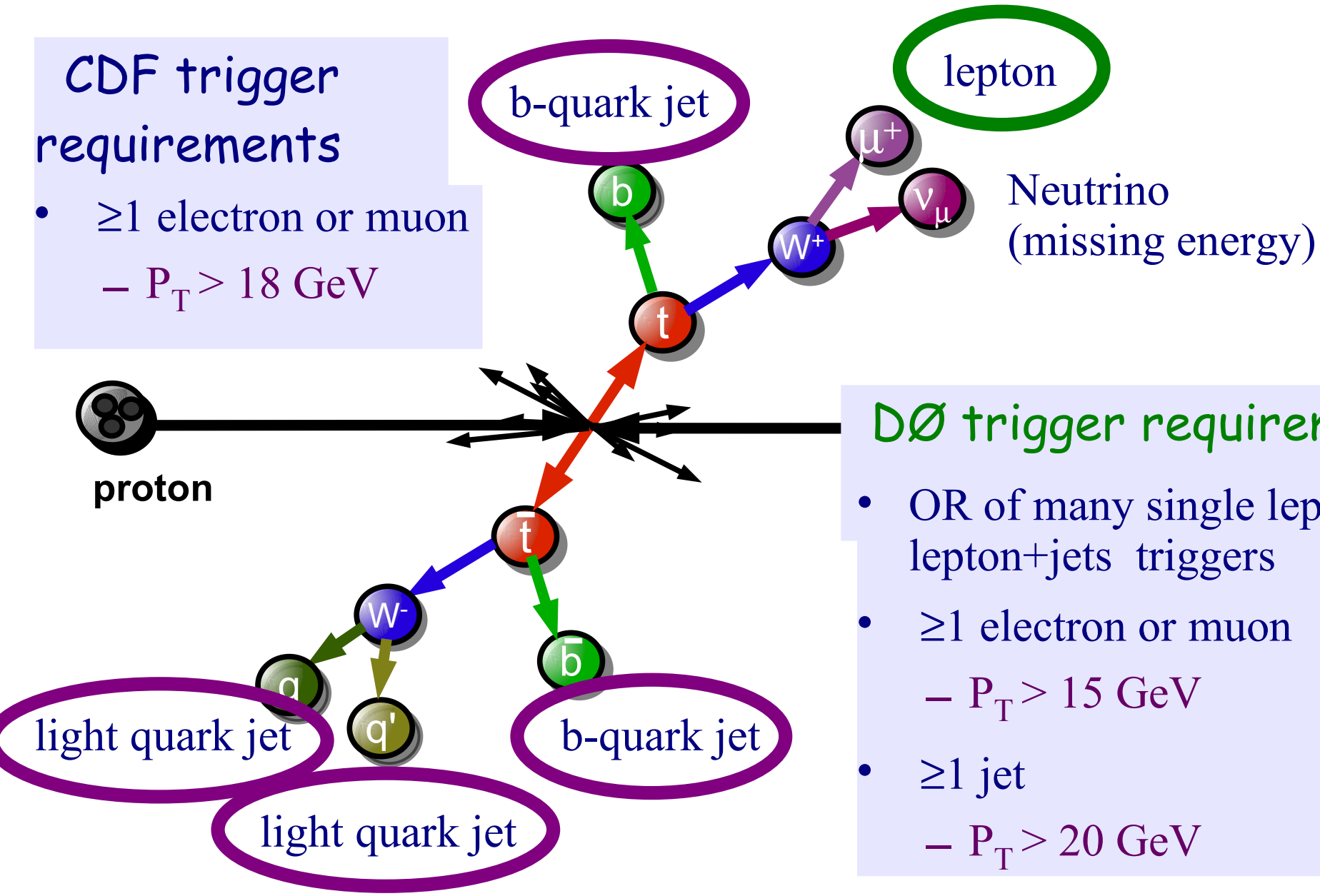
Main Backgrounds
- W+jets (dominant)
- $Z \to \tau\tau$
- single top
  - ➡ **estimated from MC**
- Mis-identified leptons
  - ➡ **estimated from Data**

- Large signal
  - Reasonable background
  - Used for many top measurements
- Basic event signature
  - One high-E_T leptons
    - $E_T > 20$ GeV
  - Missing transverse energy
    - Missing $E_T > 20$ GeV
  - At least three high-E_T jets
    - $E_T > 20$ GeV
- Expect ~ 250 events in 1 fb^{-1}
  - After b-tagging
  - S:B ~ 1:1

Trigger selection

CDF trigger requirements

- ≥1 electron or muon
  - $P_T > 18$ GeV

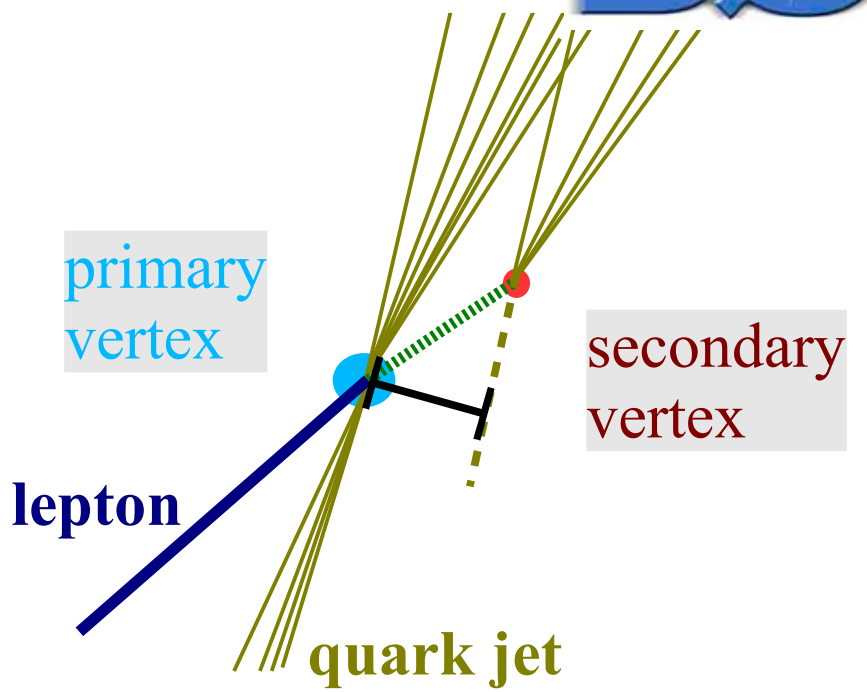


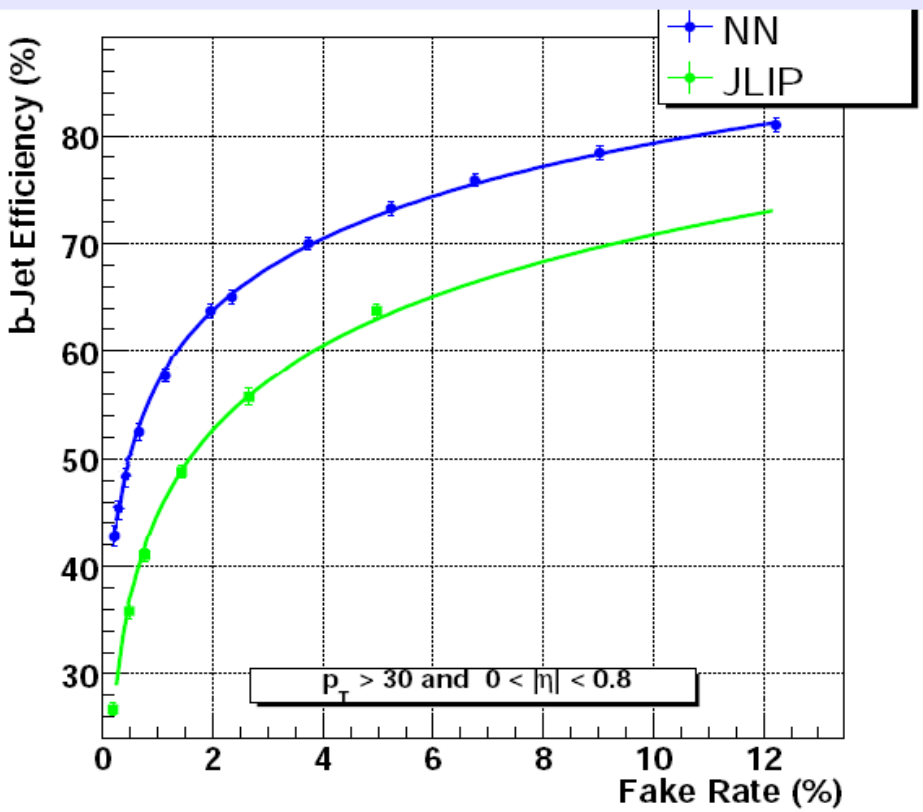
DØ trigger requirements

- OR of many single lepton, lepton+jets triggers
- ≥1 electron or muon
  - $P_T > 15$ GeV
- ≥1 jet
  - $P_T > 20$ GeV

Neural network b-quark tagging

- NN combining secondary vertex, impact parameter taggers
- Much improved performance
  - 1/3 lower fake rate for same b-quark efficiency
  - Lower systematic uncertainty

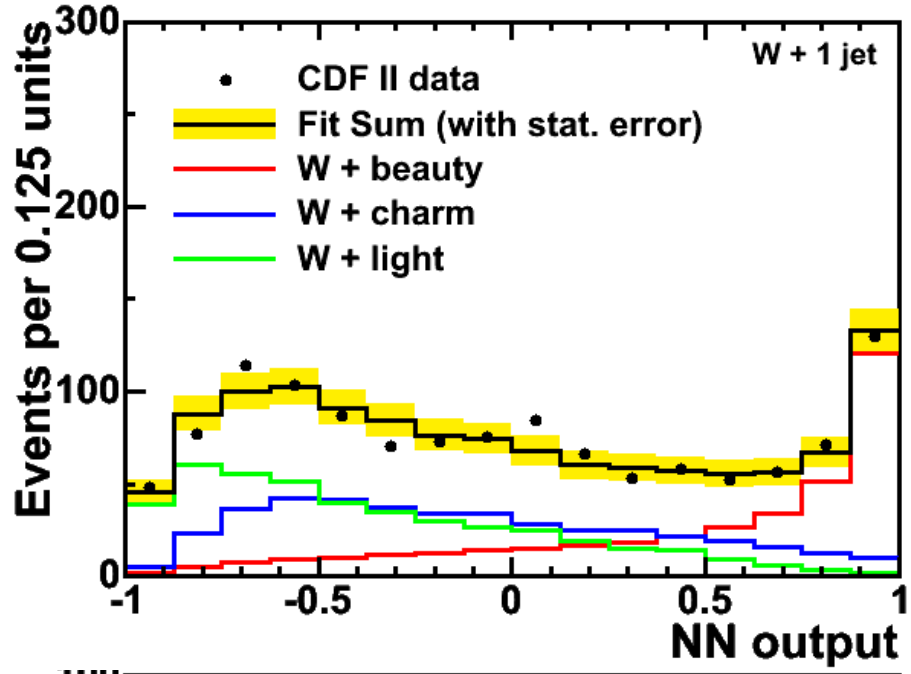


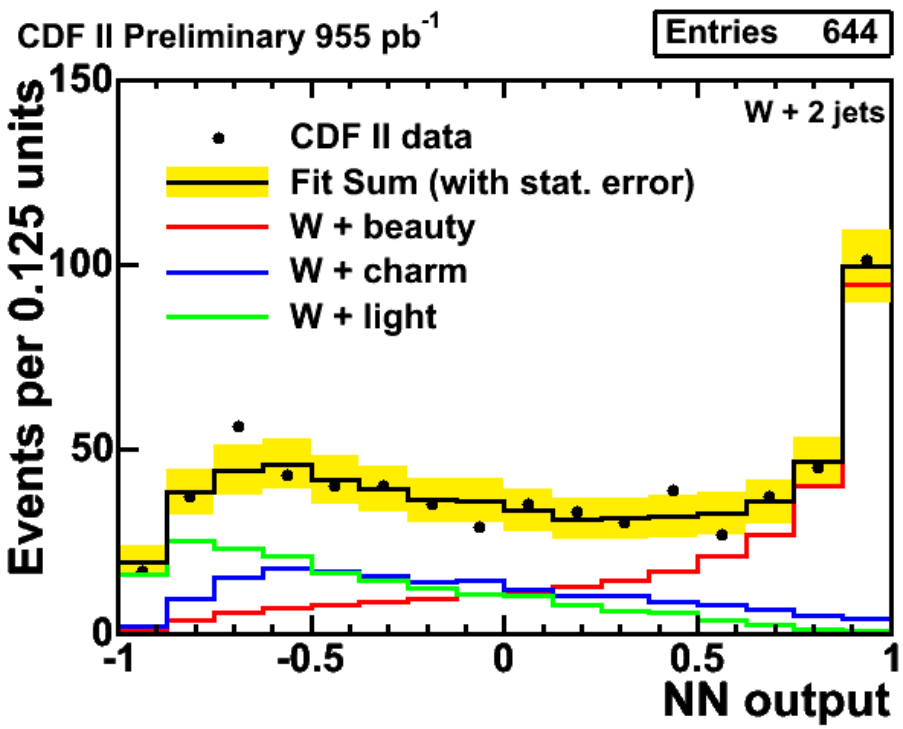


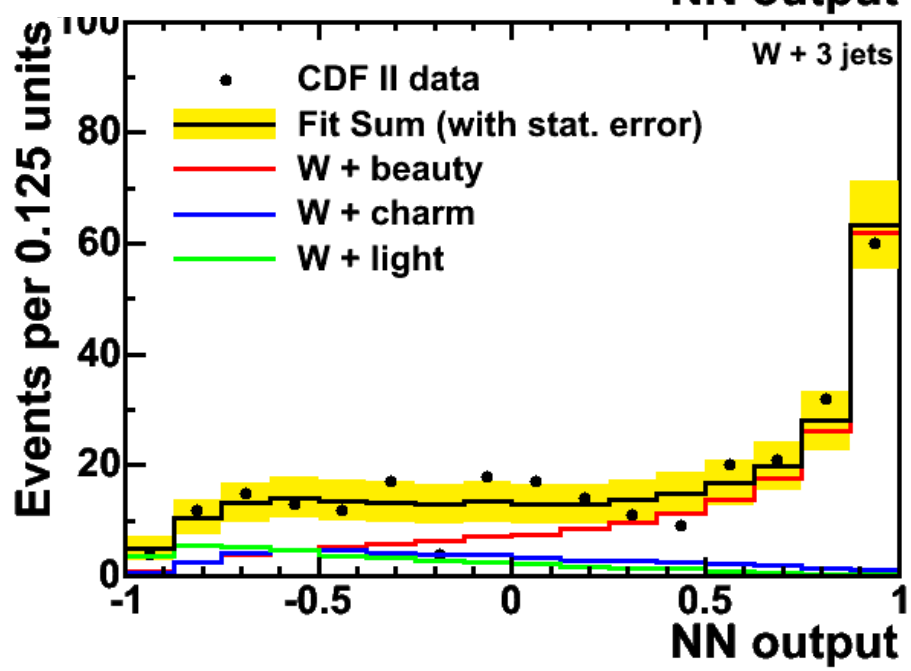
Probability to tag a jet:
- b-quark jet: ~50%
- light-quark jet: ~0.5%

Neural network b-tagging

- Use b-tag NN output to check heavy flavor composition
  - Wbb and Wcc separately

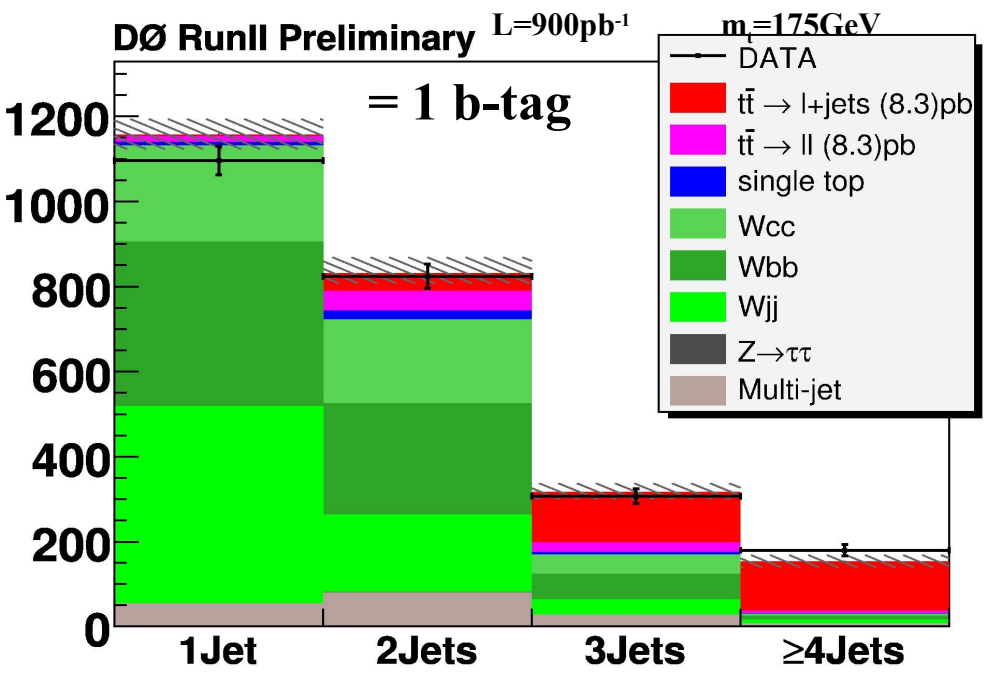


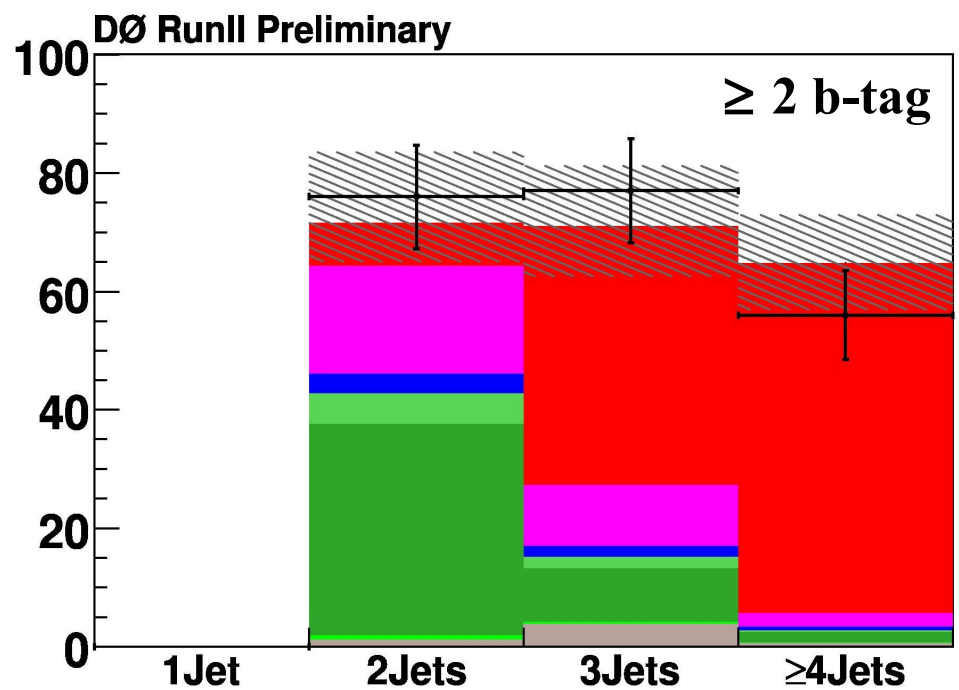




Backgrounds to lepton+jets

- Multi-jet → mis-identified isolated lepton
  - Estimated from data
- W+jets
  - Events from Alpgen+Pythia (MLM matching)
  - Normalize to data before b-tag requirement → W + light quark
  - Heavy flavor fraction as in Alpgen → no agreement with data
  - Scale up (Wbb+Wcc) by 1.5 based on data → W + heavy flavor





Systematic Uncertainty

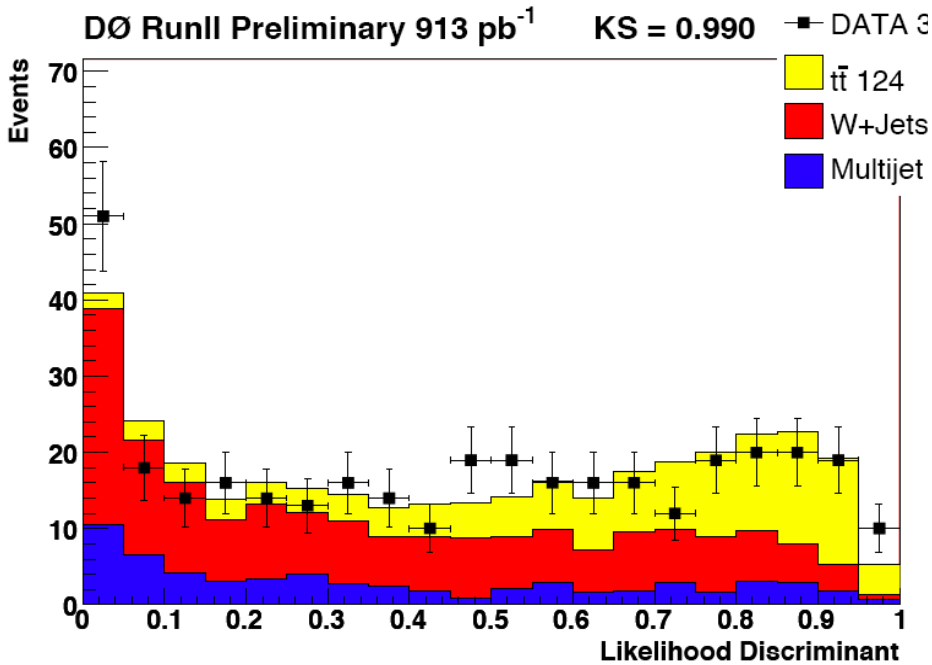
CDF systematic uncertainties

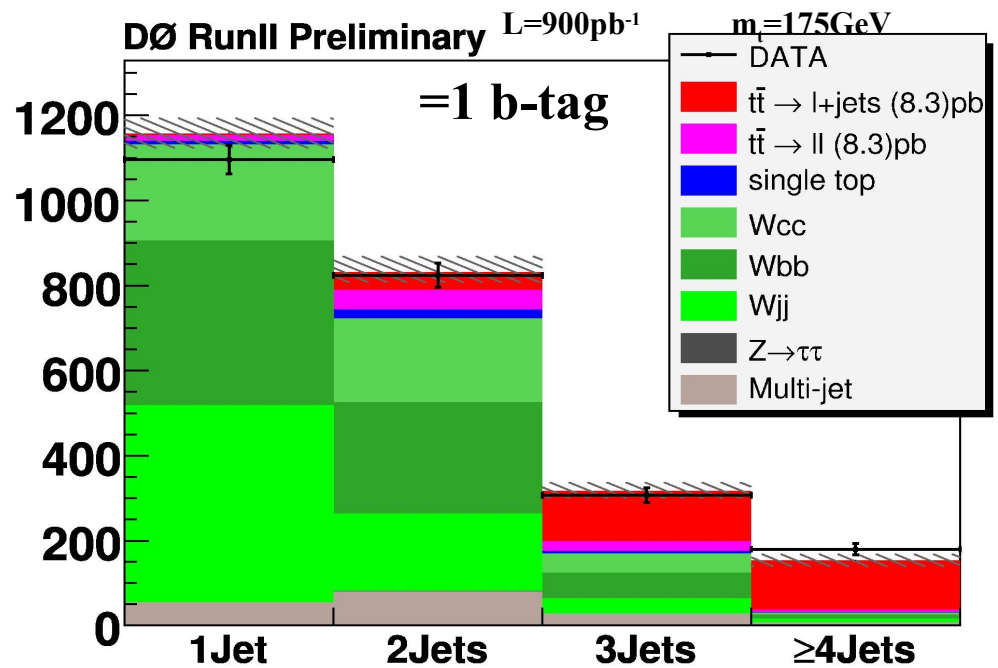
Source	Systematic (%)
b-tagging	6.5
Luminosity	6.0
PDF	5.8
Jet Energy Scale	3.0
ISR/FSR	2.6
Lepton Identification	2.0
Total	11.5

DØ systematic uncertainties

- Object ID ~ 4%
- Energy scale ~ 5%
- B-tag modeling ~ 6%
- Luminosity ~ 6.5%
- W+jets backgrounds ~ 6.5%
  - In particular flavor composition
- Total ~11%

Lepton+jets results





- Kinematic analysis
  - 6-variable likelihood discriminant
  - Require at least 4 jets

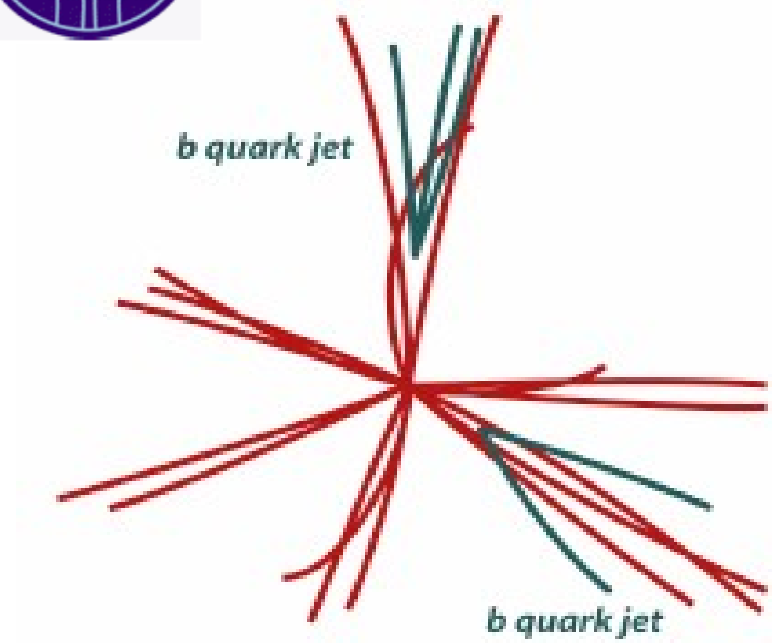
- NN b-tagging
  - Efficiency $\varepsilon \sim 55\%$ for fake rate $\sim 1\%$
  - 15% improvement

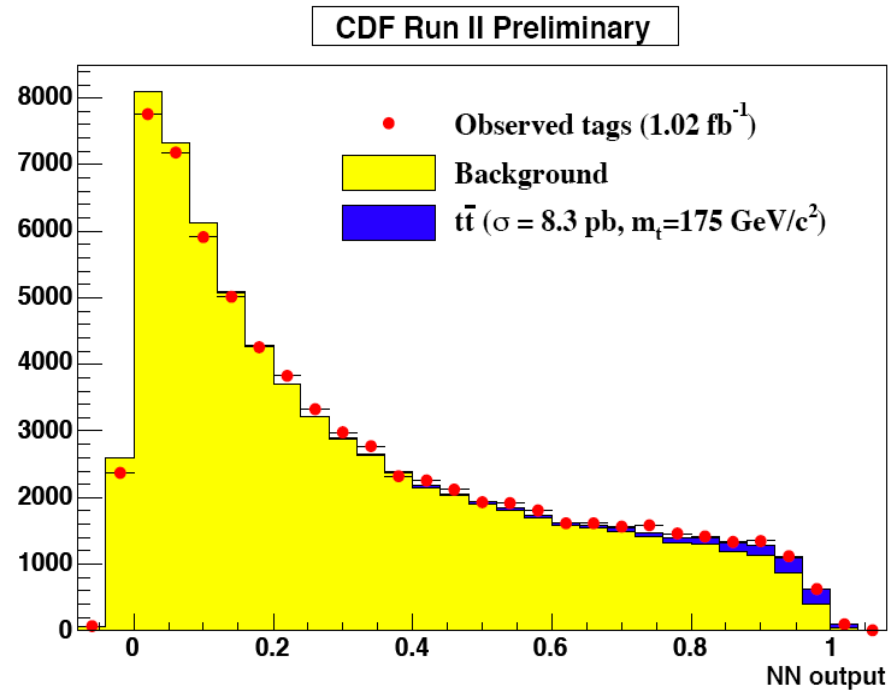
- Smallest error: $\delta\sigma/\sigma = 14\%$

$\sigma_{tt} = 6.3^{+0.9}_{-0.8} \pm 0.7 \pm 0.4$ pb

$\sigma_{tt} = 8.3\ ^{+0.6}_{-0.5}(st)^{+0.9}_{-1.0}(sys) \pm 0.5\ (l)$ pb

All-jets

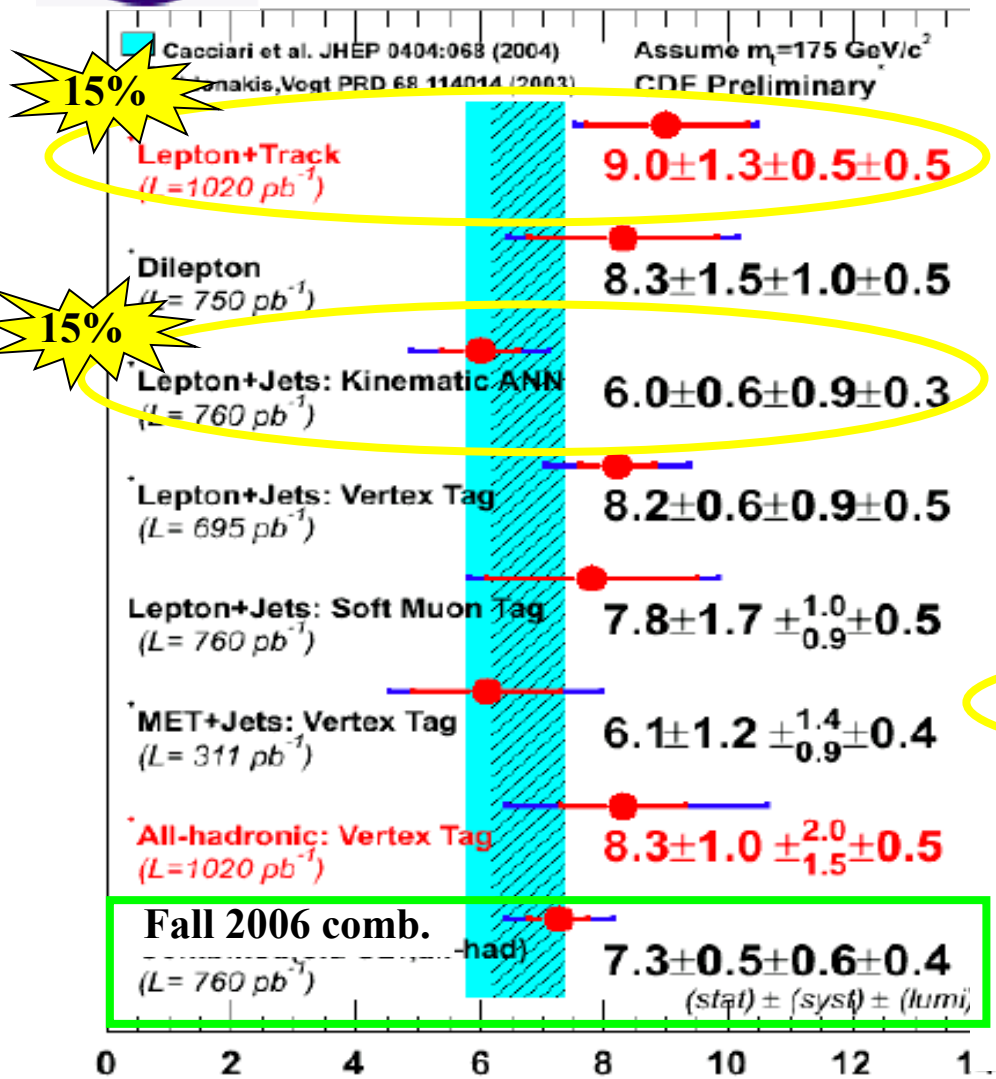


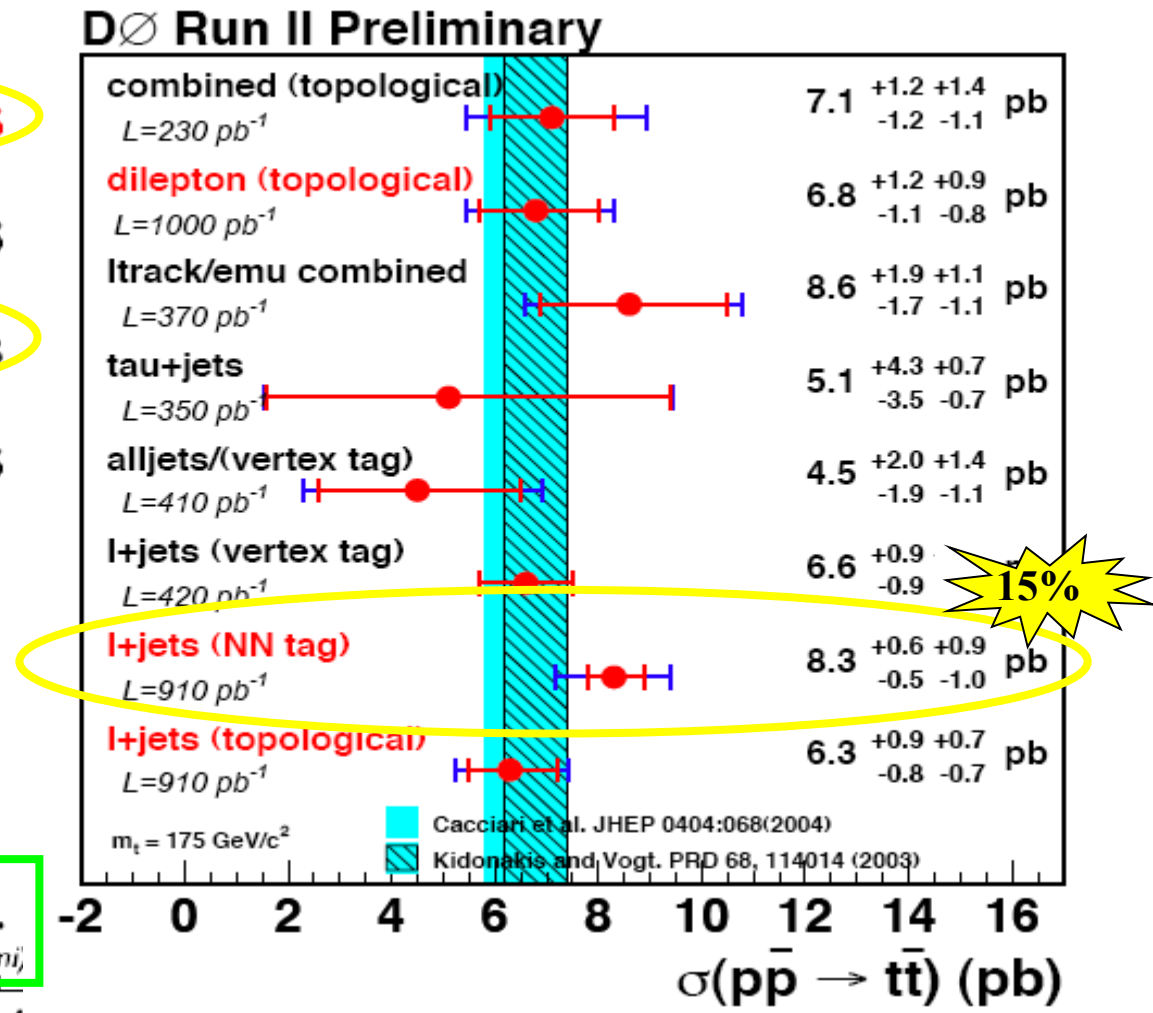


- Largest signal, overwhelming background (QCD multijets)
- Selection:
  - 6-8 jets, E_T > 15 GeV, b-tagging is essential
  - Plus multivariate analysis (CDF: 11-variable neural network)

$$\sigma_{tt} = 8.3 \pm 1.0\ (\text{stat})\ ^{+2.0}_{-1.5}\ (\text{syst}) \pm 0.5\ (\text{lumi})\ \text{pb}$$

Top pair production summary





- Calculations for top quark mass of 175 GeV
- Experimental uncertainty now at same level as theory uncertainty
- Channel combinations in progress

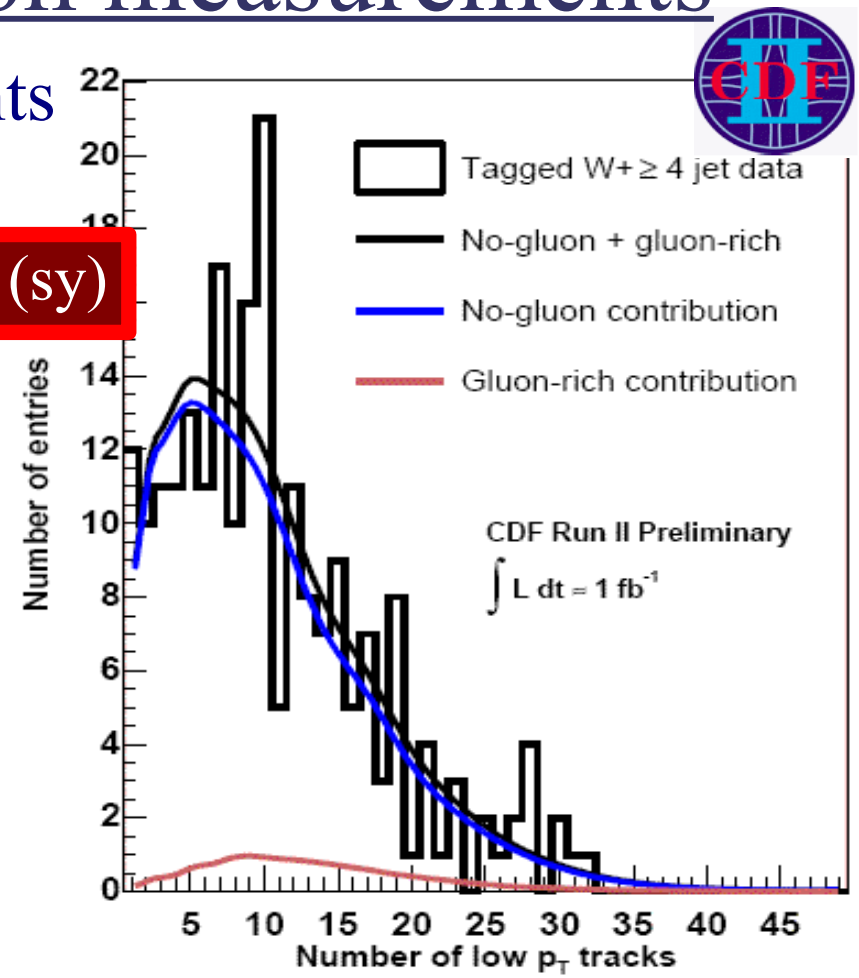
Other top pair production measurements

- Fraction of gg → tt vs qq → tt events
  - Counting low-momentum tracks

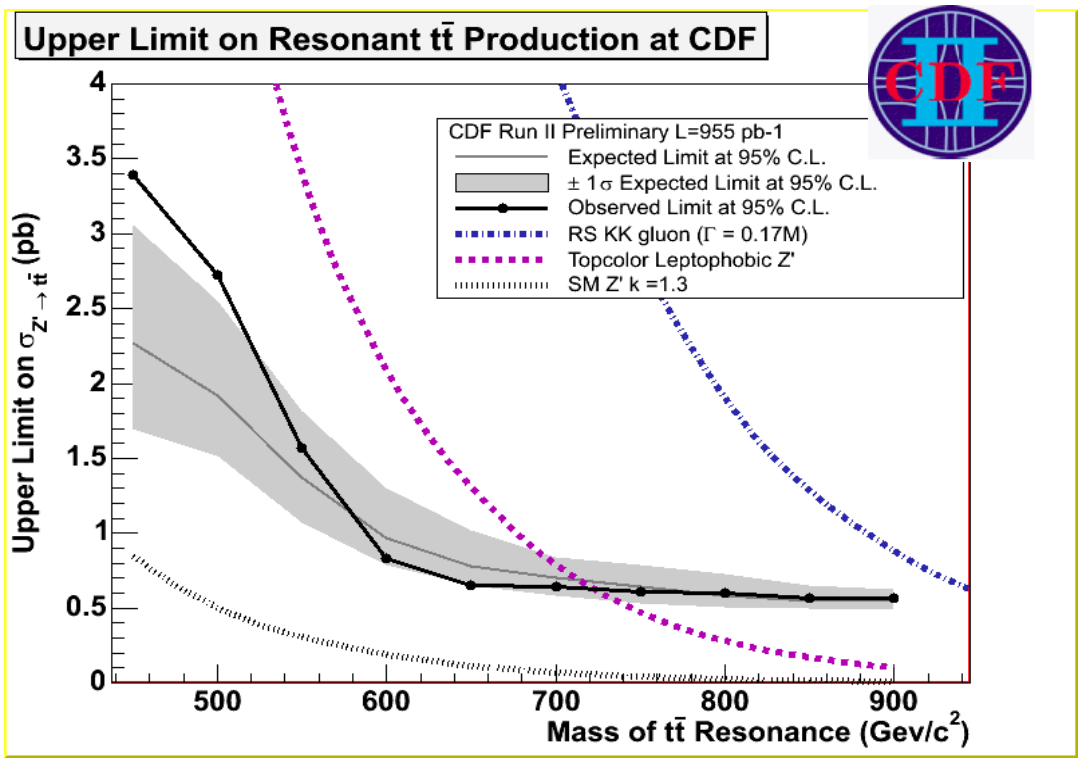
$\sigma(gg \to tt)/\sigma(qq \to tt) = 0.01 \pm 0.16\ (st) \pm 0.07\ (sy)$

  - Using a neural network

$\sigma(gg \to tt)/\sigma(qq \to tt) < 0.51$ at 95%CL

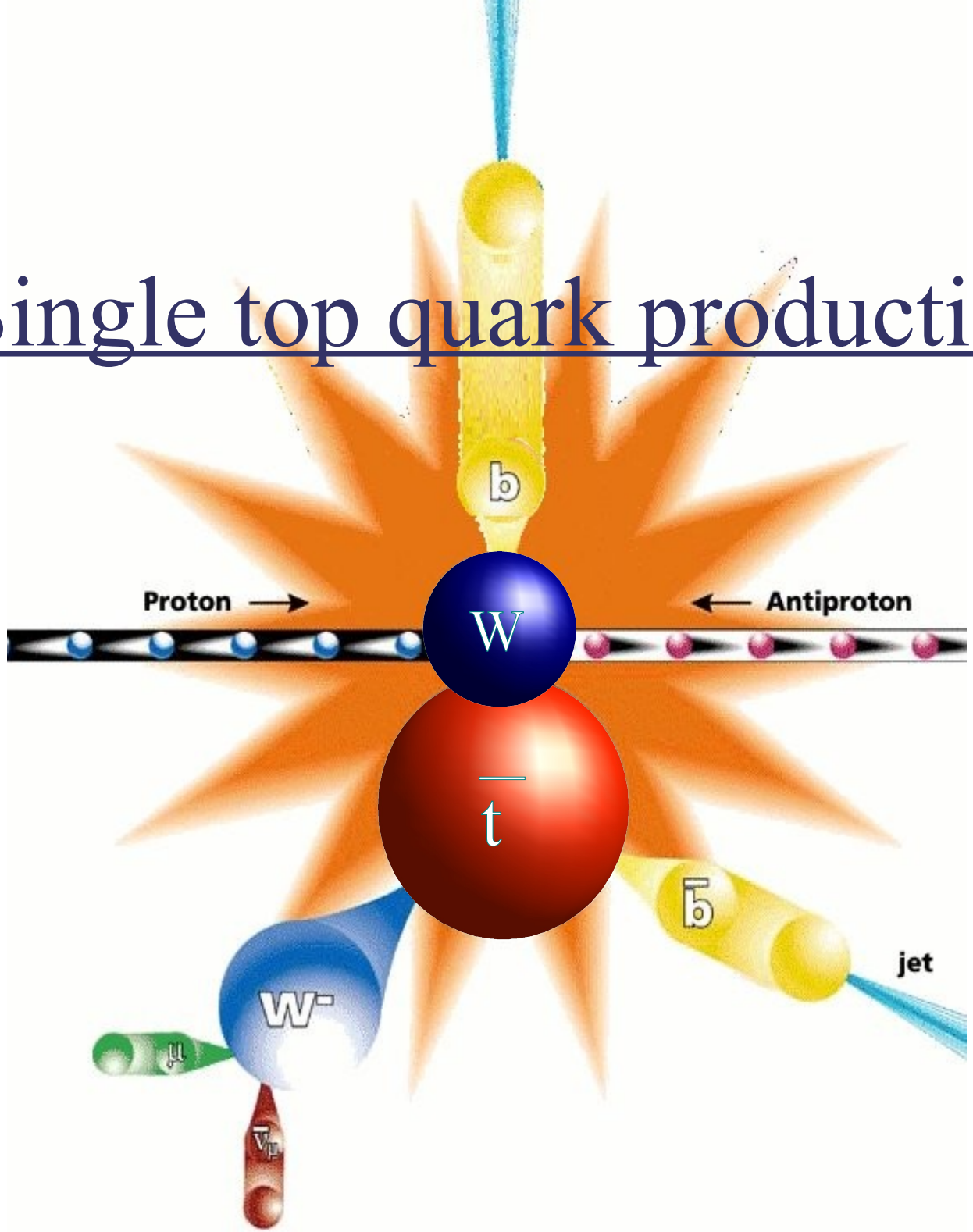


- Production through Z':

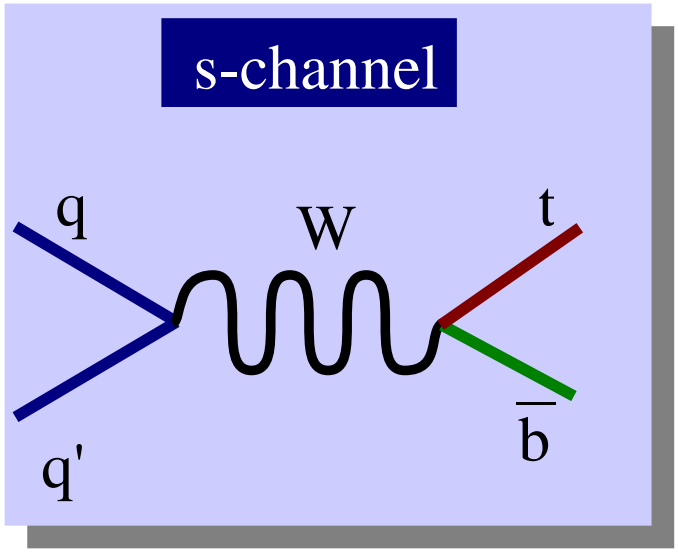


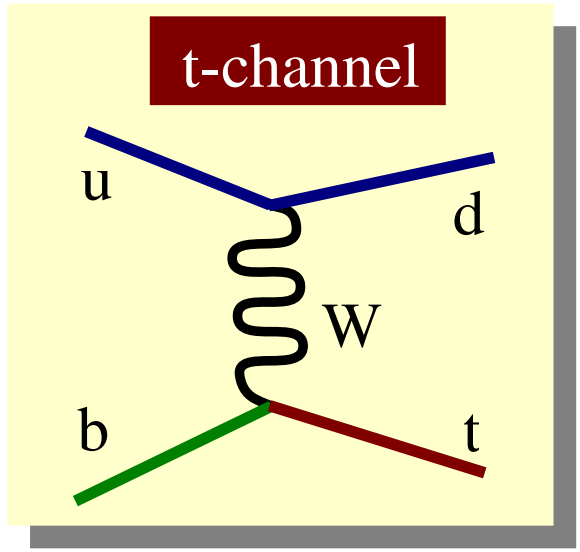
M(Z') < 680 GeV at 95%C.L.

Single top quark production



SM single top quark production



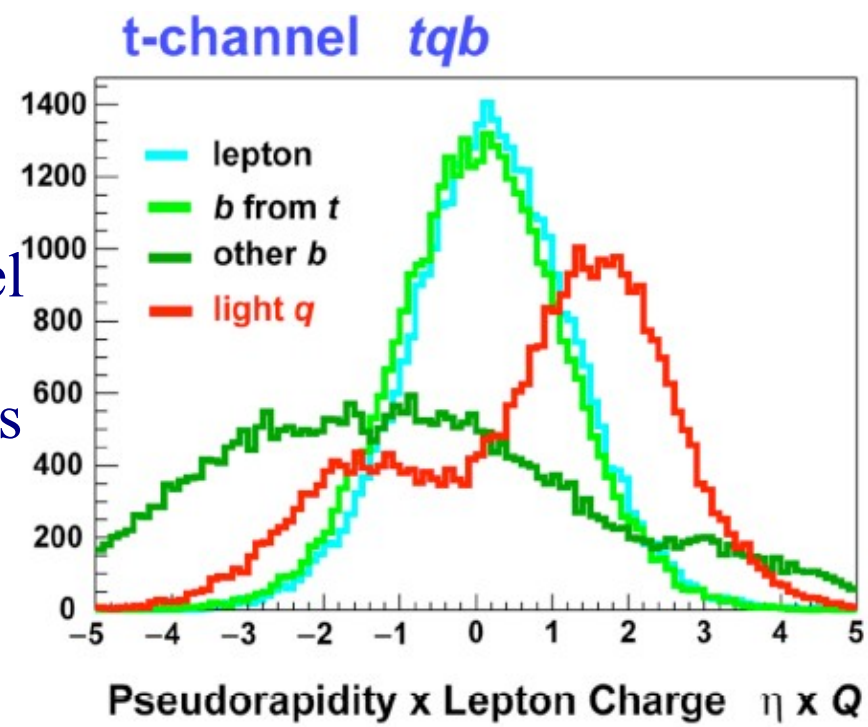


Cross section: σ_{tot} = 3 pb

σ_s = .98 pb	σ_t = 2.88

Tevatron Goals:

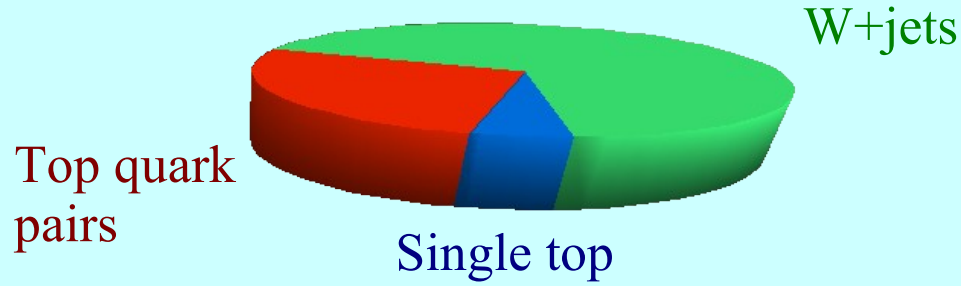
Discover single top quark production
Measure production cross sections
Look for physics beyond the standard model
Study top quark spin correlations
Understand as background to many searches

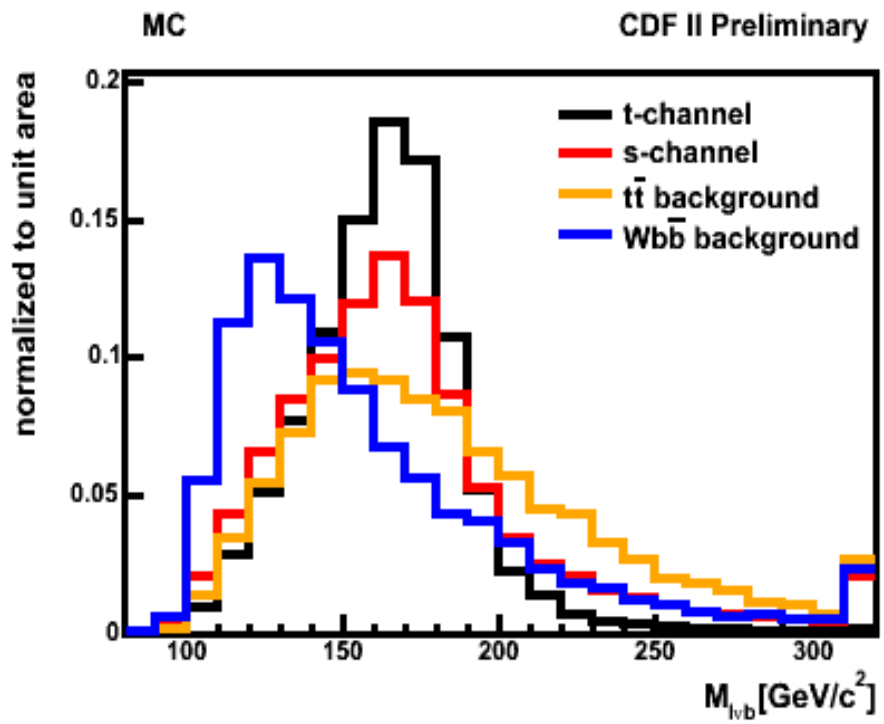


Single top event selection

- Basic event signature
  - Single lepton trigger or lepton+jets trigger
  - One high-E_T leptons
    - $E_T > 15$ GeV or 20 GeV
  - Missing transverse energy
    - Missing $E_T > 15$ GeV or 25 GeV
  - Two or three high-E_T jets (2-4 jets)
    - $E_T > 15$ GeV
  - At least one b-tag
- Expect ~ 50 events in 1 fb^{-1}
  - After b-tagging
  - S:B ~ 1:20

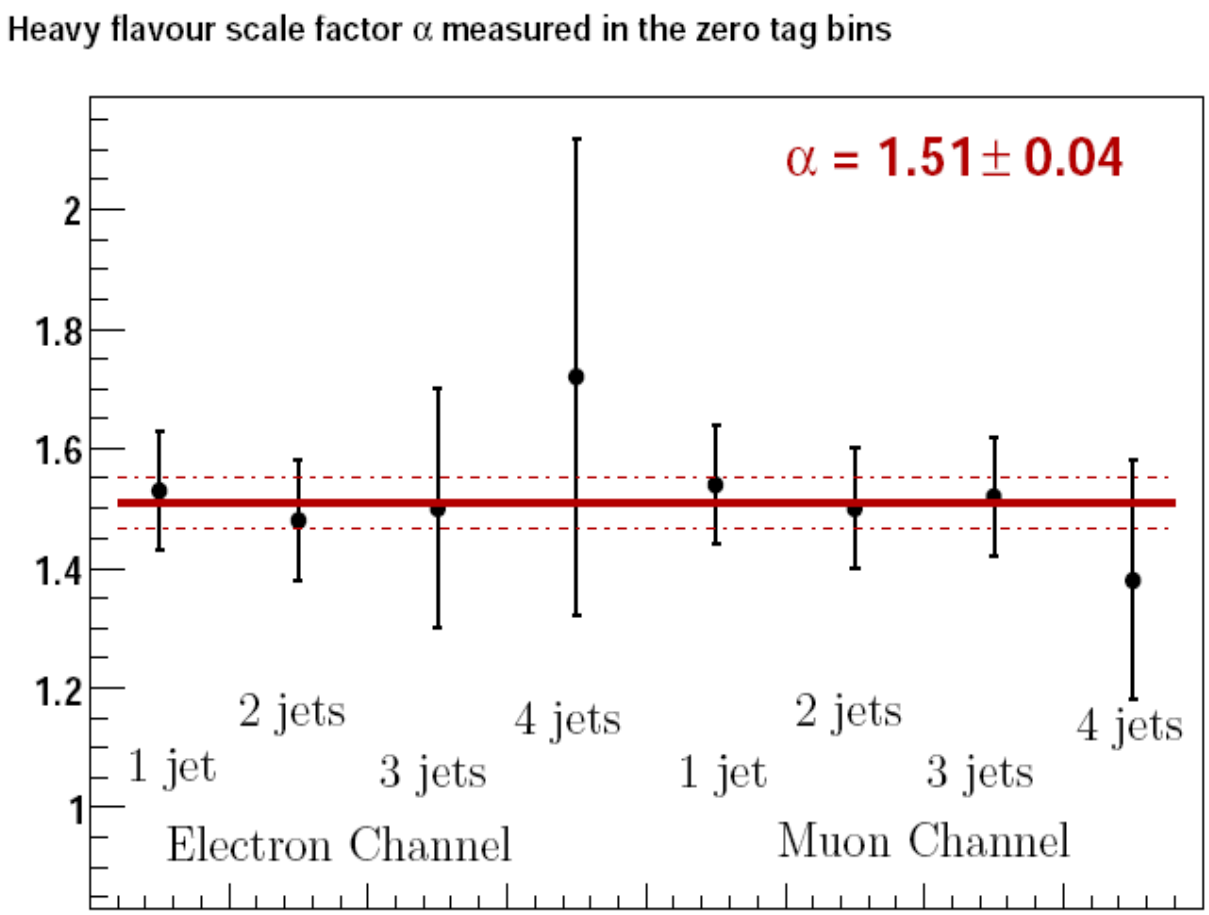
Event sample composition





Heavy flavor scale factor

- Start with MLM matched Alpgen samples
- Scale up (Wcc+Wbb) to match data
  - After all selection cuts
  - In the un-tagged sample



Multivariate Methods

Input: discriminating variables

Method: multivariate classifier

Output

Event kinematics

Object kinematics

Reconstructed top mass

Angular correlations

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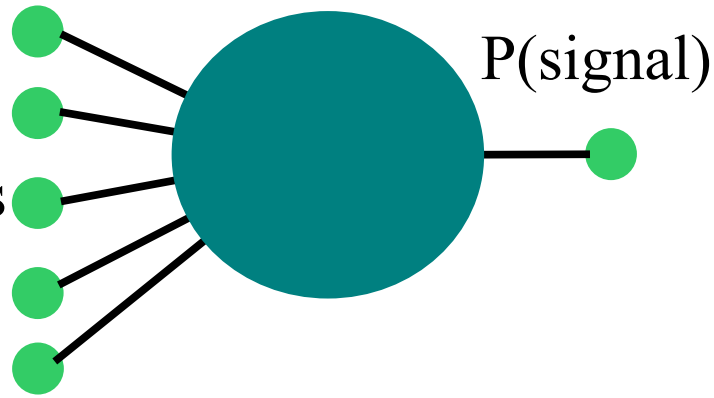
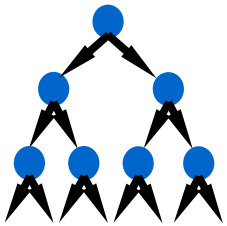
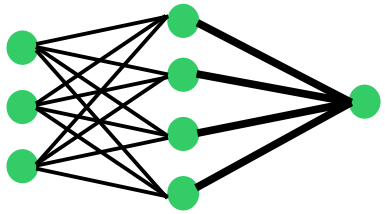


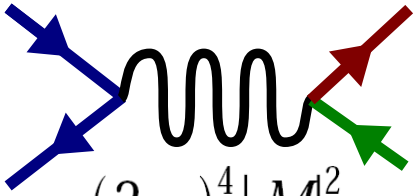
Boosted Decision Trees



Neural networks and Bayesian neural networks



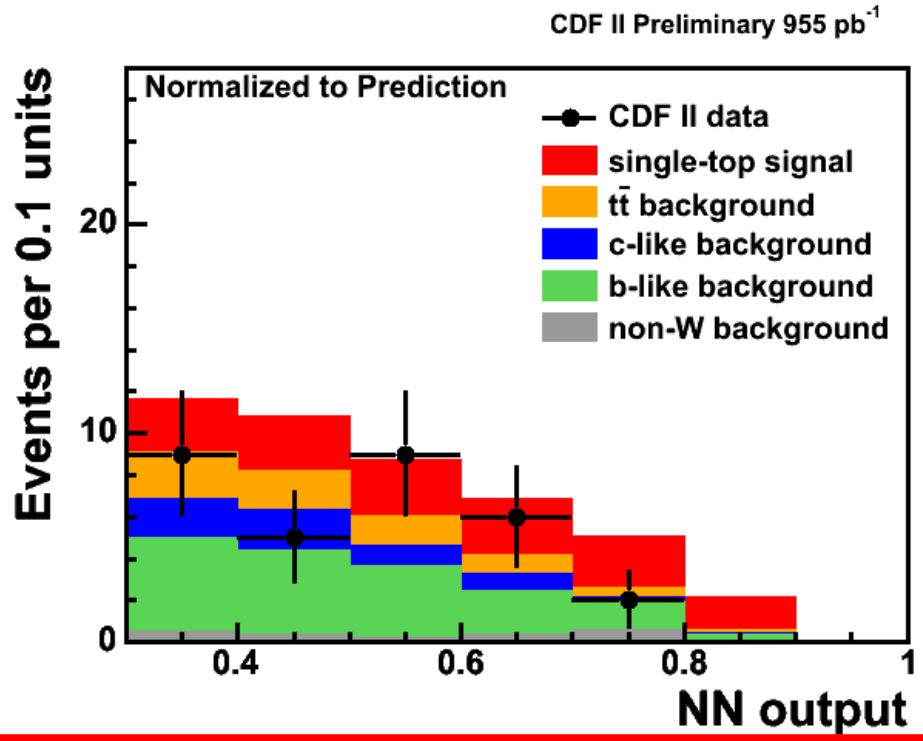
Matrix Elements



$$d^n\sigma_{hs} = \frac{(2\pi)^4 |M|^2}{4\sqrt{(q_1 q_2)^2 - m_1^2 m_2^2}} \times d\Phi_n$$

Neural network

- Neural network b-tag
  - Use distribution
- Plus 25 other variables
- Expected sensitivity
  - 2.6σ for SM s+t single top



σ(s+t single top) < 2.6 pb at 95%CL

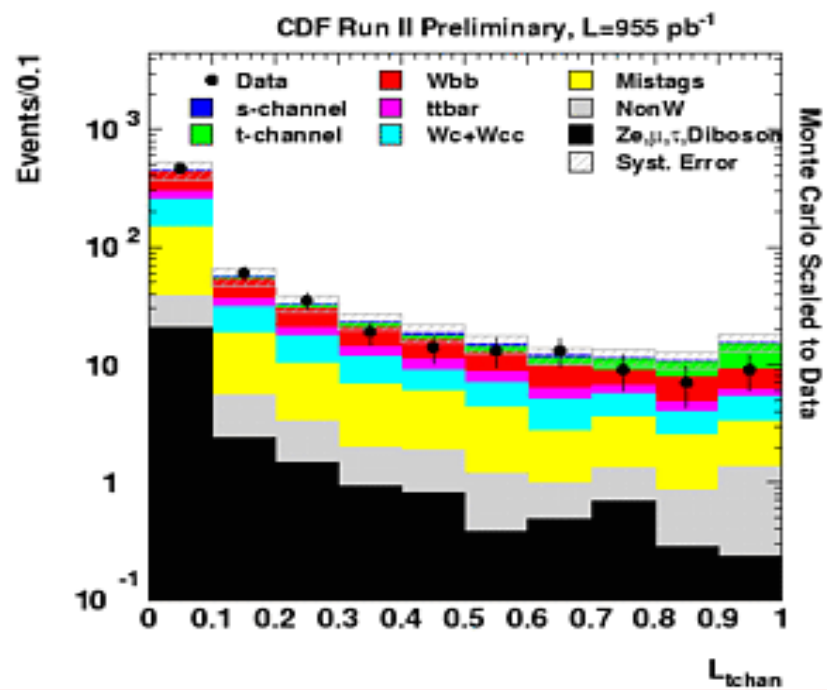
Likelihood

Form 7-variable likelihood function for t-channel search (6 variables for s-channel)

NN b-tagger

Object and event kinematics

Matrix element

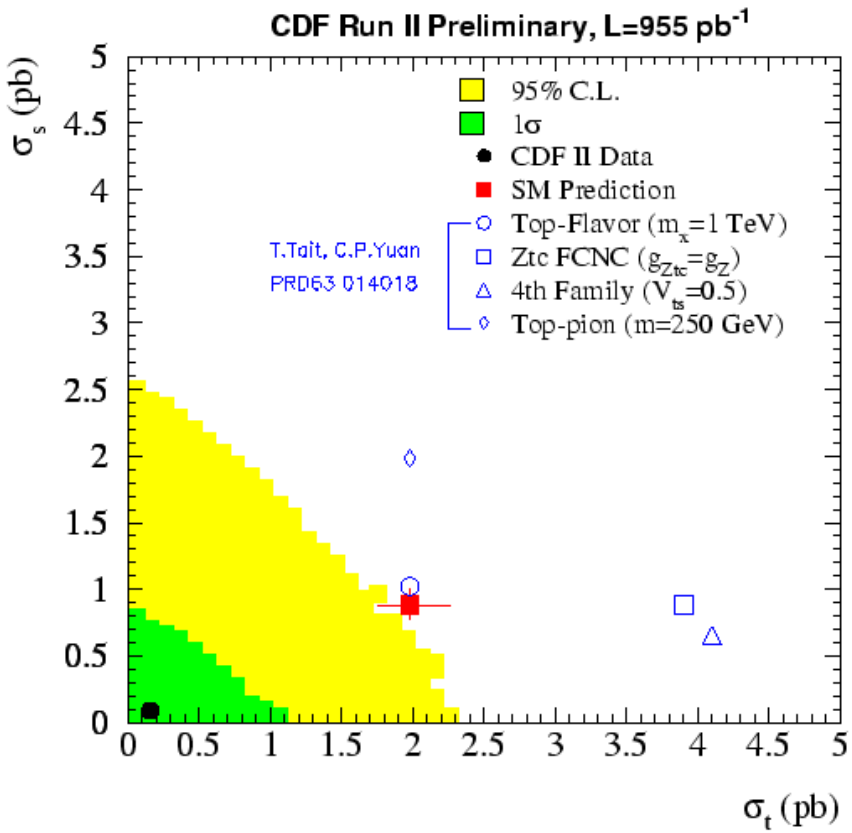


σ(s+t single top) < 2.7 pb at 95%CL

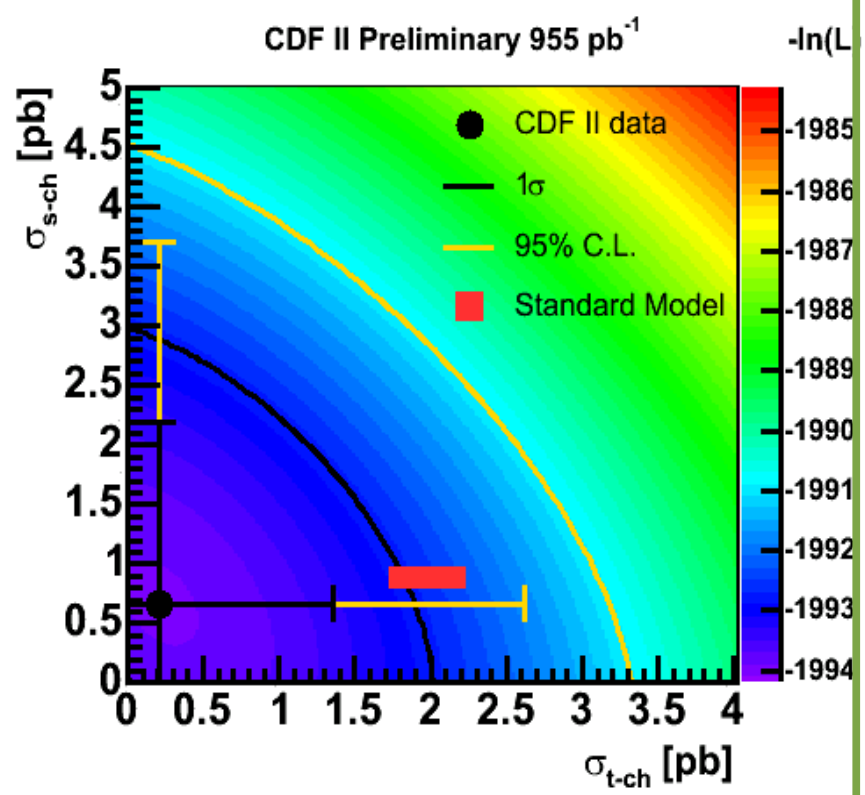
Simultaneous s-channel and t-channel analysis

- Evaluate s-channel and t-channel filters simultaneously
  - Form 2d posterior density
  - Sensitive to new physics

Likelihood analysis

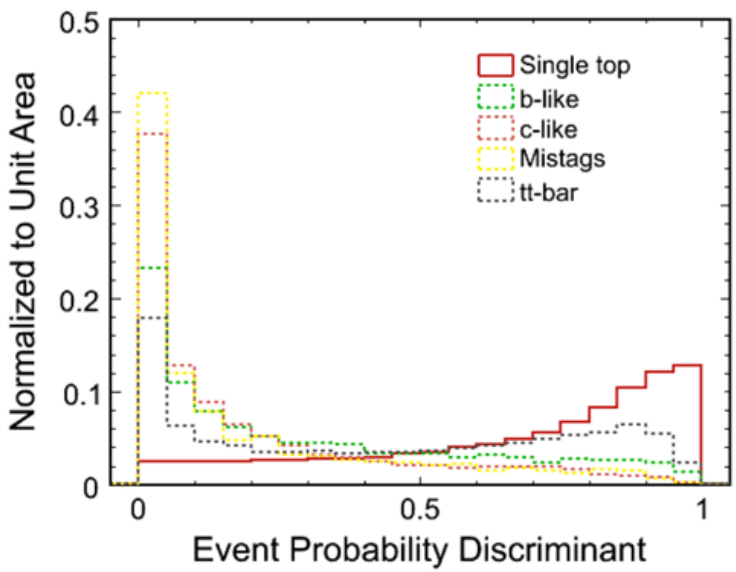


Neural network analysis

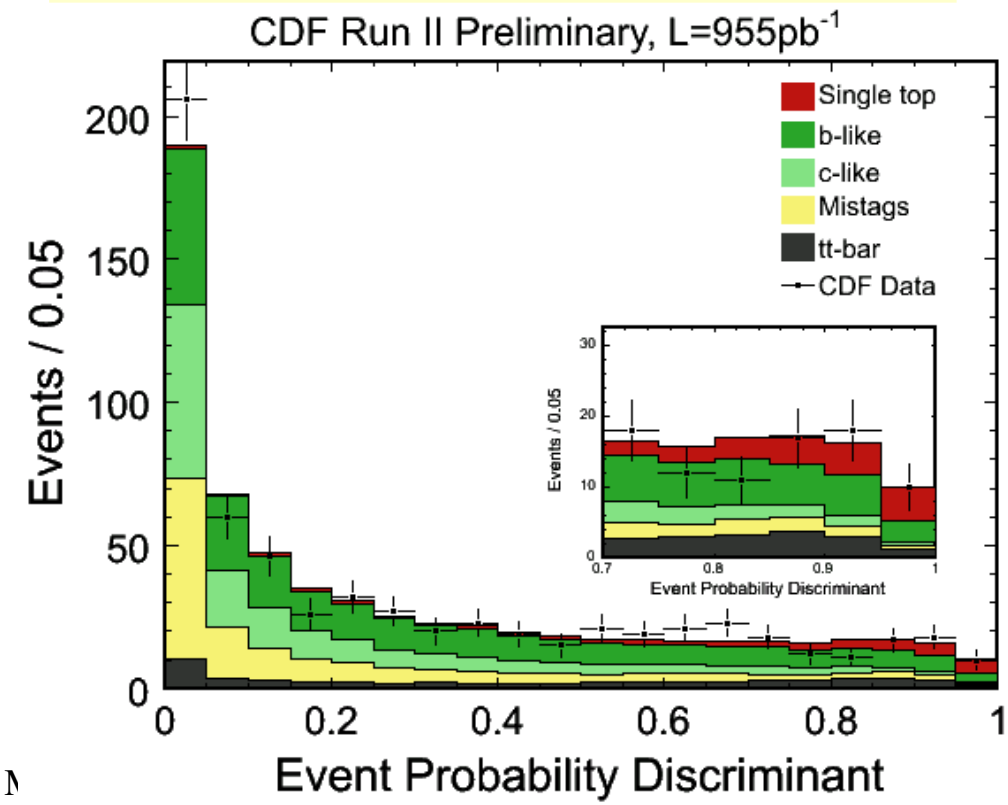


Matrix element analysis

$$EPD = \frac{b \cdot P_{\sin gletop}}{b \cdot P_{\sin gletop} + b \cdot P_{Wbb} + (1-b) \cdot P_{Wcc} + (1-b) \cdot P_{Wcj}}$$



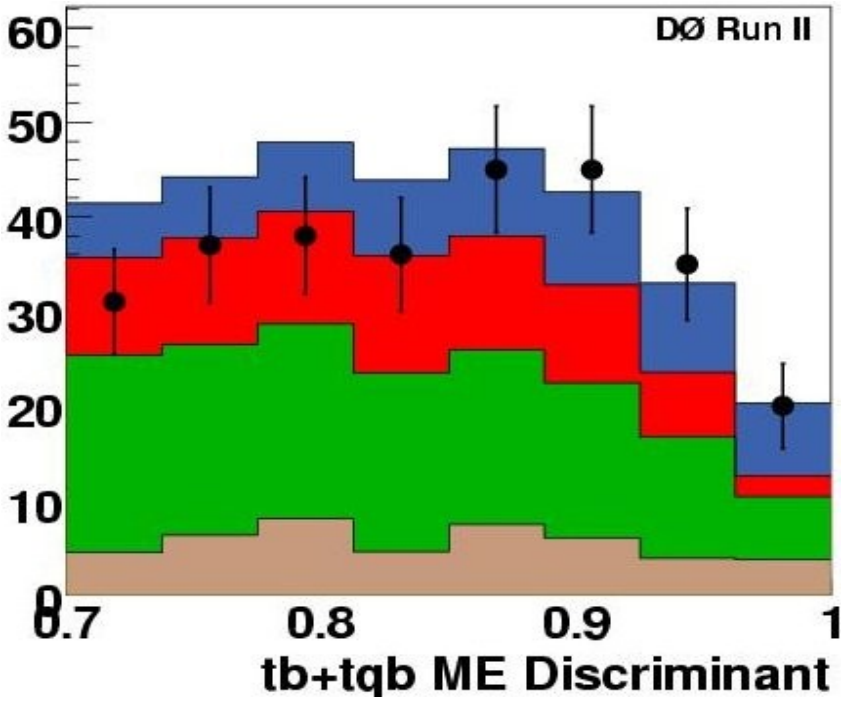
- Leading order matrix element
- Transfer functions from partons to reconstructed objects
- Integrate, integrate, integrate

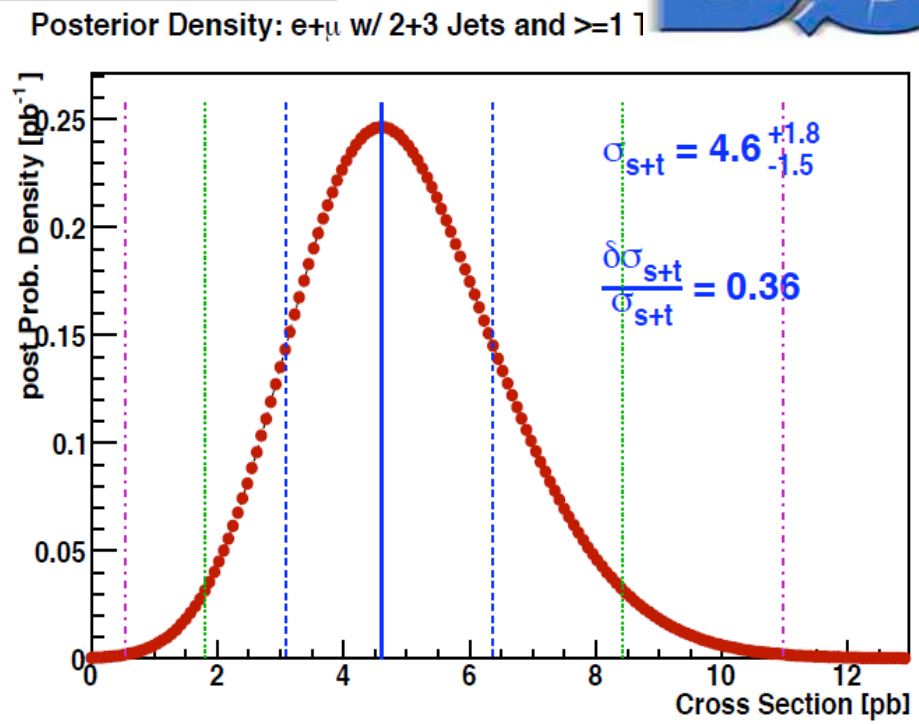


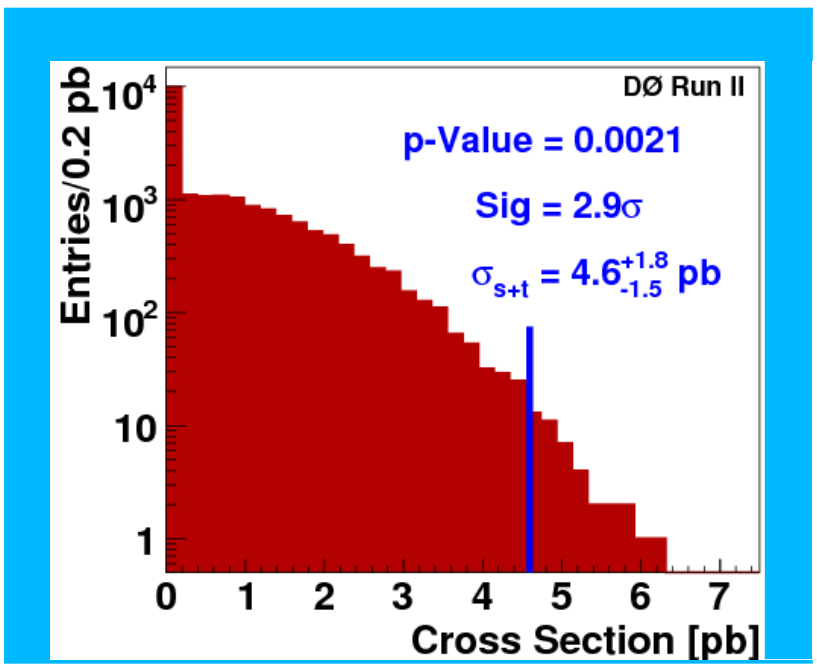
σ(s+t single top) = $2.7^{+1.5}_{-1.3}$ pb

2.3σ evidence for single top

Matrix element



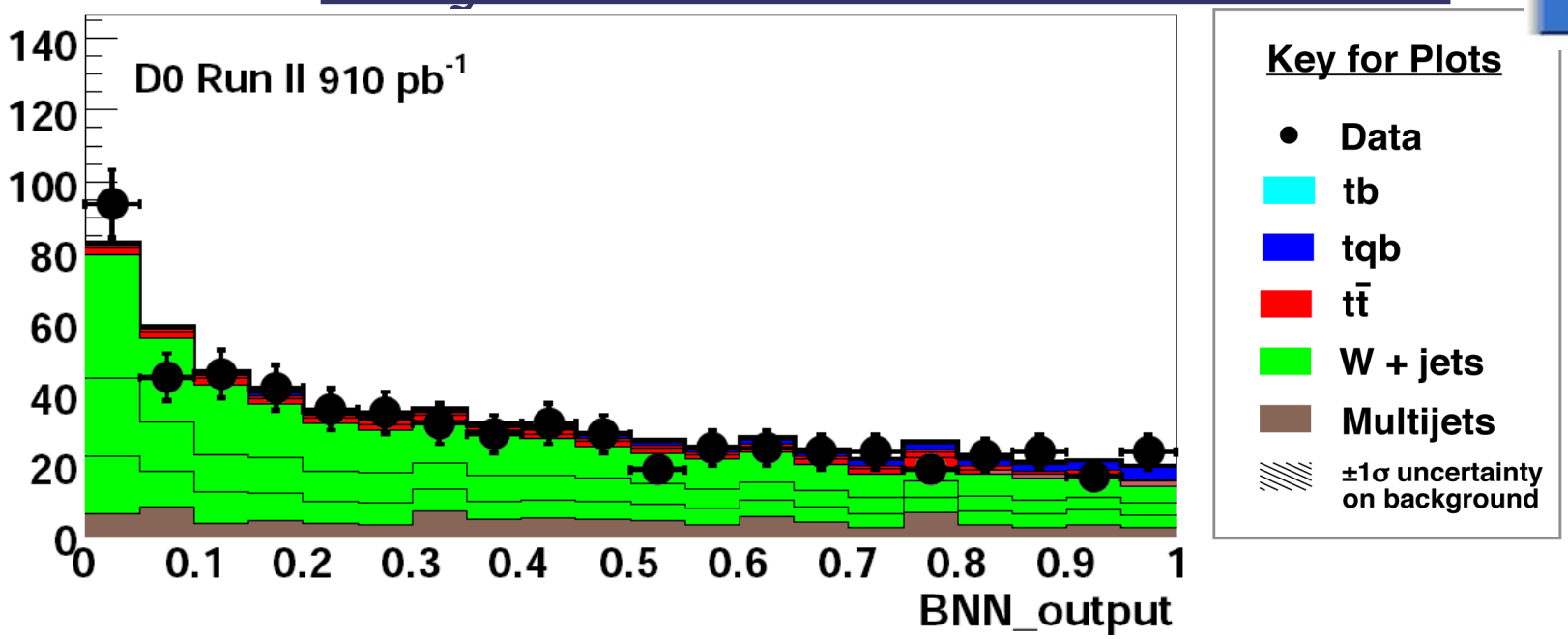


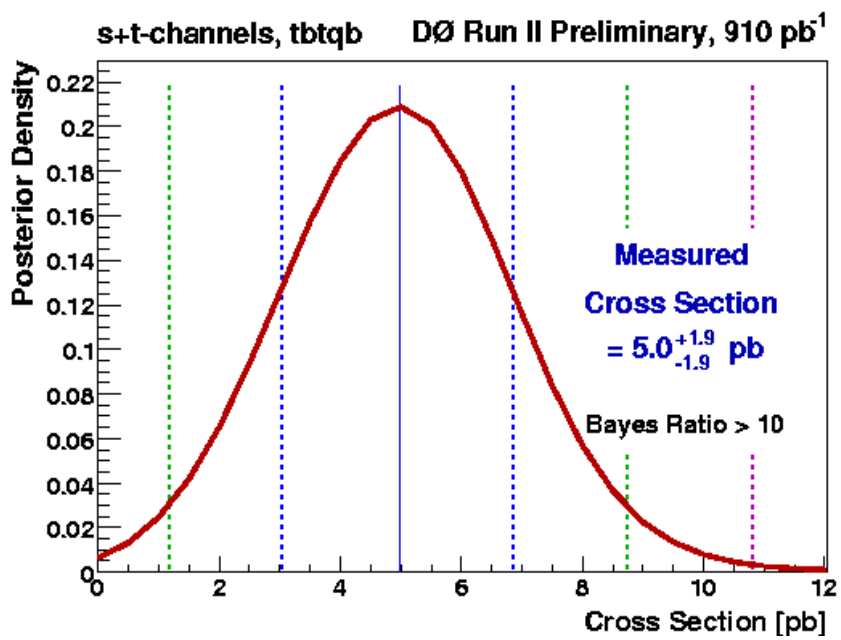


σ(s+t single top) = $4.6^{+1.8}_{-1.5}$ pb

2.9 σ evidence for single top

Bayesian neural network

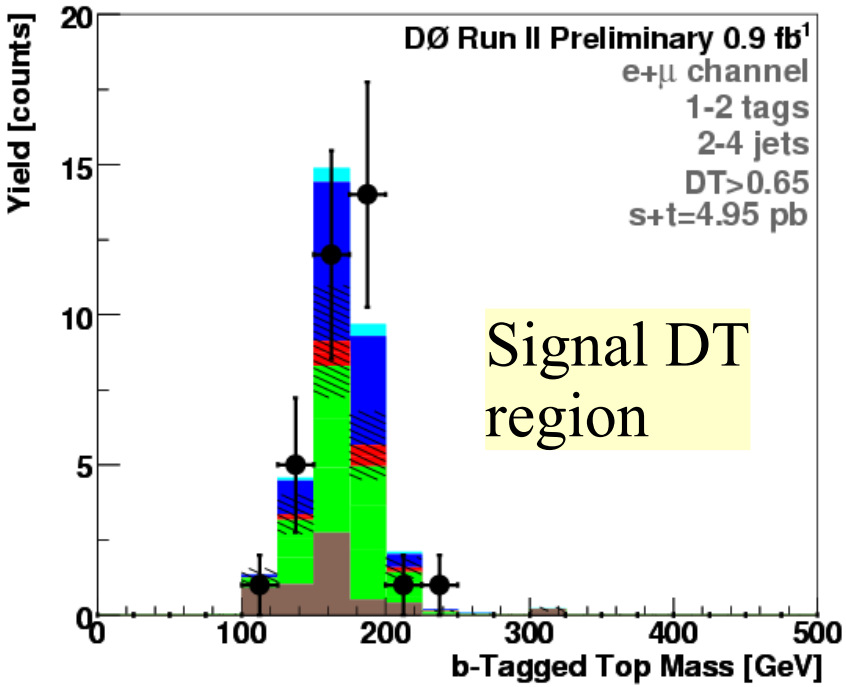


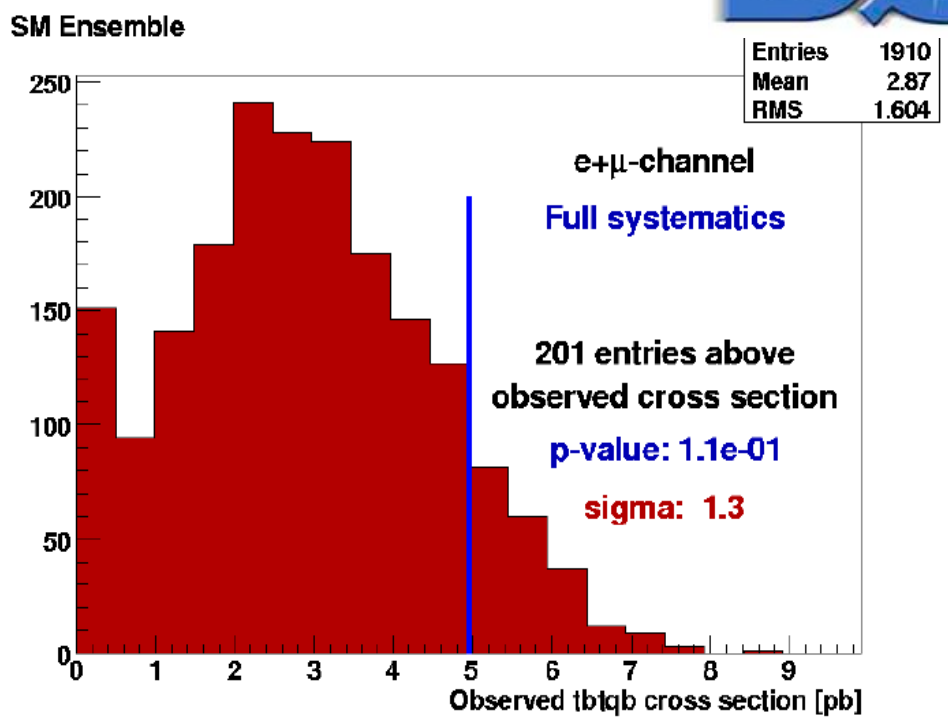


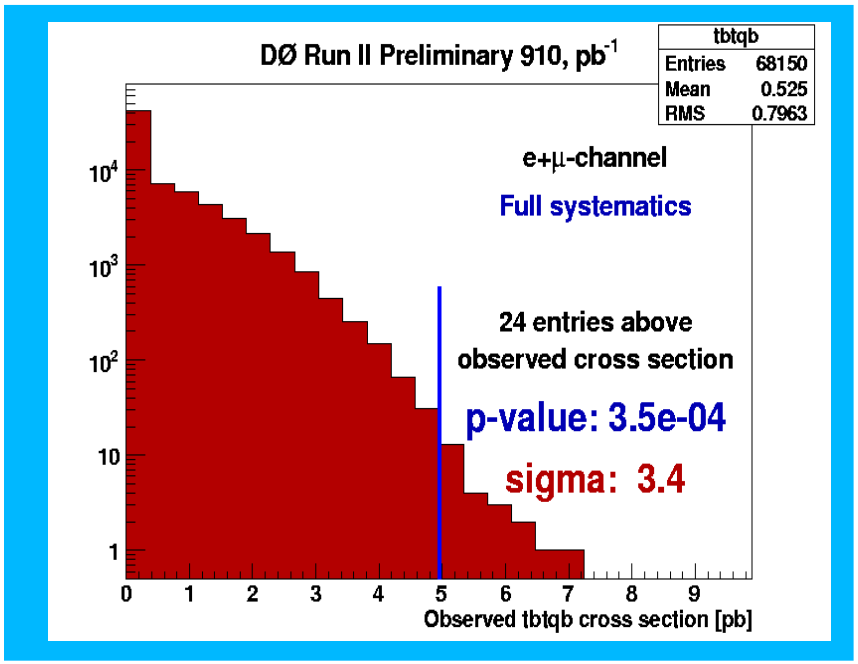
σ(s+t single top) = 5.0 ± 1.9 pb

2.3σ evidence for single top

Boosted decision trees







σ(s+t single top) = 4.6 ± **1.4** pb

3.4 σ evidence for single top

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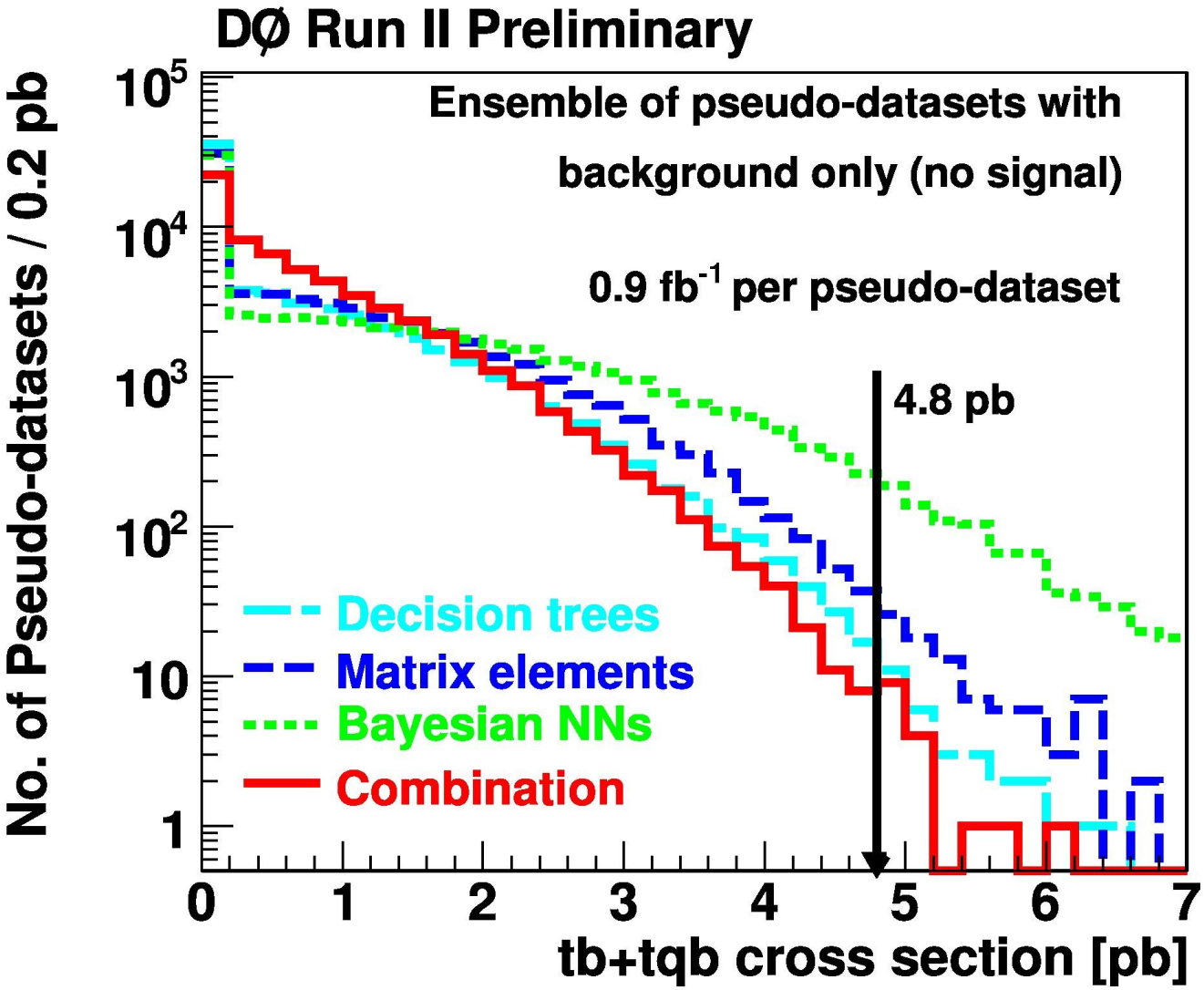
Combination

- Use BLUE method to combine analyses
  - Using large sets of ensembles for weights and correlations

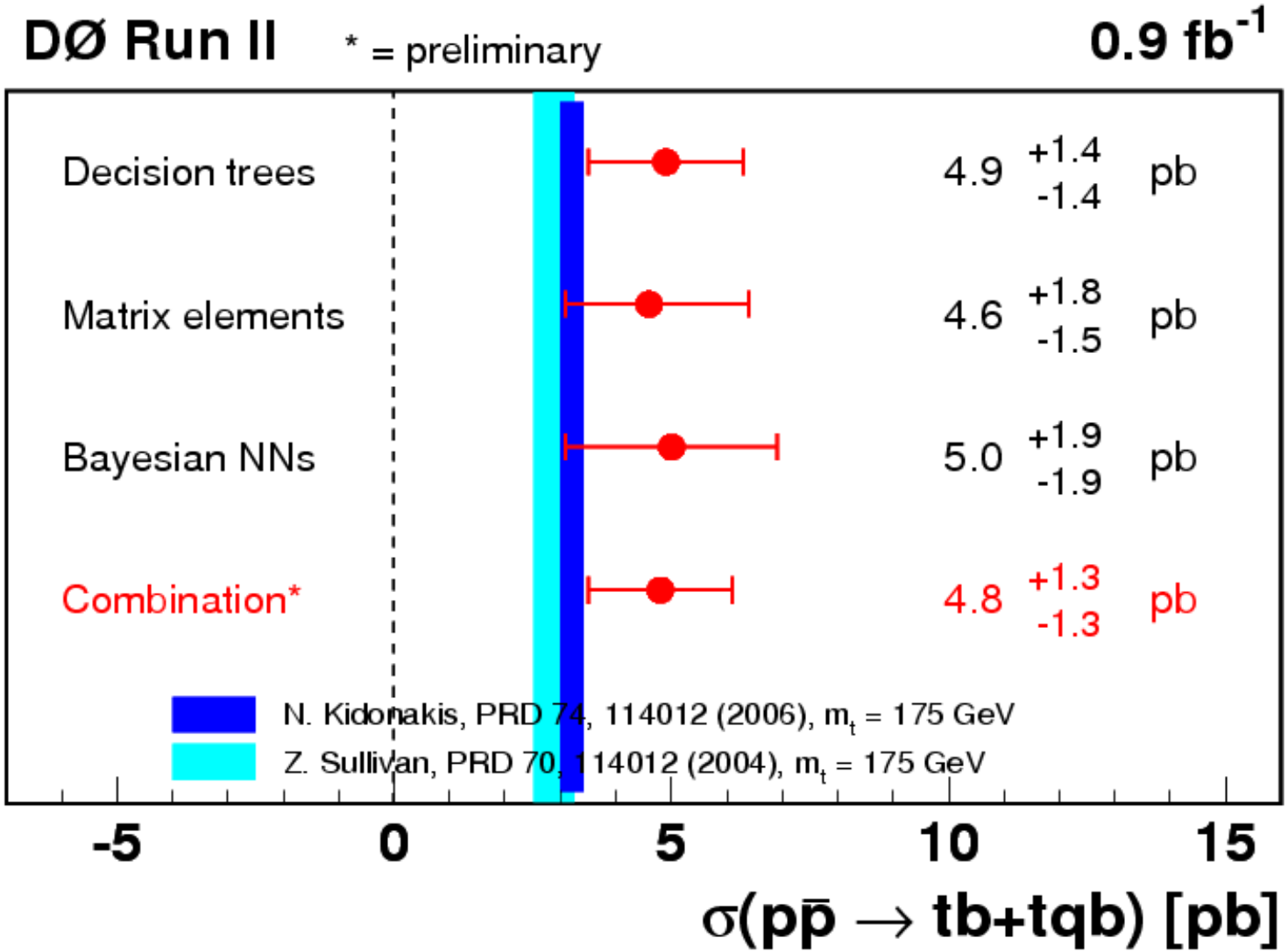


$$\rho = \begin{pmatrix} DT & ME & BNN & \\ 1 & 0.57 & 0.51 & DT \\ 0.57 & 1 & 0.45 & ME \\ 0.51 & 0.45 & 1 & BNN \end{pmatrix}$$

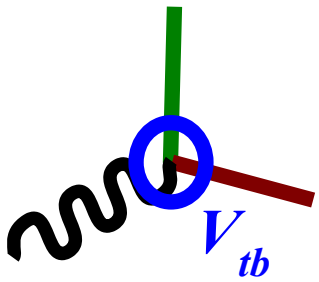
$\sigma(s+t) = 4.8 \pm \mathbf{1.8}$ pb

3.5 σ evidence for single top

Summary


DØ Run II
* = preliminary
0.9 fb^{-1}
Decision trees
4.9 +1.4 -1.4 pb
Matrix elements
4.6 +1.8 -1.5 pb
Bayesian NNs
5.0 +1.9 -1.9 pb
Combination*
4.8 +1.3 -1.3 pb
N. Kidonakis, PRD 74, 114012 (2006), m_t = 175 GeV
Z. Sullivan, PRD 70, 114012 (2004), m_t = 175 GeV
-5
0
5
10
15
$\sigma(p\bar{p} \rightarrow tb+tqb)$ [pb]

CKM matrix element $|V_{tb}|$



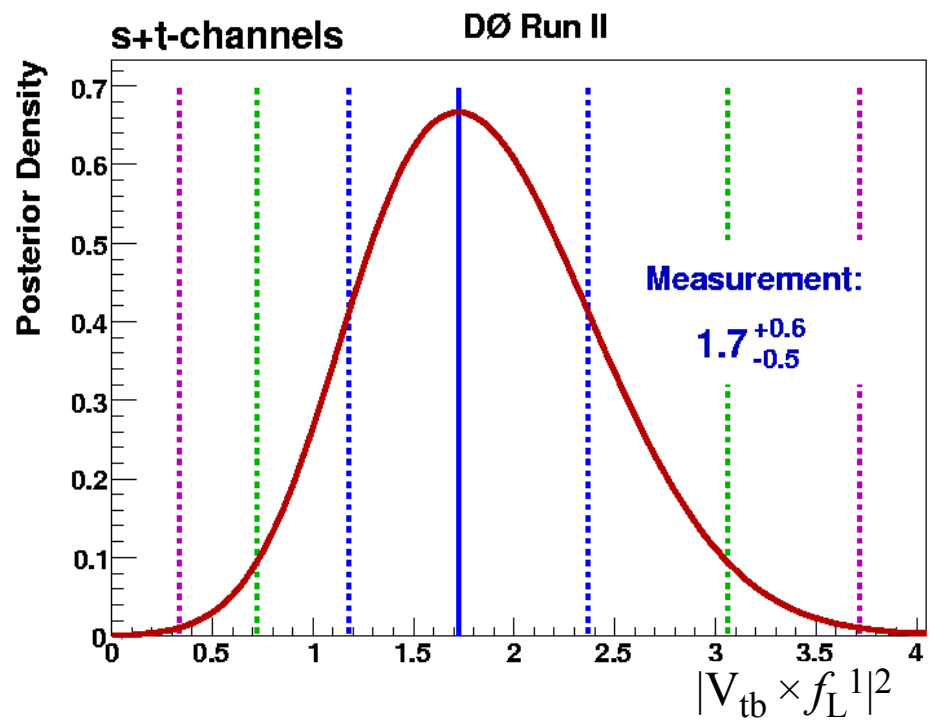
CKM Matrix

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

- 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 $f_L^1 = 1$

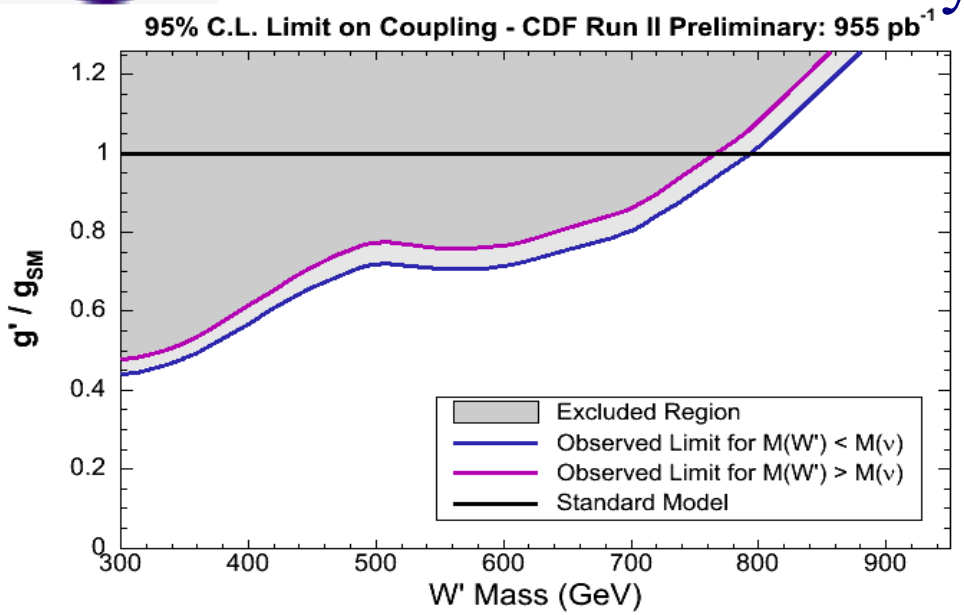
  $\rightarrow$ lower limit on V_{tb}
- At the 95% C.L.:

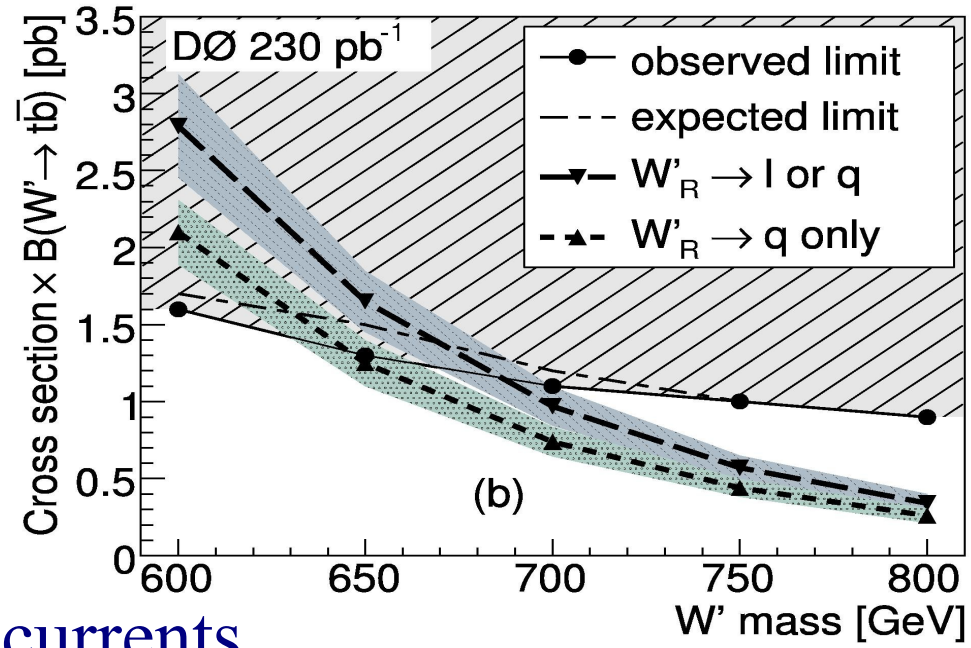
  $|Vtb| > 0.68$



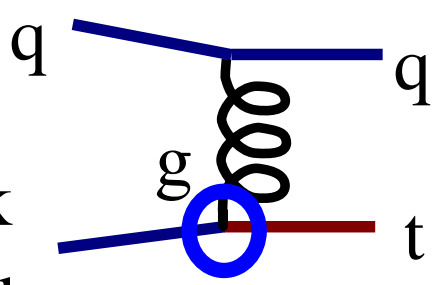
Other single top production searches

Searches for new heavy boson W'

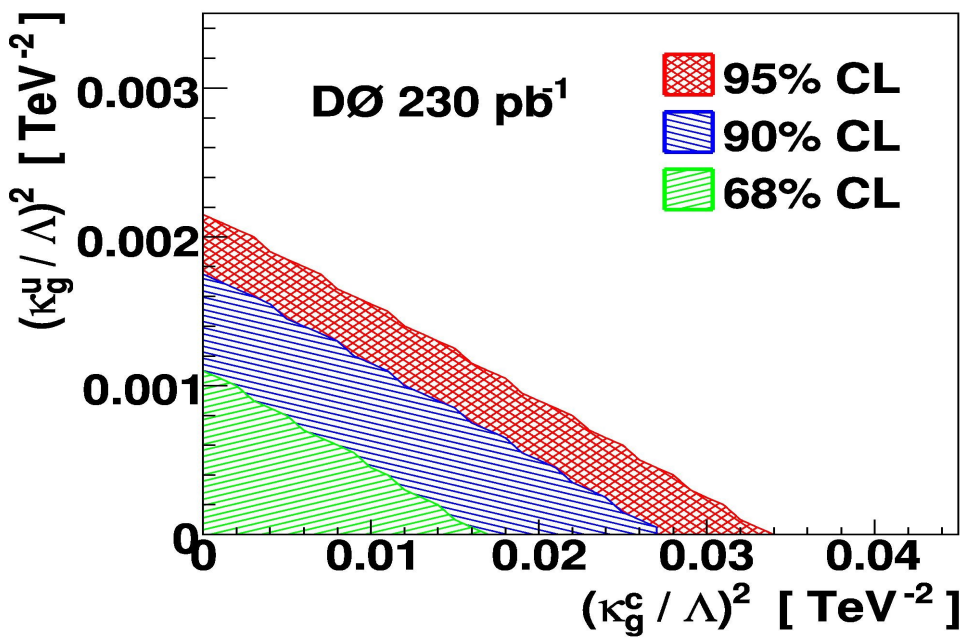




- Flavor-changing neutral currents

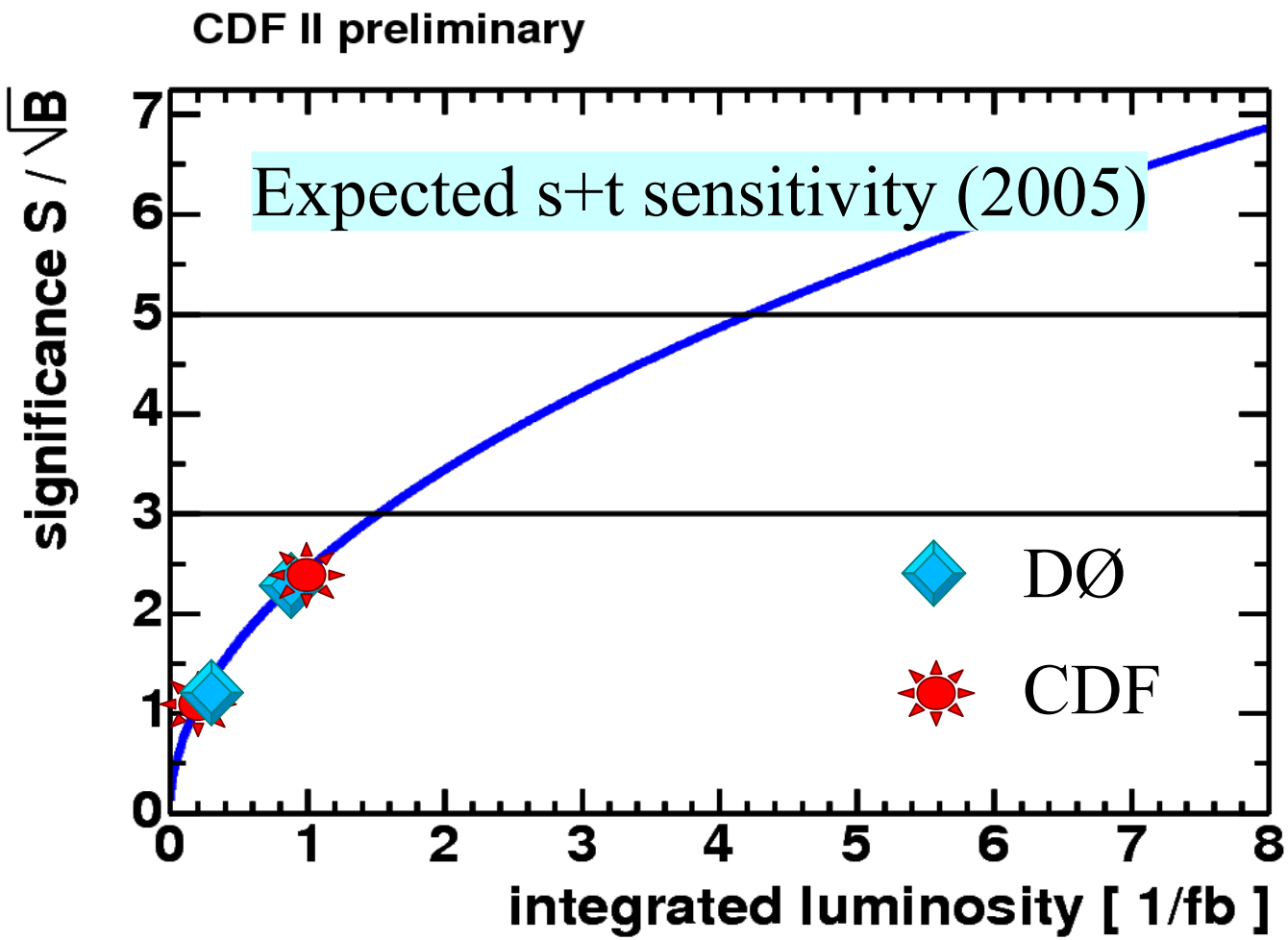


Up quark
or c quark



Prospects

- Already more than twice as much data on tape
- Smaller uncertainties / improved background modeling
- Improved acceptance (b-tagging, triggering, ...)
- More sensitive multivariate filters



Conclusions/Outlook

- Top pair production cross section measured to 12%
  - Individual measurements at 15%
  - Different decay channels
  - Systematics limited
- Single top is within reach
  - DØ has observed 3.5 σ evidence for single top quark production
  - $|V_{tb}| > 0.68$ at the 95 % C.L.
- Better than 4 σ single top sensitivity expected with 2 fb^{-1}

Questions for discussion

- How to estimate the W+jets background?
  - Normalization?
  - Shape?
  - Flavor composition?
- How sensitive are multivariate methods to parton-level modeling?
- What else would you like to see measured?