Search for single top production at CDF

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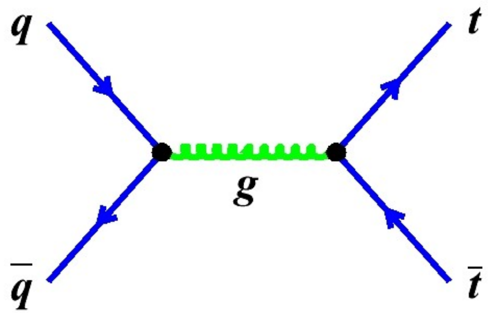
Single top quark production

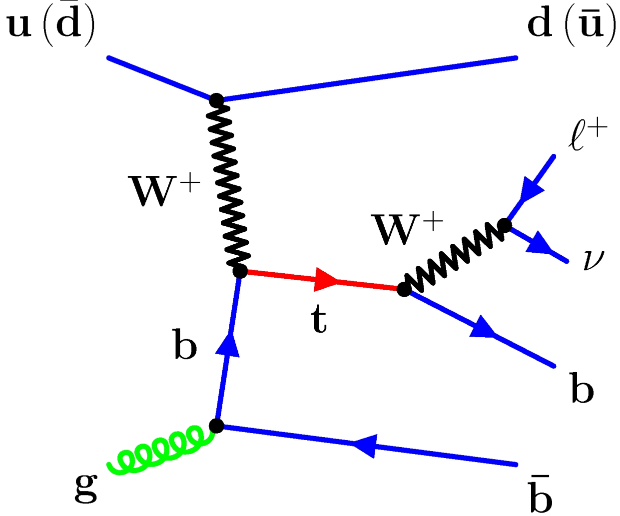
At the Tevatron, top quarks are primarily produced in pairs via the strong interaction



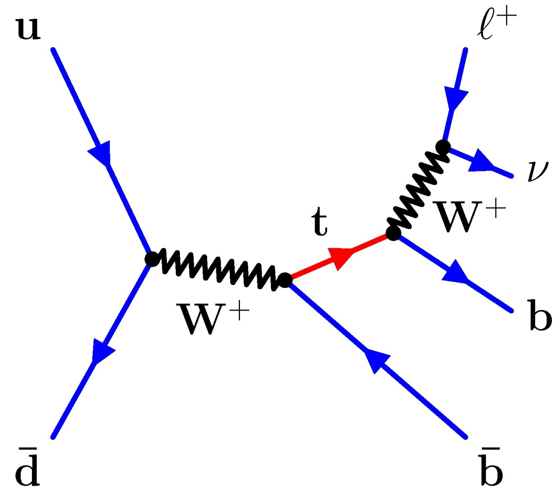
$\sigma_{tt} = 6.7 \pm 0.8$ pb

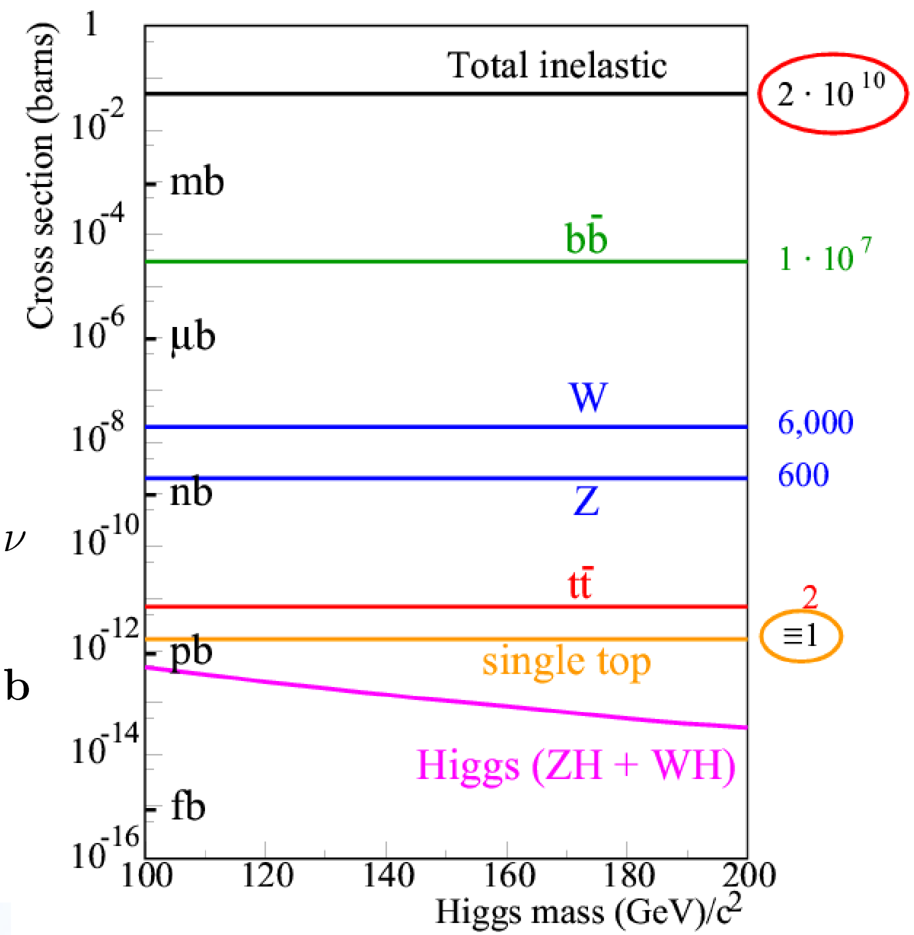
top quark production via the weak interaction

t-channel



s-channel





$\sigma_s = 0.88 \pm 0.11$ pb $\sigma_t = 1.98 \pm 0.25$ pb

B.W. Harris et al. Phys. Rev. D 66, 054024 (2002), Z. Sullivan, Phys. Rev. D 70, 114012 (2004)
compatible results: Campbell/Ellis/Tramontano, Phys. Rev. D 70, 094012 (2004)
N. Kidonakis, Phys.Rev. D 74, 114012 (2006)

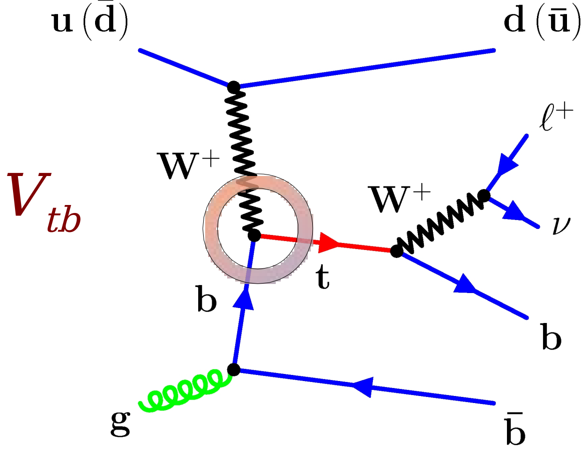
Why measure single top ?

- Source of single ~100% polarized top quarks:
  - Test V-A structure of W-t-b vertex
  - Access to the top quark spin

- Test of the SM prediction. Does it exist?
  - Cross section $\sim |V_{tb}|^2$
    ➔ allows direct measurment of V_{tb}
  - Test unitarity of the CKM matrix, .e.g. Hints for existence of a 4th generation ?

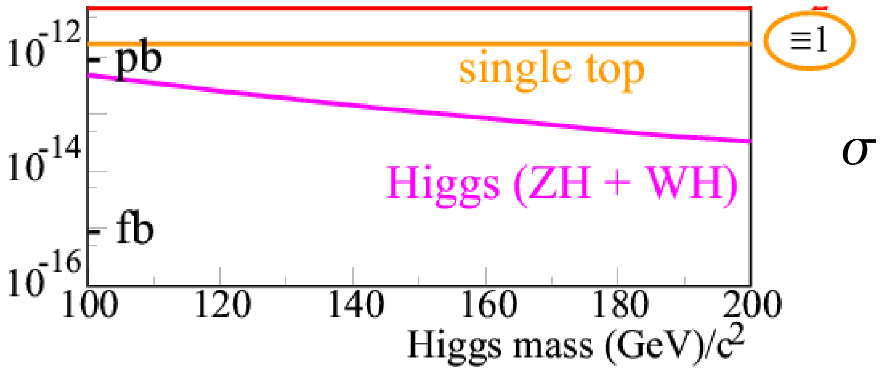
$$V_{ub}^2 + V_{cb}^2 + V_{tb}^2 \overset{?}{=} 1$$

  - Test of *b* quark structure function: DGLAP evolution

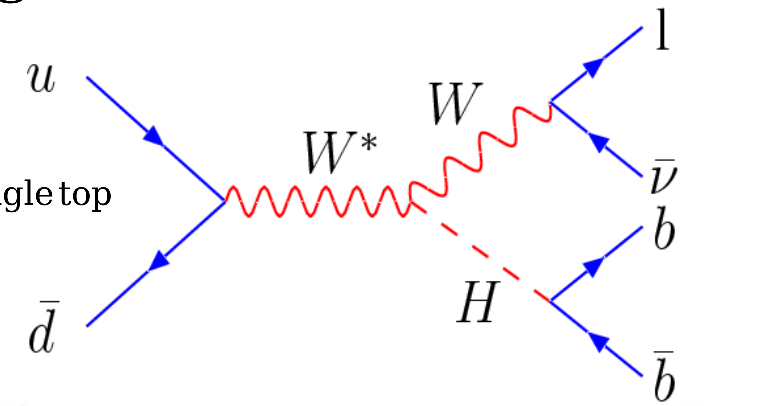


Sensitivity to new physics

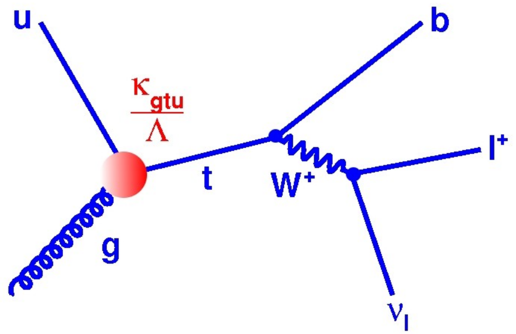
- Same final state signature as Higgs: WH, H → bbbar. Understanding single-top backgrounds is a prerequisite for Higgs searches at the Tevatron. Same tools can be applied for Higgs searches.

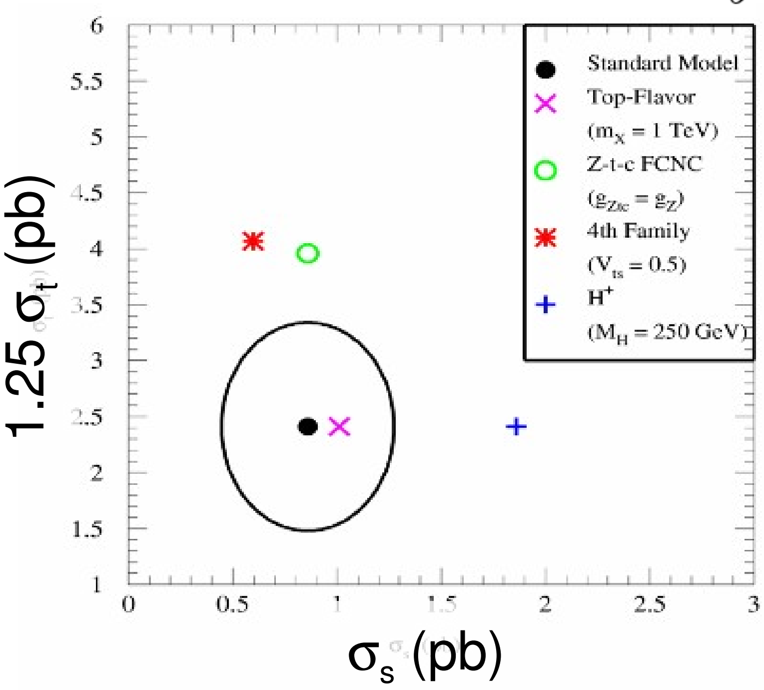


$$\sigma_{WH} \sim \frac{1}{10}\sigma_{\text{single top}}$$



- Test non-SM phenomena
  - Search W' or H^+ (s-channel signature)
  - Search for FCNC, e.g. ug → t
  - ...

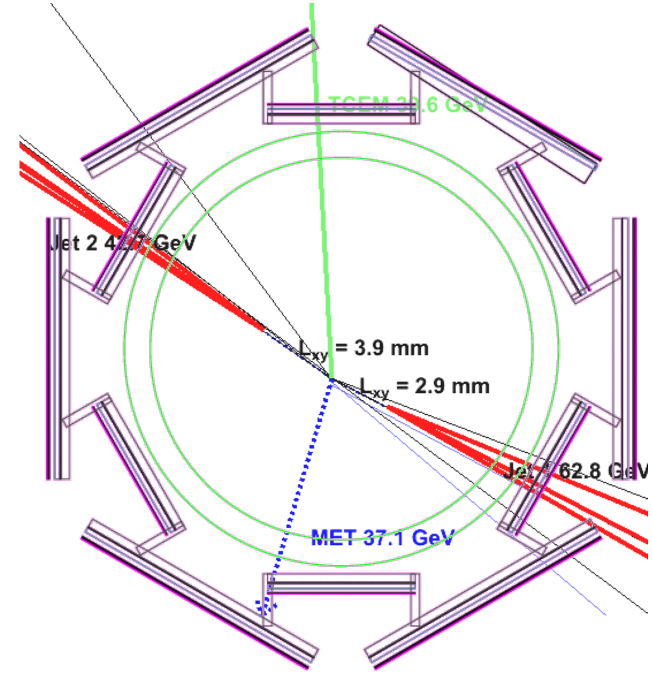




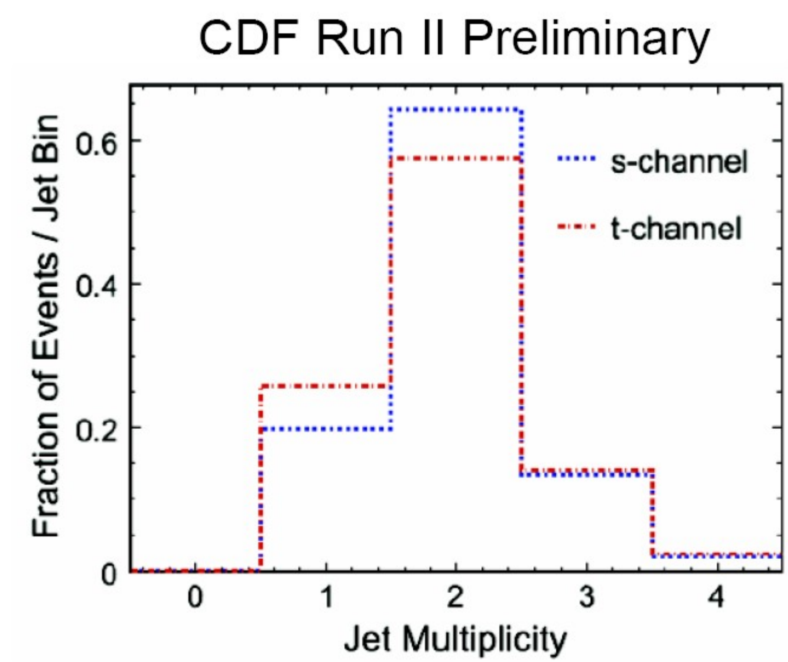
Event signature and selection

Event Selection:

- **1 Lepton,** E_T >15 GeV, |η|< 2.0
- **Missing E_T** (MET) > 25 GeV
- **2 Jets,** E_T > 15 GeV, |η|< 2.8
- **Veto** QCD, Conversions, Cosmics, Z-Veto
  - → Δϕ(Et of leading jet and MET) vs. MET
- **At least one b-tagged jet**, (secondary vertex tag)

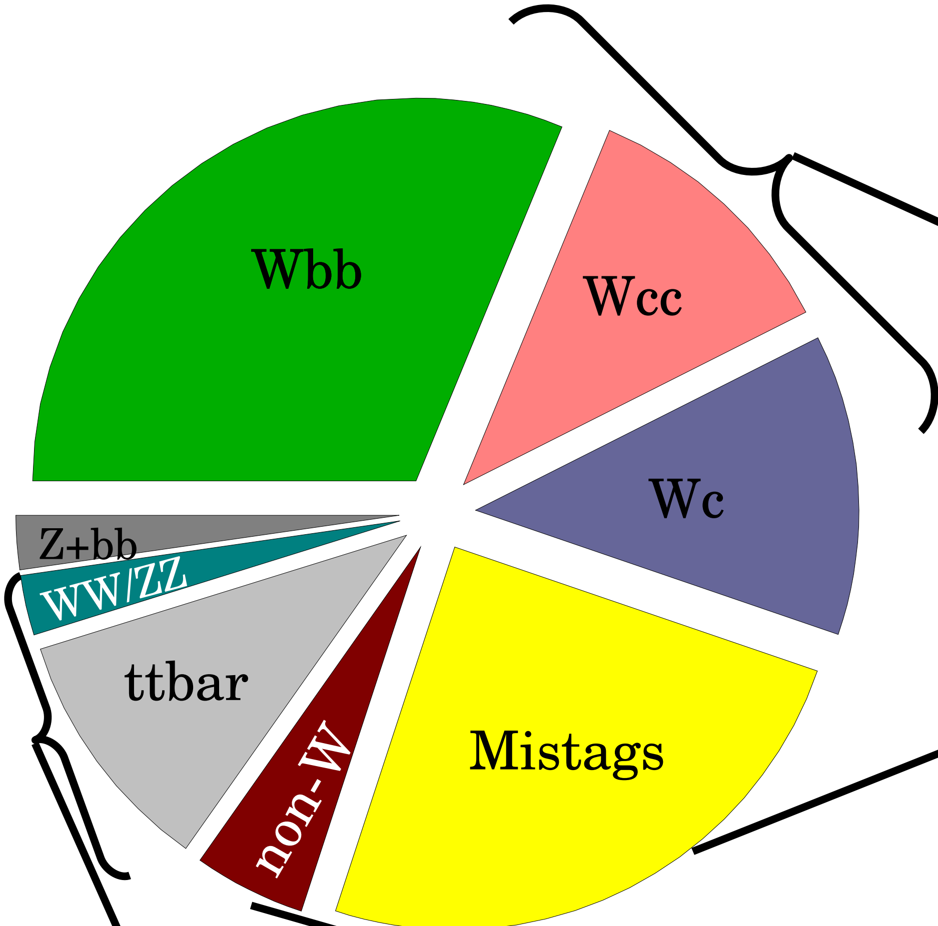


Number of events / 955 pb^{-1}	Single Top	Bkg	S/B
W(lν) + 2 jets	74	15500	~1/210
W(lν) + 2 jets + b-tag	38	540	~1/15



2 Jet bin

Background composition



W+HF jets (Wbb/Wcc/Wc)

W+jets normalization from data and heavy flavor (HF) fractions from ALPGEN Monte Carlo, calibrated in generic multijet data

Mistags (W+2jets)

- Falsely tagged light quark or gluon jets
- Mistag probability parameterization obtained from inclusive jet data

Non-*W (QCD)*

- Multijet events with semileptonic *b*-decays or mismeasured jets
- Fit low missing E_T data and extrapolate into signal region

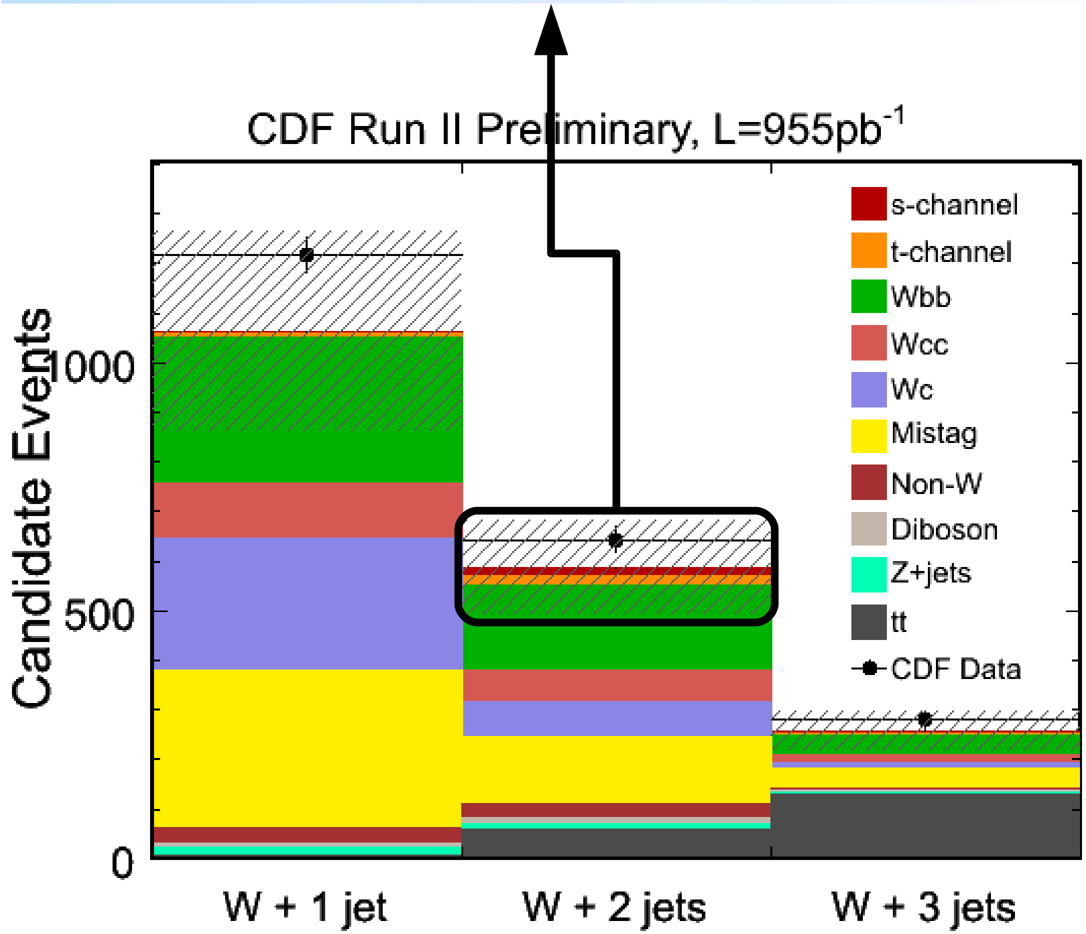
Top/EWK (WW/WZ/Z→bb, ttbar)

- MC normalized to theoretical cross-section

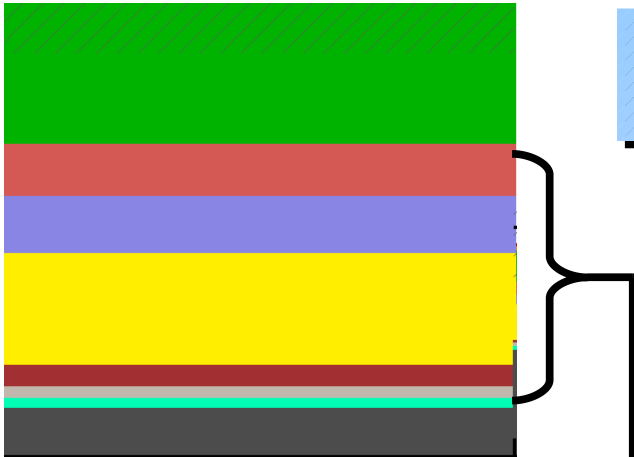
Event Yield

***s*-channel**	**15.4 ± 2.2**
***t*-channel**	**22.4 ± 3.6**
tt	**58.4 ±13.5**
Diboson	**13.7 ± 1.9**
***Z* + jets**	**11.9 ± 4.4**
Wbb	**170.9 ± 50.7**
Wcc	**63.5 ± 19.9**
Wc	**68.6 ± 19.0**
Non-*W*	**26.2 ± 15.9**
Mistags	**136.1 ± 19.7**
Single top	**37.8 ± 5.9**
Total background	**549.3 ± 95.2**
Total prediction	**587.1 ± 96.6**
Observed	**644**

Single top hidden behind background uncertainty!
➔ Makes counting experiment impossible!



Improved b jet identification



About 50% of the background in the W + 2 jets sample do **NOT** contain **b quarks** even though a secondary vertex was required!

Jet and track variables, e.g. vertex mass, decay length, track multiplicity, …

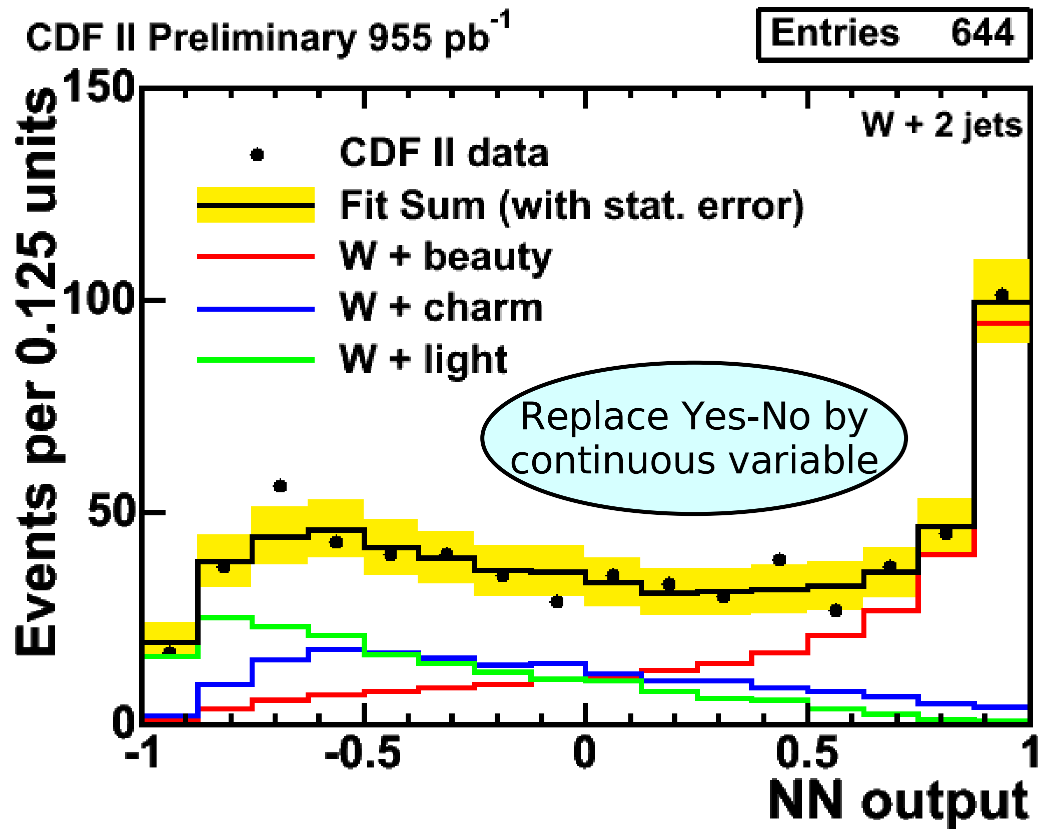
⊕

neural network

↓

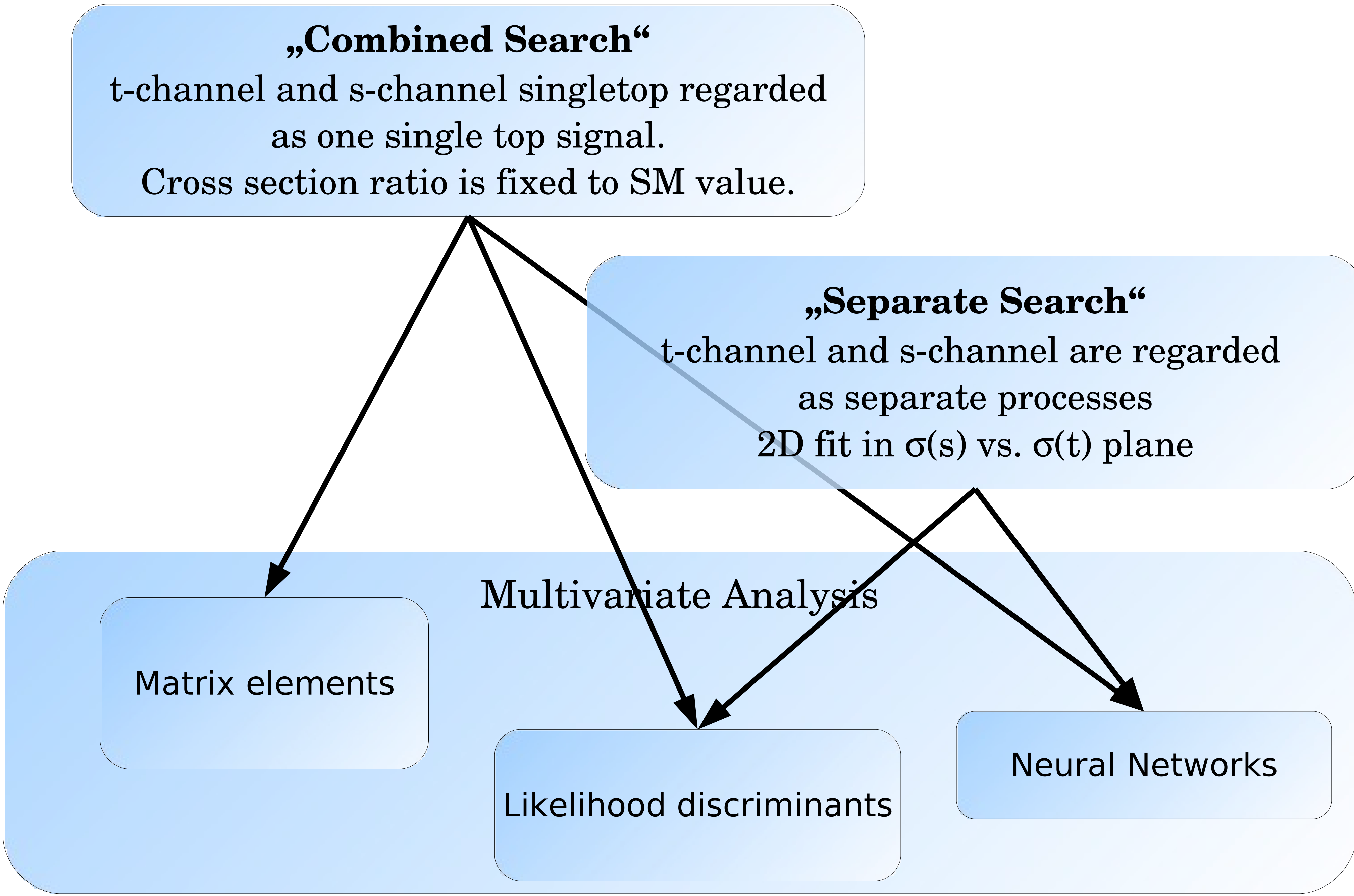
powerful discriminant

Fit to NN output for W + 2 jets events with one secondary vertex (955 pb^{-1})



mistags / charm **beauty**

Search strategy



Matrix Element Analysis

Idea: Compute an event probability P for signal and background hypotheses:

Leading Order matrix element (MadEvent)

$W_j(E_j,E_p)$ is the probability of measuring a jet energy E_j if E_p was produced.

$$P(p^\mu_\ell, p^\mu_{\mathrm{j1}}, p^\mu_{\mathrm{j2}}) = \frac{1}{\sigma}\int dE_{\mathrm{j1}}dE_{\mathrm{j2}}dp^z_\nu \sum_{\mathrm{comb}} |M(p^\mu_i)|^2 \frac{f(q_1)f(q_2)}{|q_1|\cdot|q_2|}\phi_4 W_j(E_j,E_p)$$

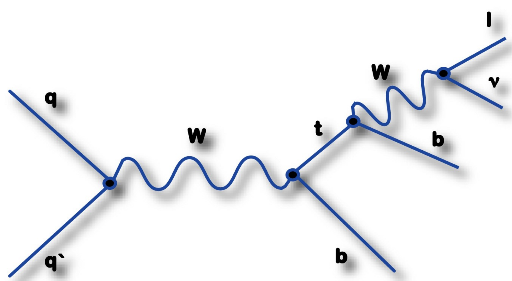
input: lepton and 2 jets 4-vectors!

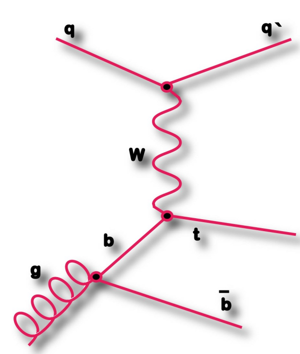
integration over part of the phase space Φ_4

parton distribution functions (CTEQ5)

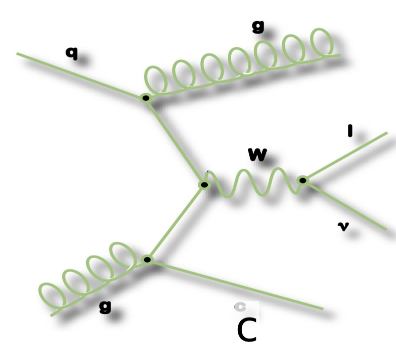
Computation of P for signal and background processes:

single-top: s-channel and t-channel

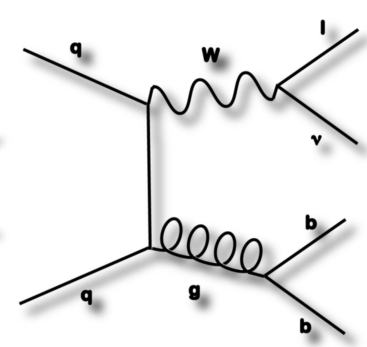




Wcj



Wbb and Wcc



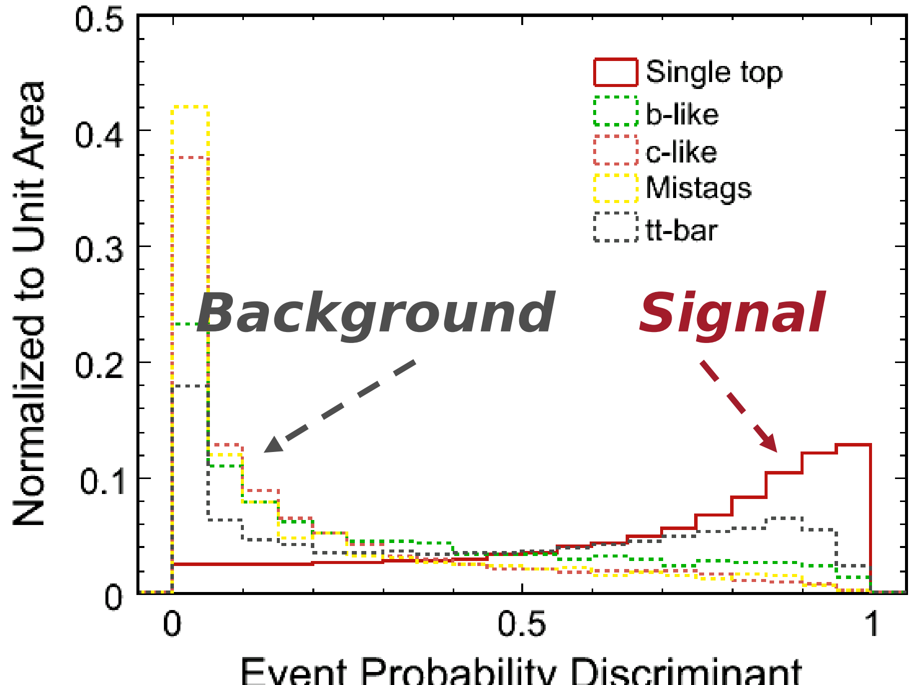
Matrix Element Discriminant

Combination of all matrix element probabilities to one discriminant:

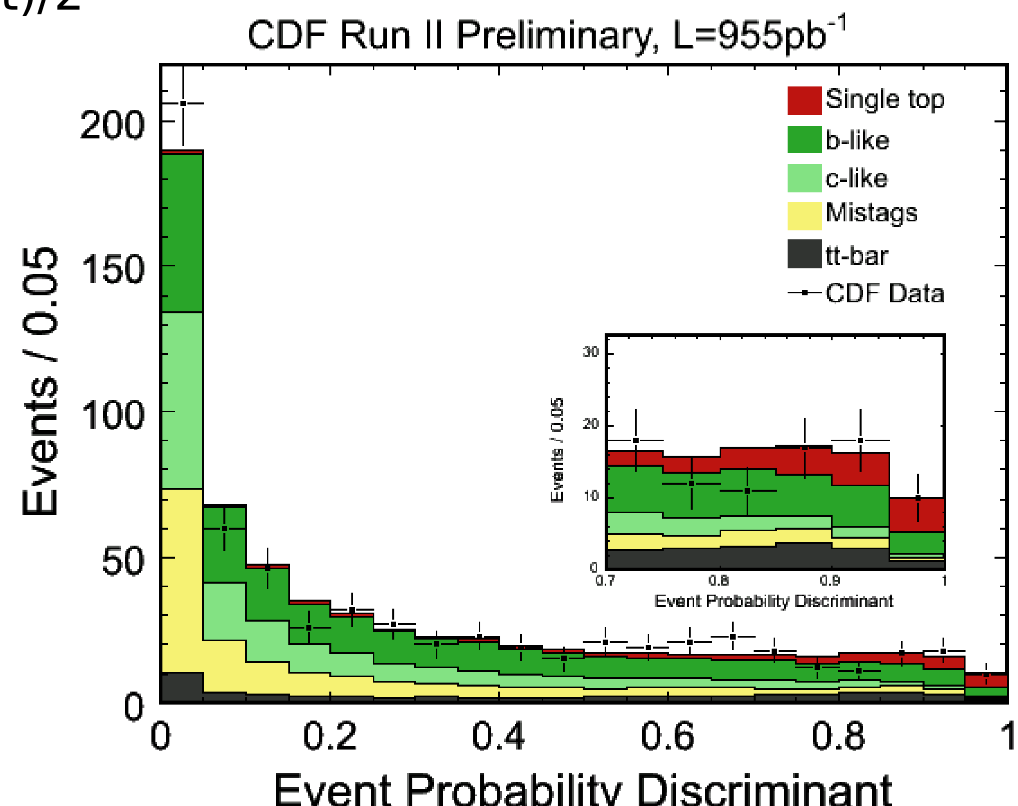
$$\text{EPD} = \frac{b \cdot (\alpha P_{\text{tch}} + \beta P_{\text{sch}})}{b \cdot (\alpha P_{\text{tch}} + \beta P_{\text{sch}} + \gamma P_{Wbb}) + (1-b)(\delta P_{Wcc} + \epsilon P_{Wcj})}$$

b = (1 + neural network b tagger output)/2

α, β, γ, δ, ε = normalisation coefficients



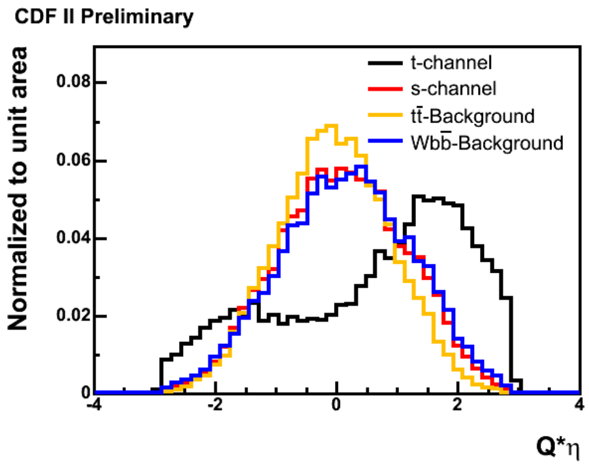
a priori sensitivity: 2.5 σ

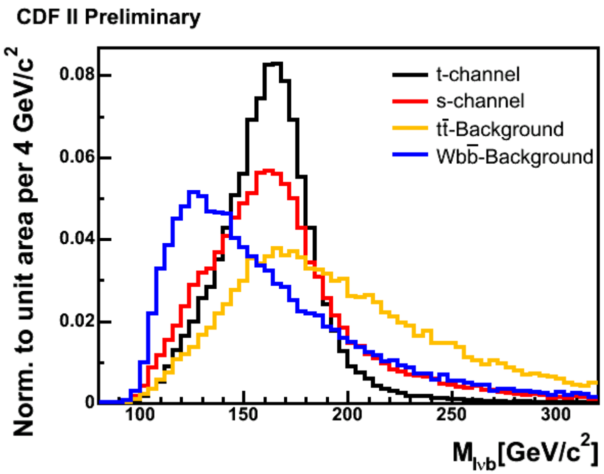


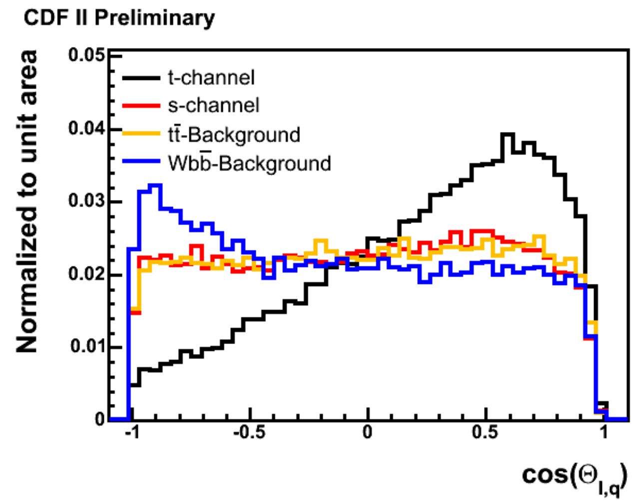
$\sigma_{\text{singletop}} = 2.7^{+1.5}_{-1.3}$ pb

Observation: 2.3 σ excess of single-top events

Neural Network Analysis







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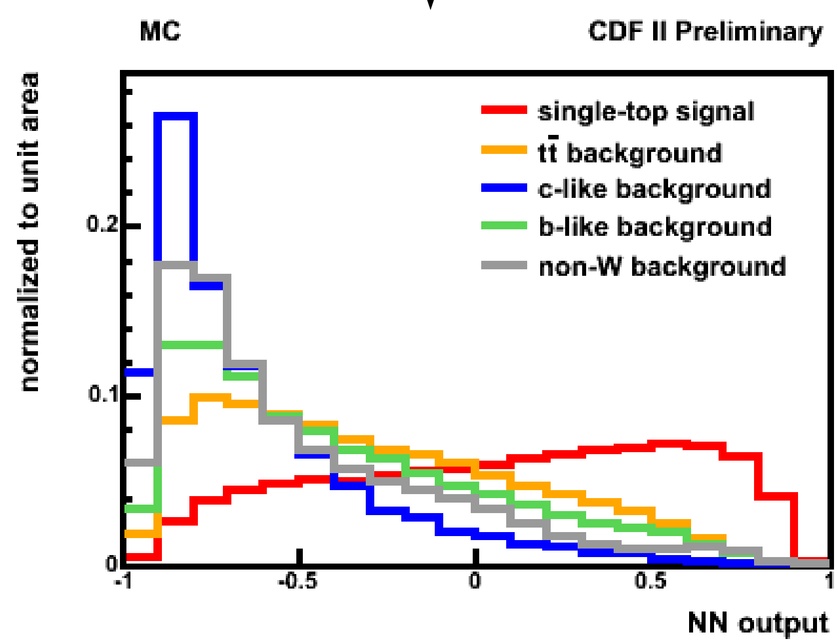
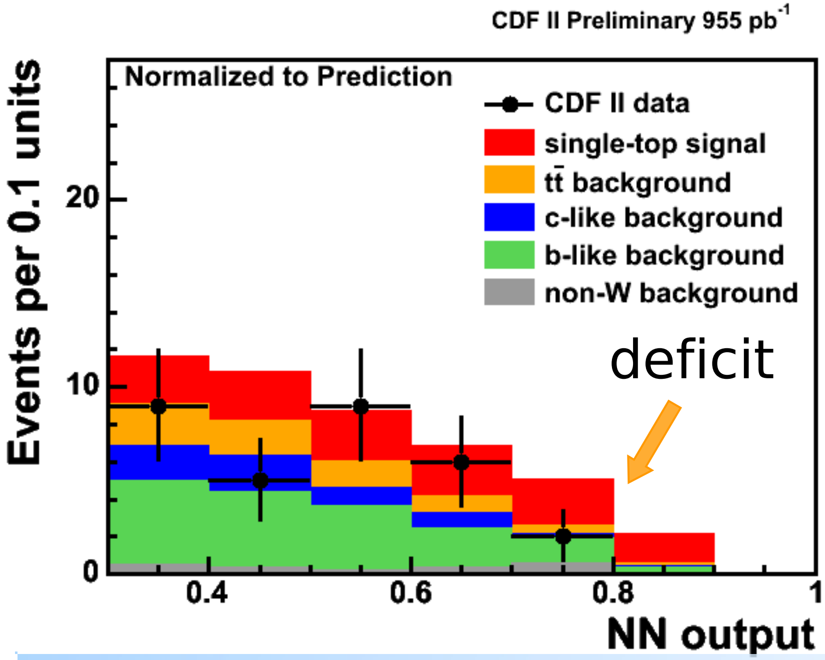
Idea:
combine many variables into one more powerful discriminant

18 variables are used, among them $Q \cdot \eta$, reconstructed top quark mass, top quark polarisation angle, Jet E_T and η, NN b tagger output, W boson , …



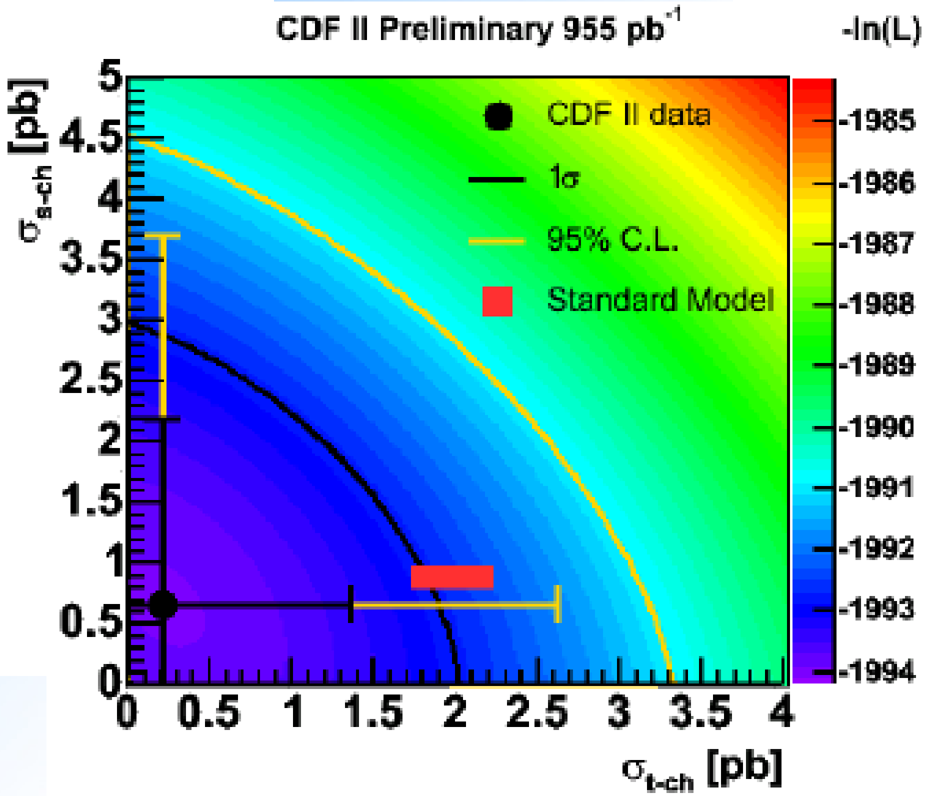
Neural Network Results

Combined Search



$\sigma_{Fit} = 0.0\ ^{+1.2}_{-0.0}$ (stat. + syst.) pb

Separate Search



σ (t-chan.) $= 0.2\ ^{+1.1}_{-0.2}$ pb (SM: 1.98 pb)

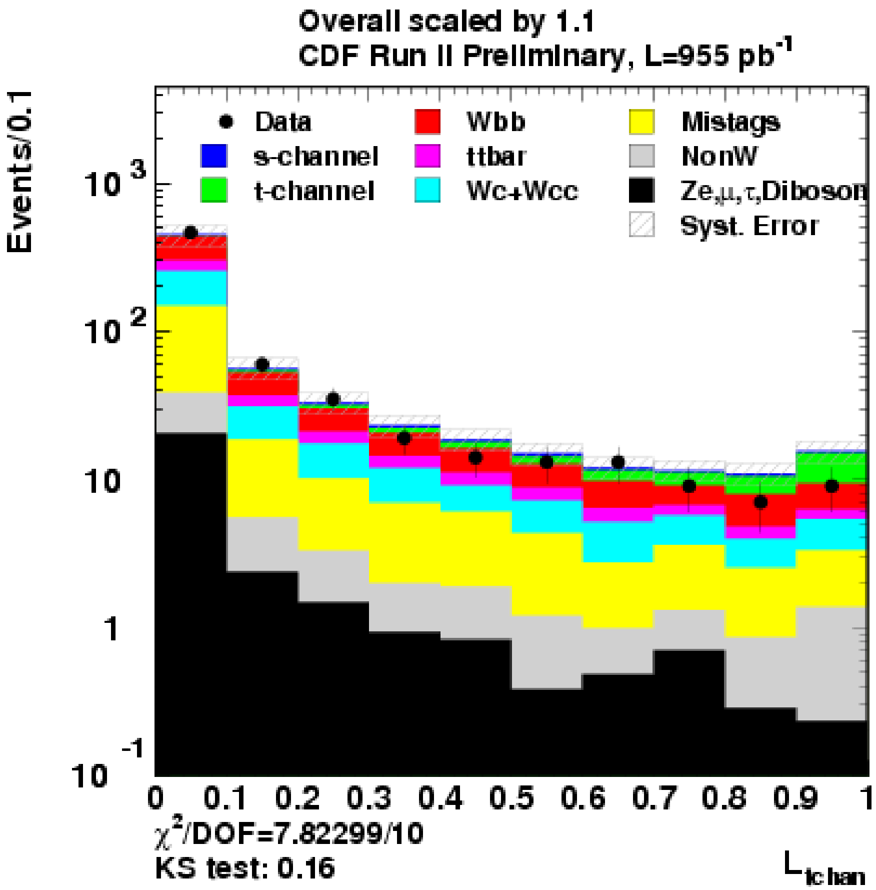
σ (s-chan.) $= 0.7\ ^{+1.5}_{-0.7}$ pb (SM: 0.88 pb)

a priori sensitivity: 2.6 σ

Likelihood Discriminants

histogram based t-channel likelihood discriminant

$$LF(\vec{x}) = \frac{\prod_{i=1}^{n_{\rm var}} p^i_{sig}(x_i)}{\prod_{i=1}^{n_{\rm var}} p^i_{sig}(x_i) + \prod_{i=1}^{n_{\rm var}} p^i_{bkg}(x_i)}$$



Observe deficit in the signal region!

Use t- and s-channel likelihood discriminants in a 2D fit

	p-value	95% C.L. limit
observed	58.3%	2.7 pb
expected	2.3% (2.0σ)	2.9 pb

p-value = probability that observation is due to background fluctuation alone

Expected limits: assume no single-top present in ensemble tests

Best fit:

$$\sigma_{\rm tchan} = 0.2^{+0.9}_{-0.2}\ \rm pb$$

$$\sigma_{\rm schan} = 0.1^{+0.7}_{-0.1}\ \rm pb$$

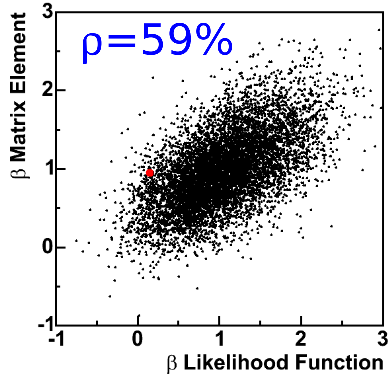
Overview and compatibility

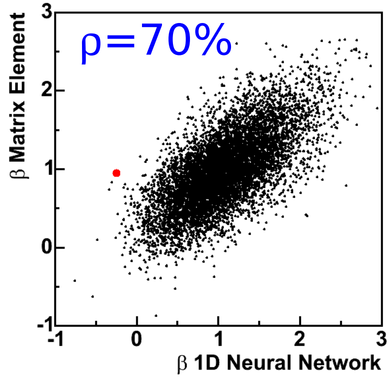
Method	Neural Networks		Matrix Elements	Likelihood Function
	1D	2D	1D	2D
Expected p-value	0.5% ≅ 2.6 σ	0.4% ≅ 2.6 σ	0.6% ≅ 2.5 σ	2.5% ≅ 2.0 σ
Observed p-value	54.6%	21.9%	1.0% ≅ 2.3 σ	58.5%

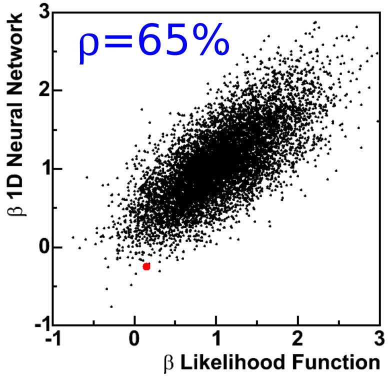
At present, CDF results (955 pb^{-1}) differ:
two analyses see no evidence, one has a signal at almost the SM rate.

Consistency of 4 analyses based on common ensemble tests assuming the SM ratio of t-channel to s-channel: 1%.

correlation







Why do the results differ

ME = Matrix Element
NN = Neural Network
LD = Likelihood Discriminant

Analyses were essentially ready in July 2006.

Differing results caused a multitude of cross checks.

Background estimate was completely redone. Background modeling was refined.

Results remained essentially unchanged.

Analyses are correlated (60 – 70%), but there are conceptual differences which allow to retrace why NN/LD classify the highest purity ME events as background like.

1. Neutrino reconstruction
   NN/LD use measured MET, ME does not, but integrates over all p_z values.
   NN chooses the smaller p_z solution, LD uses best χ^2 of kinematic fit.

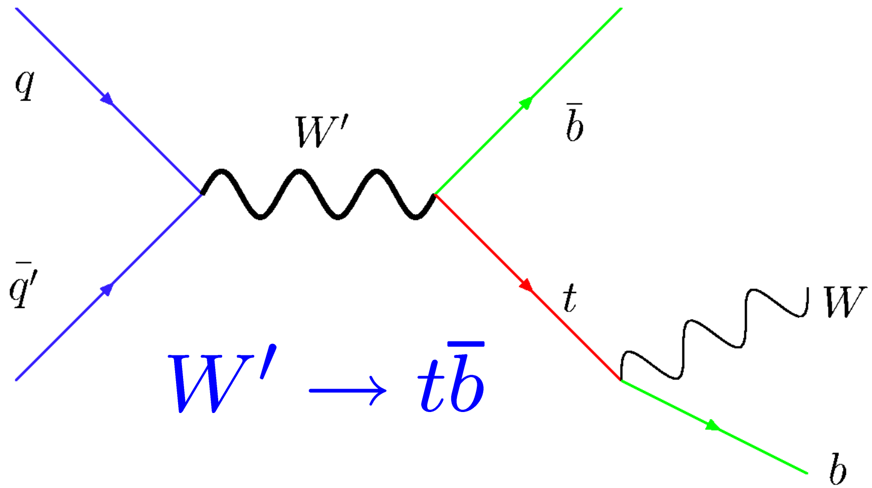
2. Choice of b jet for top quark reconstruction
   LD chooses based on kinematic fit. In 1-tag events NN takes the tagged jet, in 2-tag events NN chooses according to q· .
   ME calculates weighted sum over both possibilities.

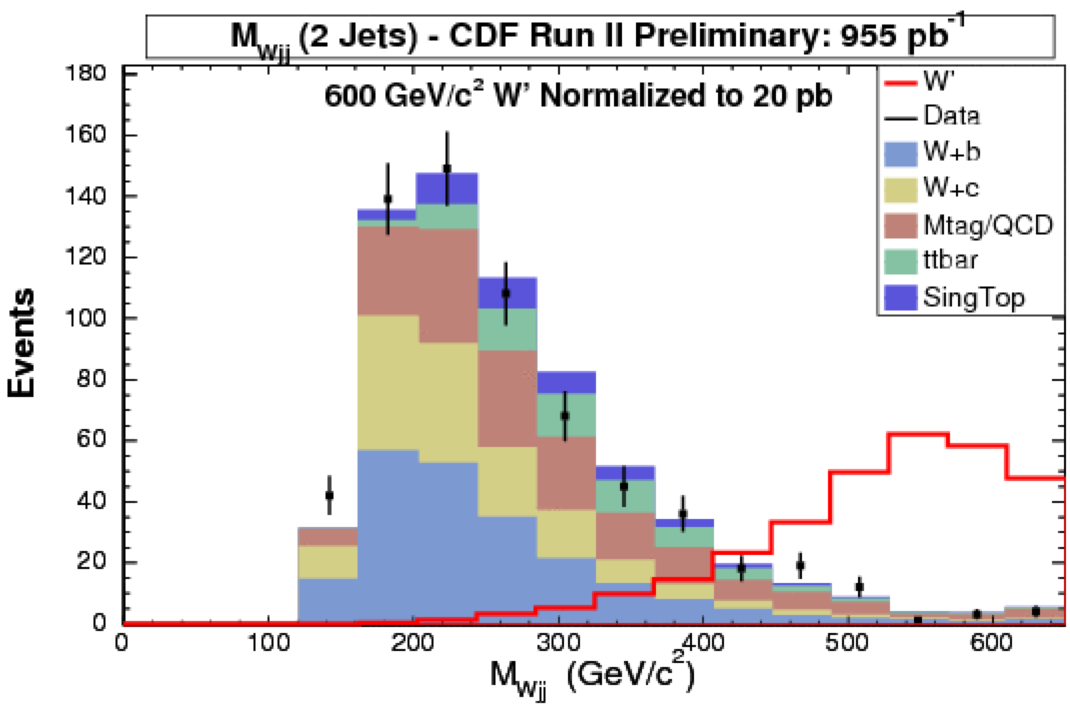
3. NN uses soft jet information (8 GeV < E_T < 15 GeV), ME and LD do not.

4. ME uses transfer functions, NN/LD use standard jet corrections.

Search for W' → tb events

- W' occurs in some extensions of the SM with higher symmetry.
- Complementary to searches in W' eν / μν (e.g. W‘ of leptophobic nature).
- Select W + 2 or 3 jets events.
- Background estimate same as SM singel top search.
- Use M(l jj) as discriminant
- Neglect interference with SM W boson.



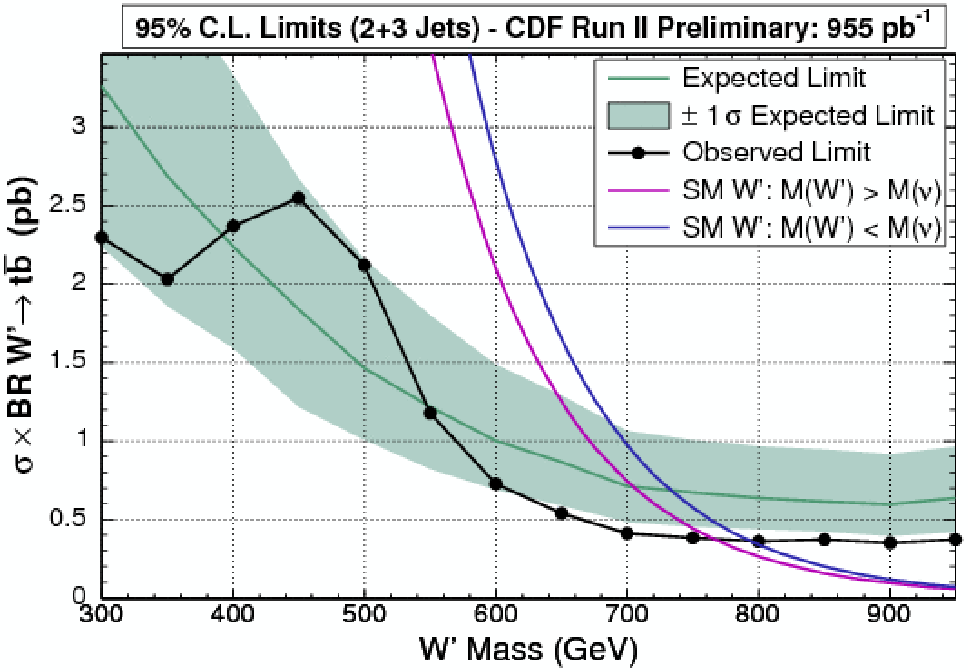


Mass limits on W'

Observe no evidence for resonant W‘ production.

Experimental result: Upper limits on σ · BR(W’→tb) range from 2.5 pb to 0.4 pb.

Mass limits: Based on the theoretical cross section prediction (Z. Sullivan, Phys. Rev. D 66, 075011, 2006)



Improved mass limits:

M(W') > 760 GeV if $M(W'_R) > M(\nu_R)$

M(W') > 790 GeV if $M(W'_R) < M(\nu_R)$

latest DØ limits:

$M(W'_L) > 610$ GeV

$M(W'_R) > 630$ GeV (670 GeV)

Phys. Lett. B 641, 423 (2006)

Previous limit of CDF Run I:

$M(W'_R) > 566$ GeV

Phys. Rev. Lett. 90, 081802 (2003)

Conclusion & Outlook

- Exciting times for single-top analysts !
  sensitivity of individual analyses: ≈ 2.5 σ (955 pb^{-1})

- 3 CDF analyses give different results:

matrix elements	neural networks	likelihood ratio
2.3 σ excess	no evidence	no evidence
$\sigma(s+t) = 2.7^{+1.5}_{-1.3}$ pb	$\sigma(s+t) < 2.6$ pb	$\sigma(s+t) < 2.7$ pb
	$\sigma(t) < 2.6$ pb	
	$\sigma(s) < 3.7$ pb	

- Single-top analyses are a benchmark for Higgs searches, especially WH at the Tevatron.

- Updated analyses using 1.5 fb^{-1} are imminent!
  Sensitivity will be well above 3 σ for each single analysis.

- New, improved mass limits on $W' \rightarrow tb$:
  $M(W') > 760$ GeV if $M(W'_R) > M(\nu_R)$
  $M(W') > 790$ GeV if $M(W'_R) < M(\nu_R)$

Backup

Top mass reconstruction

1) Neutrino Pz:

$$(p_l + p_\nu)^2 = m_W^2$$

- Neutrino p_x, p_y from MET
- P_z from W-mass constraint

- This yields two solutions:
  Smaller solution is correct 67.6%

2) M_{lb} reconstruction:

- Assumption that tagged jet is from top
- In double tagged events, take jet with larger Q_{lep} x η_{jet}

Parton/Jet matching	t-channel	s-channel
1 tag	96.6%	51.1%
2 tags	61.9%	68.5%

- Works well for t-channel only