Measurement of Single Top-Quark Production at CDF

B. R. Haydon, "Napoleon Bonaparte", National Portrait Gallery, London

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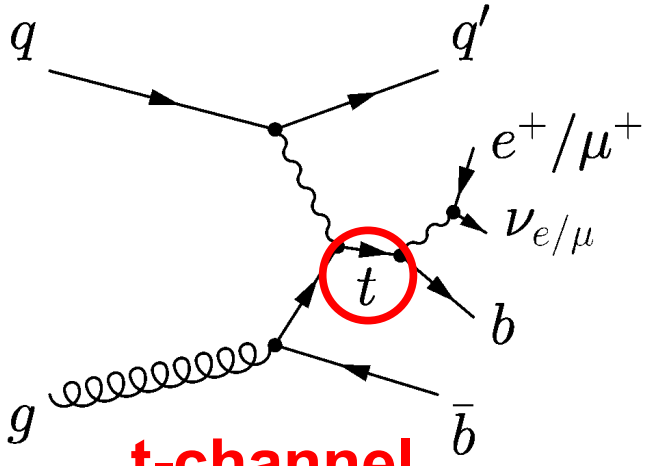
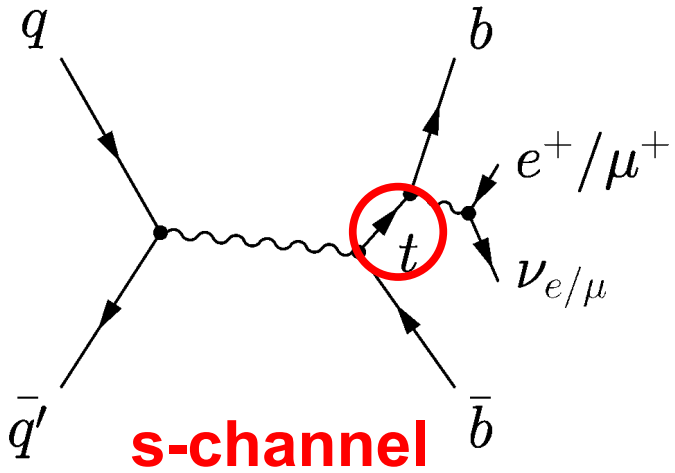
On behalf of the CDF Collaboration

top2008 - Isola d'Elba, Italy - May 18-24, 2008

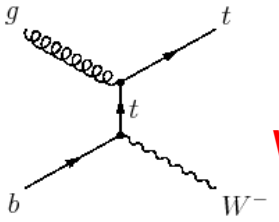
Single Top-Quark Production



t-channel



s-channel



Wt production $\sigma_{Wt} \approx 0.1$ pb

- test of Standard Model (V-A, …)
- direct measurement of $|V_{tb}|^2$
- test of b-quark structure function
- same channel as WH @ Tevatron
- proving ground for WH

Standard Model prediction:

$\sigma_{\text{t-channel NLO}} = 2.0 \pm 0.3$ pb

$\sigma_{\text{s-channel NLO}} = 0.9 \pm 0.1$ pb

$\sigma_{\text{single top NLO}} = 2.9 \pm 0.4$ pb

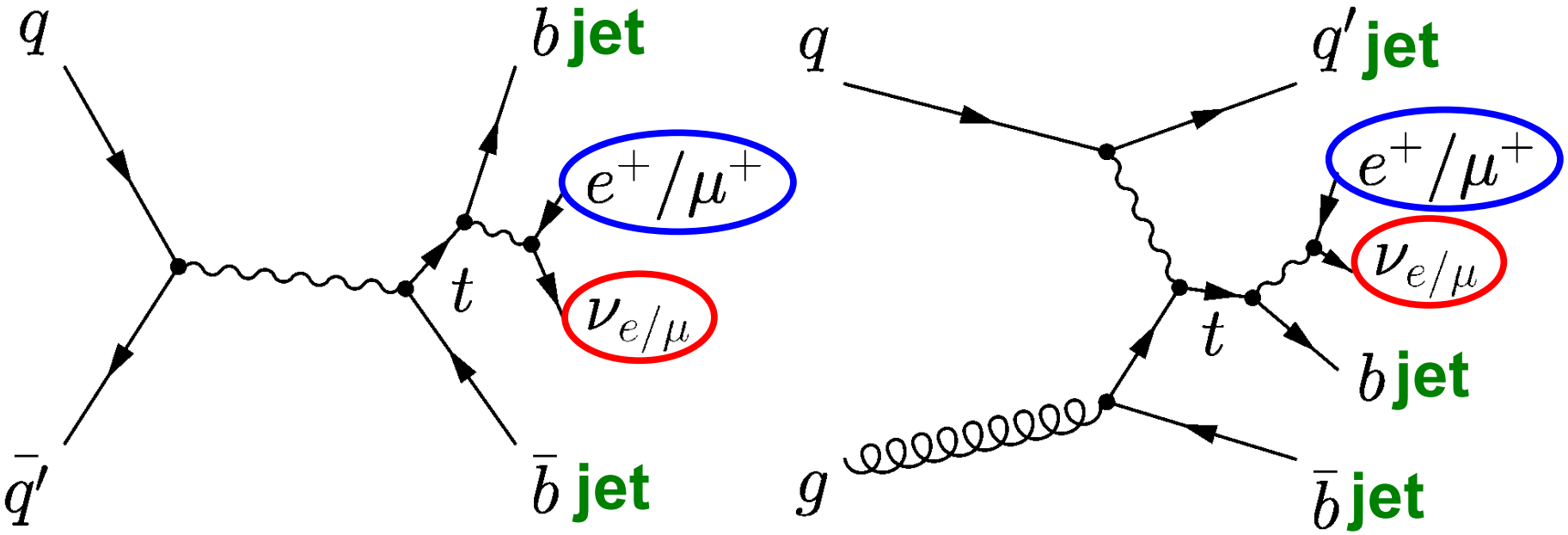
Harris et al., Phys. Rev. D 66, 054024
Sullivan, Phys. Rev. D 70, 114012

Tait, Phys. Rev. D 61, 034001

Event Signature

top quark decay ~100% in W-boson and b-quark

↳W → l + ν



- **exact 1 isolated charged lepton** (e/μ) E_T > 20 GeV
- **missing transverse energy** MET > 25 GeV
- **2 or 3 jets** (E_T > 20 GeV, |η|< 2,8)
  with 1 or 2 jets with reconstructed secondary vertex (b-tag)
- complex QCD-veto, Z-veto, …

Single-Top and Bkg Estimate

Determined from MC

Single-Top, Diboson, Z+jets

and top pair production:

$$N_{pred} = \sigma_{theo} \cdot \epsilon_{evt} \cdot \int \mathcal{L}\, dt$$

Determined from MC and Data

W+HF jets: W+jets normalization from data,

HF-fraction from ALPGEN MC

(calibrated in W+1jet side-band)

tagging eff. from ALPGEN MC

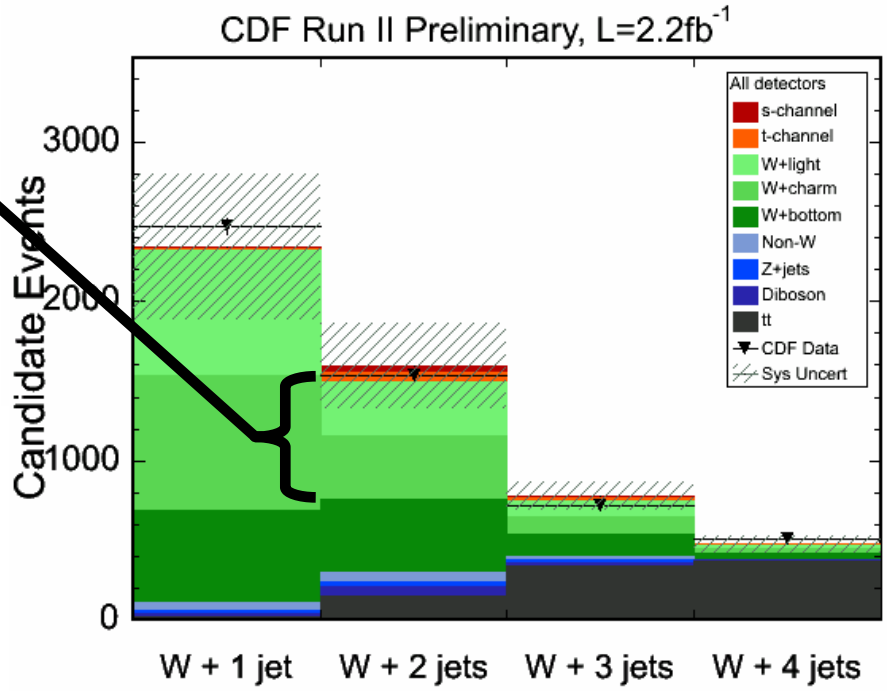
Determined from Data

W+LF jets (negative tage rates)

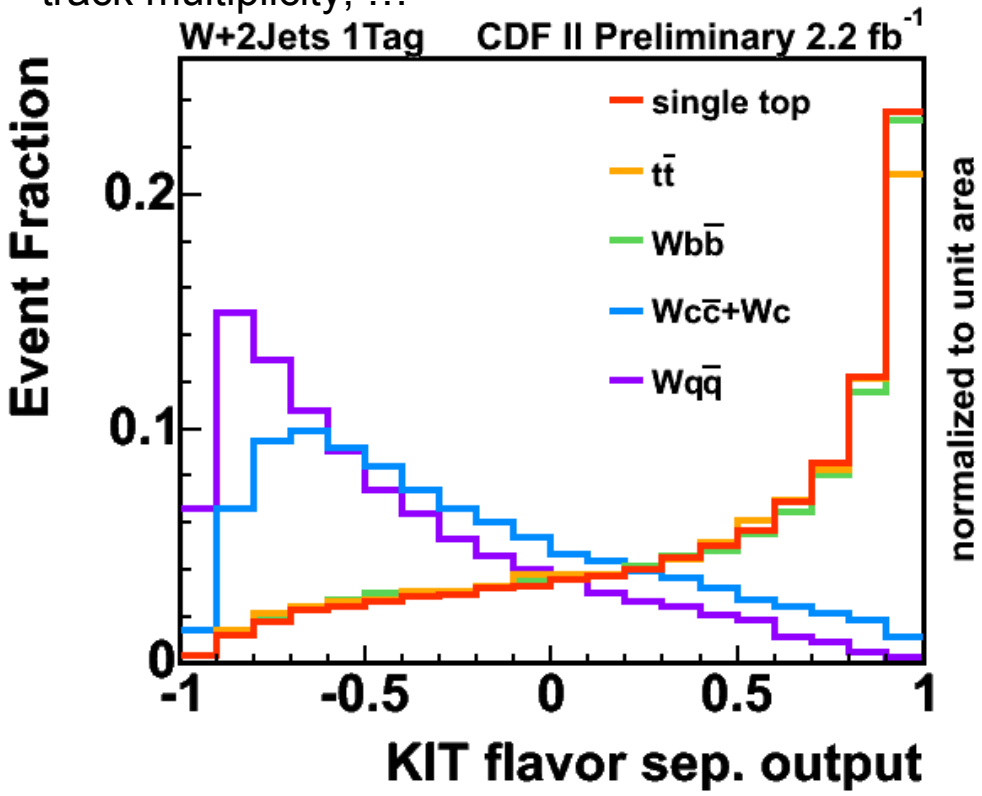
and QCD events (MET fit)

Jet Flavor Separator

~50% of all events do NOT contain b quarks even though a secondary vertex was required!

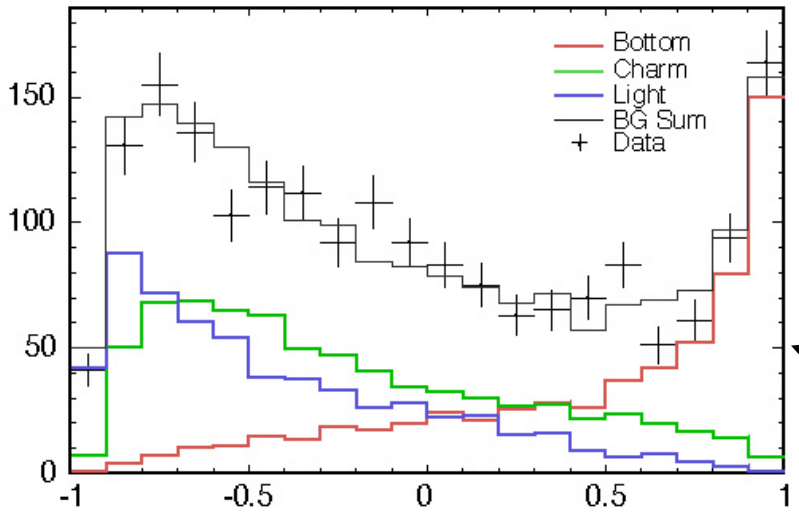


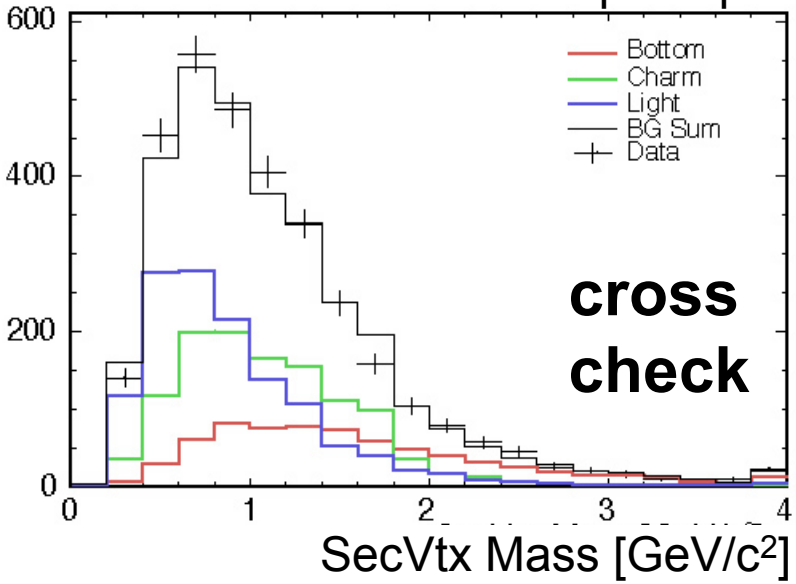
Train neural network with input from jet and track variables, e.g. vertex mass, decay length, track multiplicity, …



up to 20% gain in sensitivity!

W + Heavy Flavor Calibration

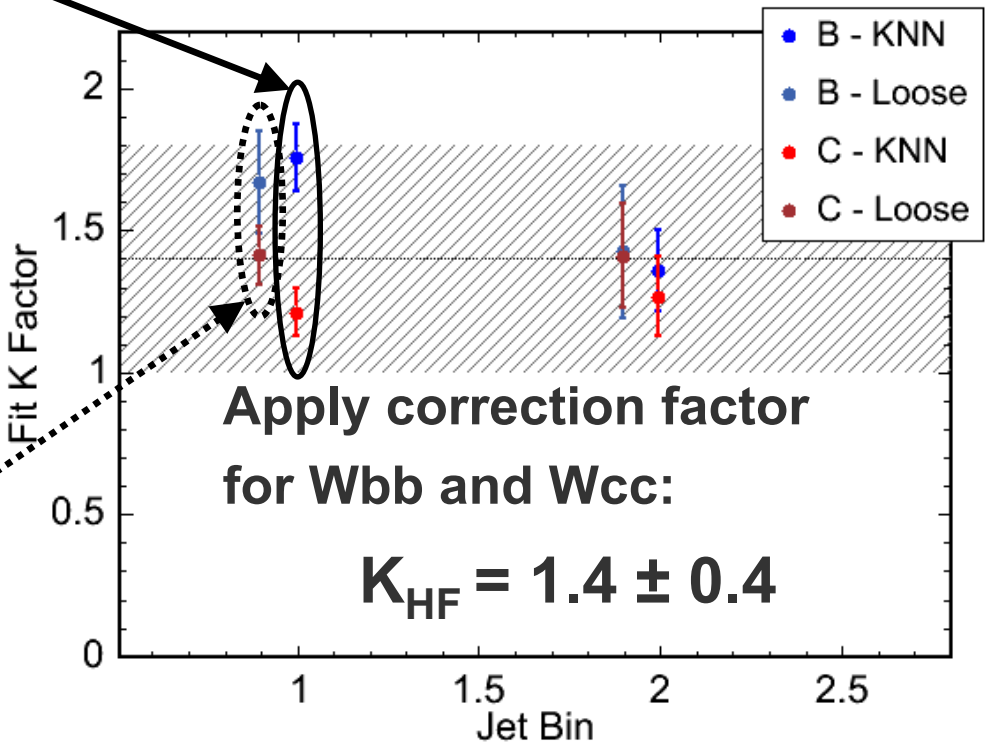




Use ALPGEN predictions of kinematic distribution but mistrust ALPGEN rates

Use b-tagged W+1-jet data control sample to estimate the HF fractions

Three-parameter fit to **bottom**/**charm**/**light** templates of KIT flavor separator distribution



QCD Rate Estimate

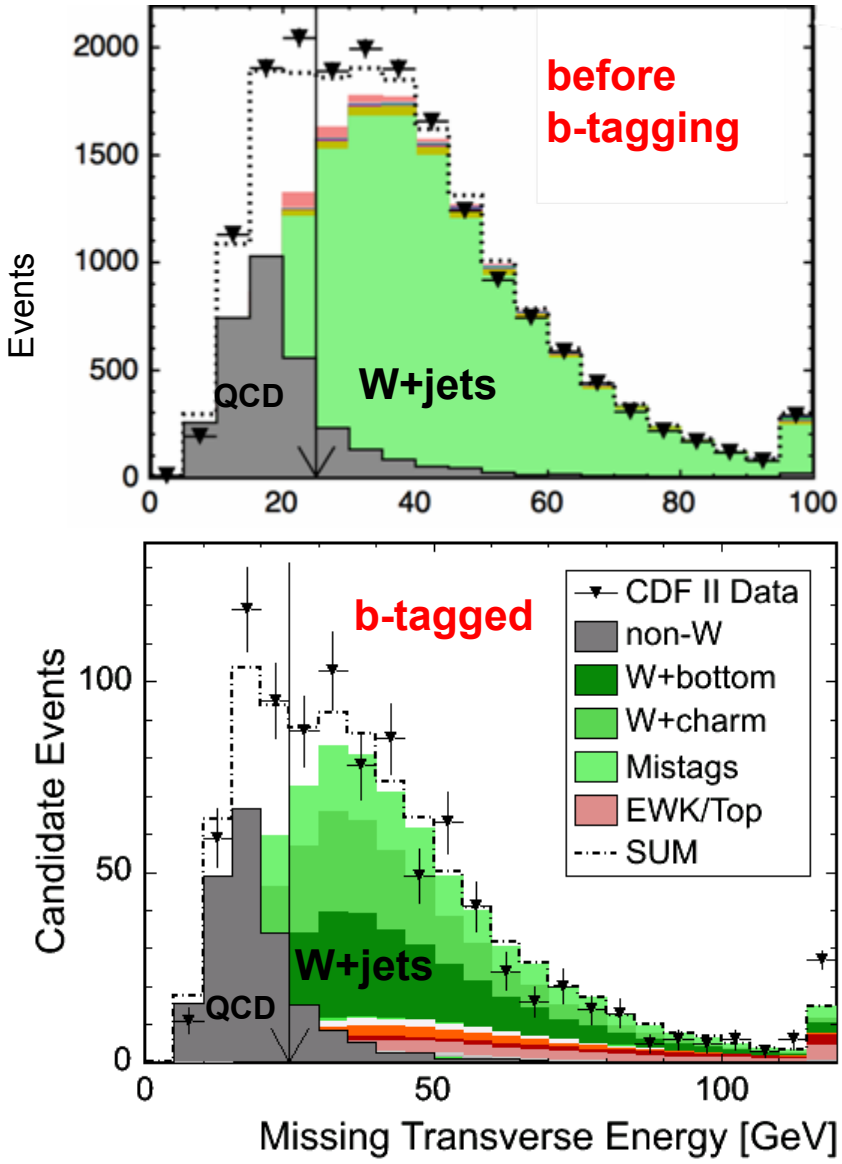
- Apply complex QCD-veto

- MC models of inclusive jet+MET
  production not precise enough

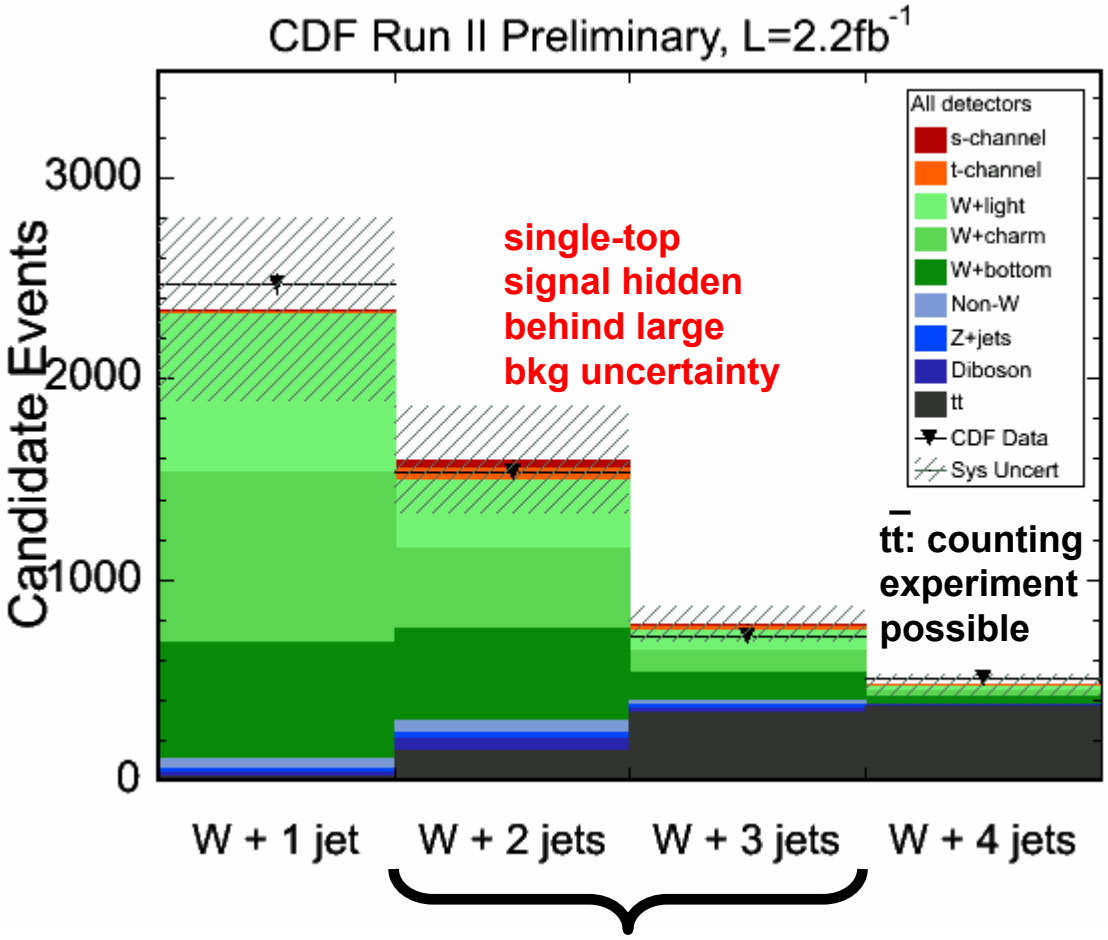
- Use data samples to model kinematic:
  - "anti-lepton": lepton candidates
    which pass all but two of the non-kinematic
    lepton-ID requirements
  - "jet-leptons": Multijet events
    where one jet fakes the lepton

- Perform fits to MET distributions and extract
  QCD content with MET > 25 GeV

- Uncertainty on QCD rate: 40%



Single-Top- and Bkg Estimate



signal region divided into 1 or 2 b-tags, e.g. 4 independent channels

Analyses Details

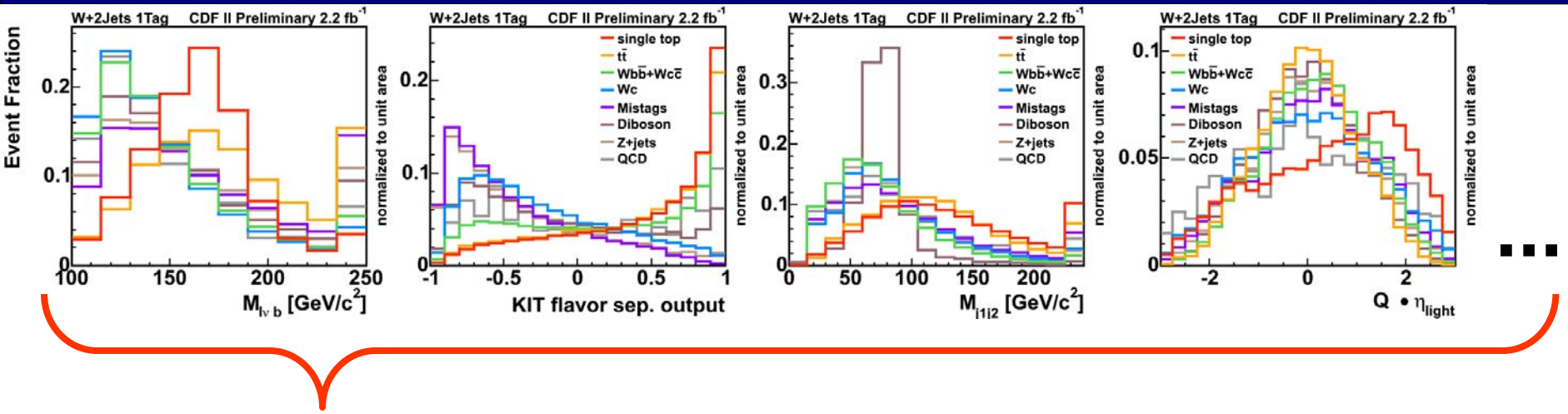
Search for Single-Top

t- and s-channel combined @ SM ratio	**t- and s-channel separately**
Neural Networks **Likelihood Function** **Matrix Elements** **Boosted Decision Trees** **Combination**	**Neural Networks** s-channel only: **Likelihood Function**

optimization of apriori separation power done individually
remaining treatment identical, e.g.

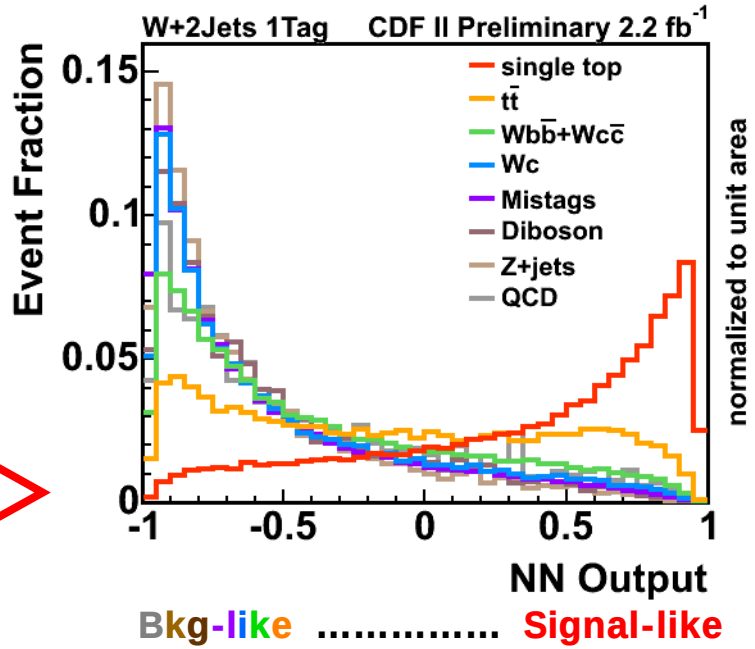
- event selection (QCD-veto, divide into 4 independent channels, …)
- signal + bkg predictions (Wbb/cc rate calibration, QCD rate MET fits, …)
- signal + bkg models
- systematic rate and shape uncertainties

Neural Network Analysis

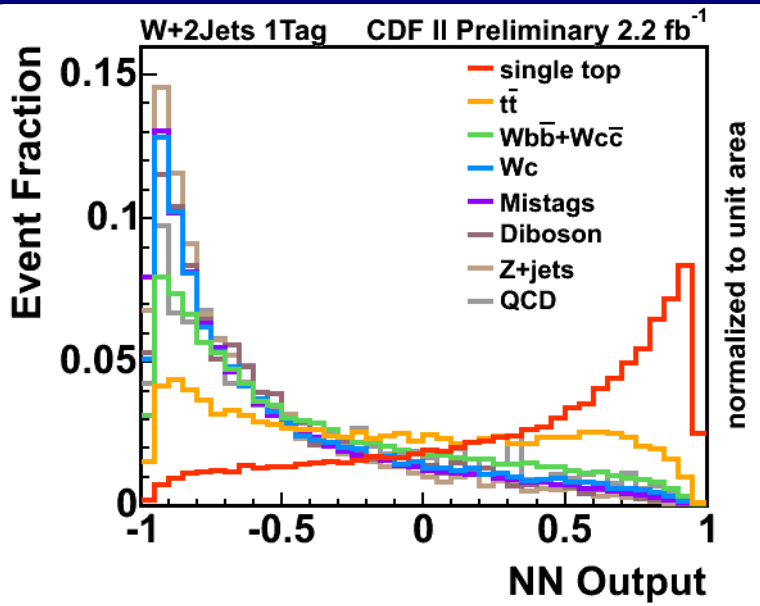


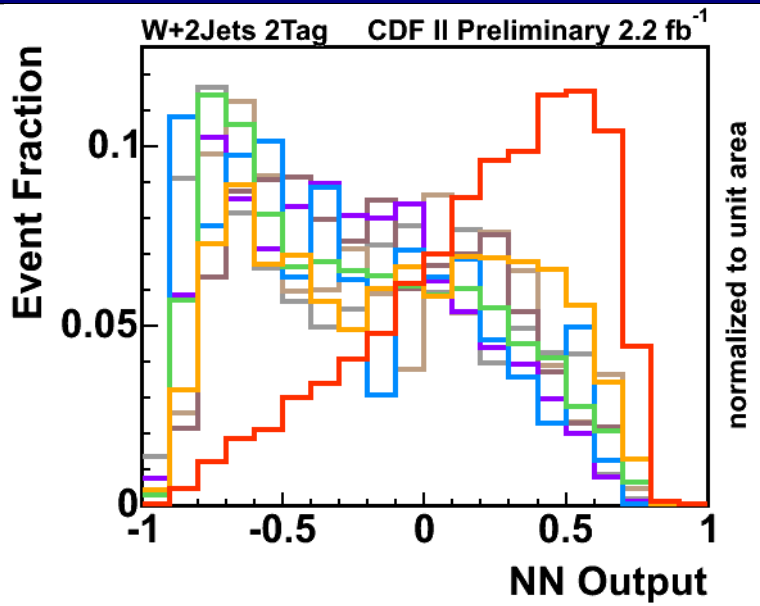
Training in 4 channels

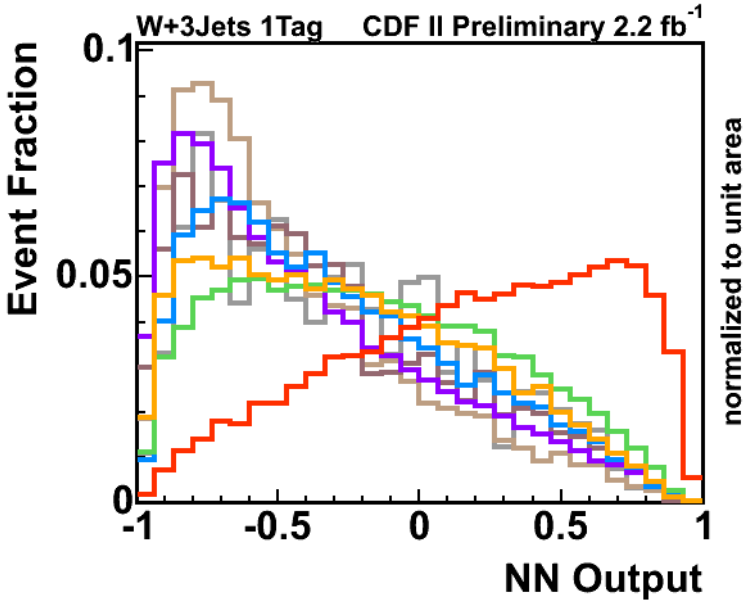
- NeuroBayes® package
- Signal:Bkg ratio 50:50
- Bkg mixed as predicted by SM
- up to ~80K training events
- ~10 to 20 input variables
- 15 hidden nodes
- 1 output node: “NN Output”

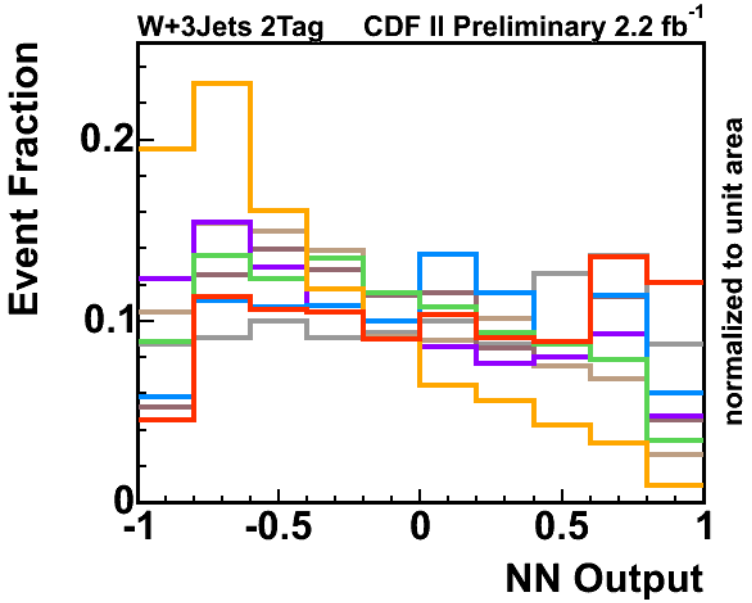


Fit Templates in 4 Channels









Systematic Uncertainties

Syst. Uncertainty	Rate	Shape
Jet Energy Scale	0...16%	☑
Initial state radiation	0...11%	☑
Final state radiation	0...15%	☑
Parton Distribution Function	2...3%	☑
MC Generator	1...5%	
Event Detection Efficiency	0...9%	
Luminosity	6%	
NN Flavor-Separator		☑
Mistag model		☑
Q2 scale in ALPGEN MC		☑
Input variable mismodeling		☑
Wbb+Wcc normalization	30%	
Wc normalization	30%	
Mistag normalization	17...29%	
Top-pair normalization & mtop	23%	☑

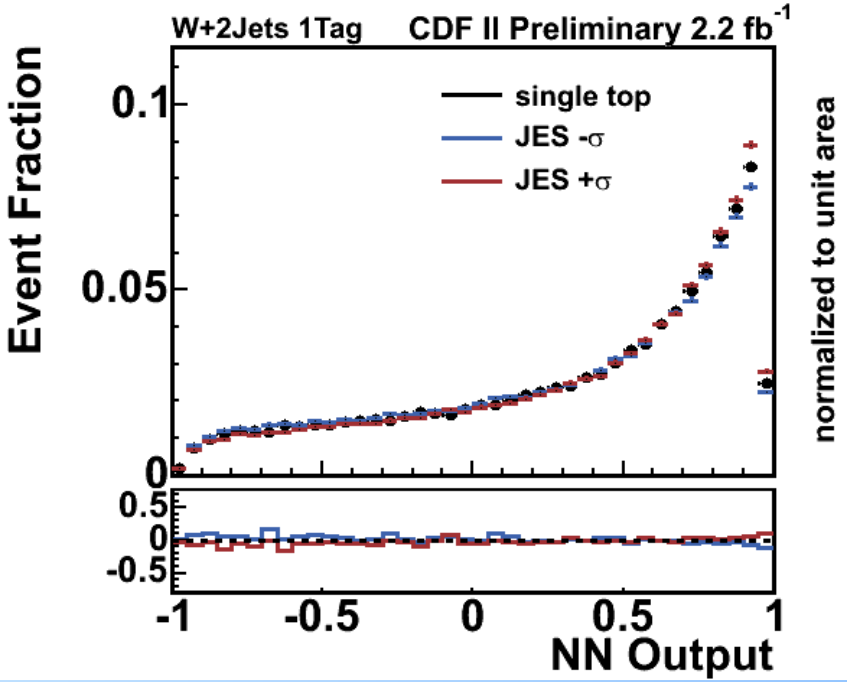
Systematic Uncertainties (e.g. JES)

Estimate of syst. uncertainties of the

a) rates: difference in acceptance between syst. and default sample

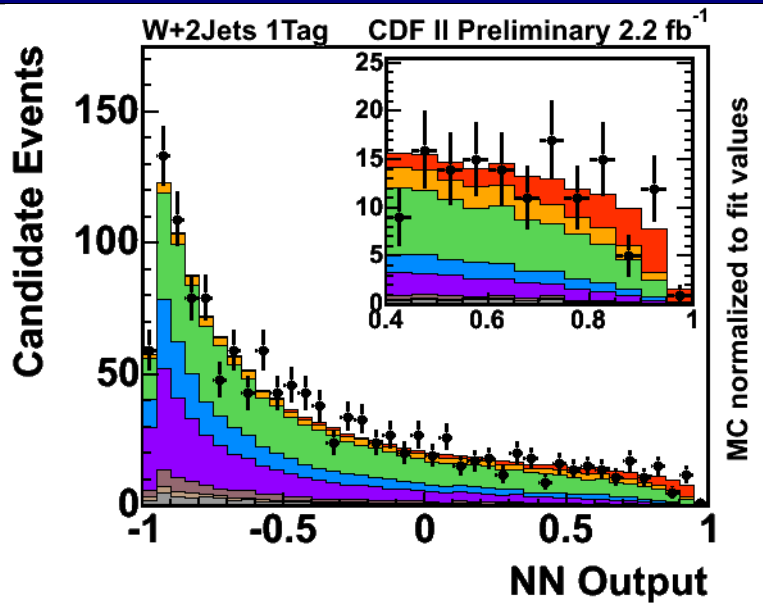
process	2jets 1tag	2jets 2tags	3jets 1tag	3jets 2tags
t-ch	-1.1/0.6 %	4.8/-3.5 %	-10.4/10.6 %	-5.7/4.3 %
s-ch	-0.1/-0.6 %	1.2/-1.9 %	-8.3/9.4%	-7.2/7.4 %
single-top	-0.8/0.2 %	1.8/-2.2 %	-9.1/9.9 %	-6.6/6.1 %
$t\bar{t}$	9.8/-9.4 %	8.1/-7.5 %	4.6/-5.1 %	5.4/-5.2 %
$Wc\bar{c}$+$Wb\bar{b}$	7.0/-6.9 %	10.8/-10.6 %	8.4/-7.7 %	11.0/-12.1 %
Wc	7.0/-6.3 %	11.3/-10.3 %	8.2/-6.9 %	13.9/-15.8 %
Z+jets	-5.3/5.4 %	5.0/-5.0 %	-10.8/14.0 %	-5.0/5.0 %
Diboson	-2.7/1.7 %	-3.0/1.5 %	-12.4/11.9 %	-11.0/11.0 %

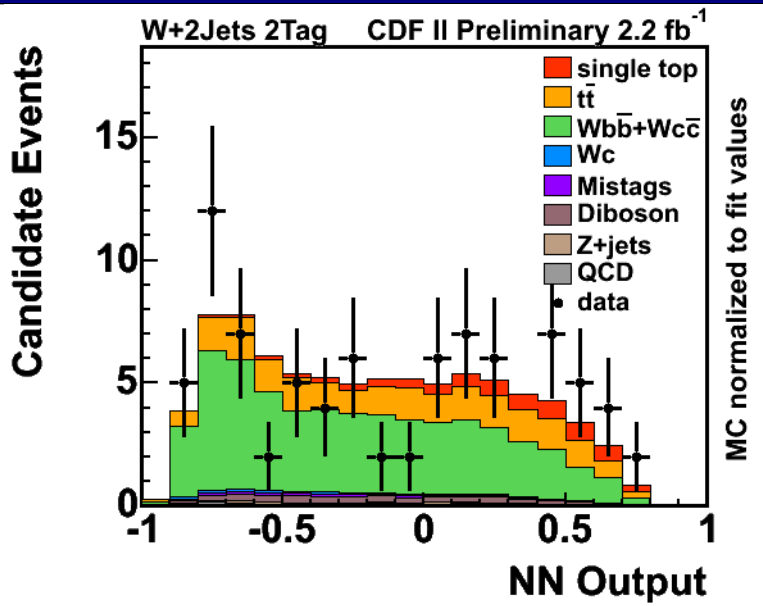
b) shape of the "NN Output":
bin-wise difference of normalized syst. and default shape

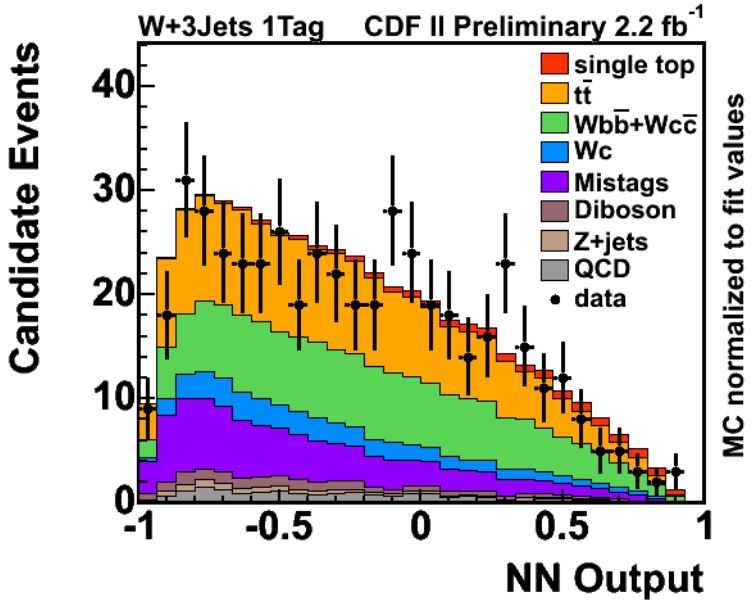


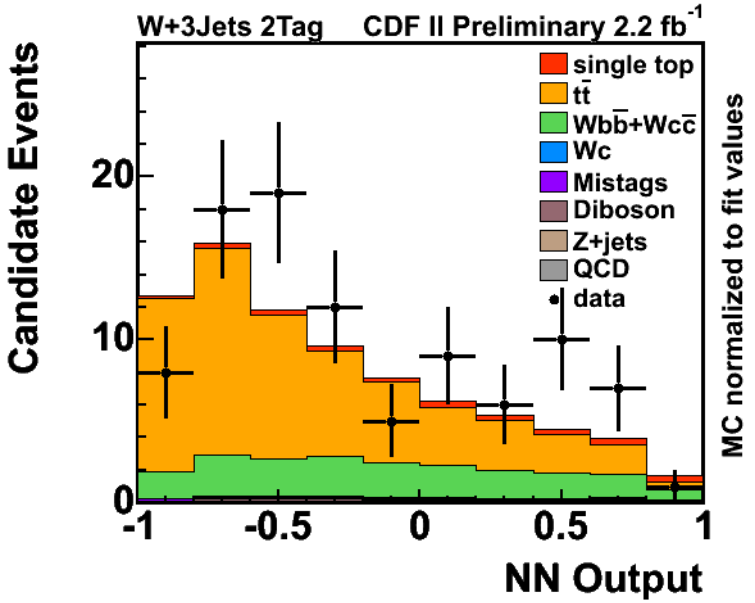
rate and shape uncertainties of same syst. source are treated correlated in the fit.

Simultaneous Likelihood-Fit to Data

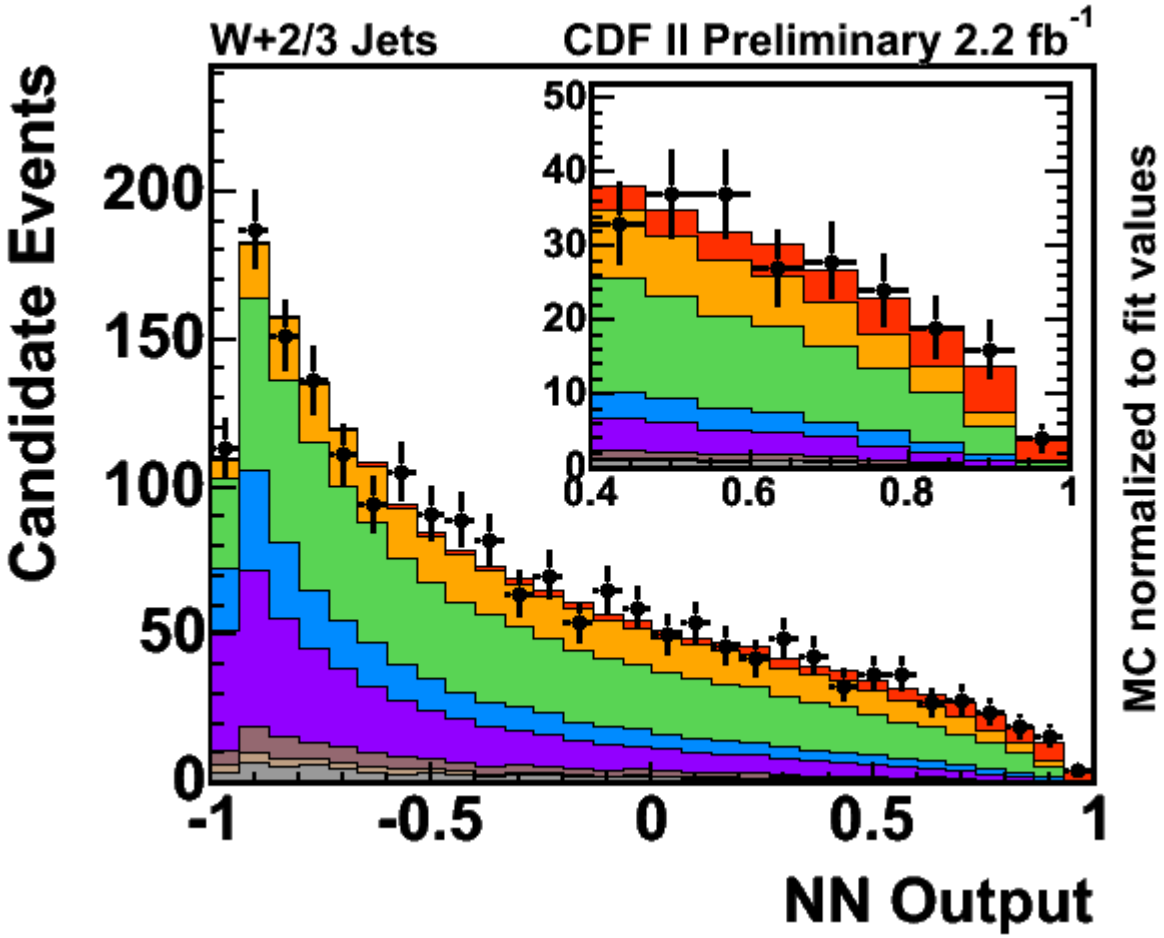








Result

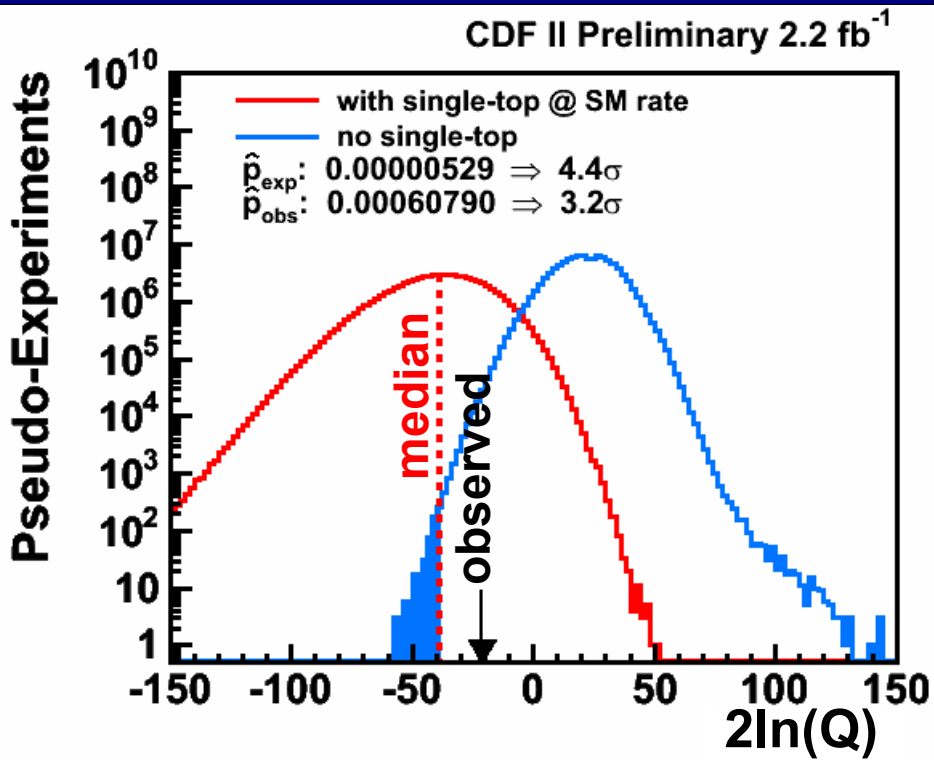


$$\sigma_{\text{single top}} = 2.0^{+0.9}_{-0.8}\,(\text{stat.} + \text{syst.})\ \text{pb}$$

Significance

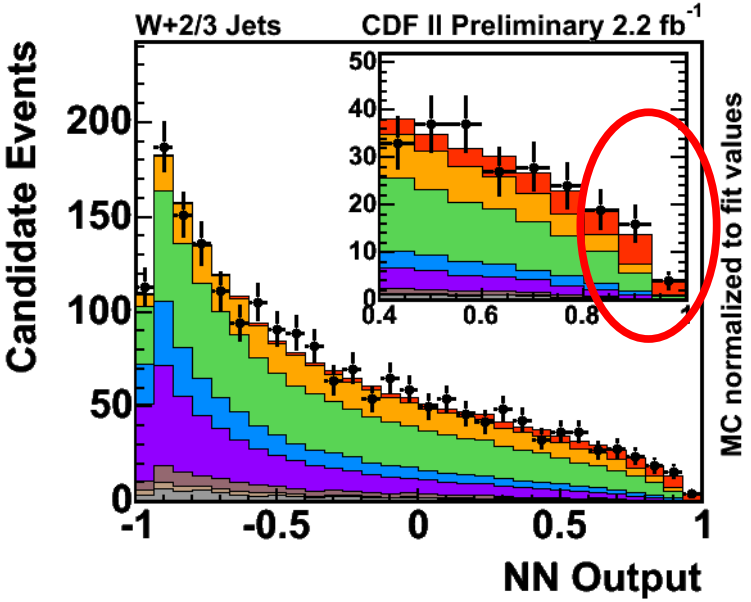
- Modified frequentist approach
- Perform pseudo experiments (PE) with and without SM single top
  - Fluctuate all syst. uncertainties in PE
  - Binned likelihood fit for each PE:
    reduced likelihood as a function of the single-top cross section

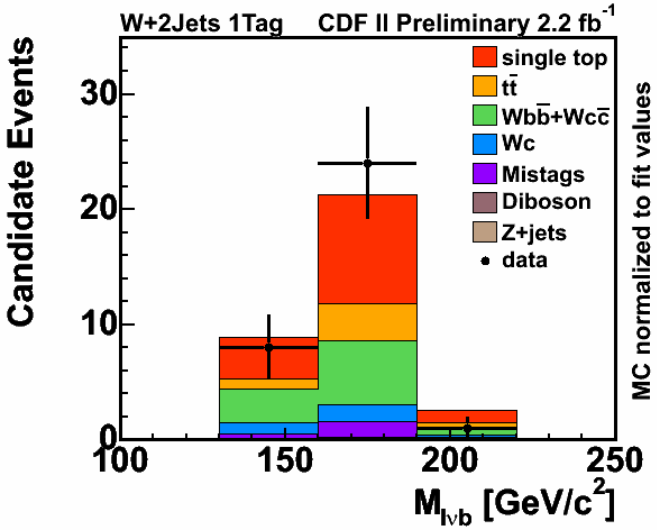
- $Q = L_{reduced}(\sigma_{s+t} = SM)/L_{reduced}(\sigma_{s+t} = 0)$

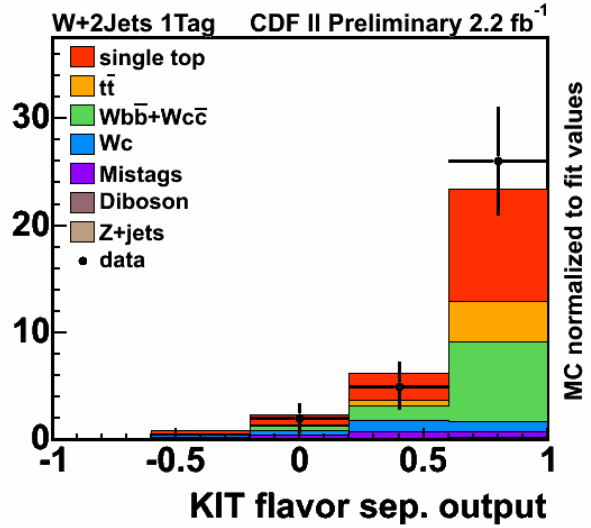


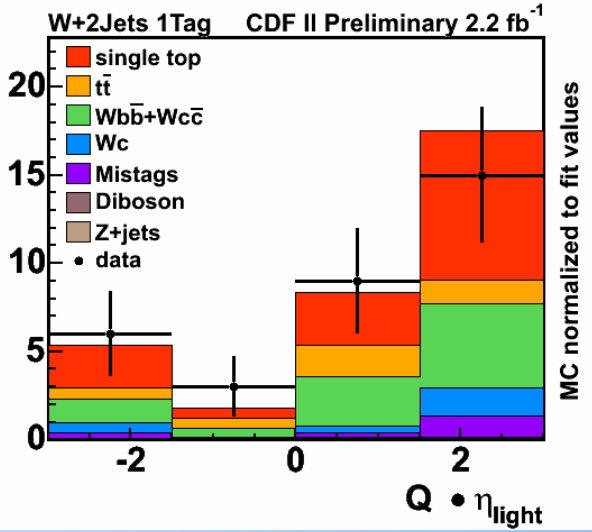
exp. Significance:	**4.4σ**
obs. Significance:	**3.2σ**

Events with „NN Output“ > 0.8

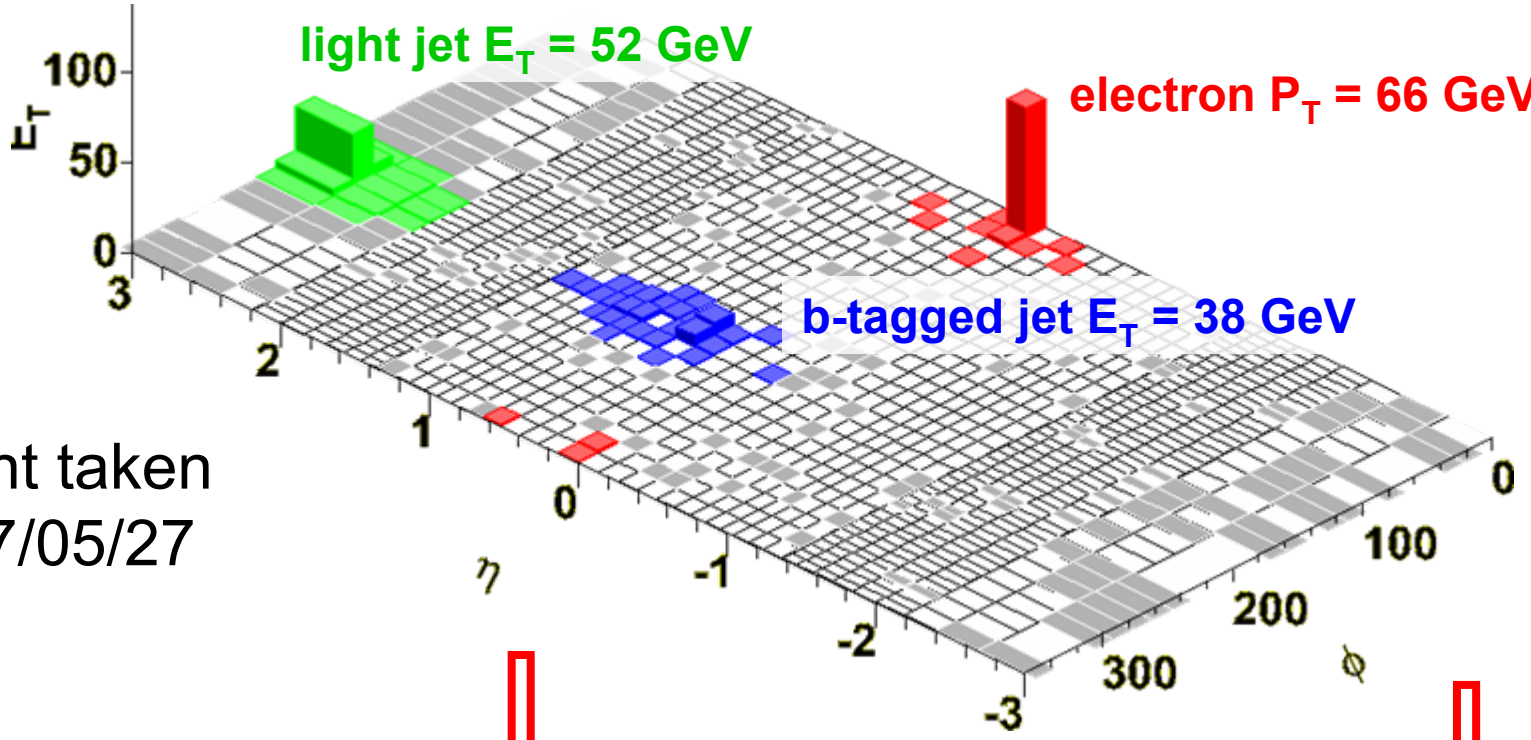




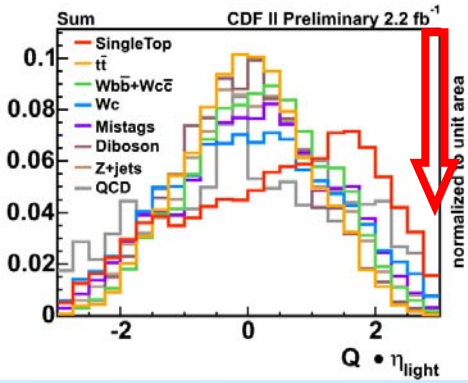


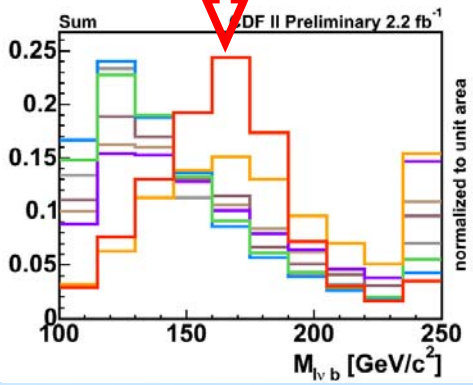


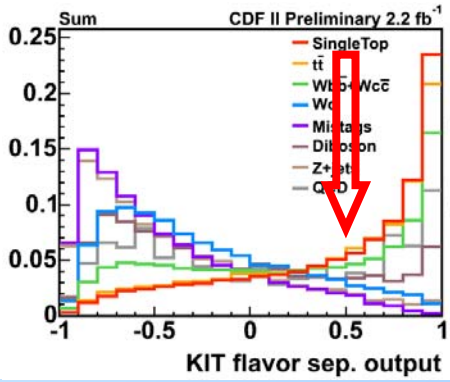
Golden Electron Event with „NN Output“ = 0.93

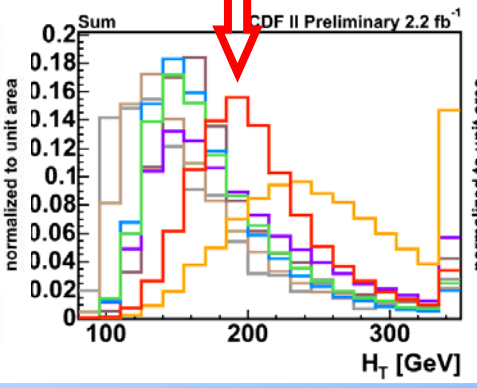


Event taken
2007/05/27



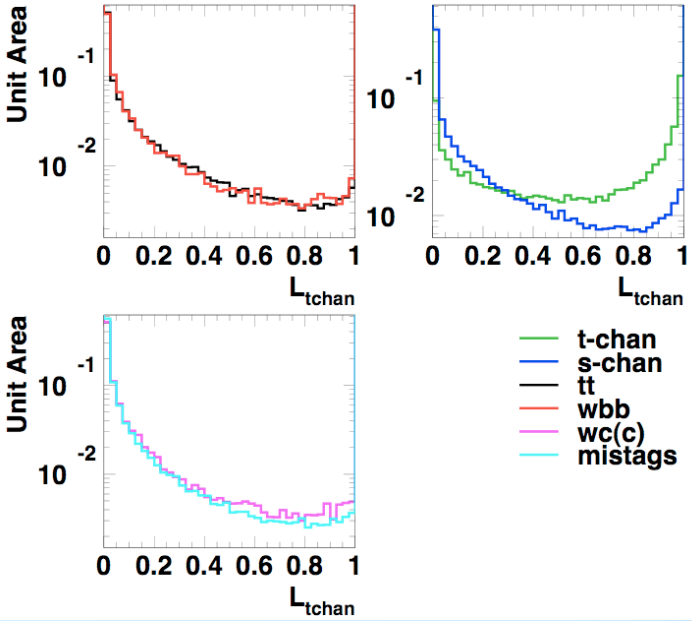


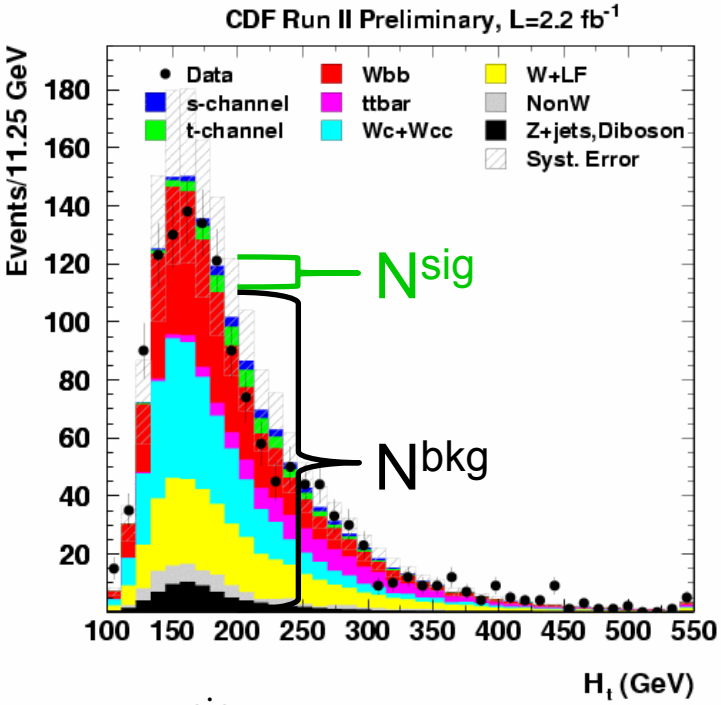




Multivariate Likelihood Function Analysis

histogram based binned likelihood function (LEP style) with 7-10 variables



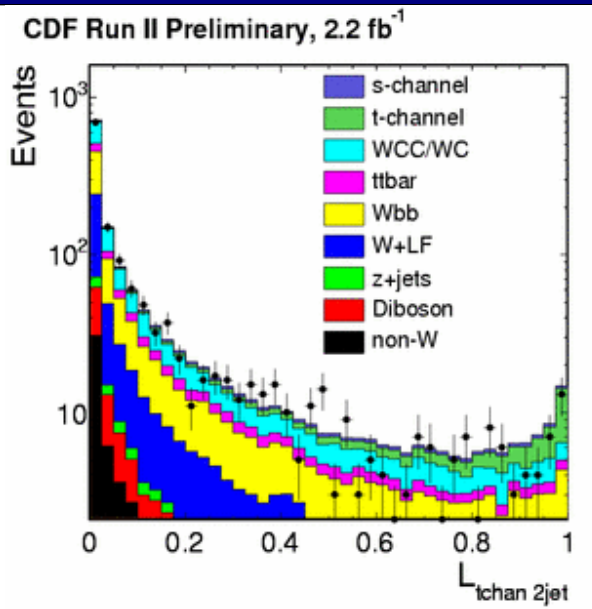


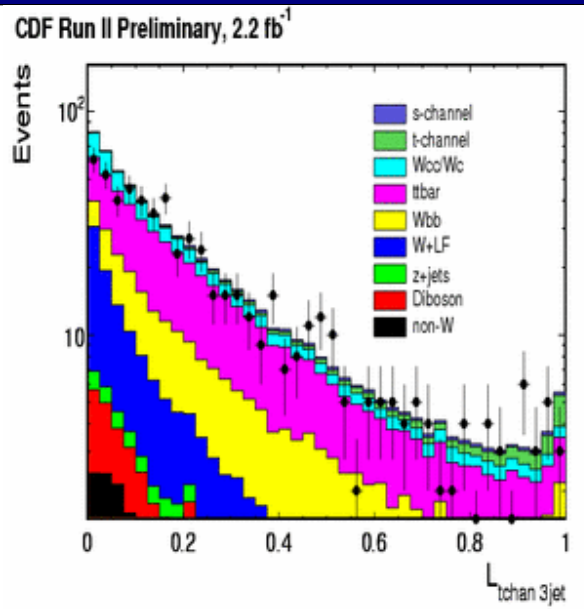
optimized for t-channel

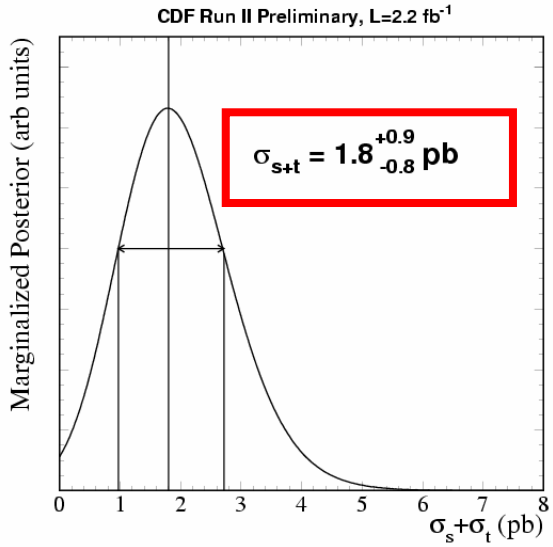
$$p_i^{sig} = \frac{N_i^{sig}}{N_i^{sig} + N_i^{bkg}}$$

$$L(x) = \frac{\prod p_i^{sig}(x_i)}{\prod p_i^{sig}(x_i) + \prod p_i^{bkg}(x_i)}$$

Multivariate Likelihood Function Analysis







exp. Significance:	**3.4σ**
obs. Significance:	**2.0σ**

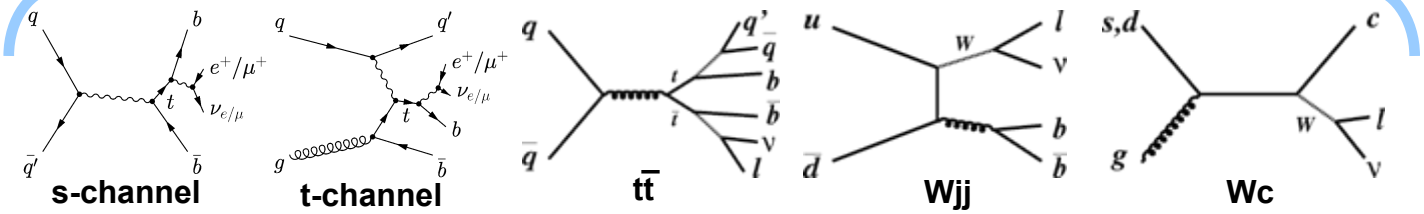
Matrix Element Analysis

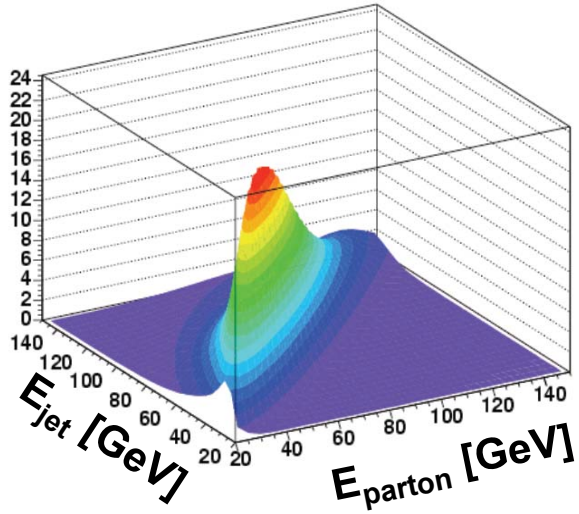
Compute an event probability P for signal and background hypotheses:

input: lepton and jet 4-vectors!	Integration over part of the phase space	Leading Order matrix elements	Parton distribution functions (CTEQ6)

$$P(p_i^{\mu}, p_{j1}^{\mu}, p_{j2}^{\mu}) = \frac{1}{\sigma} \int d\rho_{j1} d\rho_{j2} dp_{\nu}^{z} \sum_{comb} \phi_4 \, |M(p_i^{\mu})|^2 \, \frac{f(q_1) f(q_2)}{|q_1||q_2|} W_{jet}(E_{jet}, E_{part})$$

Probability of measuring a jet energy E_j if E_p was produced.



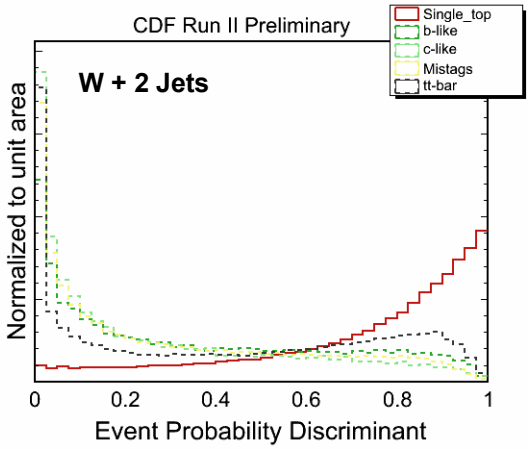


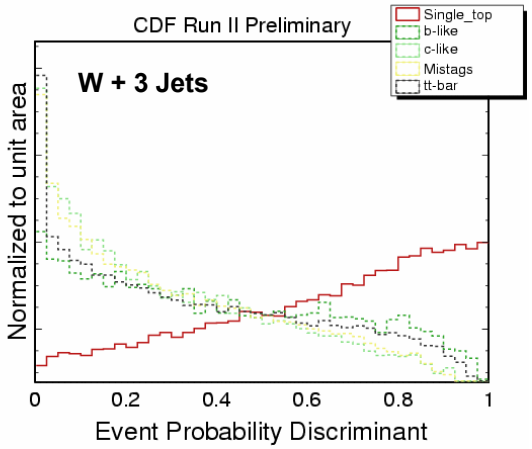
Combine the signal and background probability densities into a single **E**vent **P**robability **D**iscriminant:

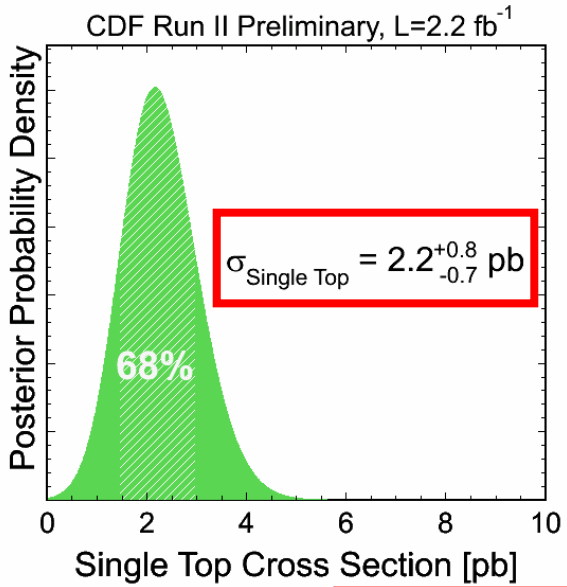
$$EPD = \frac{b \cdot P_{Singletop}}{b \cdot P_{Singletop} + b \cdot P_{Wbb} + b \cdot P_{tt} + (1-b) \cdot P_{W+charm} + (1-b) \cdot P_{W+light}}$$

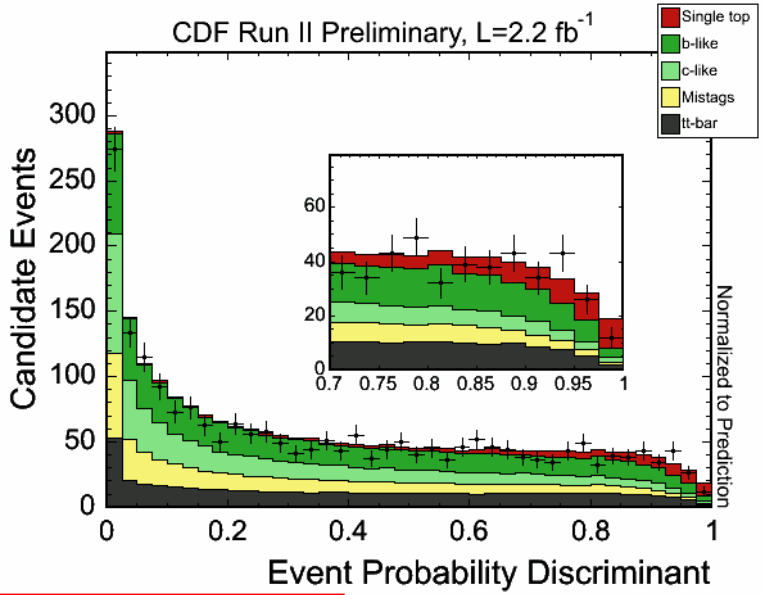
b is b-probability from KIT flavor separator

Matrix Element Analysis



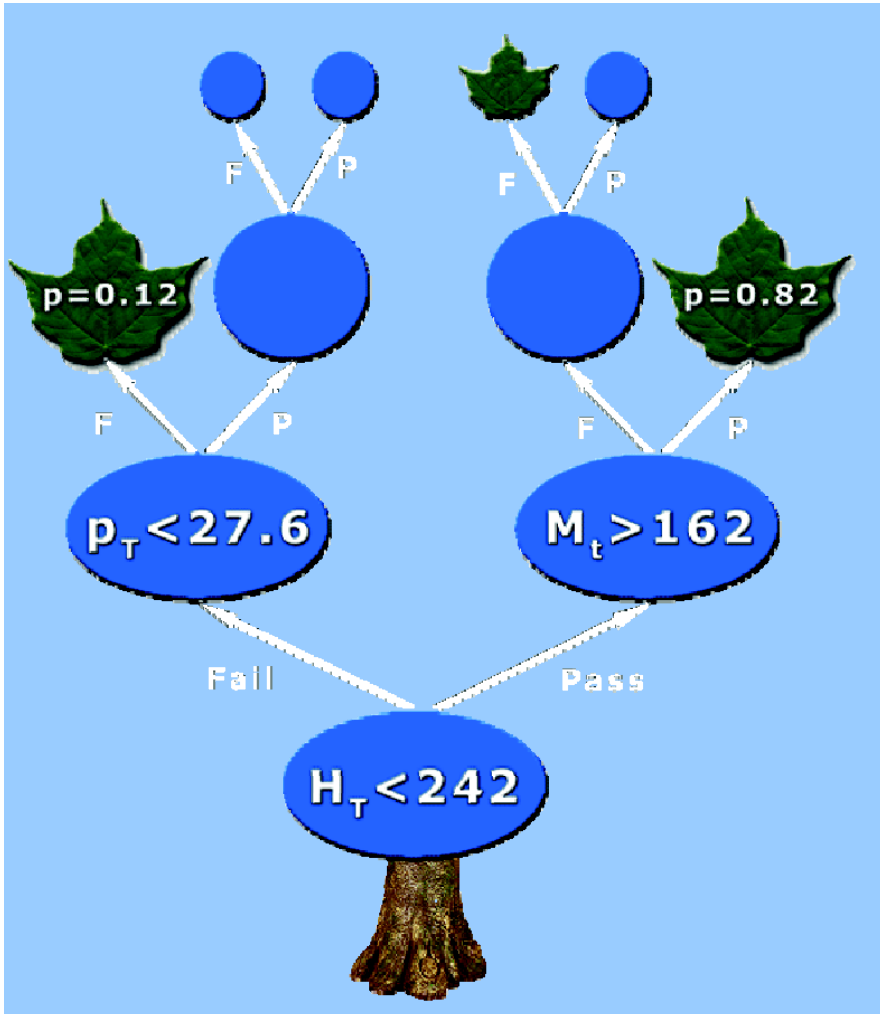






exp. Significance:	**4.5σ**
obs. Significance:	**3.4σ**

Boosted Decision Trees Analysis



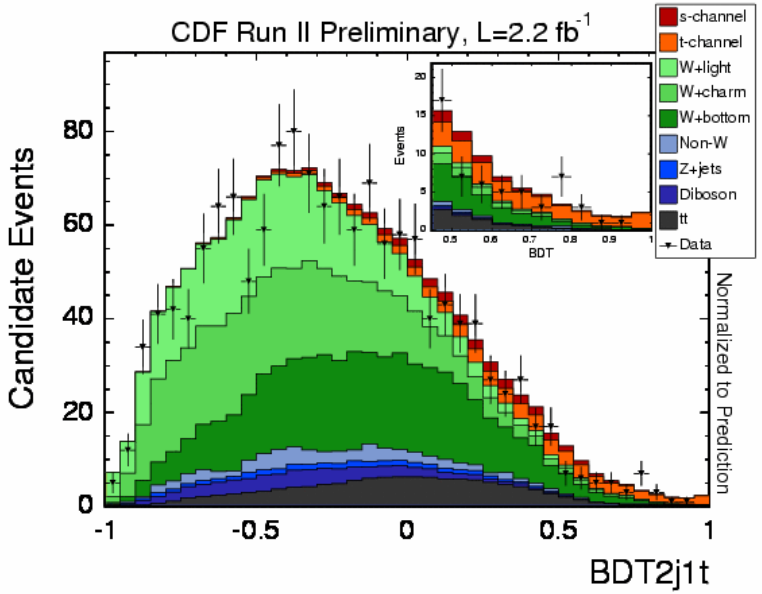
Use many input variables (>20), non-discriminating variables are automatically ignored, but don't degrade the performance

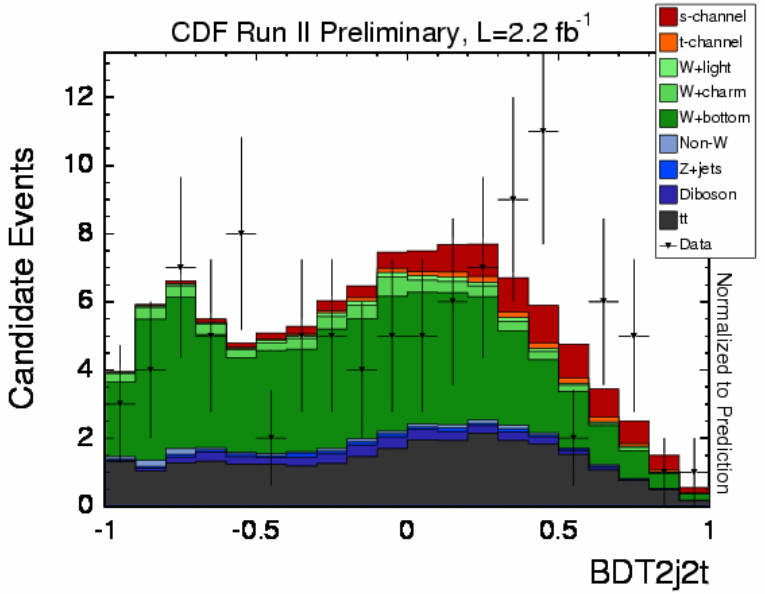
Optimize series of binary cuts with training sample

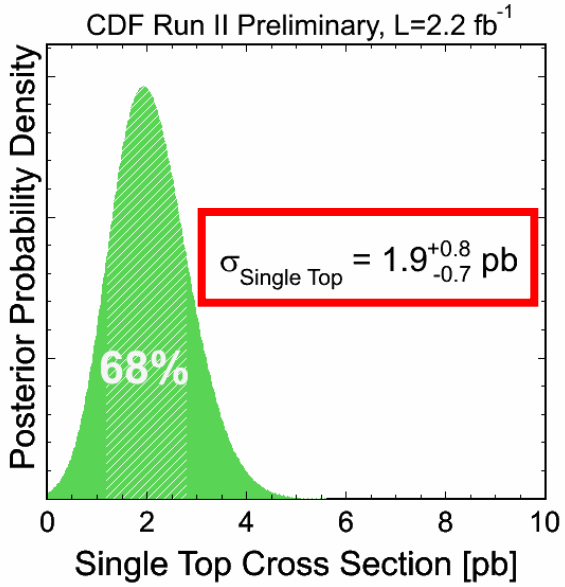
Calculate for each leaf purity
p = s/(s+b)
and sort events by output purity

Create series of “boosted“ trees by re-weighting based on value of misclassification

Boosted Decision Trees Analysis



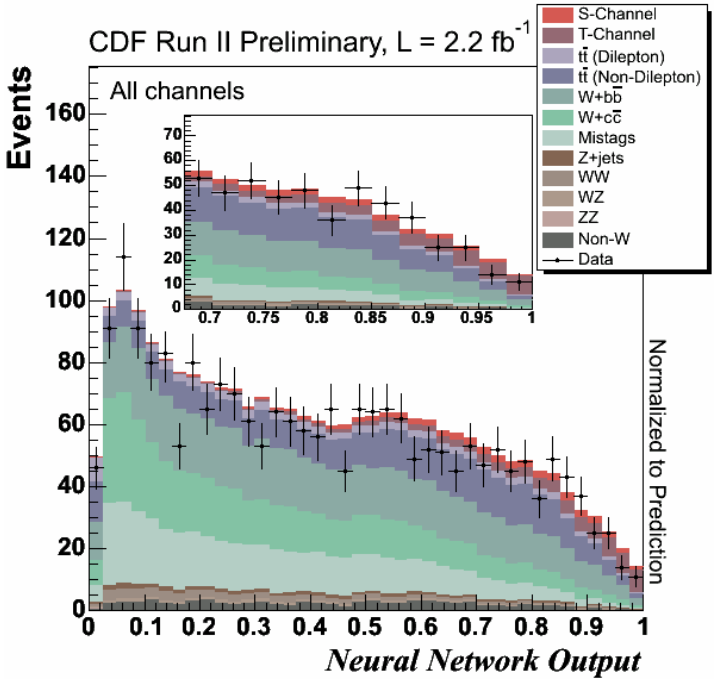


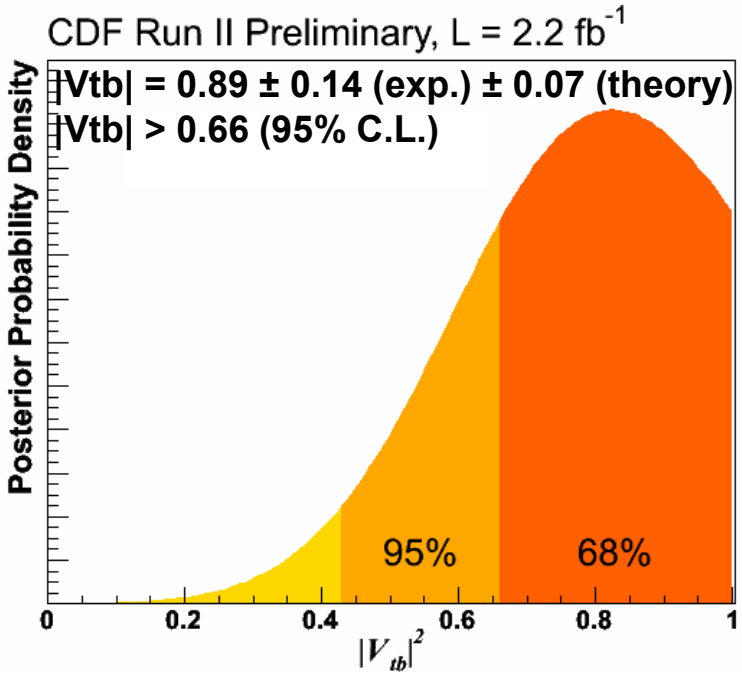


exp. Significance:	**4.6σ**
obs. Significance:	**2.8σ**

Combination of NN, LF, ME

Combine Neural Network, Likelihood Function, and Matrix Elements analyses discriminants in each channel as inputs to a neural network





Combination:
$\sigma_{\text{single-top}} = 2.2 \pm 0.7$ pb

B.L.U.E. cross check
$\sigma_{\text{single-top}} = 2.1^{+0.7}_{-0.6}$ pb

exp. Significance: 5.1σ
obs. Significance: 3.7σ

LF Separate s-channel Search

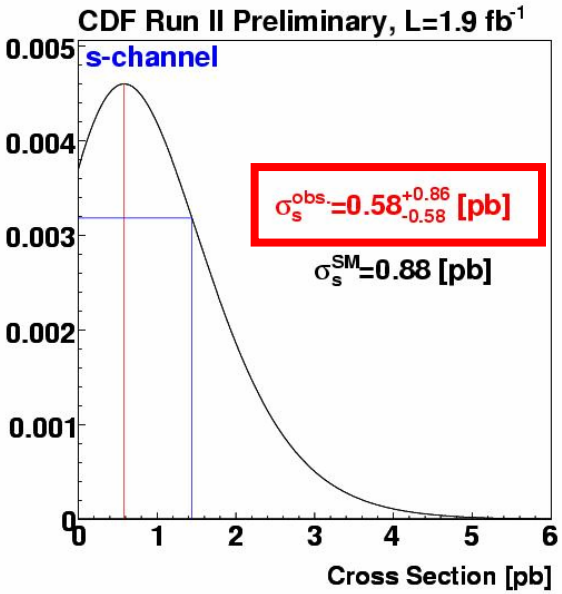
Use double b-tagged events with
- 2 secondary vertices
- 1 sec. vertex and a “loose” b-tag (jet probability tagger)

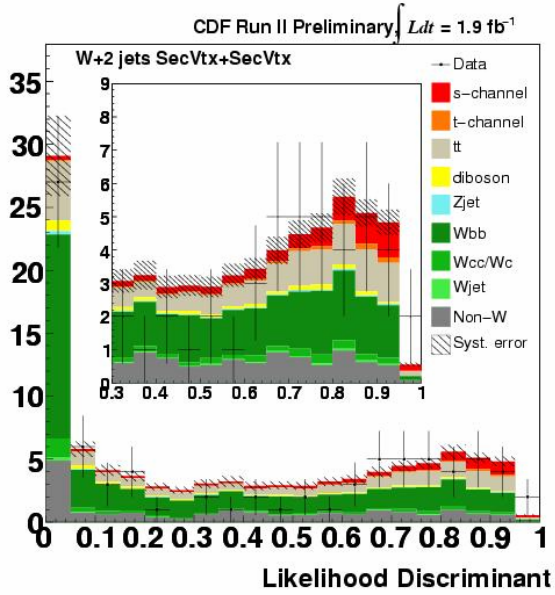
No QCD veto applied since QCD bkg small

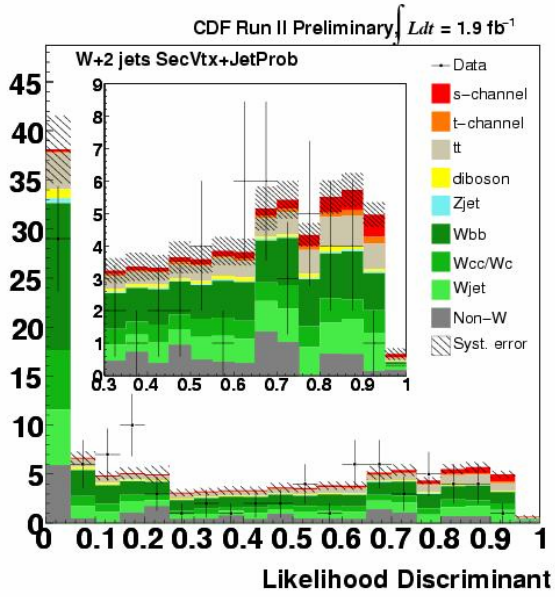
Use only W+2jet events, only 1.9 fb^{-1} of data

Use Likelihood function as multivariate analysis

Assume SM t-channel (very low)

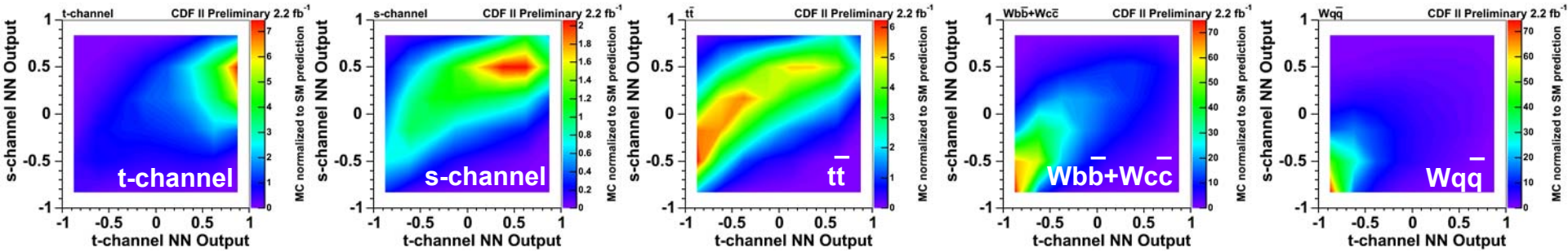




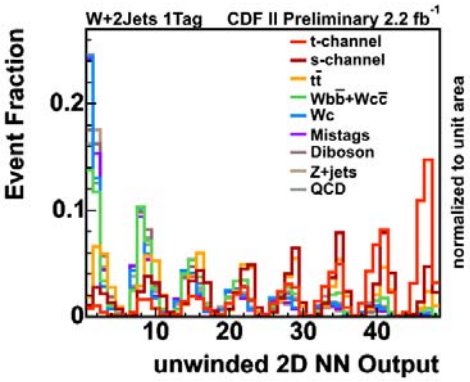


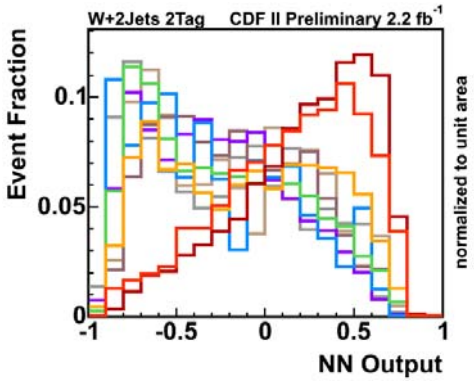
NN Separate s- and t-channel Search

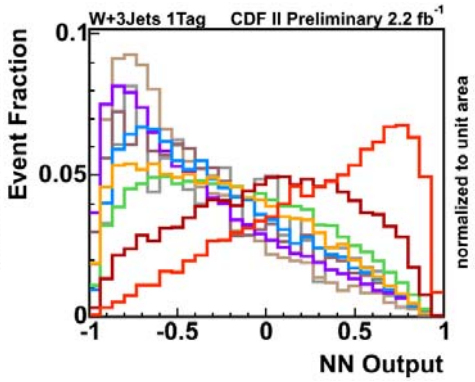
- Build t- and s-channel templates from the networks of the combined search for a 2 parameter likelihood fit to data
- Add an additional s-channel network in 2 Jets 1 Tag channel to build 2D discriminant apriori s-channel sensitivity improvement of ~15%

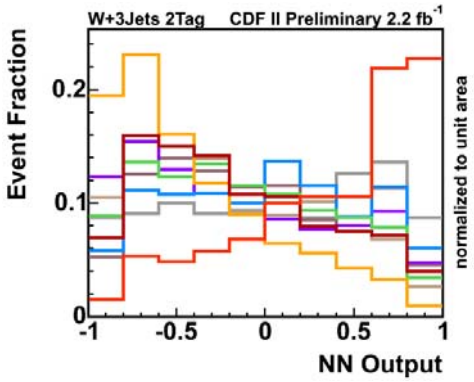


unwind 2D discriminant bin by bin

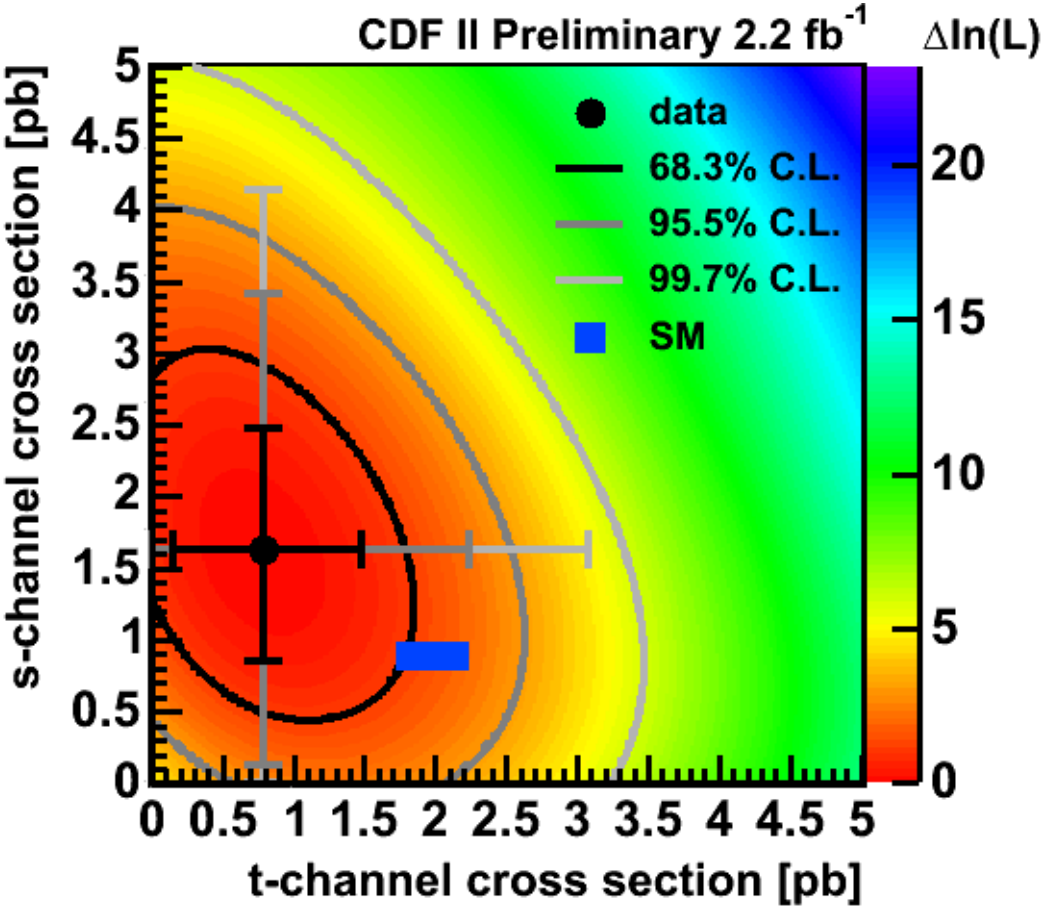






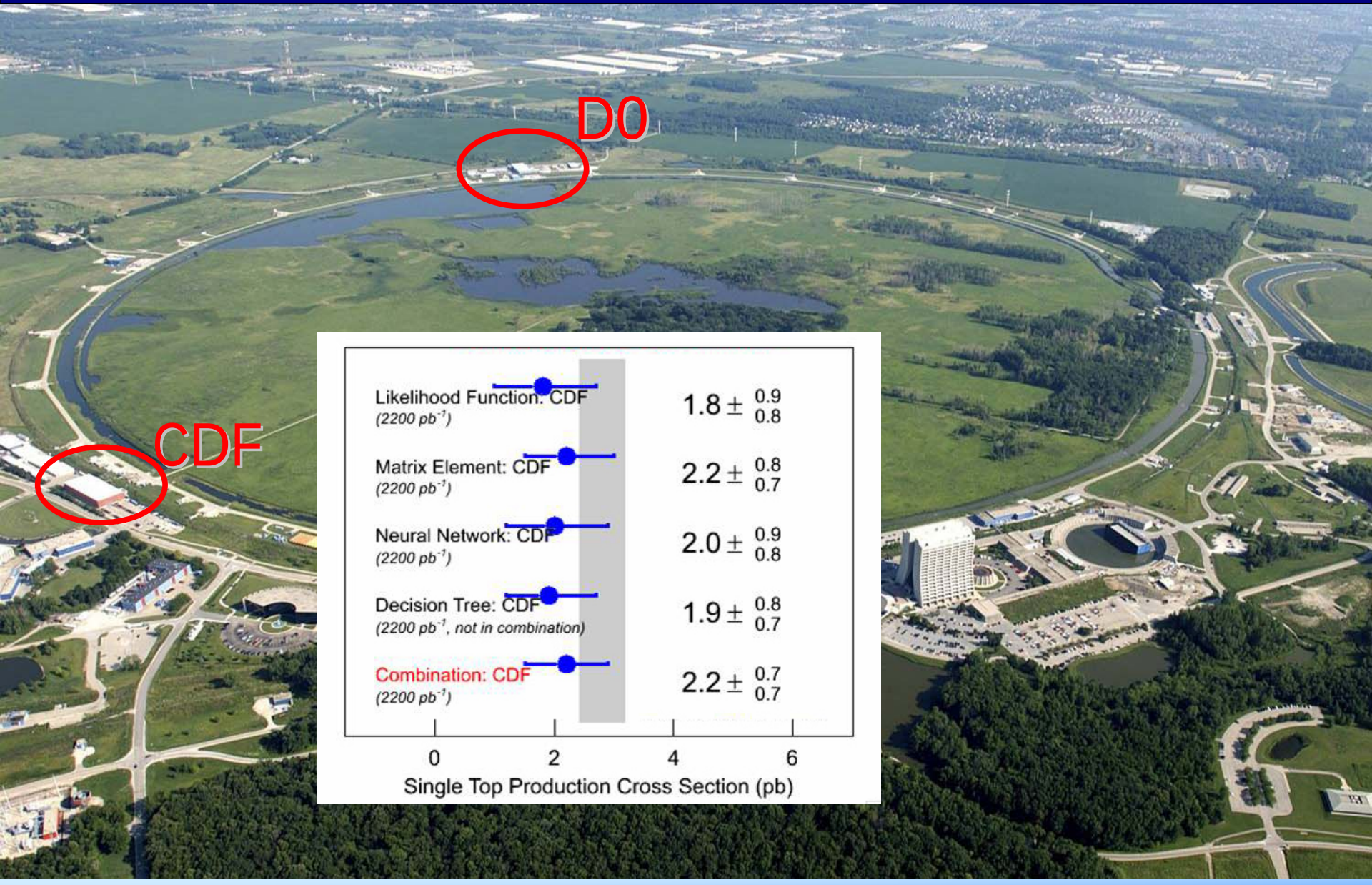


NN Separate s- and t-channel Search



$$\sigma_{\mathrm{t-channel}} = 0.8^{+0.7}_{-0.6}\,(\mathrm{stat.} + \mathrm{syst.})\ \mathrm{pb}$$
$$\sigma_{\mathrm{s-channel}} = 1.6^{+0.9}_{-0.8}\,(\mathrm{stat.} + \mathrm{syst.})\ \mathrm{pb}$$

Summary


D0
CDF
Likelihood Function: CDF
(2200 pb^{-1})
$1.8 \pm {}^{0.9}_{0.8}$
Matrix Element: CDF
(2200 pb^{-1})
$2.2 \pm {}^{0.8}_{0.7}$
Neural Network: CDF
(2200 pb^{-1})
$2.0 \pm {}^{0.9}_{0.8}$
Decision Tree: CDF
(2200 pb^{-1}, not in combination)
$1.9 \pm {}^{0.8}_{0.7}$
Combination: CDF
(2200 pb^{-1})
$2.2 \pm {}^{0.7}_{0.7}$
0
2
4
6
Single Top Production Cross Section (pb)