Single Top Search at D0

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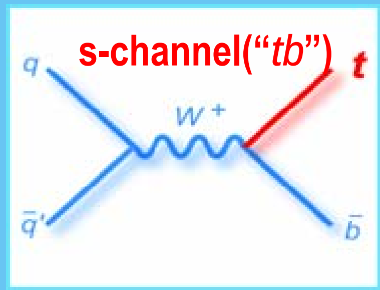
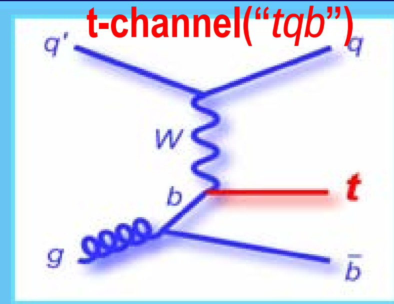
For the D0 Collaboration

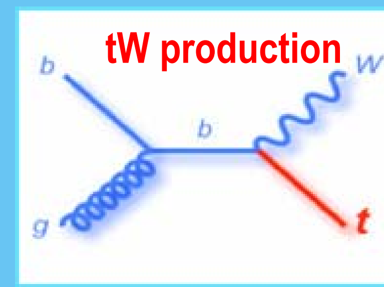
Outline

- **Single Top Search**
  - Introduction and Motivation
  - Event Signatures and Selection
  - Multivariate Techniques
  - Statistical Analysis
- **… and Beyond**
  - Measuring $|V_{tb}|$
  - Search for W'
  - Search for Charged Higgs
- **Conclusions / Outlook**

Single Top Production







	s-channel	t-channel	tW
Tev:	σ ~1 pb	σ ~ 2pb	σ ~0.25 pb
LHC:	σ ~11 pb	σ ~ 235pb	σ ~95 pb

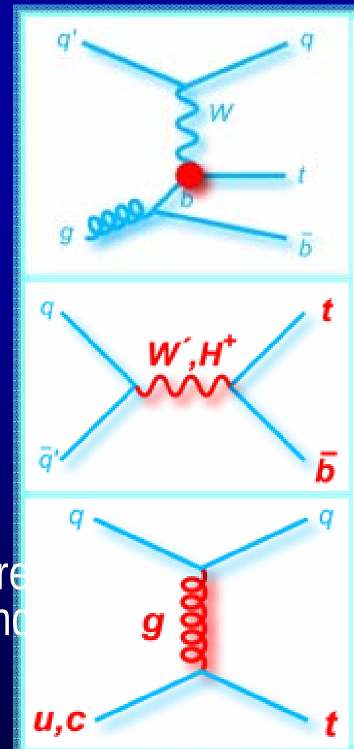
Motivation:

- **Prediction of SM not observed so far**
- **Study *Wtb* coupling in top production**

  Measure $|V_{tb}|$ directly: $\sigma \propto |V_{tb}|^2$
- **Cross sections sensitive to new physics**

  s-channel: resonances (heavy *W′* boson, charged Higgs boson, Kaluza-Klein excited W_{KK}, technipion, etc.), t-channel: flavor-changing neutral currents ($t - Z / \gamma / g - c / u$ couplings), Fourth generation of quarks
- **Top properties**

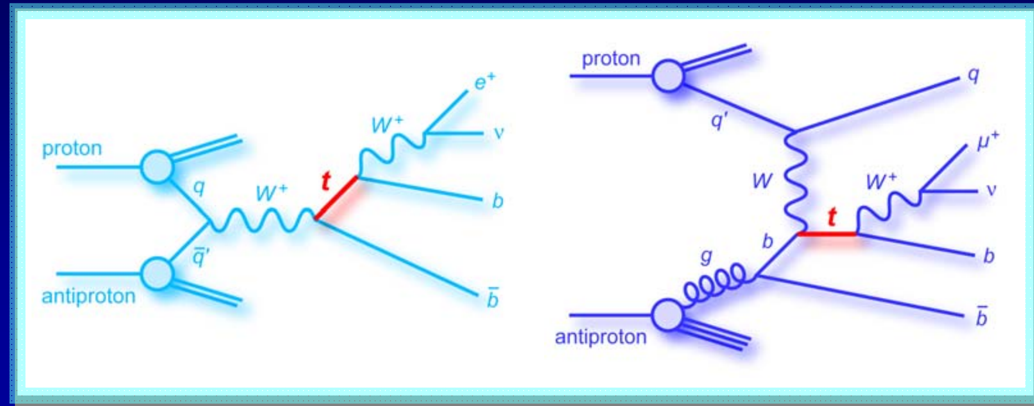
  Polarized top quarks – spin correlations measurable in decay products, Measure top quark partial decay width and lifetime, CP violation (same rate for top and antitop?)
- **Similar search for *WH* associated Higgs production**



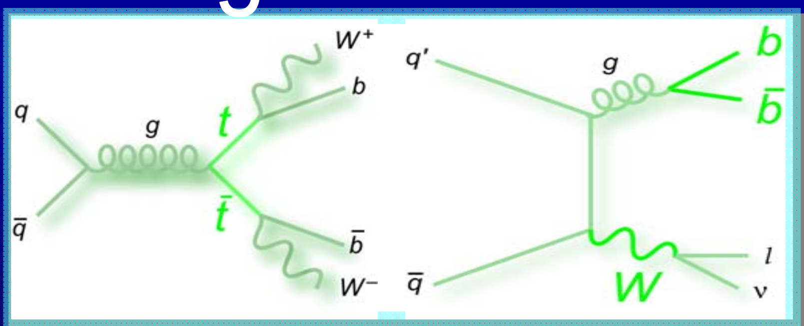
Event Signatures and Event Selection

- One isolated electron or muon, missing Transverse Energy, at least two or more jets with at least one b-tagged jet

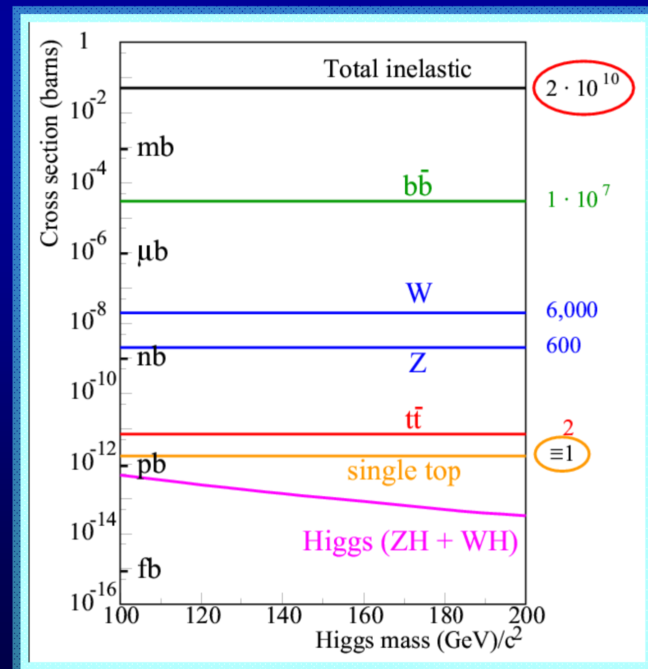
$e:$	$p_T > 15\,GeV, \lvert\eta\rvert < 1.1$
$\mu:$	$p_T > 18\,GeV, \lvert\eta\rvert < 2.0$
Missinng E_T	$15 < MET < 200\,GeV$
Jets	$2-4, p_T > 15\,GeV, \lvert\eta\rvert < 3.0$
	$p_{T,1} > 25\,GeV, \lvert\eta\rvert < 2.5$
	$p_{T,2} > 20\,GeV$
B – jet	1 or 2



Backgrounds



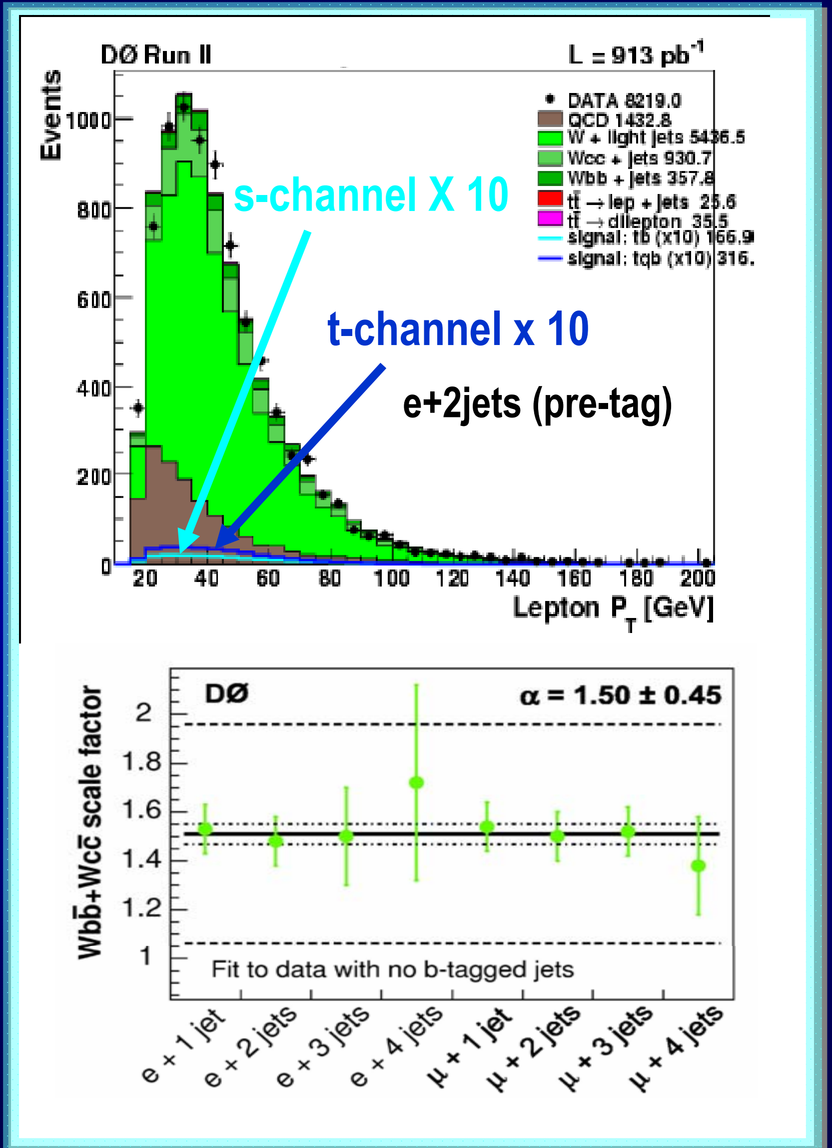
- **Top pairs, W+jets, and Multijets are the main processes that can mimic these signatures**
- **Single top signal is negligible compared to these backgrounds**



Signal and Background Modeling

- *Single top signal:*
  - Modeled using SINGLETOP based on COMPHEP
  - Reproduces NLO kinematic distributions
  - PYTHIA for parton hadronization
- ***W+jets* background:**
  - Event kinematics and flavor composition modeled using Alpgen generator
  - Normalized to data before b tagging and after subtracting other backgrounds
  - Additional scale factor ~1.5 for Wbb and Wcc
- **Multijet background:**
  - Modeled using data with a non-isolated lepton and jets
- ***Top* pair backgrounds**
  - Modeled using ALPGEN
  - Normalized to theoretical prediction
- *Diboson (WW,WZ,ZZ)*
  - Small contribution

  Included in W+jets via normalization to data



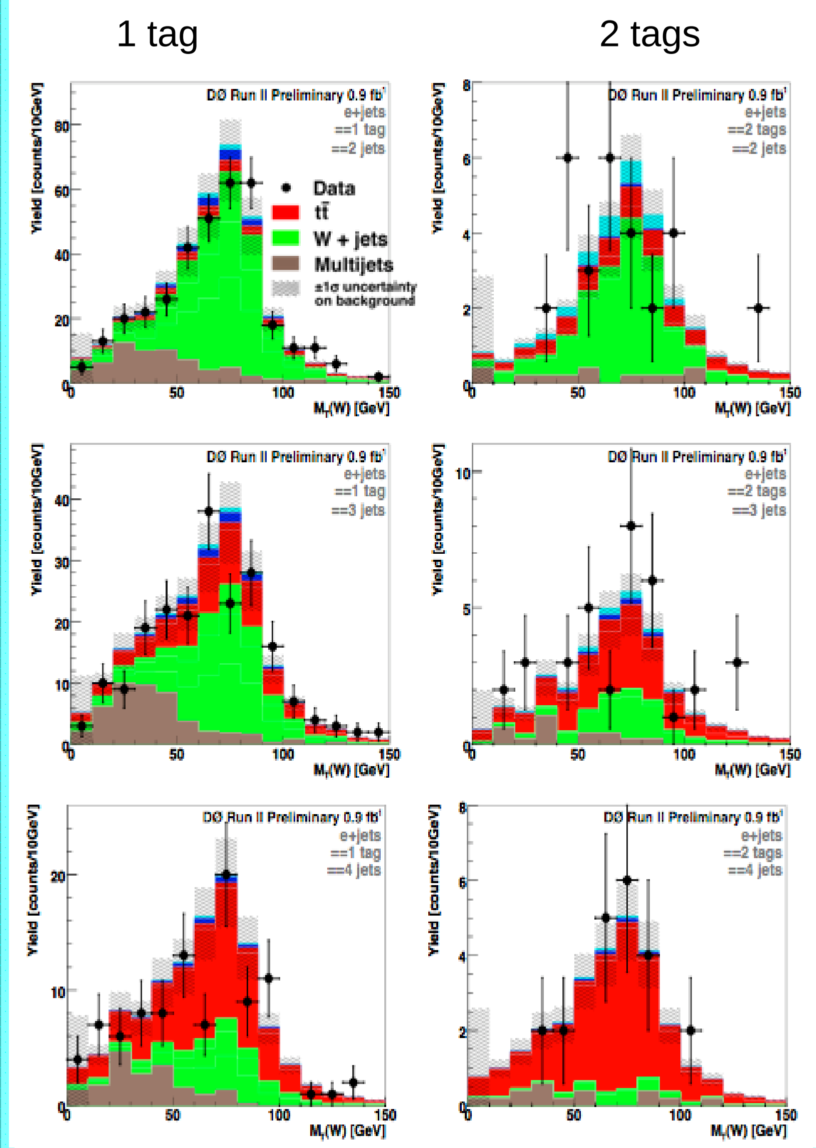
Event Yields After B-Tagging

Sensitivity significantly increased after requiring b-tagging, e.g. in 2 jets channel:

	S/B	S/√B
Before b-tagging	~1/200	~ 0.6
After b-tagging (1+2 b-tags)	~1/18	~ 1.5

Source	Event Yields in 0.9 fb^{-1} Data Electron+muon, 1tag+2tags combined 2 jets	3 jets	4 jets
tb	16 ± 3	8 ± 2	2 ± 1
tqb	20 ± 4	12 ± 3	4 ± 1
$t\bar{t} \to ll$	39 ± 9	32 ± 7	11 ± 3
$t\bar{t} \to l$+jets	20 ± 5	103 ± 25	143 ± 33
$W+b\bar{b}$	261 ± 55	120 ± 24	35 ± 7
$W+c\bar{c}$	151 ± 31	85 ± 17	23 ± 5
$W+jj$	119 ± 25	43 ± 9	12 ± 2
Multijets	95 ± 19	77 ± 15	29 ± 6
Total background	686 ± 41	460 ± 39	253 ± 38
Data	697	455	246

- **Single top signal is smaller than total background uncertainty**
- **Counting events is not a sensitive enough method**



Systematic Uncertainties

- **Uncertainties are assigned for each signal and background component in all analysis channels**
- **Most systematic uncertainties apply only to normalization**
- **Two sources of uncertainty also affect the shapes of distributions**
  - **jet energy scale**
  - **tag-rate functions for *b*-tagging MC events**

- **Correlations between channels and sources are taken into account**

Cross section uncertainties are dominated by the statistical uncertainty, the systematic contributions are all small

Source of Uncertainty	Size
Top pairs normalization	18%
W+jets & multijets normalization	18–28%
Integrated luminosity	6%
Trigger modeling	3–6%
Lepton ID corrections	2–7%
Jet modeling	2–7%
Other small components	Few %
Jet energy scale	1–20% ★
Tag rate functions	2–16% ★

★ Uncertainties that also affect the shapes of the distributions

Search Strategy and Analysis Steps

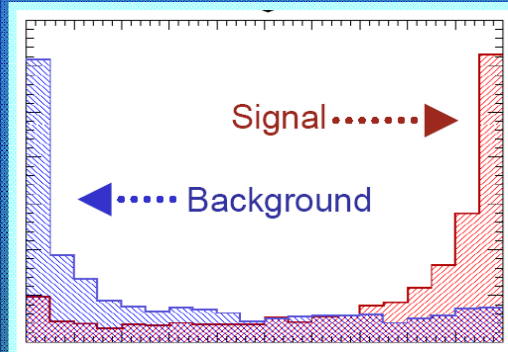
- **Maximize the signal acceptance**
  - Particle ID definitions set as loose as possible
  - Transverse momentum thresholds set low, pseudo-rapidities wide
  - As many decay channels used as possible – this analysis shown in red box
  - Channels analyzed separately since S:B and background compositions differ

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

Signal acceptances (including BR)	tb	tqb
2-4 jets	~3.2%	~2.1%

- **Separate signal from background using multivariate techniques**
  - Boosted Decision Trees
  - Matrix Elements
  - Bayesian Neural Networks

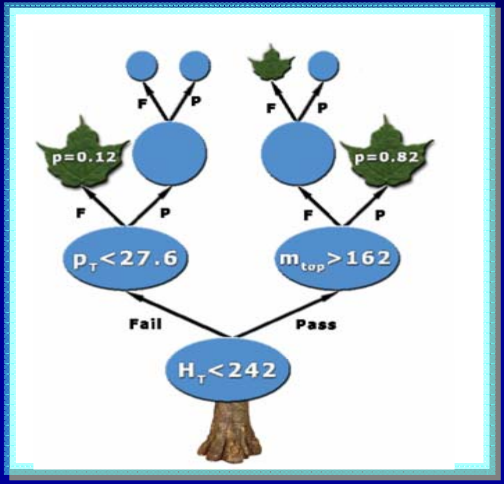


Event Discriminant

- **Check discriminant performance using data control samples**
- **Use discriminant output to measure cross section and significance**

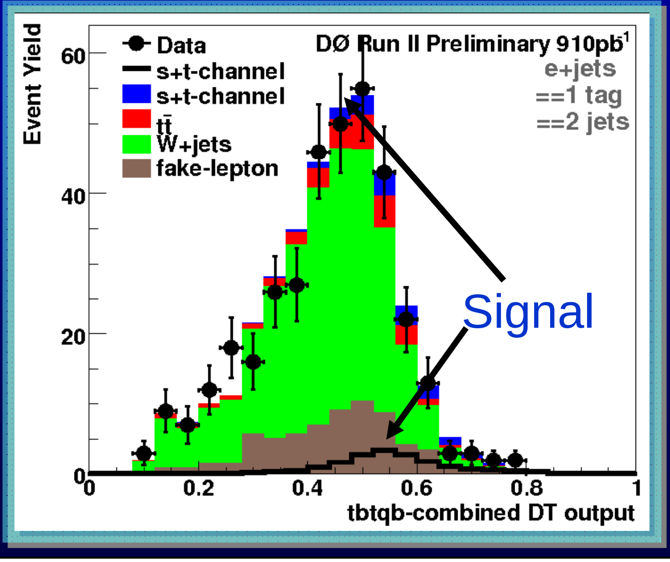
Signal-Background Separation Using Boosted Decision Trees

- **Machine-learning technique, widely used in social sciences, some use in HEP**
  - **Start at first "node" :** For each variable, find splitting value with best separation between two children (mostly signal in one, mostly background in the other)
  - **Select variable and splitting value** with best separation to produce two "branches". Repeat recursively on each node
  - **Stop** when improvement stops or when too few events are left Decision tree output for each event = leaf purity closer to 1(0) for signal (background)



$$Purity = \frac{N_{Signal}}{N_{Signal} + N_{Background}}$$

- **Improve performance of DT by using adaptive boosting , which averages over many trees, diluting the piecewise nature of the DT output**
- **Trained 36 sets of trees:** (*tb+tqb, tb, tqb*) **x (*e*,μ) x (2,3,4 jets) x (1,2 *b*-tags)**
- **Separate analyses for *tb* and *tqb* allow access to different types of new physics**



Signal-Background Separation Using Matrix Elements

Consider 2-jet and 3-jet events

- Use the 4-vectors of all reconstructed leptons and jets
- Use matrix elements of main signal and background Feynman diagrams to compute an event probability density for signal and background hypotheses

differential cross section (LO matrix element)

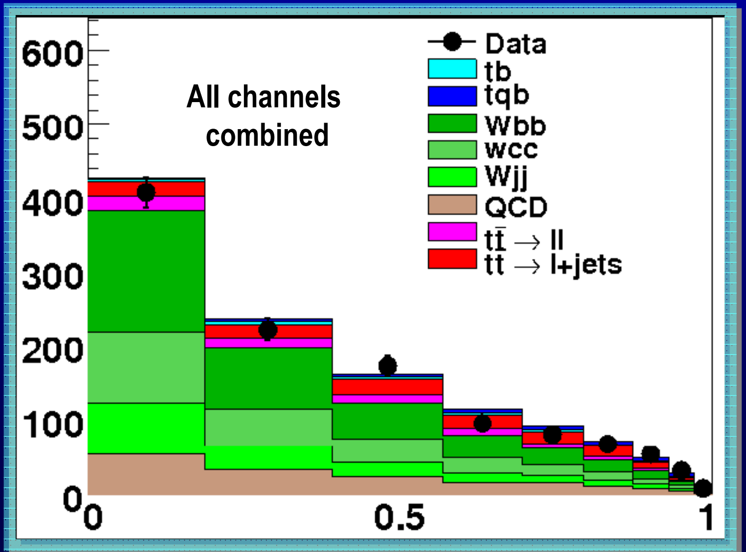
parton distribution functions

transfer function: mapping from parton-level variables (y) to reconstruction-level variables (x)

$$P_i(\vec{x}) = \frac{1}{\sigma} \int \ldots \int \sum_{comb} d^n \sigma_i(\vec{y}) dq_1 dq_2 f(q_1) f(q_2) W(\vec{x} \mid \vec{y})$$

- Calculate a discriminant using above probability:

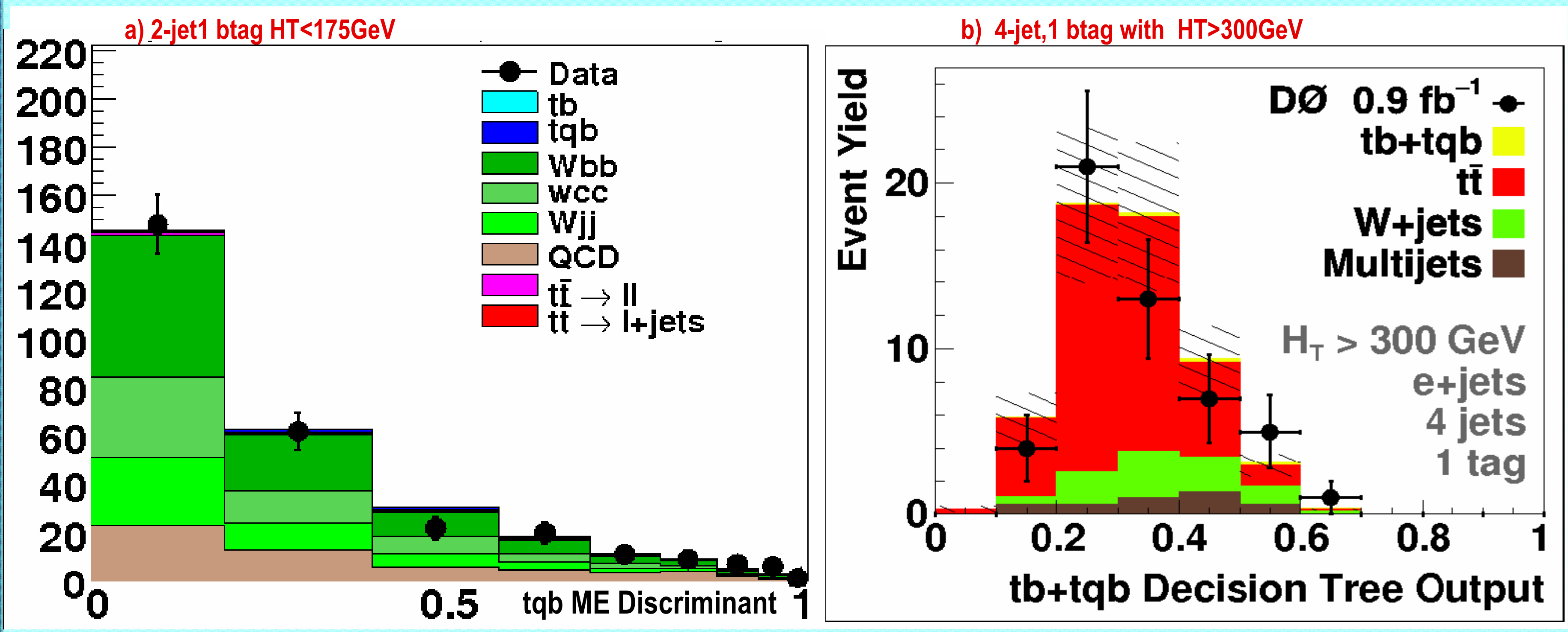
$$D_S(\vec{x}) = \frac{P_S(\vec{x})}{P_S(\vec{x}) + P_{bckg}(\vec{x})}; \qquad S = tb \text{ or } tqb$$



Cross Checks

Validate a background model in side-band regions without looking at single top candidates.

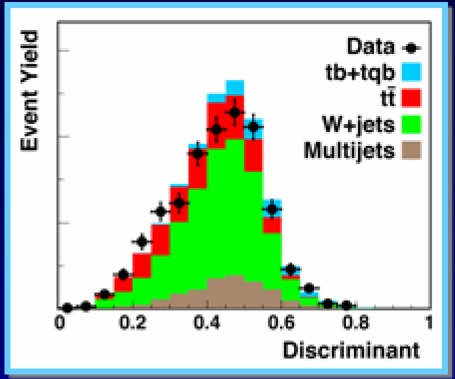
- **a) An enriched W+jets background**
- **b) An enriched top pair background**

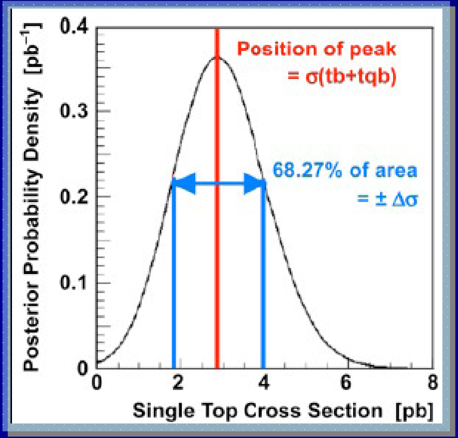


Statistical Analysis

Cross Section Measurement

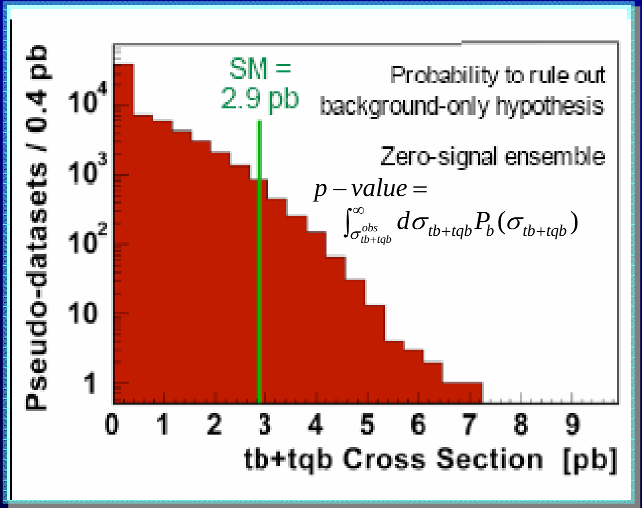
- **Calculate cross sections using binned likelihood fits of (floating) signal + (fixed) background to data**
- **Compute posterior probability density of tb+tqb using Bayes' theorem:**
  - Flat positive-defined prior for the cross section
  - Systematic uncertainties are treated as Gaussian nuisance parameters
- **There are 12 distributions with 100 bins each that go into this calculation**





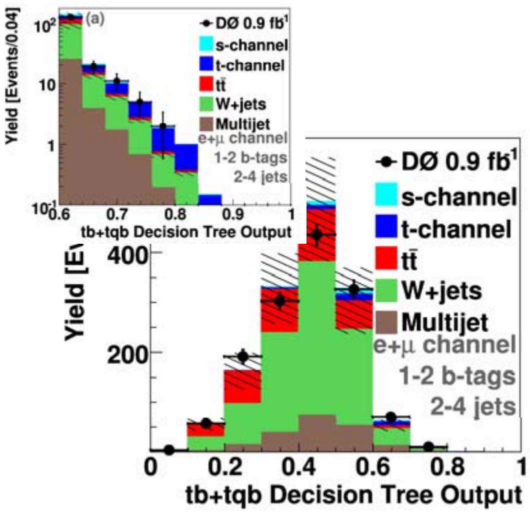
Significance

- Use the ensemble of zero-signal pseudo-datasets to find what fraction give a cross section at least as large as the measured value: the "measured p-value"
- Convert p-value to "measured significance

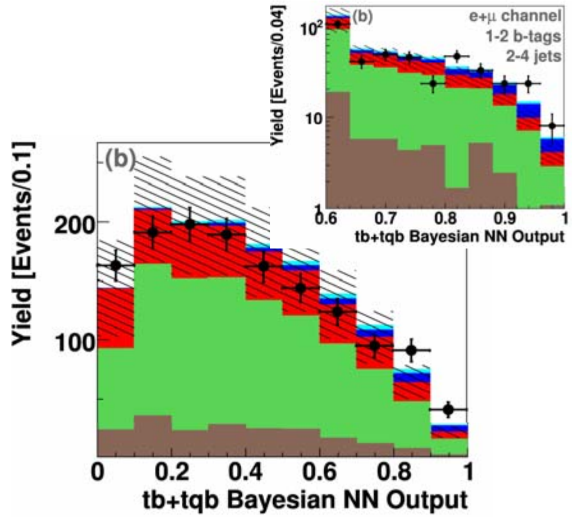


Results

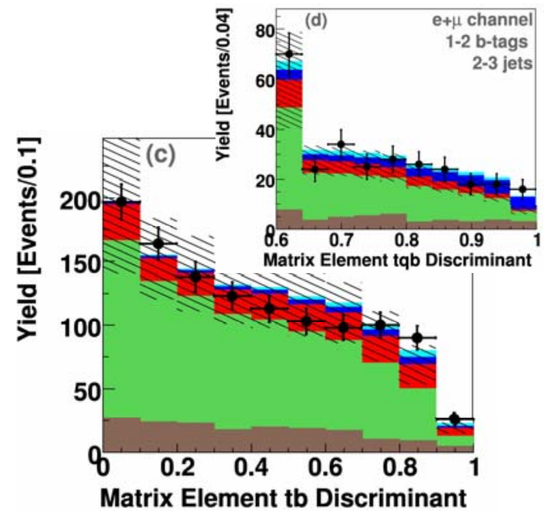
Decision Trees



Bayesian NN



Matrix Element



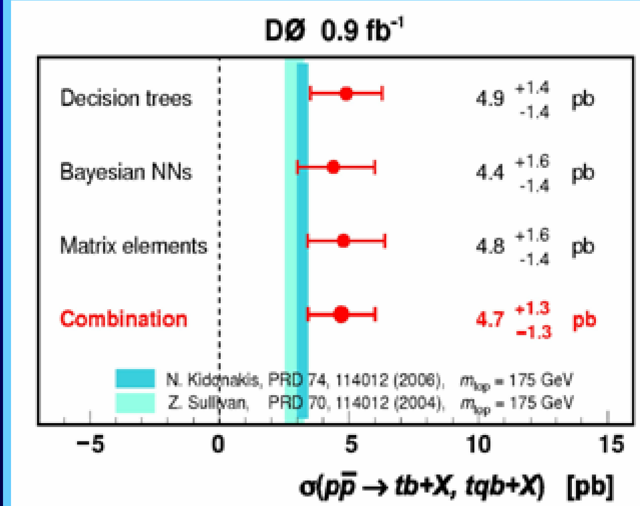
	Decision Trees	Bayesian NN	Matrix Element
Expected p-value:	1.8% (2.1 σ)	1.6% (2.2 σ)	3.1% (1.9 σ)
Observed p-value:	0.037% (3.4 σ)	0.083% (3.1 σ)	0.082% (3.2 σ)

Combination

Three measurements are not 100% correlated
A combination of these measurements gives:

$$\sigma_{tb+tqb} = 4.7 \pm 1.3\ pb \Rightarrow$$ Significance of $3.6\ \sigma$

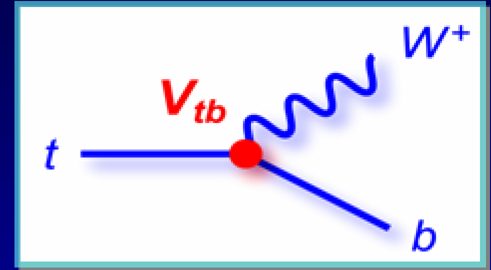
Evidence for single top production!!



Measuring $|V_{tb}|$

General form *Wtb* vertex:

$$\Gamma^{\mu}_{Wtb} = -\frac{g}{\sqrt{2}} V_{tb} \left\{ \gamma^{\mu} \left[f_1^L P_L + f_1^R P_R \right] - \frac{i\sigma^{\mu\nu}}{M_W} (p_t - p_b)_{\nu} \left[f_2^L P_L + f_2^R P_R \right] \right\}$$



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

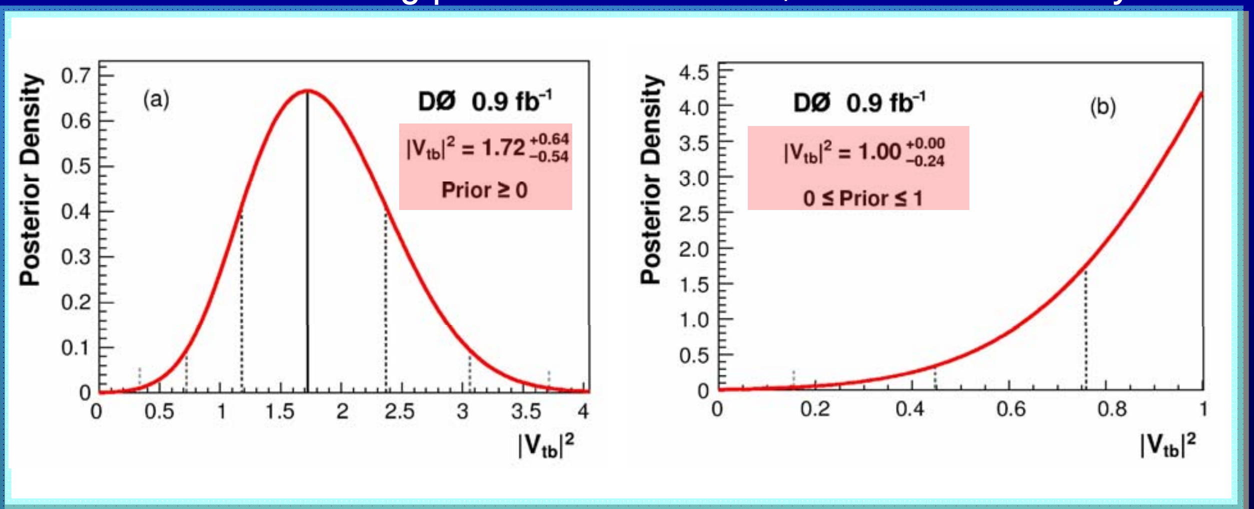
Within the SM:

- 3-generation and unitary CKM matrix $V_{tb} \sim 1$
- CP conserving pure V–A interaction:

$$f_1^L = 1,\ f_1^R = f_2^L = f_2^R = 0$$

Measure V_{tb} assuming:

- No constraint on number of generation and unitarity of CKM matrix
- CP conserving pure V-A interaction, but not necessarily of SM strength



Strength of $V-A$ interaction

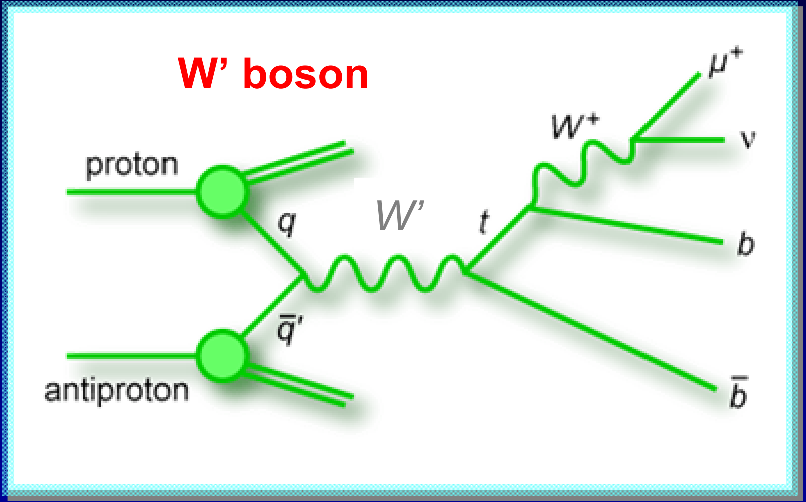
$$|V_{tb} f_1^L| = 1.3 \pm 0.2$$

assuming $f_1^L = 1$:

$$0.68 \leq |V_{tb}| \leq 1 \ @\ 95\%\ CL$$

Search for W' Boson

- **Heavy gauge bosons (W', Z') are predicted by many extensions to the SM**
- **The single top quark decay channel is a promising searching ground for a W' that interacts hadronically**
  - Relatively small QCD background in comparison to light jet channels
- Only s-channel is interesting (resonance)
  - W' contribution to the other channels is too small



$$L = \frac{V_{ij}}{2\sqrt{2}} g_W \overline{f}_i \gamma^\mu \left[a_{ij}^R (1+\gamma^5) + a_{ij}^L (1-\gamma^5) \right] W' f_j + h.c.$$

Left and right couplings of W' boson to quarks

W' Analysis Strategy

- Two cases:
  - Purely left-handed W'
  - Purely right-handed W'

- **L-handed W' bosons that interfere with the SM W->tb process**
  Interference contribution is important and should be taken into account in simulation (Phys. Lett. B 655, 245, 2007) May reduce the total rate by as much as (16-33)% (depends on W' mass and its couplings)

- **R-handed W' bosons that do not have the SM interference**

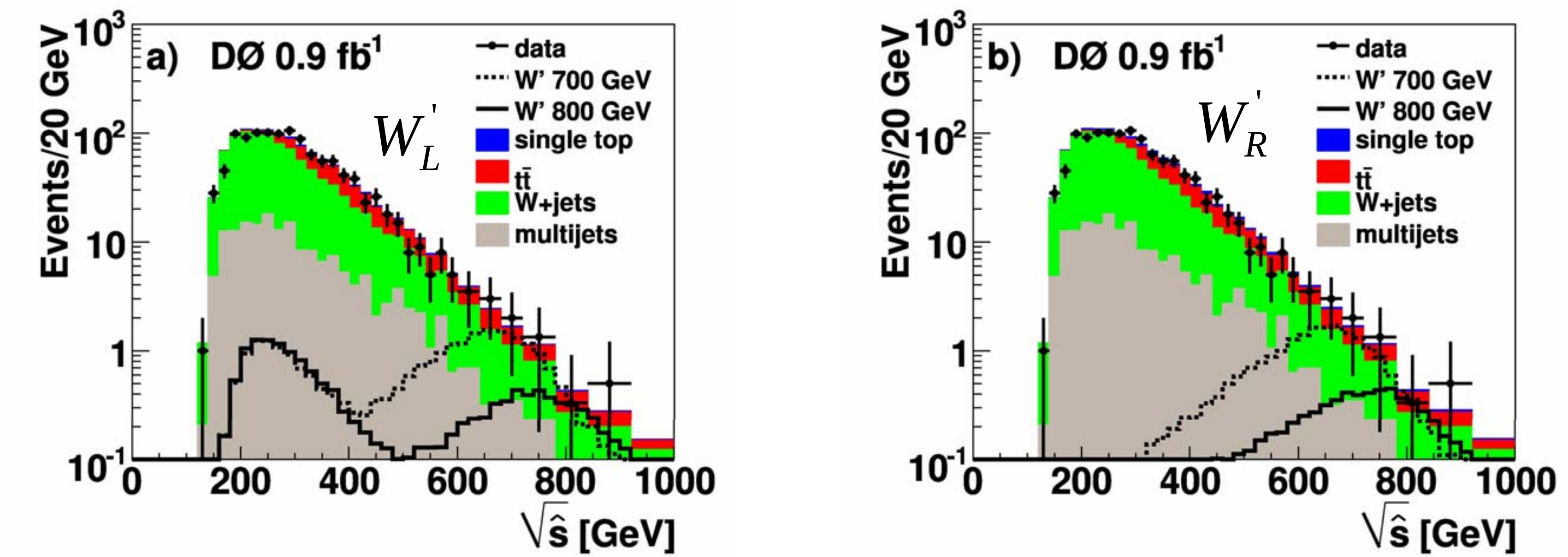
  Case a) $M_{\nu R} < M_{W'}$
  - Leptonic decay channels are open (l,q)
  - Same cross-section as W'_L with no interference

  Case b) $M_{\nu R} > M_{W'}$
  - Only decays to quarks are allowed (qq)
  - W'_R cross section x B(W'->tb) larger than that of Case (a)

W' Signal Modeling and Selection

- **W' MC generated using CompHEP and includes the W/W' interference for the left-handed samples**
  - Samples: generated with masses:
    600, 650, 700, 750, 800, 850, 900 GeV
- **Selection is Similar to single top analysis**
  - Consider the SM single top quark production as background
  - t-channel is background for L-handed sample with W'/W interference
  - Both s-and t-channel are background for W'_R

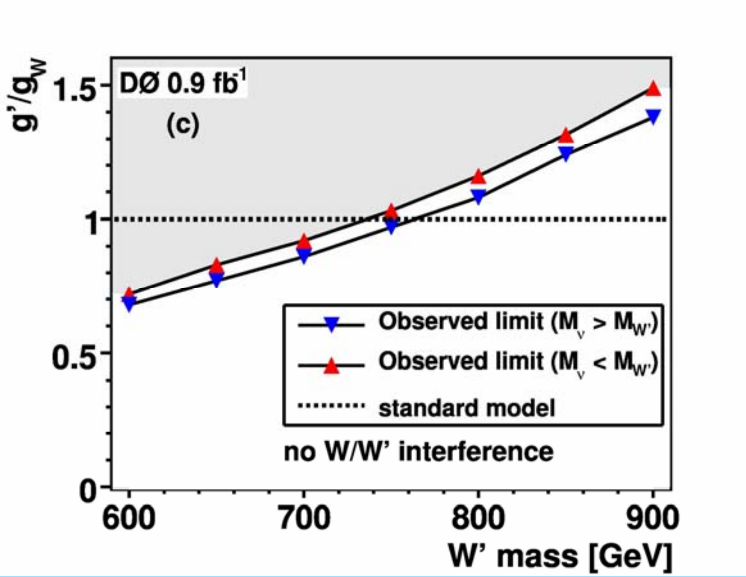
Perform binned likelihood analysis using the distribution $\sqrt{\hat{s}}$

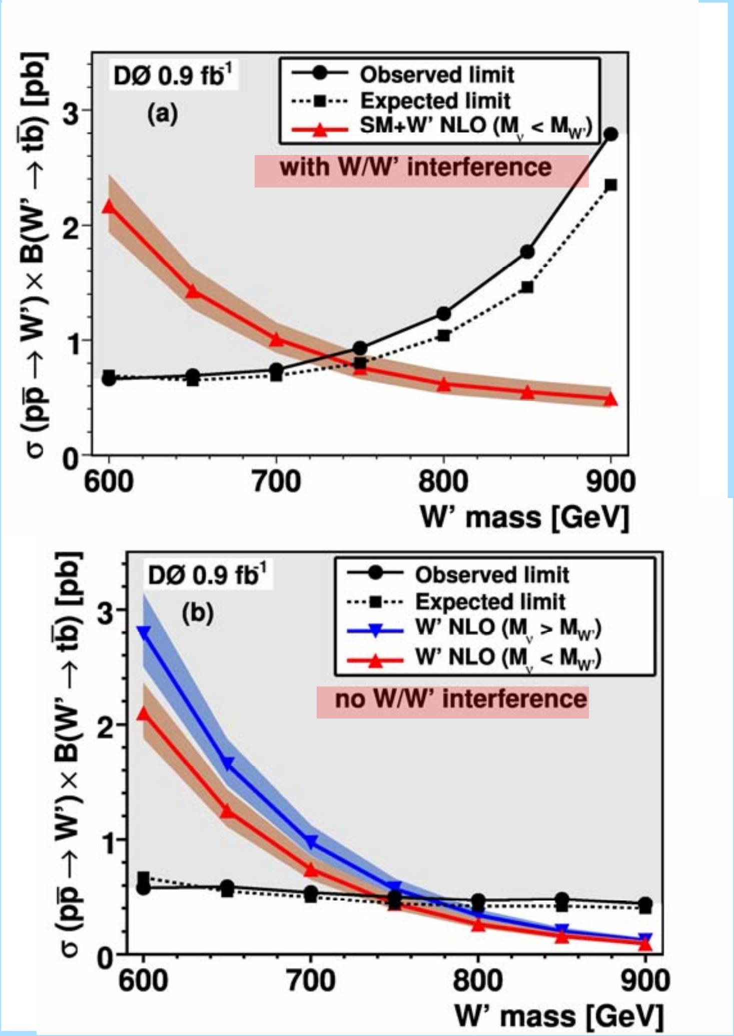


Results

- 95% C.L. confidence limits are set for the L, R W' boson mass and couplings
- Only use the part of the distribution where $\sqrt{\hat{S}}$ > 400 GeV
- Include all systematic uncertainties used for the single-top-analyses
  - W_L'mass > 731 GeV
  - W_R'mass(l,q) > 739 GeV
  - W_R'mass (qq) > 768 GeV

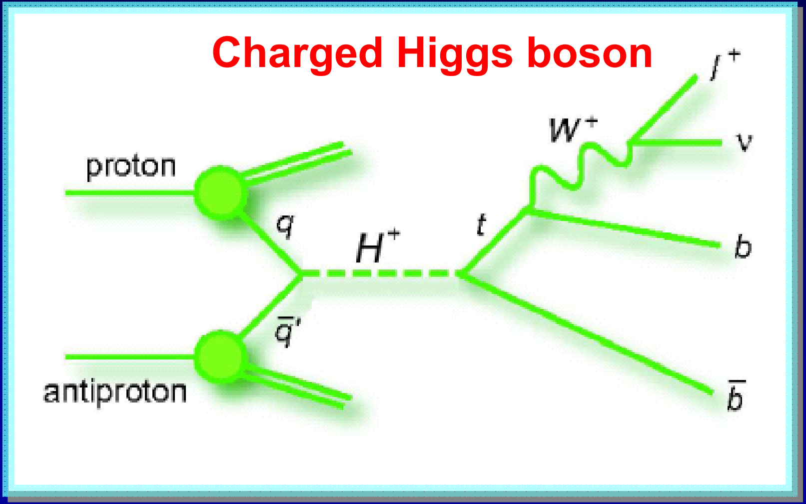
Exclude gauge couplings above 0.68 at Mw'= 600GeV





Single Top to Charged Higgs

- **No "charged" Higgs boson in the standard model**
- **Extension of SM Higgs**
  – Two-Higgs Doublet Model (2HDM) leads to five physical Higgs bosons: two neutral scalars h0 and H0, one neutral pseudoscalar A0 and two charged scalars H^+, H^-



- **2HDMs differentiated by strategies used to avoid FCNC**
  - **Type-I:** One doublet gives mass to all quarks and leptons
  - **Type-II:** One doublet gives mass to up-type quarks and neutrinos; Other doublet gives mass to down-type quarks and charged leptons (e.g. MSSM)
  - **Type-III:** Two doublets contribute to mass of quarks and leptons, ξ is the top-charm mixing parameter [H.-J. He and C.-P. Yuan, PRL 83 (1999) 28]
- Cross sections can be sizable: $\sigma \times \beta$ ~ 10 pb (Type-I), ~ 0.5 pb (Type-II) with $\tan\beta = 100$, ~ 0.1 pb (Type-III) with $\xi = 5$
  – Cross section decreases with mH^+ due to the limited amount of energy in the CM

Charged Higgs: Signal Modeling

- **Use CompHEP to simulate** $p\bar{p} \to H^{+} \to t\bar{b}$

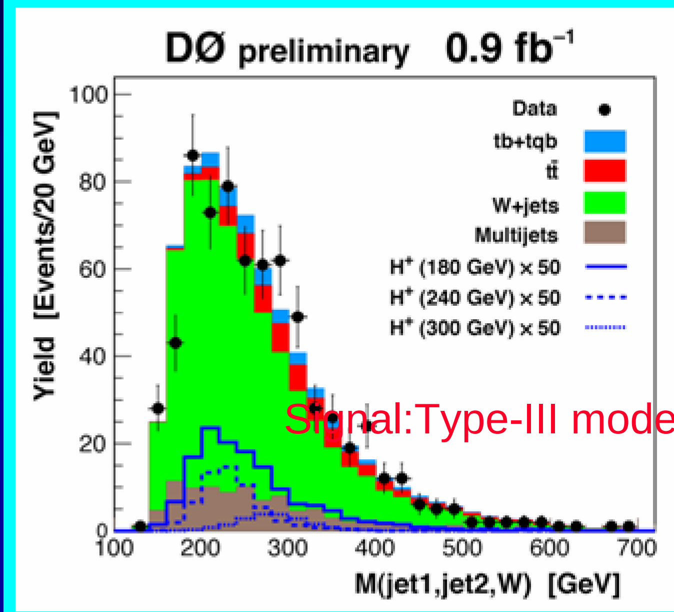
$$\mathcal{L} = \frac{g_w}{2\sqrt{2}} V_{ij} H^{+} \bar{q}_i \left[g_L^{ij} \left(1-\gamma^5\right) + g_R^{ij} \left(1+\gamma^5\right)\right] q_j$$

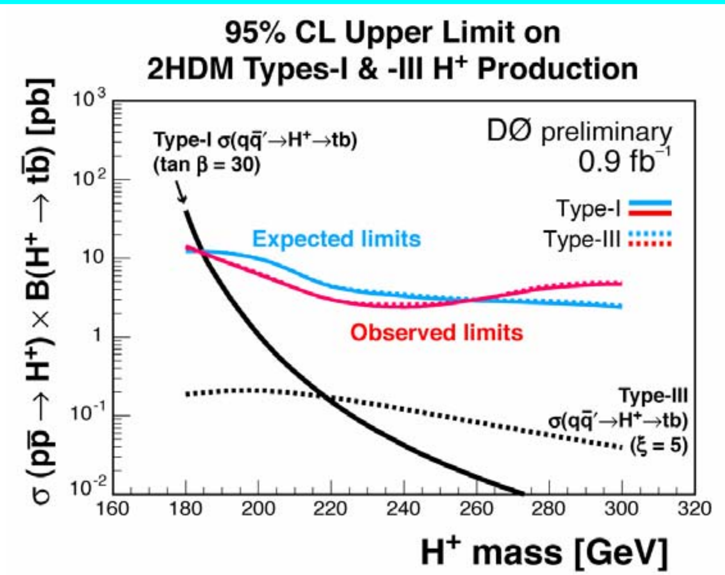
  - **To be as model independent as possible, produced left-handed samples with** $g_L^{ij} = 1, g_R^{ij} = 0$ **and right-handed samples with** $g_L^{ij} = 0, g_R^{ij} = 1$**,** combine them in different proportions to simulate a desired 2HDM with a predetermined polarization
    - **Type-I:** proportion is equal (1:1) for all tanβ
    - **Type-II:** proportion varies with tanβ
      - For tanβ > 10, right-handed coupling dominates
      - For tanβ < 0.1, left-handed coupling dominates
      - For 0.1 < tanβ < 10, the fractions are in transition:

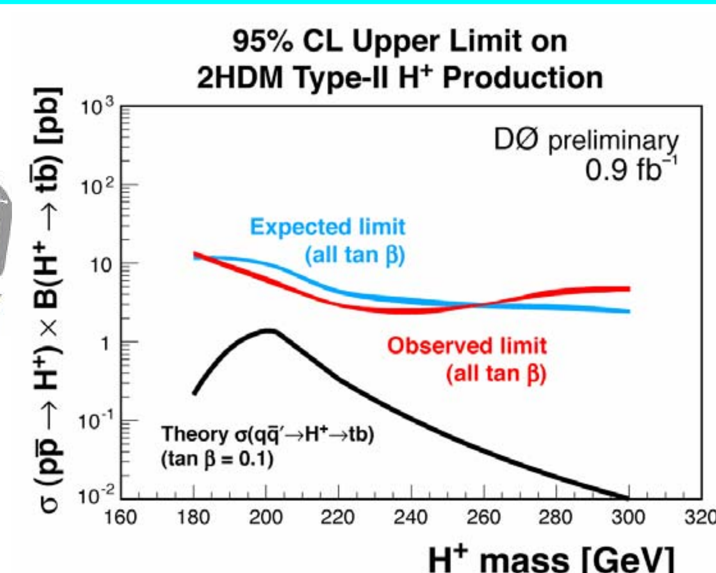
        special case is 1:1 when tanβ= 1
    - **Type-III:** right-handed coupling dominates, the fraction of left-handed sample < 10 -5 for all ξ
- **Mixture of left- and right-handed samples does not take into account interference term ~** $g_L g_R$ *:* Analysis not sensitive to small change in kinematics
- Produced samples for mH+ = 180, 200, 220, 240, 260, 280, 300 GeV

Charged Higgs: Results

- $H^+ \to t\bar{b}$ **reconstructed invariant mass showed to be the most sensitive variable and is used to construct binned likelihood function**
- **Input all 4 channels separately:**
  - Electron, Muon; two jets; One and Two Tags
- Include all systematic uncertainties used for the single top analyses:
  - Systematic uncertainties for the backgrounds
  - JES/TRF uncertainties evaluated using signal MC





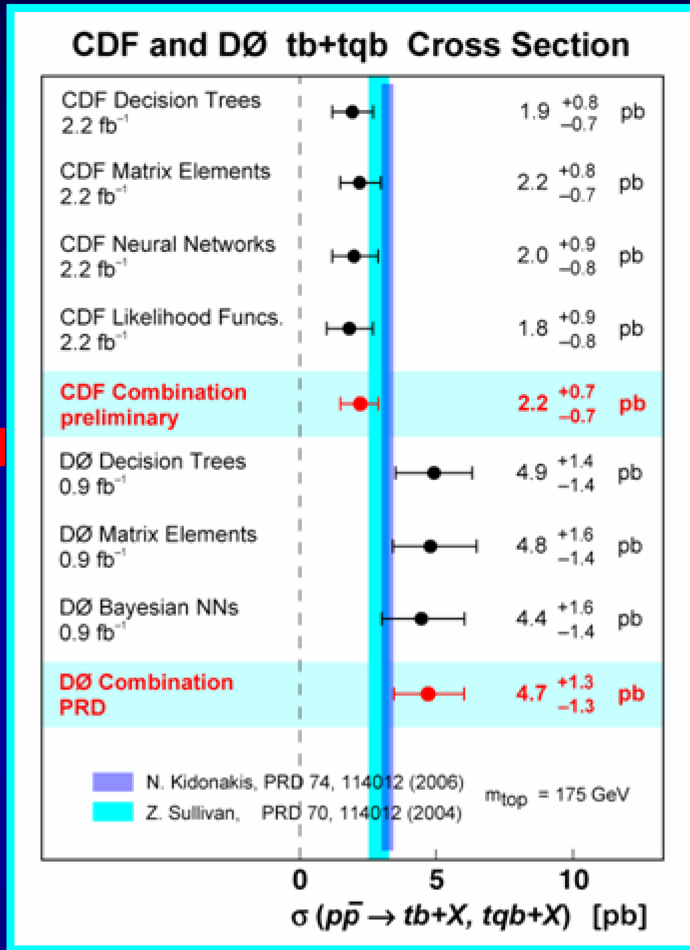


Conclusion / Outlook

- **First Evidence for Single Top Production**
- **First direct measurement of $|V_{tb}|$**

  $0.68 < |V_{tb}| \leq 1$ at 95% C.L.

- **First search for charged Higgs decaying to *tb* final state**
  - Complementary to other charged Higgs searches
  - Exclusion region of parameter space for 2HDM Type-I
- **Search for W' decaying to *tb* final state**
  - limits on left and right W' masses and couplings
- **We are working on (along with 5σ discovery) making this list a little bit longer and plan to repeat these measurements with more data**



....single top search is a gold mine
and we are digging deeper than ever ...

Decision Tree Variables

Object Kinematics

- p_T(jet1)
- p_T(jet2)
- p_T(jet3)
- p_T(jet4)
- p_T(best1)
- p_T(notbest1)
- p_T(notbest2)
- p_T(tag1)
- p_T(untag1)
- p_T(untag2)

Angular Correlations

- ΔR(jet1,jet2)
- $\cos(\text{best1,lepton})_{\text{besttop}}$
- $\cos(\text{best1,notbest1})_{\text{besttop}}$
- $\cos(\text{tag1,alljets})_{\text{alljets}}$
- $\cos(\text{tag1,lepton})_{\text{btaggedtop}}$
- $\cos(\text{jet1,alljets})_{\text{alljets}}$
- $\cos(\text{jet1,lepton})_{\text{btaggedtop}}$
- $\cos(\text{jet2,alljets})_{\text{alljets}}$
- $\cos(\text{jet2,lepton})_{\text{btaggedtop}}$
- $\cos(\text{lepton},Q(\text{lepton})\times z)_{\text{besttop}}$
- $\cos(\text{lepton,besttopframe})_{\text{besttopC}}$
- $\cos(\text{lepton,btaggedtopframe})_{\text{btagg}}$
- $\cos(\text{notbest,alljets})_{\text{alljets}}$
- $\cos(\text{notbest,lepton})_{\text{besttop}}$
- $\cos(\text{untag1,alljets})_{\text{alljets}}$
- $\cos(\text{untag1,lepton})_{\text{btaggedtop}}$

Event Kinematics

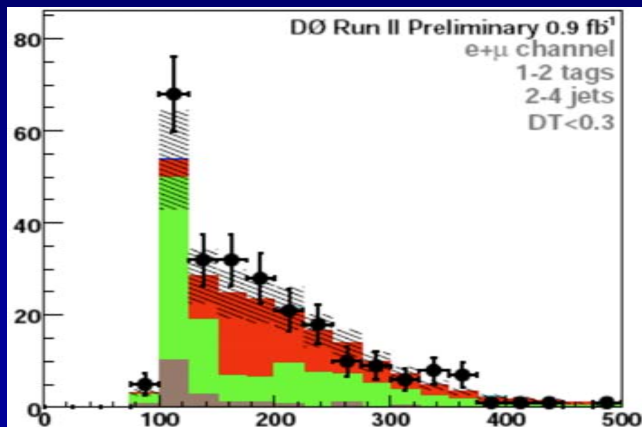
- Aplanarity(alljets, W)
- $M(W$,best1) ("best" top mass)
- $M(W$,tag1) ("b-tagged" top mass)
- H_T(alljets)
- H_T(alljets−best1)
- H_T(alljets−tag1)
- H_T(alljets, W)
- H_T(jet1,jet2)
- H_T(jet1,jet2, W)
- M(alljets)
- M(alljets−best1)
- M(alljets−tag1)
- M(jet1,jet2)
- M(jet1,jet2, W)
- M_T(jet1,jet2)
- $M_T(W)$
- Missing E_T
- p_T(alljets−best1)
- p_T(alljets−tag1)
- p_T(jet1,jet2)
- Q(lepton)$\times\eta$(untag1)
- $\sqrt{\hat{s}}$
- Sphericity(alljets, W)

- **Same list of variables used for all analysis channels**
- **Adding more variables does not degrade the performance**
- **Reducing the number of variables always reduces sensitivity of the analysis**

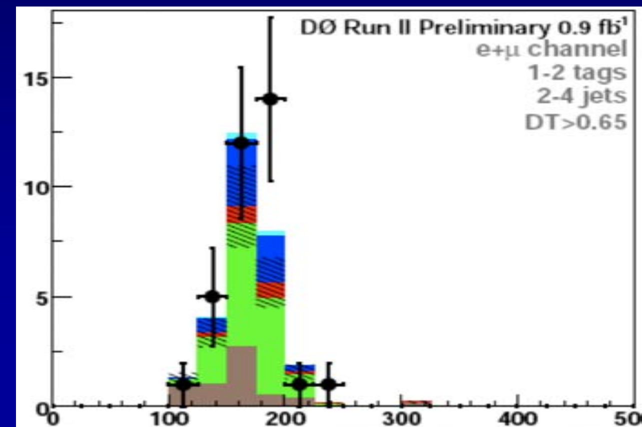
DT Event Characteristics

DT Discriminant < 0.3

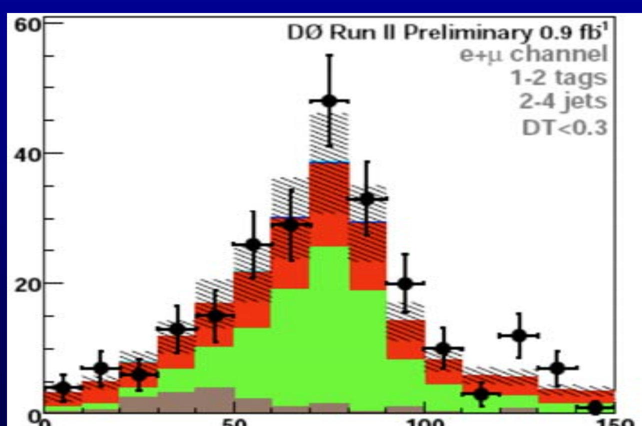
DT Discriminant > 0.65



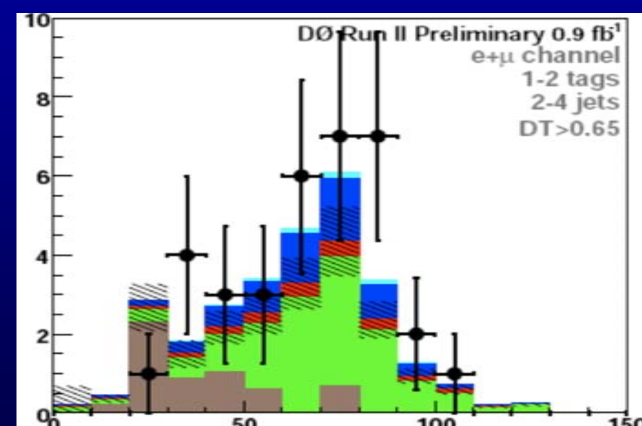
Mass (lepton,E_T,btagged-jet) [GeV]



Mass (lepton,$\not{E}_T$,btagged-jet) [GeV]



W Transverse Mass [GeV]



W Transverse Mass [GeV]