Single-Top-Quark Physics at CDF

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LPC Seminar, Clermont-Ferrand

September 19, 2008

Introduction

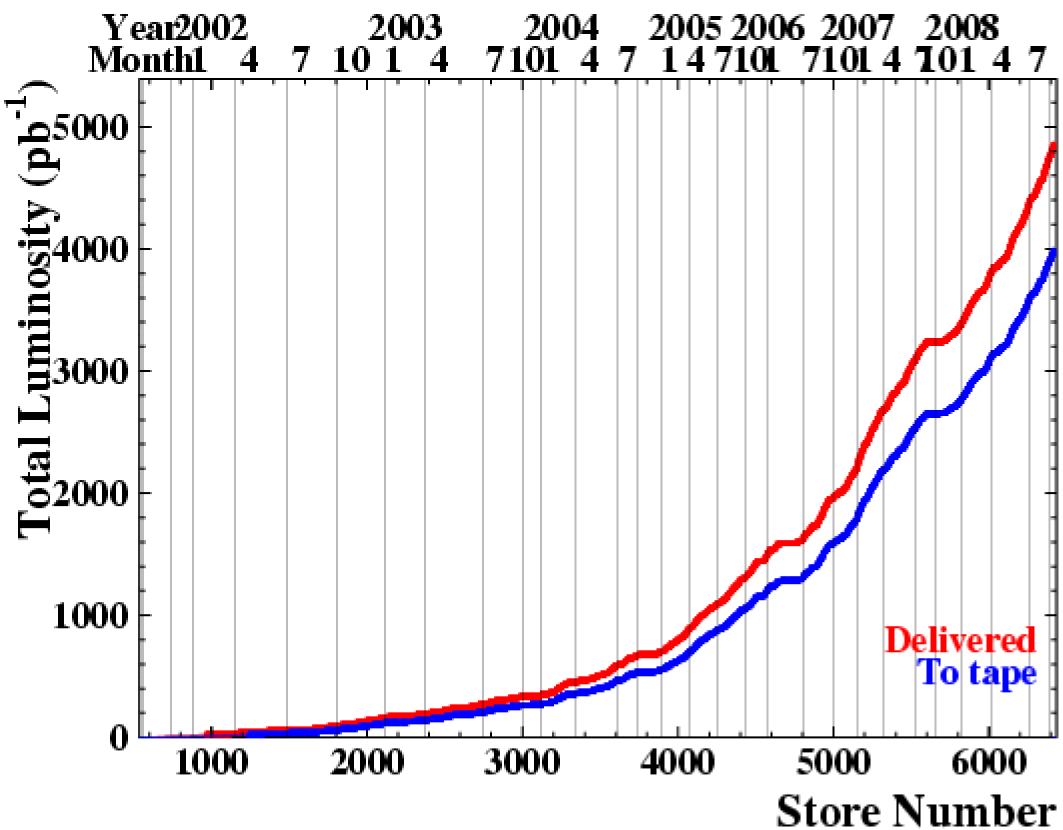
Multivariate techniques

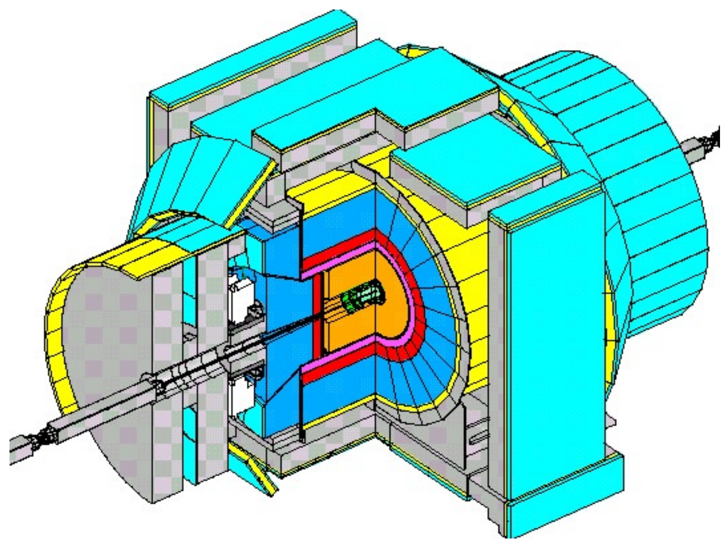
Cross section results

Beyond the SM searches

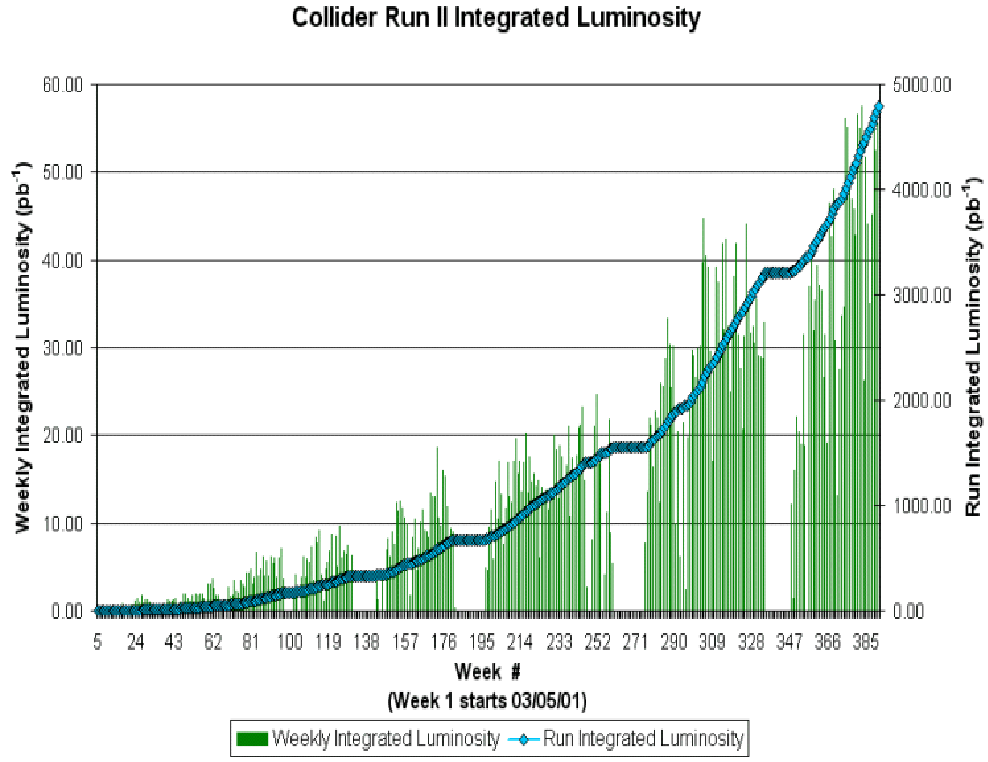
CDF at the Tevatron

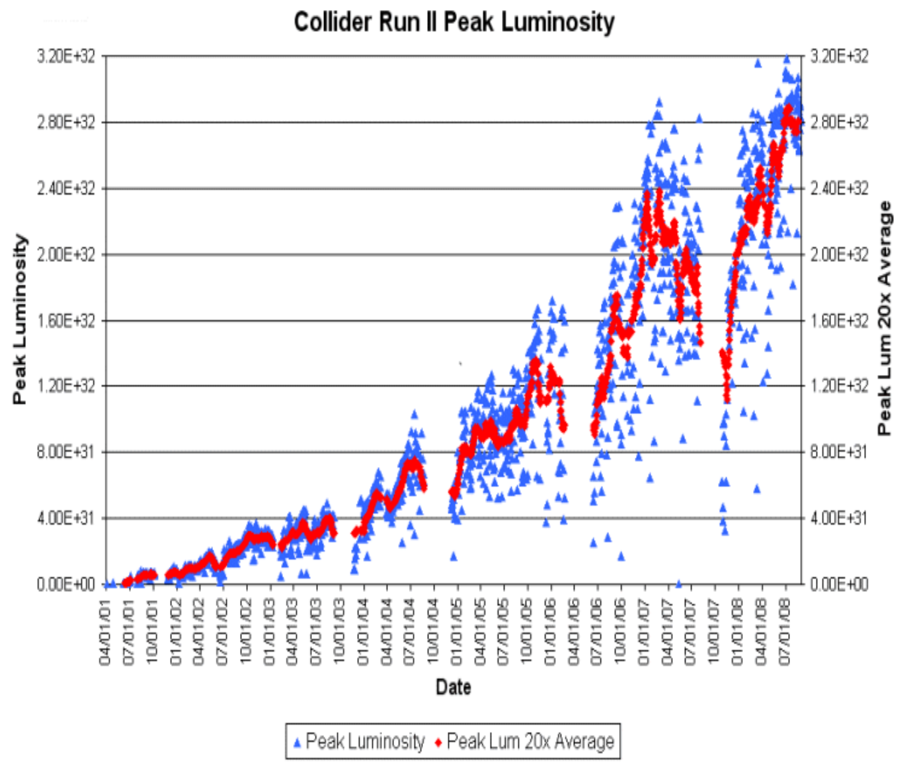
- Tevatron and CDF performance:
  - CDF recorded 4 fb^{-1}
  - Today's analyses use up to 2.7 fb^{-1}





Tevatron Luminosity



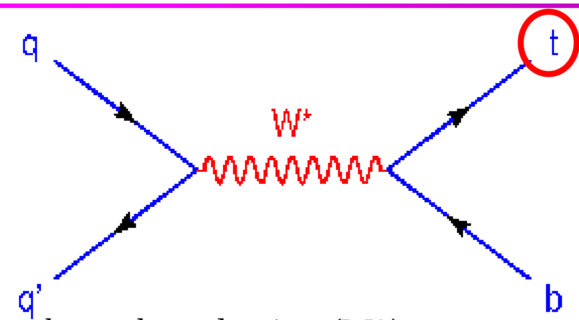


Single Top Production

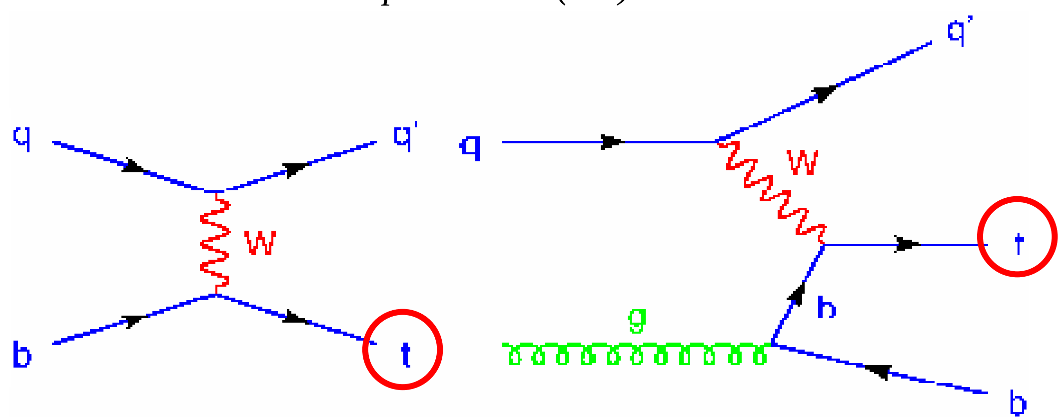
- At the Tevatron, top quarks are:
  - Mostly produced in pairs (7pb):
    - qq annihilation (85%)
    - gg fusion (15%)
  - Also electroweak (single-top):
    - s-channel
    - t-channel
    - Wt associated production
      - **0.3pb; neglected**

Evidence D0: PRL 98 18102 (2007)

Evidence CDF: arXiv 0809.2581 (2008)



s-channel production (W)*



t-channel production (Wg fusion)

$s^{1/2}$ =*1.96TeV*	NLO Cross-sections
t-channel	1.98±0.25 pb
s-channel	0.88±0.11 pb

M_{top} = 175 GeV/c^2

B.W. Harris et al.: Phys. Rev. D 66, 054024, Z. Sullivan hep-ph/0408049

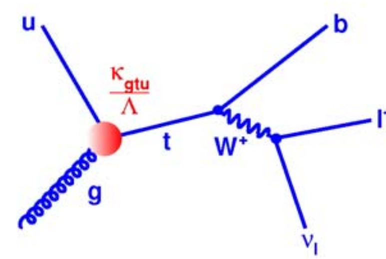
Compatible results: Campbell et al, Phys. Rev. D 70, 094012 (2004).
N. Kidonakis, Phys.Rev. D 74, 114012 (2006)

Motivation

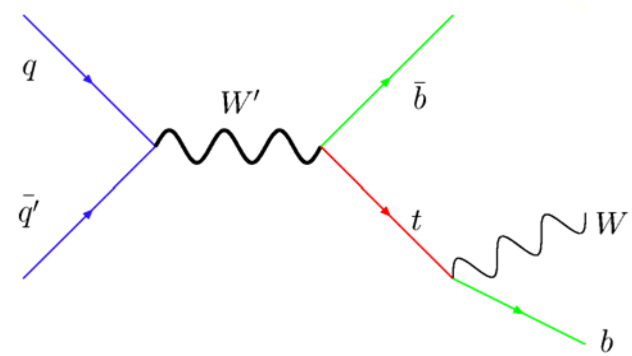
- Predicted by SM – we should observe it:
  - Cross section $\propto |V_{tb}|^2$
  - Test the unitarity of the CKM matrix
    - 4^{th} generation needed?
  - Source of ~100% polarized top quarks
  - Test of b quark structure function: DGLAP evolution

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

- Prerequisite for an intermediate mass Higgs at the Tevatron
  - WH with $H \to b\bar{b}$ has similar final state
  - Background estimation is crucial



- Test of several new physics phenomena:
  - Flavor-changing neutral currents: *tug*, *Ztc*, etc
  - Heavy *W'* (or charged Higgs) production
  - Anomalous *W-t-b* couplings
  - …

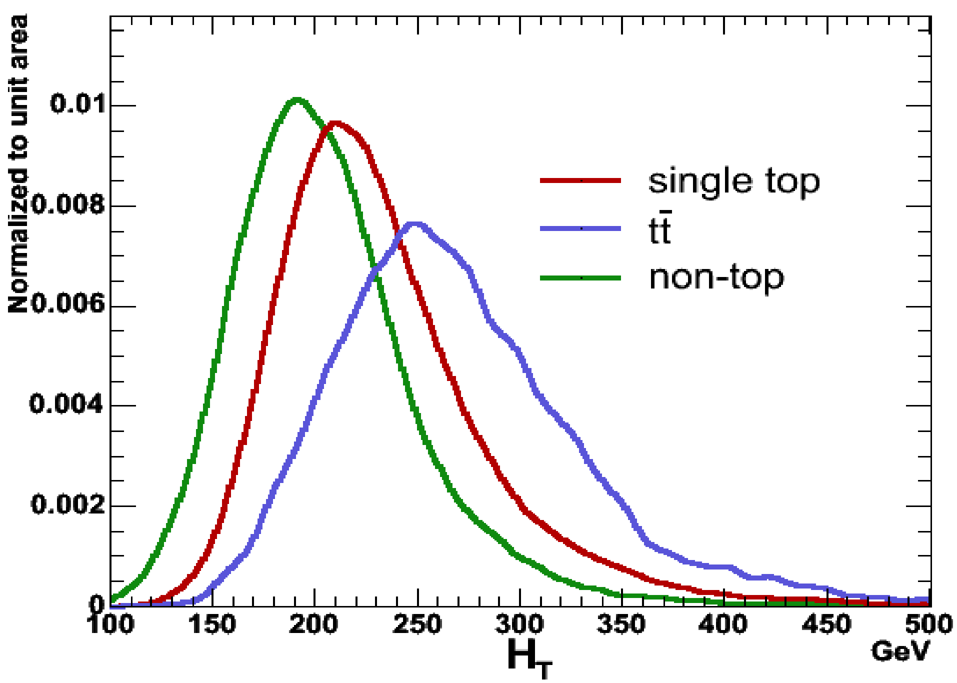


Why is it Challenging?

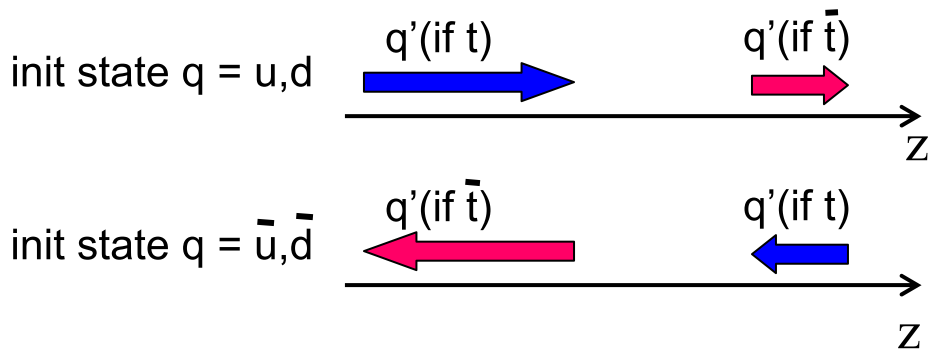
- Small cross section 3 pb – not the main problem!
- Huge backgrounds. In 1 fb^{-1}:
  - $W \to \ell\nu$ + 2 jets S/B=1/200, S/√B = 0.6
  - $W \to \ell\nu$ + 2 jets +≥1btag: S/B=1/15, S/ √B = 1.5 (S~40, B~600)
  - *$W \to \ell\nu$ + 2 jets +≥1btag + discrim: S/B=1/3, S/ √B = 2.5*

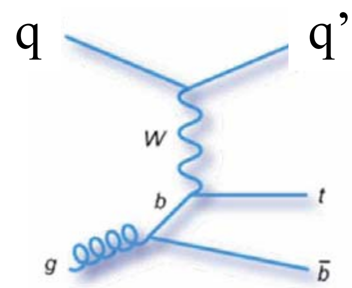
- Backgrounds:
  - *W*+heavy flavor (*Wbb, Wcc, Wc*)
  - *W*+light flavor (mistags)
  - Diboson, *Z*-decays, non-*W*
  - Top pair production

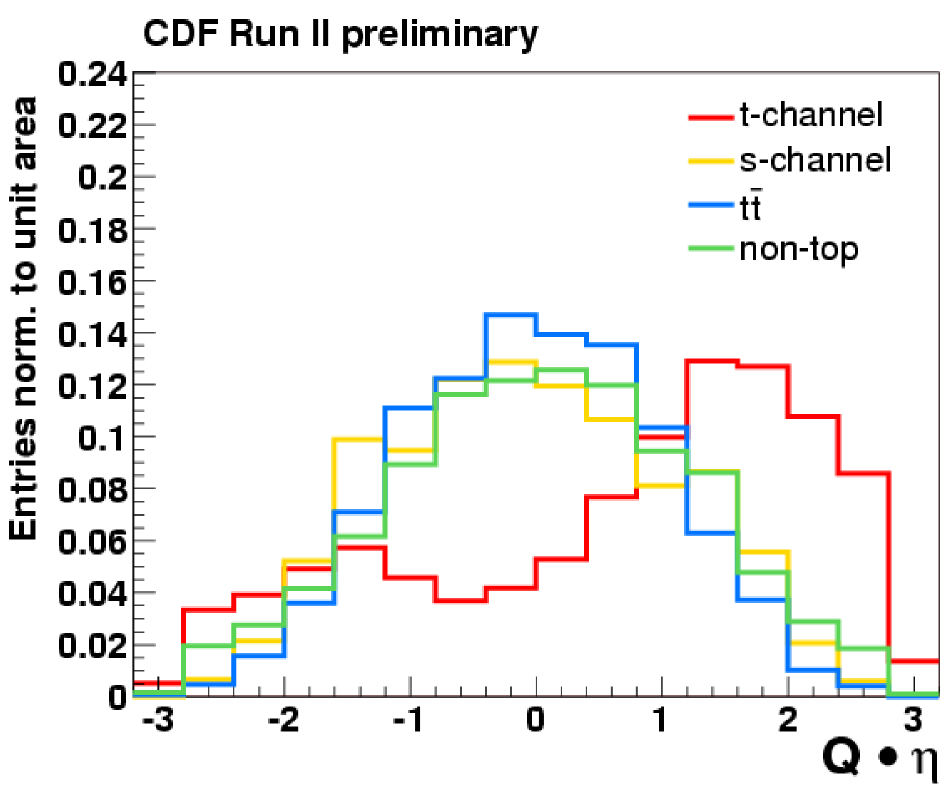
- Signal MC modeling:
  - MadEvent+Pythia ~NLO

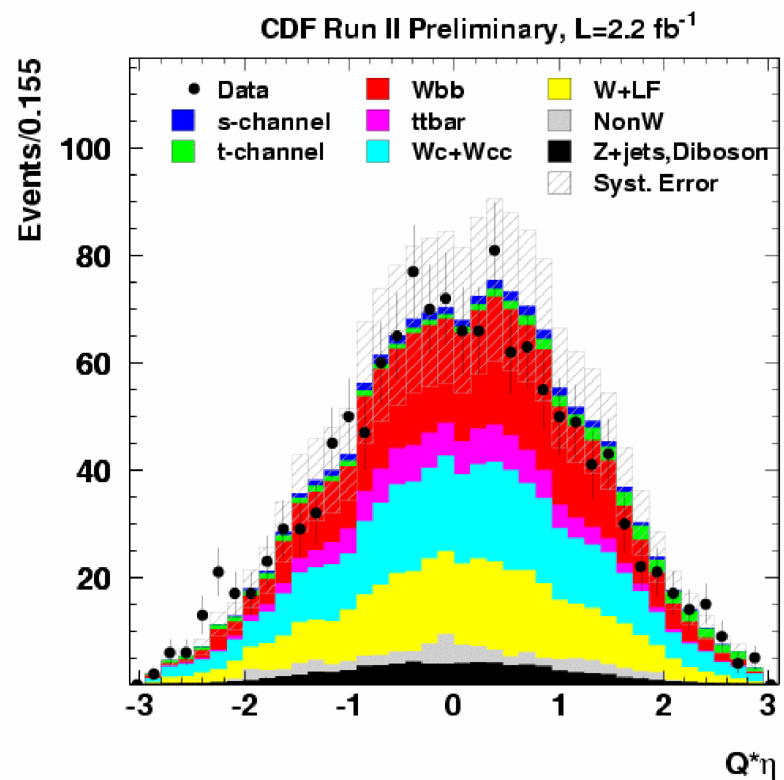


Angular variables









CDF Analyses

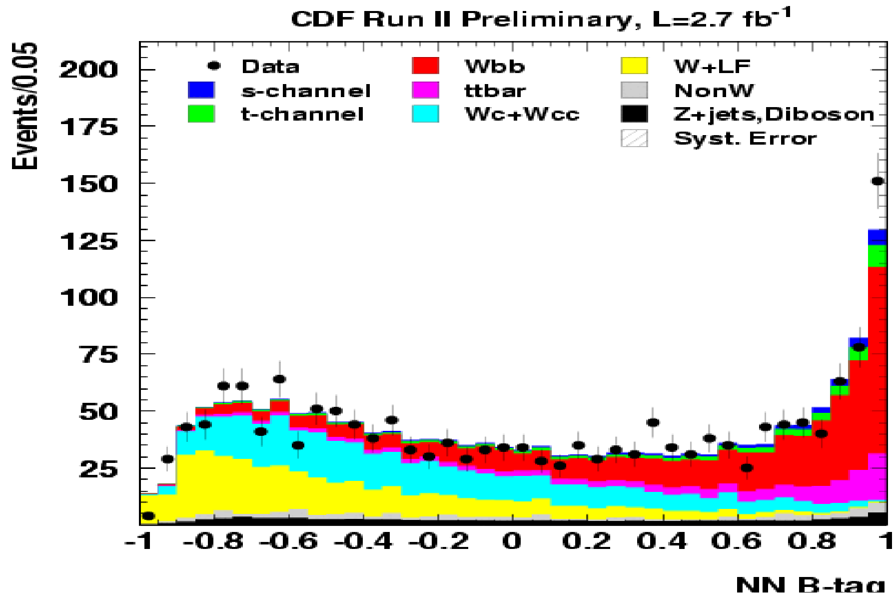
- Three most recent analyses (2.7 fb^{-1})
  - Likelihood Function
    - t-channel
    - s-channel (extended double tag sample)
  - Matrix Element
  - Neural Networks
  - Boosted Decision Trees
  - All 4 analyses use common selection criteria (same dataset and MC samples)

- Select events with basic features expected of single top events
  - A high-P_T lepton (20 GeV or more)
  - Large Missing-E_T (25 GeV or more)
  - Two or more jets (typically 20 GeV or more) -- Use high-η jets!
  - One or more b-tags
  - Veto $Z \rightarrow$leptons, cosmics, conversions

CDF Analyses

- Three most recent analyses (2.7 fb^{-1})
  - Multivariate Likelihood Function
    - t-channel
    - s-channel (extended double tag sample)
  - Matrix Element
  - Neural Networks
  - Boosted Decision Trees
  - All 4 analyses use common selection criteria (same dataset and MC samples)
  - *Combination of the analyses in progress*

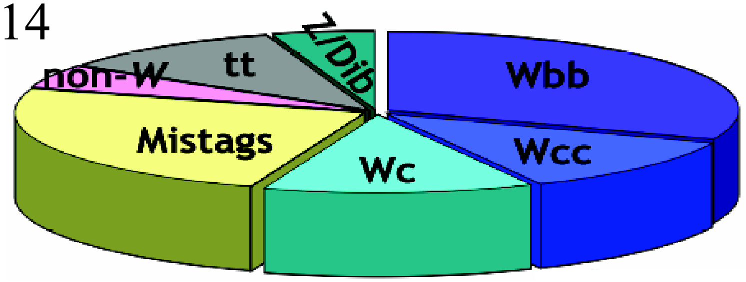
- All analyses use a neural networks b-tag extension
- NN b-tagger applies to secondary vertex tags; uses information such as:
  - Vertex mass, decay length, number of tracks, etc.



Event Yield

Process	Two-jet events	Three-jet events
s-channel	49.3 ± 7.0	16.3 ± 2.3
t-channel	74.3 ± 10.9	22.3 ± 3.2
W+bottom	549.1 ± 165.5	169.8 ± 51.3
W+charm	453.5 ± 139.9	126.7 ± 39.0
W+light	410.7 ± 51.0	125.5 ± 15.8
tt-bar	173.5 ± 24.8	410.5 ± 58.4
Diboson/Z+jets	105.6 ± 12.1	39.0 ± 4.6
Non-W	75.6 ± 30.2	27.4 ± 11.0
Total prediction	1891.6 ± 312.4	937.5 ± 108.3
Observed	1874	902

S/B(2j)=1/14



S/B (3j)=1/24

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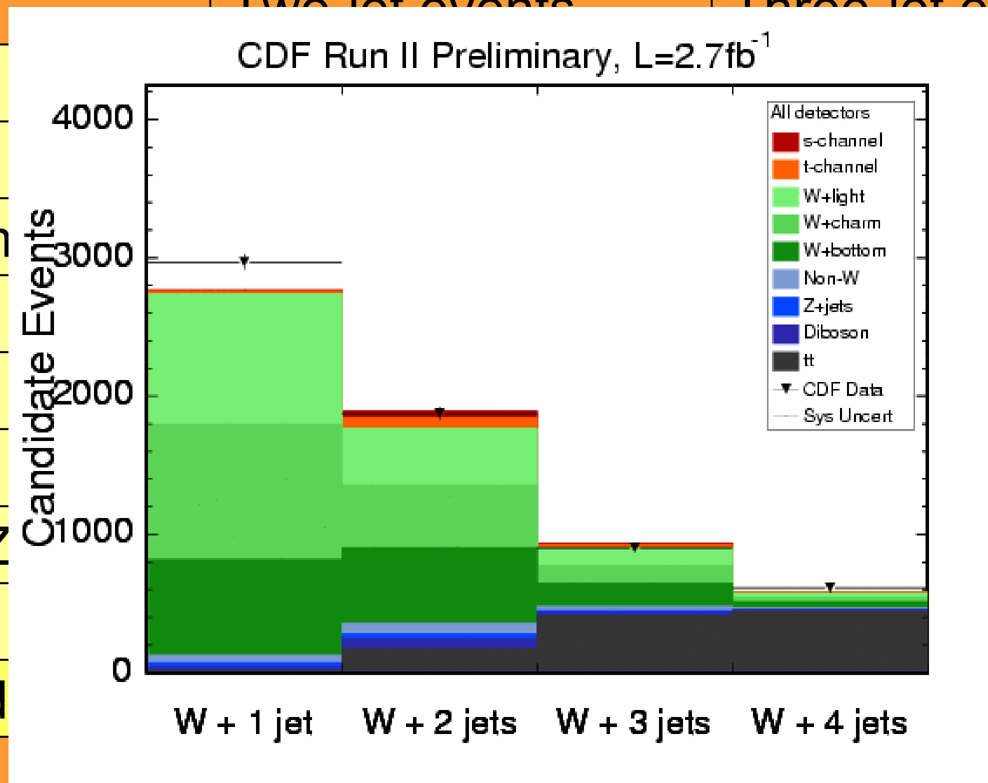
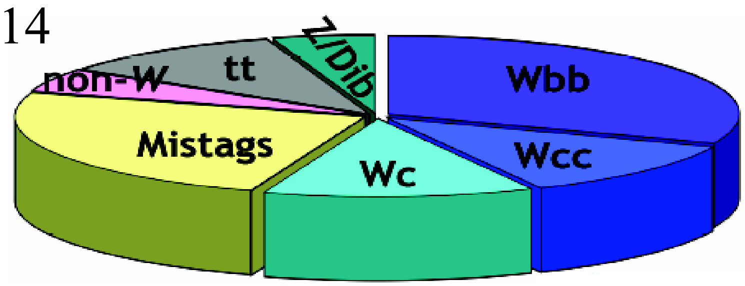
Event Yield

Process	Two jet events	Three jet events
s-channel		
t-channel		
W+bottom		3
W+charm		0
W+light		8
tt-bar		4
Diboson/Z		
Non-W		
Total pred		3.3
Observed		



S/B(2j)=1/14

S/B (3j)=1/24



LF analysis

- Single Top signature: W(e,μ+MissET) and 2/3 tight jets, ≥1b-tag

- The Problem: Jet Energies not Well-Measured
  - $\not{E}_T$ imprecisely measured
  - Ambiguities in:
    - choosing the Pz(ν) solution
    - choosing b quark from top decay (s-channel)
- Use a χ^2 in which we float P_b, $E_T\,\nu$, $\Phi\nu$
  - central values = measured values
  - uncertainties derived from HEPG comparisons with reconstructed values

$$\chi^2 = \frac{(P_b - P_b^{obs})^2}{\sigma_{P_b}^2} + \frac{(\not{E}_T - \not{E}_T^{obs})^2}{\sigma_{\not{E}_T}^2} + \frac{(\not{\Phi}_\nu - \not{\Phi}_\nu^{obs})^2}{\sigma_{\not{\Phi}_\nu}^2} + \frac{(M_{\ell\nu b} - M_t)^2}{\sigma_{M_t}^2} + Y(\mathrm{Im}(P_z))^2$$

- Without looking at the b-tag, minimize χ^2 under four scenarios
  - 2 choices of which jet is labeled 'b from top decay'
  - 2 neutrino solutions

LF variables

Form a combined probability:

i: variable index, k: sample index (s or t) ji: histogram bin

Four background classes used: Wbb, tt, Wcc/Wc and mistags

$$p_{ik} = \frac{f_{ij_ik}}{\sum_{m=1}^{5} f_{ij_ik}}$$

$$\mathcal{L}_k(\{x_i\}) = \frac{\prod_{i=1}^{n_{var}} p_{ik}}{\sum_{m=1}^{5} \prod_{i=1}^{n_{var}} p_{im}}$$

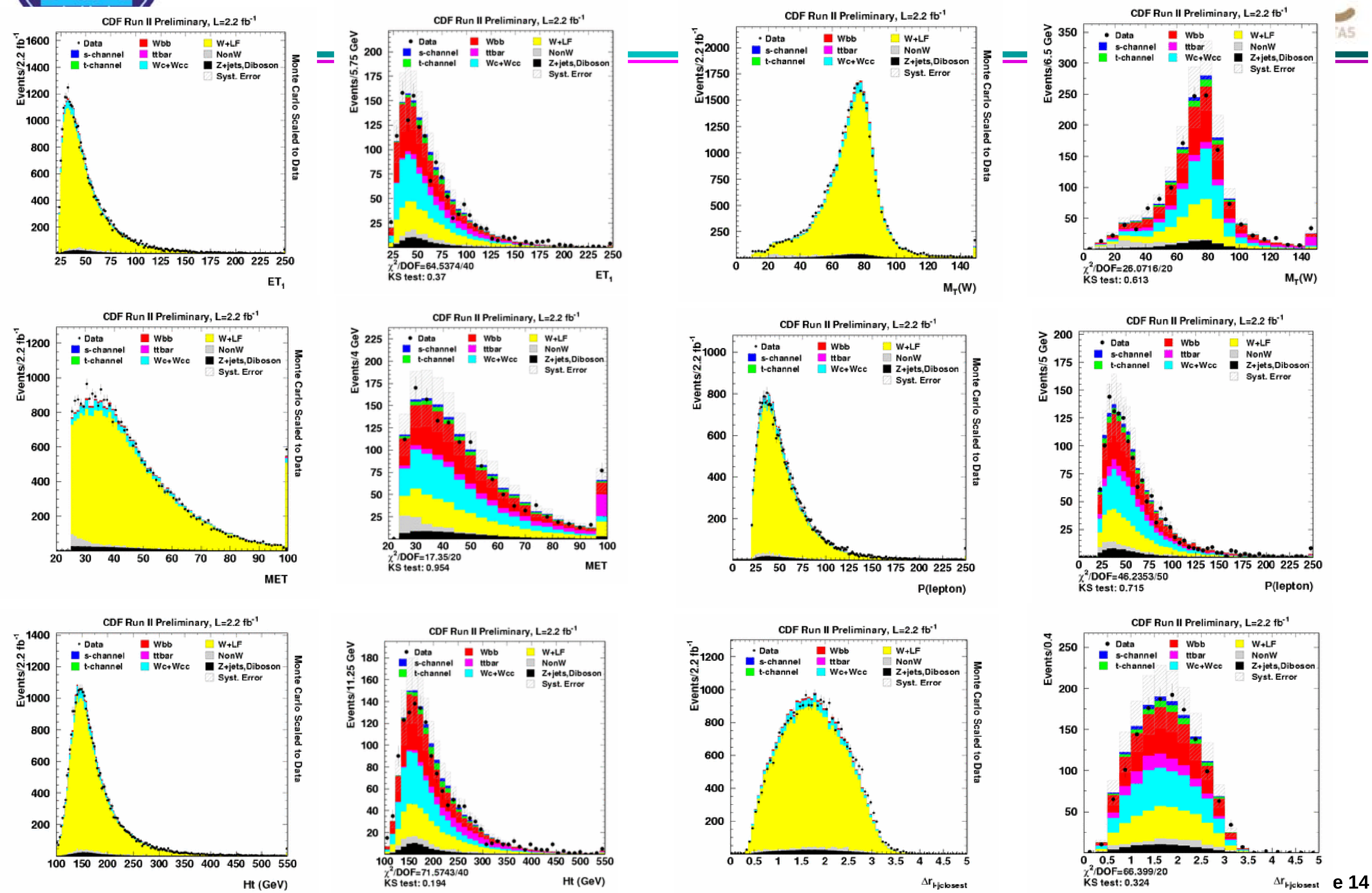
t-channel LF Variables:

- H_T
- χ^2 from kinematic fitter
- $\cos\theta_{lepton,other\text{-}jet}$ in top decay frame
- $Q^*\eta$
- m_{jj}
- $\log(ME_{t\text{-}chan})$ from MADGRAPH
- NN(b); Neural Net b-tag output
- 3 jet variables similar

s-channel LF Variables:

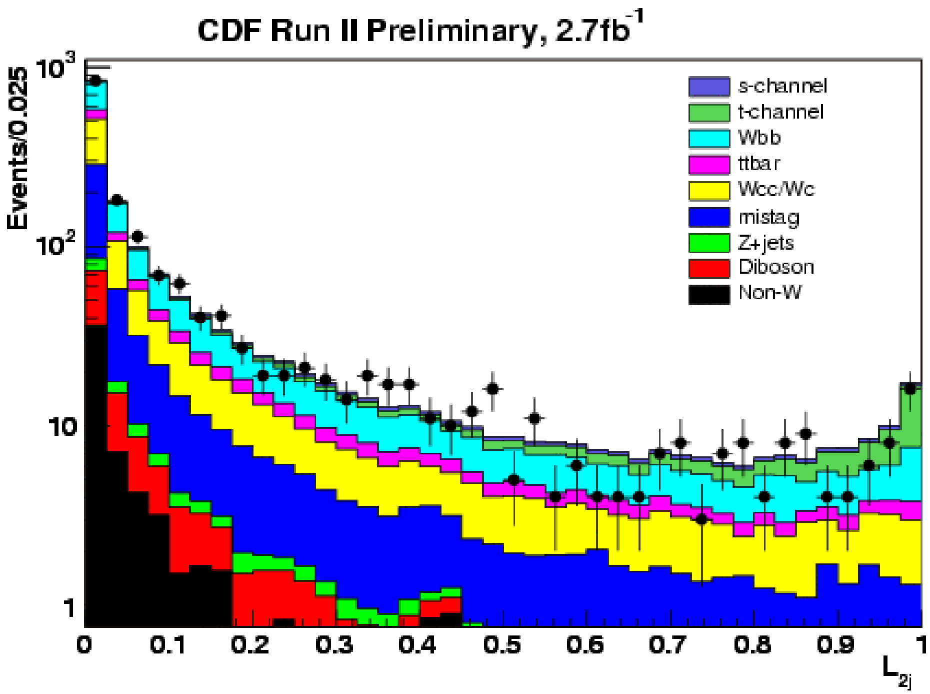
- Mlνb(hybrid,s-chan)
- log(HT*Mlνb)
- E_T(jet 1)
- log(MEt-chan)
- HT
- NN(b)

Checks…

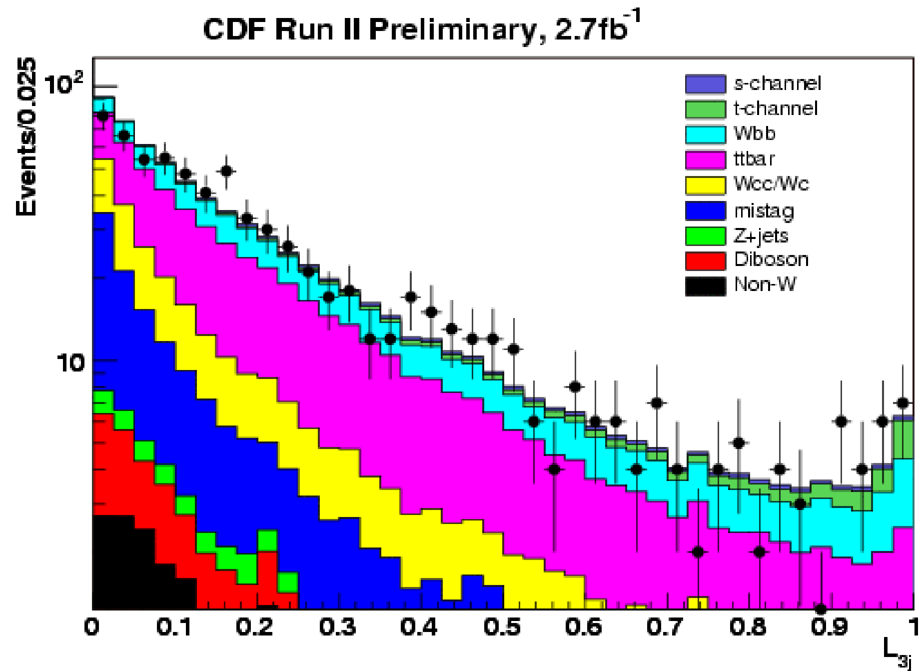

CDF Run II Preliminary, L=2.2 fb^{-1}
Data
s-channel
t-channel
Wbb
ttbar
Wc+Wcc
W+LF
NonW
Z+jets,Diboson
Syst. Error
Monte Carlo Scaled to Data
Events/2.2 fb^{-1}
ET$_1$
Events/5.75 GeV
χ^2/DOF=64.5374/40
KS test: 0.37
M$_T$(W)
Events/6.5 GeV
χ^2/DOF=26.0716/20
KS test: 0.613
MET
Events/4 GeV
χ^2/DOF=17.35/20
KS test: 0.954
P(lepton)
Events/5 GeV
χ^2/DOF=46.2353/50
KS test: 0.715
Ht (GeV)
Events/11.25 GeV
χ^2/DOF=71.5743/40
KS test: 0.194
$\Delta r_{l\text{-}jclosest}$
Events/0.4
χ^2/DOF=66.399/20
KS test: 0.324

Data. t-chan LF

2-jet t-chan discriminant



3-jet t-chan discriminant

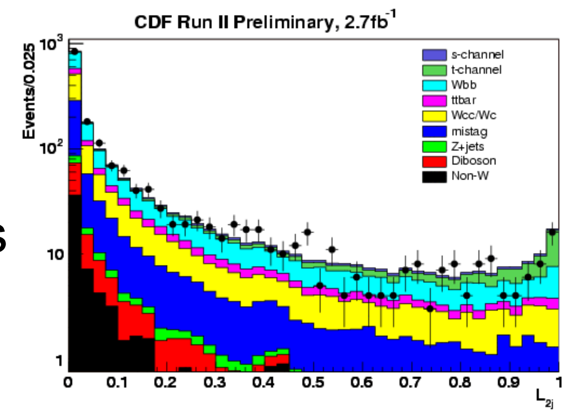


SM predictions shown -- no fitting is done.
Slight deficit seen in the signal region

P-value:
2.6σ obs
3.8σ median expected

Test Statistic

- CL_s method used in Higgs searches at LEP
- Test between two hypotheses:
  - H1: Data is described by signal and backgrounds
  - H2: Data is described by backgrounds only.



- Poisson probabilities:

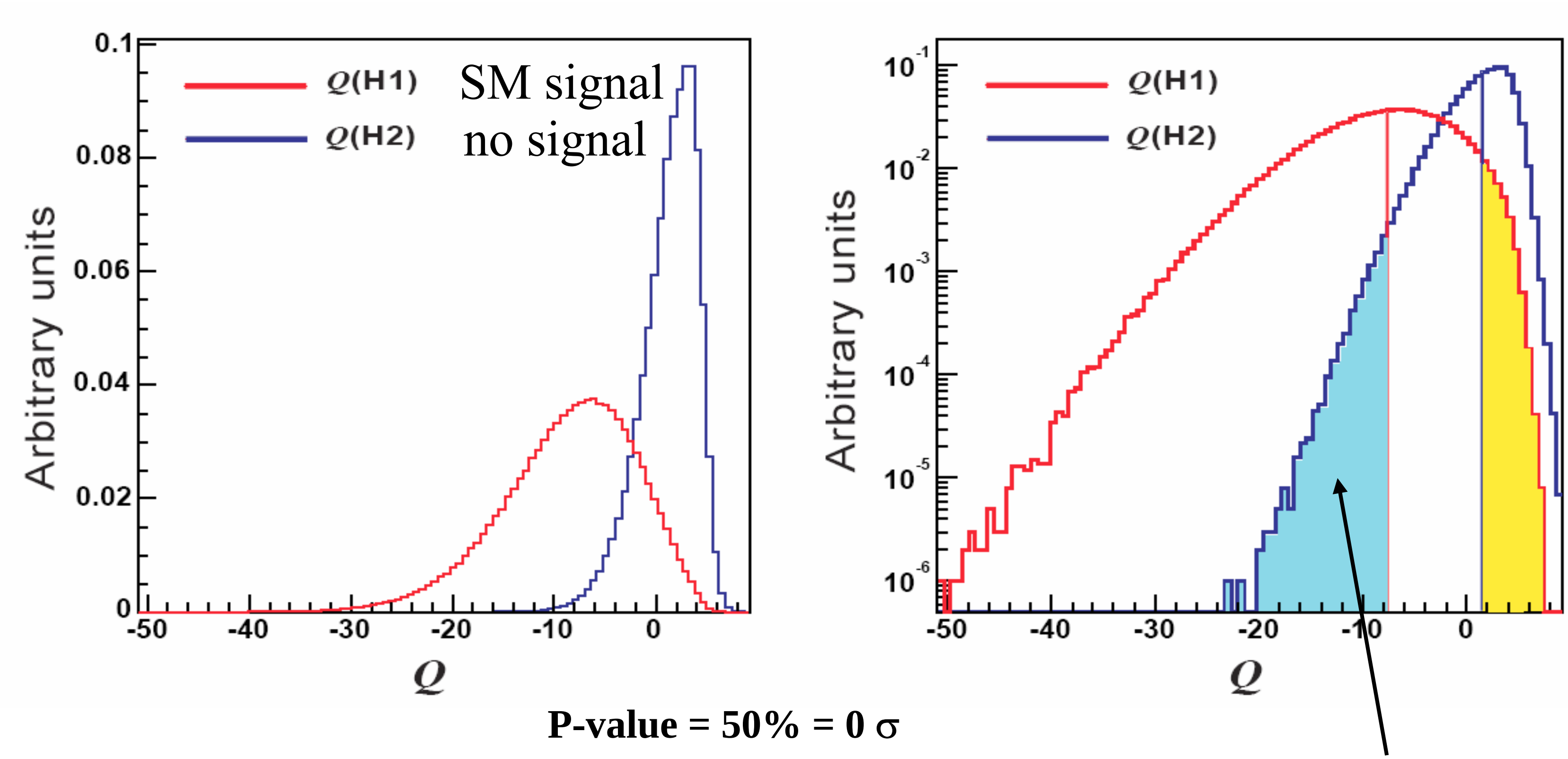
$$P(data \mid H1) = \prod_{i=i}^{N_{bins}} P^i = \prod_{i=1}^{N_{bins}} \frac{\mathbf{e}^{n_i^{H1}} \cdot (n_i^{H1})^{d_i}}{d_i!}$$

- Test statistics $Q = -2\log[P(data|H1)/P(data|H2)]$

$$Q = const - 2 \cdot \sum_{i=1}^{N_{bins}} d_i \ln \frac{n_i^{H1}}{n_i^{H2}}$$

Statistical Method

Exclusion (yellow) and Discovery (blue)



P-value = 50% = 0 σ

P-value = 5% = 1.6 σ

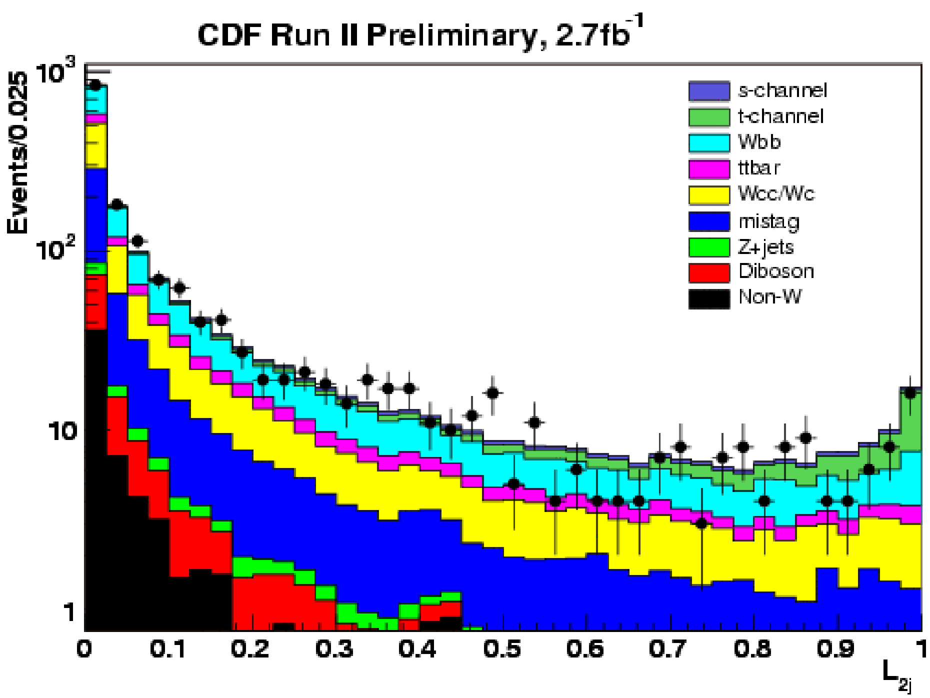
P-value = 1% = 2.3 σ

P-value = 0.1% = 3.1 σ

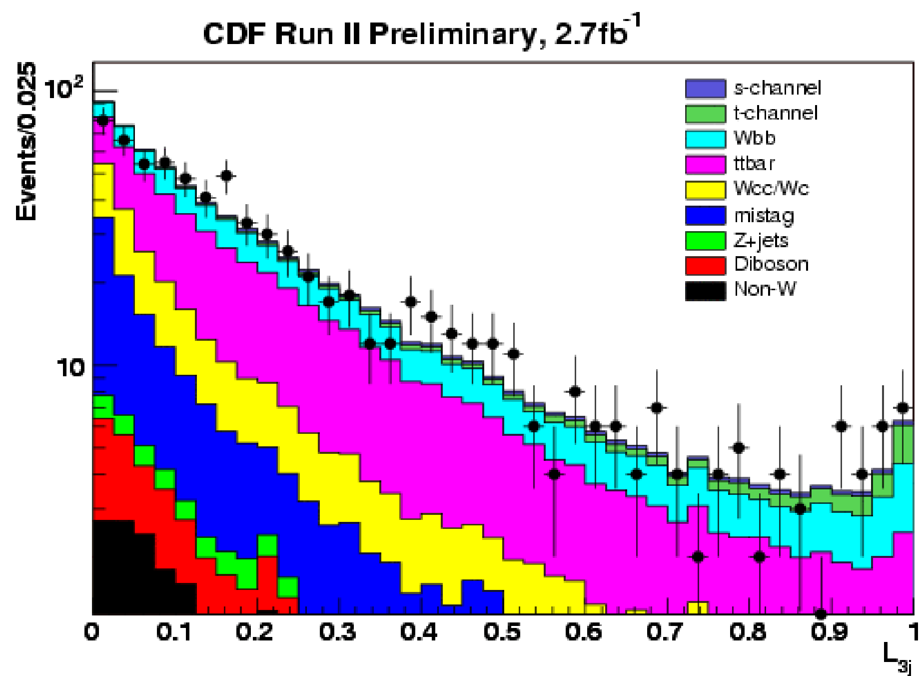
p-value: smaller is better

Data. t-chan LF

2-jet t-chan discriminant



3-jet t-chan discriminant

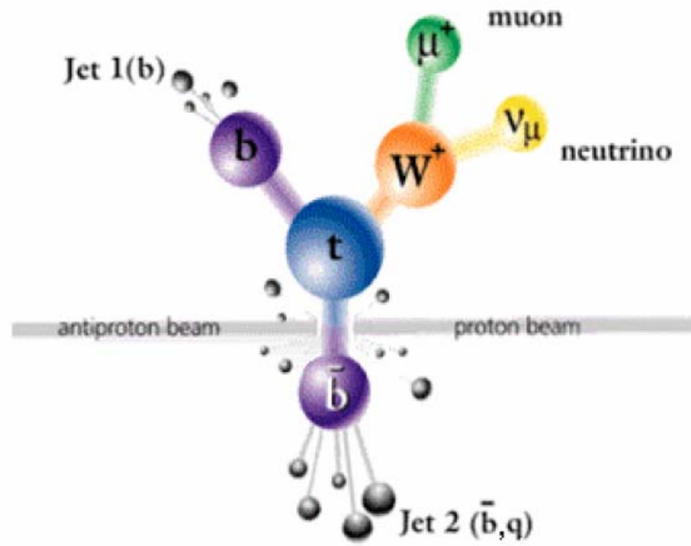


SM predictions shown -- no fitting is done.
Slight deficit seen in the signal region

P-value:
2.6σ obs
3.8σ median expected

Matrix Element Analysis

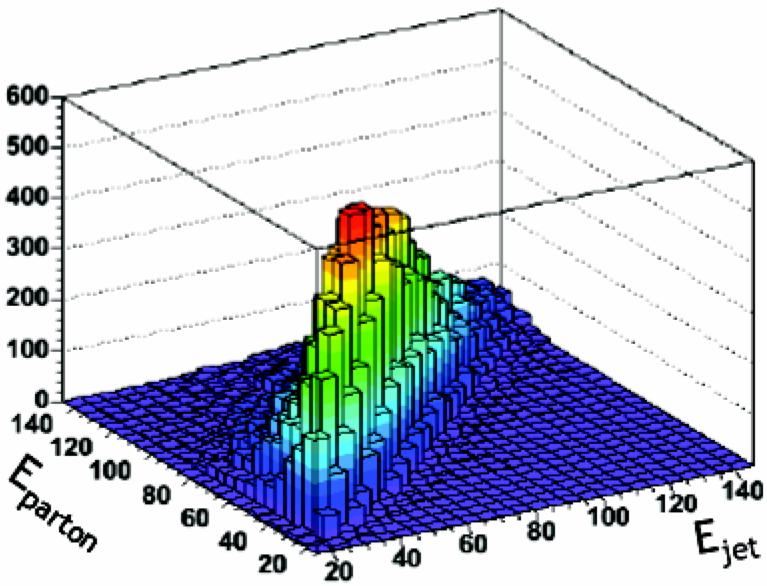
- s-channel and t-channel probabilities:
  - $2(in) + 12(final) = 14$ degrees of freedom
  - $3(e) + 4$(jet angles) $+ 3(P_{in}=P_{fin}) + 1(E_{in}=E_{fin}) = 11$ constraints
  - $14 - 11 = 3$ integrals => Integrate over neutrino p_z and jet energy of both jets
  - Change variables $p_z \rightarrow m_W$ because $|M|^2$ is almost negligible, except near the Breit-Wigner poles
  - Both neutrino solutions are considered at each integration step and sum over 2 combinations of jets



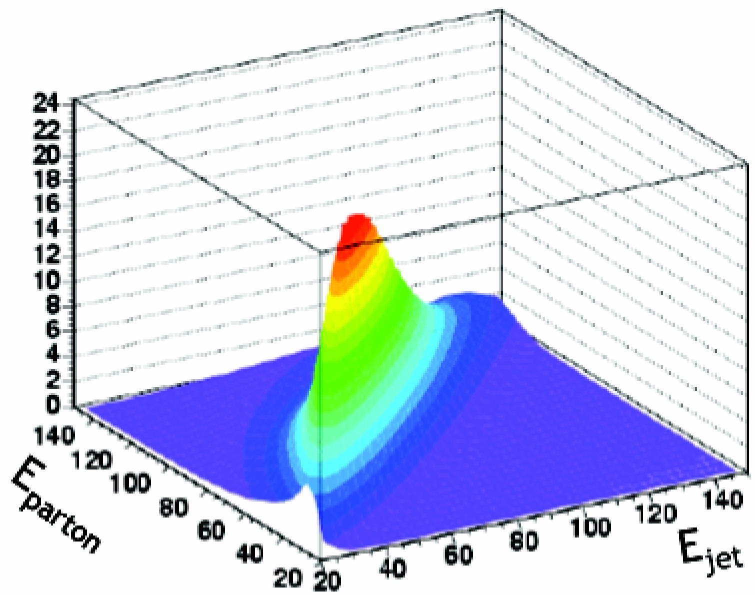
$$P(x,\alpha) = \frac{1}{\sigma} \int d\rho_b d\rho_{\bar{b}} dm_W^2 \sum_{comb,\nu} |M(\alpha)|^2 \frac{f(q_1)f(q_2)}{|q_1||q_2|} \phi_4 W_{jet}(x,y)$$

Transfer Functions

Full simulation vs parton energy:



Double Gaussian parameterization:



Double Gaussian parameterization:

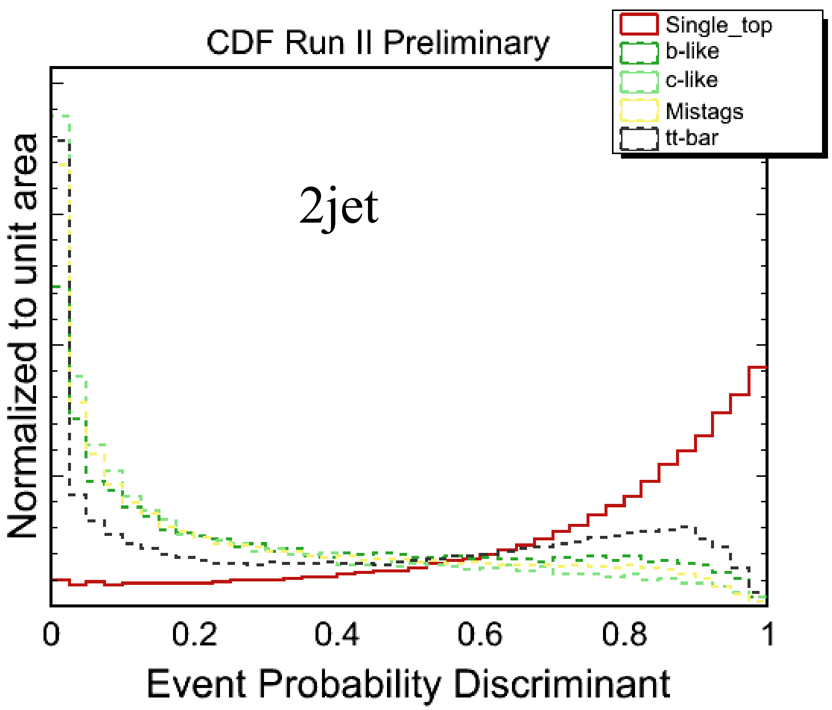
$$W_{jet}(E_{jet}, E_{parton}) = \frac{1}{\sqrt{2\pi}(p_1 + p_2 p_5)}[\exp\frac{-(\delta_E - p_1)^2}{2p_2^2} + p_3 \exp\frac{-(\delta_E - p_4)^2}{2p_5^2}]$$

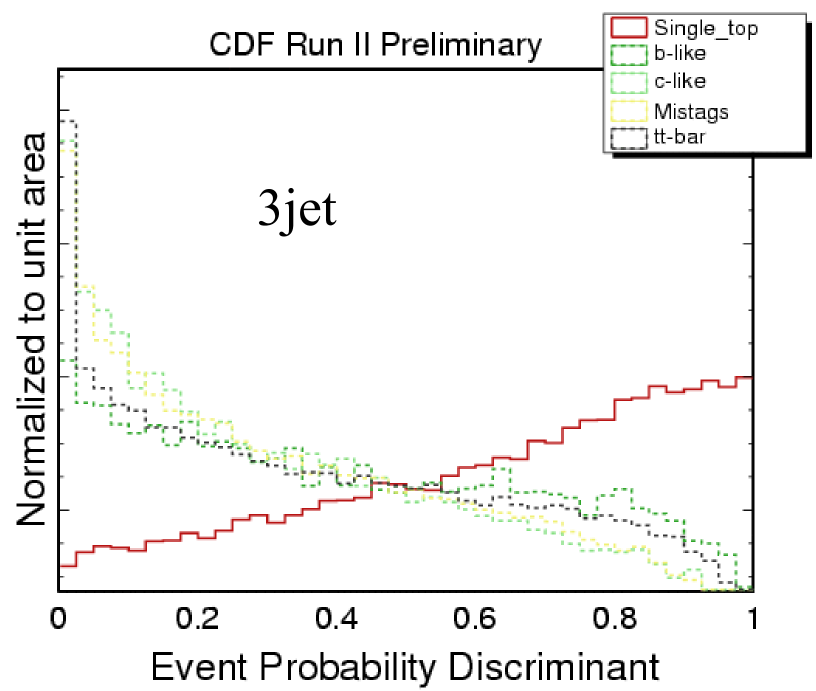
where: $p_i = a_i + b_i E_{parton}$ $\delta E = (E_{parton} - E_{jet})$

Probability Discriminant

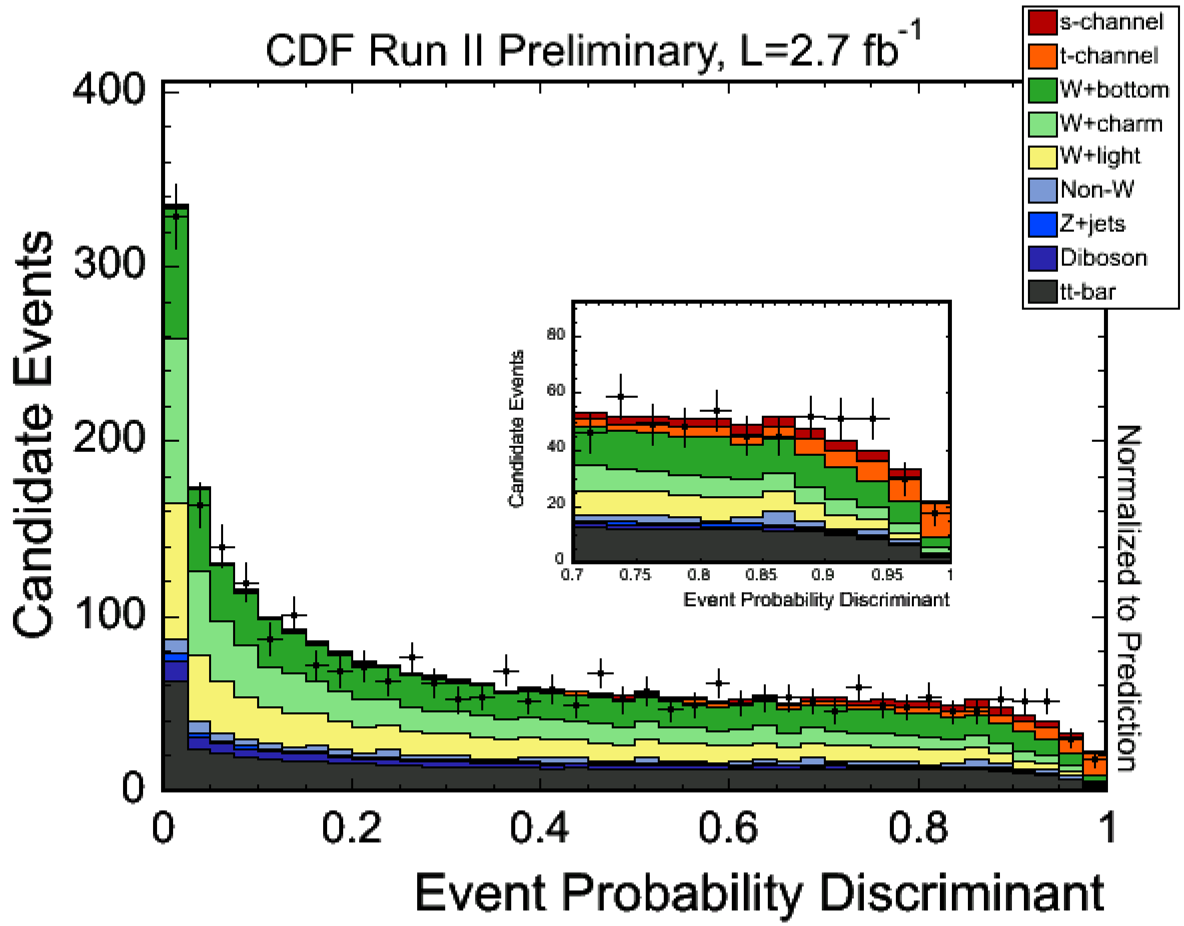
b = NN b-tag value

$$EPD = \frac{b \cdot P_{\text{singletop}}}{b \cdot P_{\text{singletop}} + b \cdot \left(P_{Wb\bar{b}} + P_{t\bar{t}}\right) + (1-b) \cdot \left(P_{Wc\bar{c}} + P_{Wcj} + P_{Wgg}\right)}$$





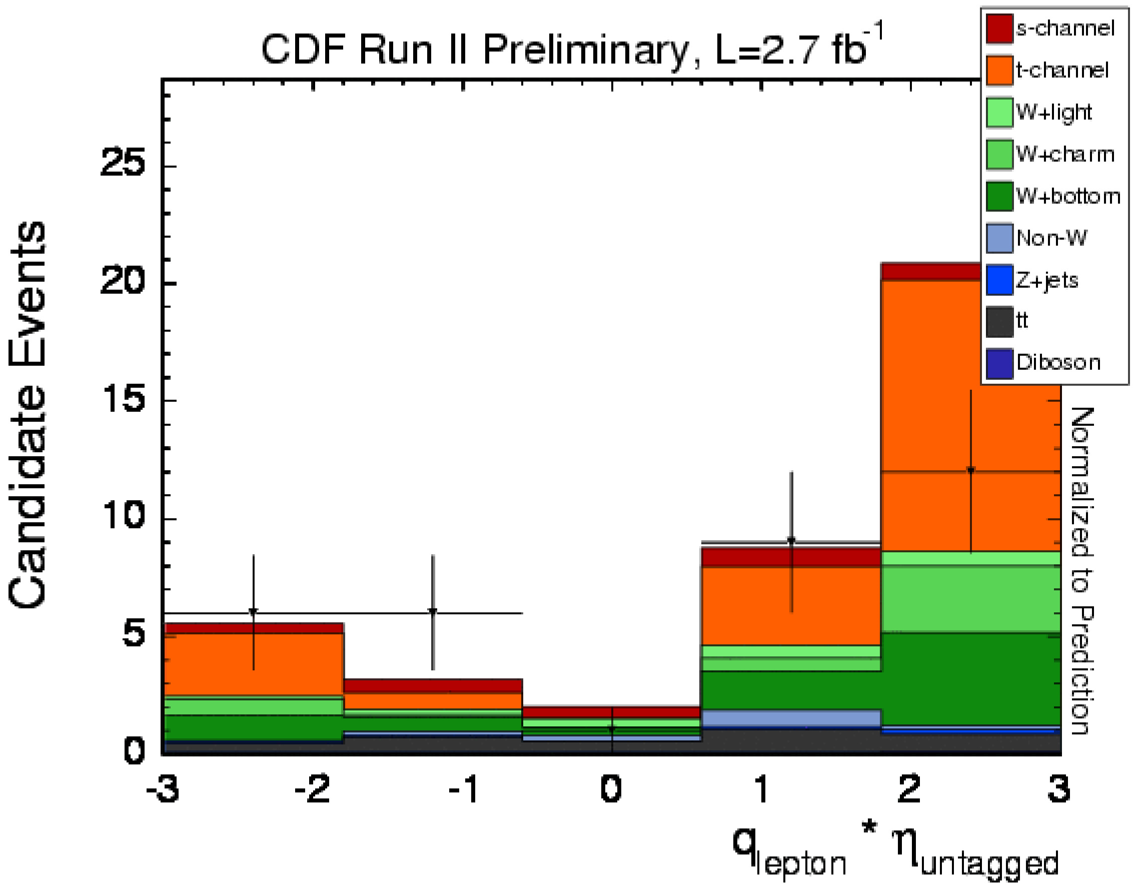
Data Result



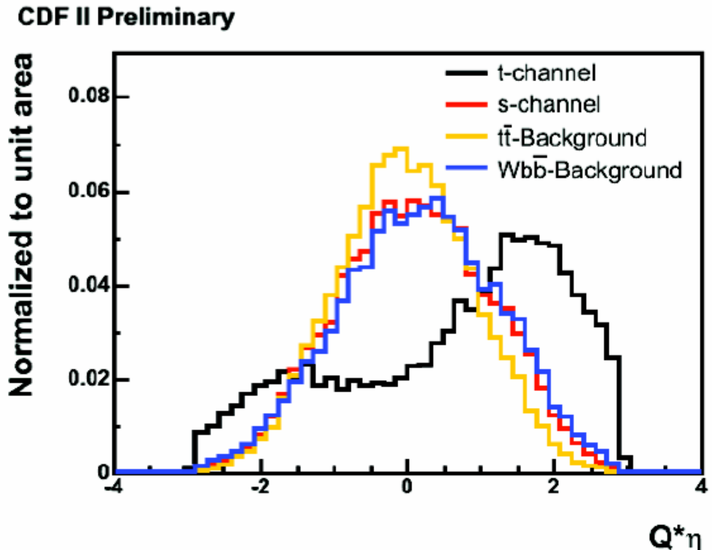
4.2σ obs

4.8σ median expected

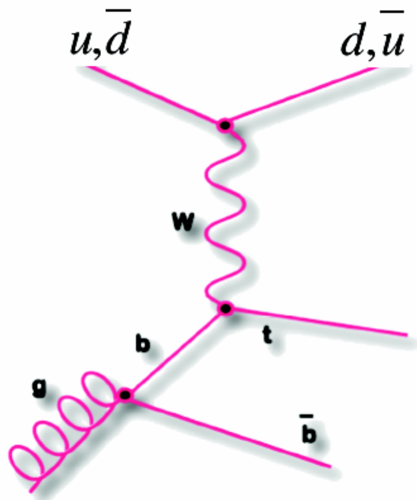
Check: High EPD > 0.95

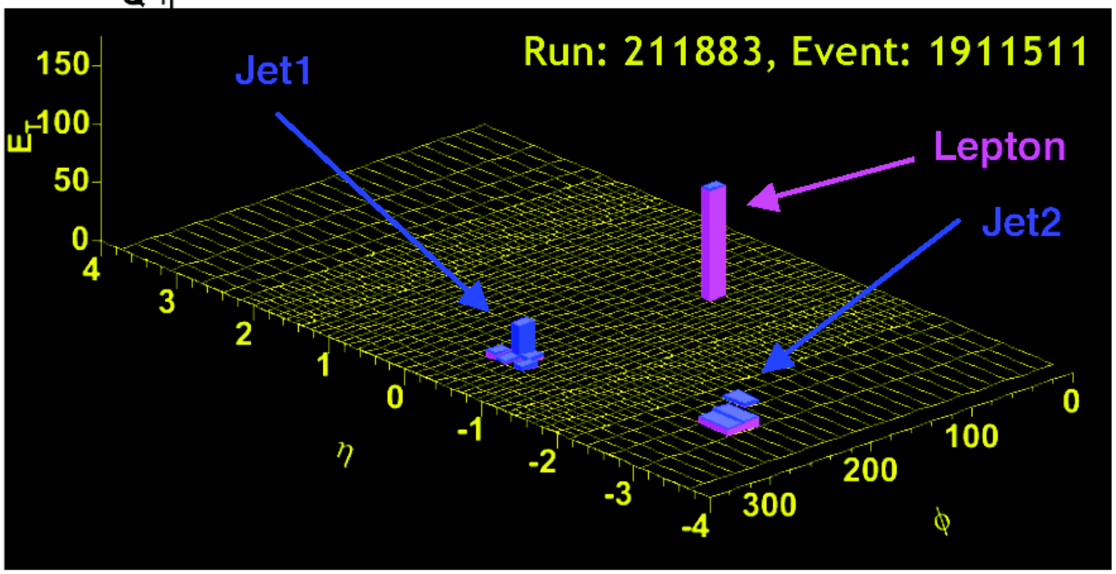


Single top like event



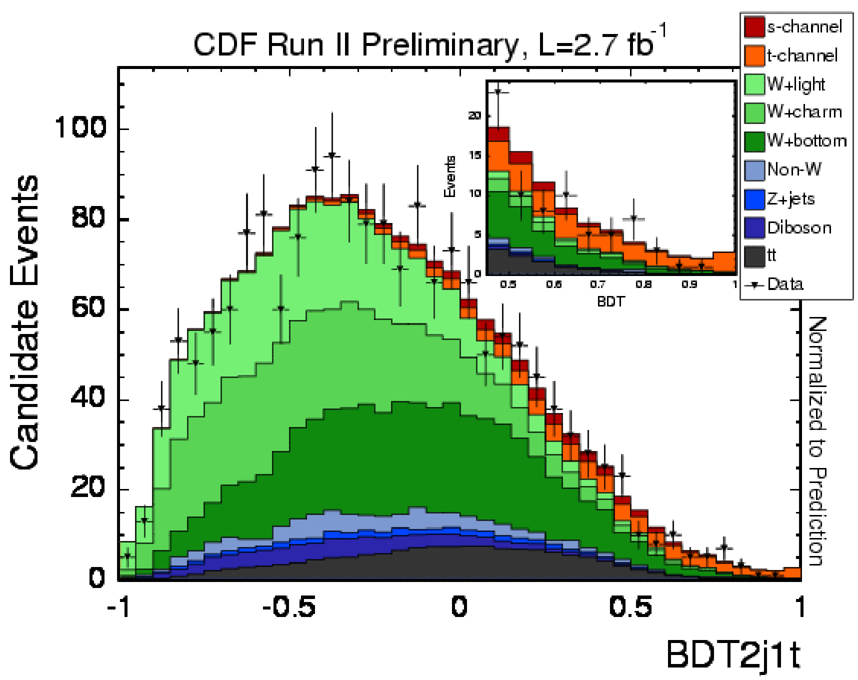
Central Electron Candidate
Charge: -1, Eta=-0.72
MET=41.85, MetPhi=-0.83
Jet1: Et=46.7 Eta=-0.61 b-tag=1
Jet2: Et=16.6 Eta=-2.91 b-tag=0
QxEta = 2.91 (t-channel signature)
EPD=0.95

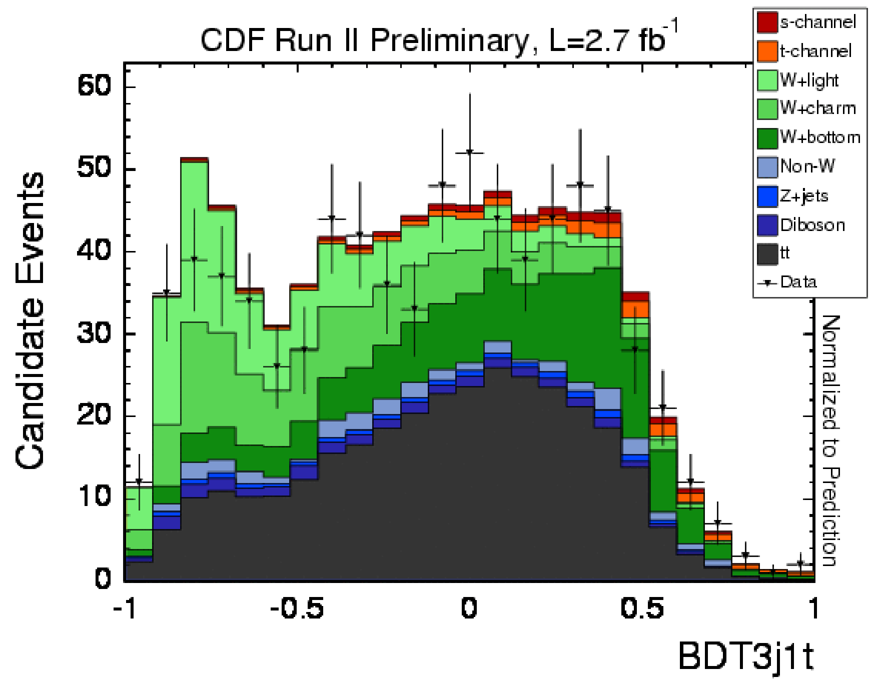




Boosted Decision Trees

- 22 variables (2j); 30 variables (3j)





3.6σ obs

4.9σ median expected

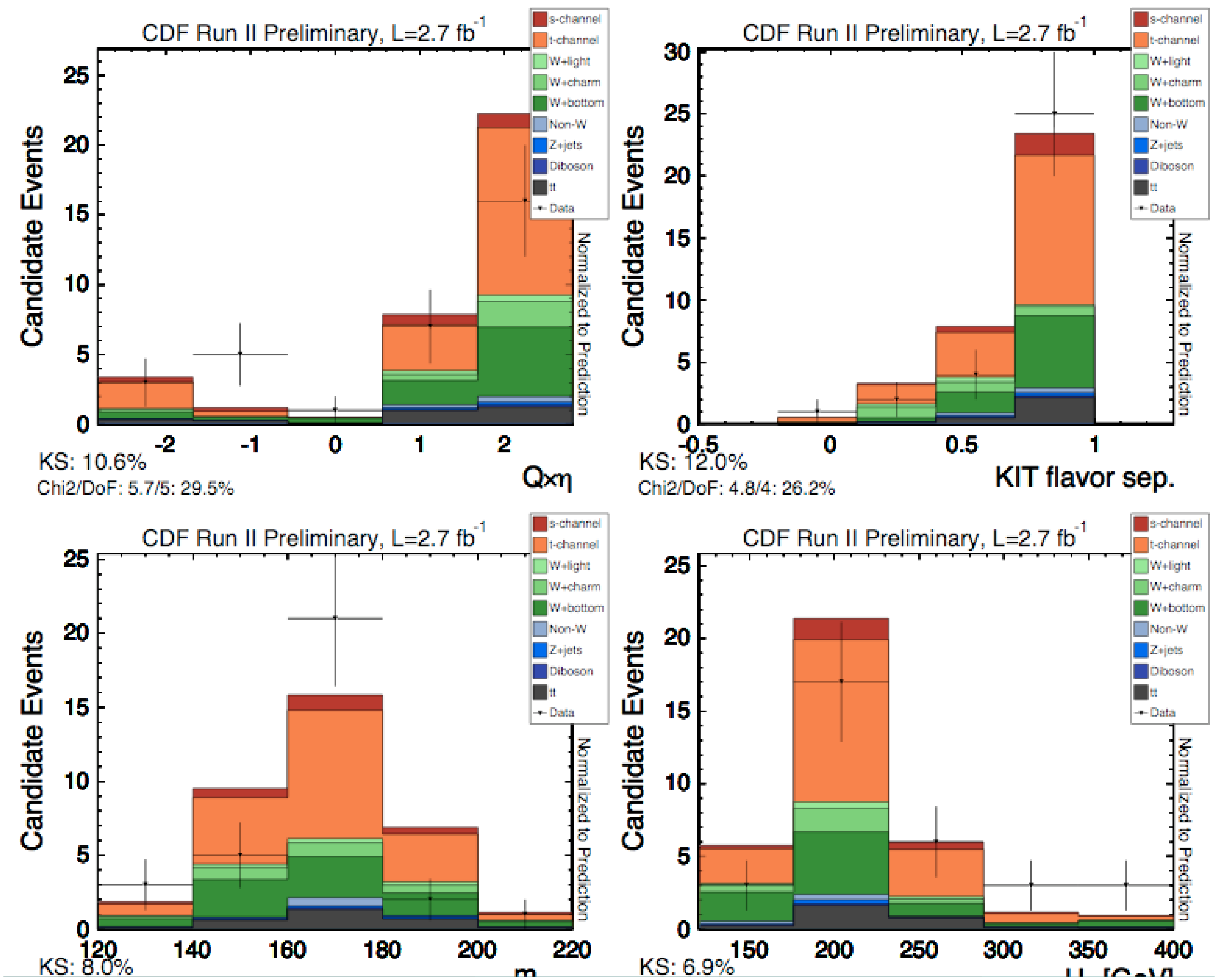
BDT variables (W+2j)

	2-jets, 1-tag		2-jets, 2-tag	
Rank	Variable	Variable Importance	Variable	Variable Importance
1	KaNN	4.597e-01	mJ1J2	7.453e-02
2	mJ1J2	1.799e-01	Mlnub	6.599e-02
3	QEta	1.077e-01	wmt	6.453e-02
4	Mlnub	4.684e-02	MetJ1DPhi	5.142e-02
5	J1Et	4.570e-02	Mlnuj1j2	4.805e-02
6	wmt	1.890e-02	KaNN	4.656e-02
7	J2Et	1.874e-02	cosLepJ1	4.645e-02
8	LepPt	1.639e-02	J1Eta	4.563e-02
9	cosLepJ1	1.572e-02	J1Et	4.522e-02
10	MetLepDPhi	1.481e-02	J2Et	4.424e-02
11	J2Eta	1.063e-02	LepEta	4.366e-02
12	LepEta	8.744e-03	MetJ2DPhi	4.339e-02
13	Mlnuj1j2	8.106e-03	LepJ2DPhi	4.252e-02
14	Ht	7.755e-03	cosLepJ2	4.249e-02
15	MetJ1DPhi	7.589e-03	MetLepDPhi	4.098e-02
16	LepJ1DPhi	6.232e-03	LepJ1DPhi	3.886e-02
17	cosLepJ2	6.035e-03	LepPt	3.869e-02
18	met	4.676e-03	QEta	3.850e-02
19	MetJ2DPhi	4.174e-03	met	3.840e-02
20	J1Eta	3.922e-03	J2Eta	3.573e-02
21	WEta	3.881e-03	Ht	3.227e-02
22	LepJ2DPhi	3.839e-03	WEta	3.188e-02

BDT variables (W+3j)

	3-jets, 1-tag		3-jets, 2-tag	
Rank	Variable	Variable Importance	Variable	Variable Importance
1	KaNN	3.846e-01	QEta	7.785e-02
2	mJ2J3	7.124e-02	Ht	5.032e-02
3	wmt	5.449e-02	Mlnub	4.698e-02
4	mJ1J3	5.358e-02	mJ2J3	4.100e-02
5	Ht	4.978e-02	mJ1J2	3.864e-02
6	QEta	4.729e-02	mJ1J2J3	3.735e-02
7	Mlnub	3.924e-02	MetLepDPhi	3.677e-02
8	mJ1J2J3	2.642e-02	wmt	3.632e-02
9	J3Et	2.609e-02	J1Eta	3.573e-02
10	J2Eta	2.549e-02	cosLepJ1	3.447e-02
11	mJ1J2	2.490e-02	J2Et	3.400e-02
12	cosLepJ1	2.370e-02	J3Et	3.324e-02
13	LepPt	1.910e-02	mJ1J3	3.307e-02
14	LepEta	1.774e-02	J2Eta	3.275e-02
15	MetLepDPhi	1.382e-02	cosLepJ3	3.046e-02
16	J1Eta	1.373e-02	J1Et	3.017e-02
17	LepJ1DPhi	1.223e-02	WEta	2.993e-02
18	cosLepJ2	1.069e-02	MetJ2DPhi	2.988e-02
19	cosLepJ3	9.661e-03	LepJ1DPhi	2.898e-02
20	J1Et	8.641e-03	KaNN	2.894e-02
21	MetJ3DPhi	8.278e-03	LepEta	2.873e-02
22	MetJ2DPhi	8.256e-03	LepJ3DPhi	2.855e-02
23	met	8.141e-03	Mlnuj1j2j3	2.828e-02
24	MetJ1DPhi	7.496e-03	MetJ3DPhi	2.692e-02
25	LepJ3DPhi	6.743e-03	cosLepJ2	2.616e-02
26	J2Et	6.133e-03	LepPt	2.518e-02
27	LepJ2DPhi	6.035e-03	MetJ1DPhi	2.508e-02
28	WEta	5.932e-03	LepJ2DPhi	2.204e-02
29	Mlnuj1j2	5.417e-03	met	2.160e-02
30	Mlnuj1j2j3	5.108e-03	Mlnuj1j2	2.060e-02

High score BDT>0.6



Neural Networks Analysis

- Similar to the Likelihood Function, but:
  - More input variables
  - Correlation among input variables accounted for

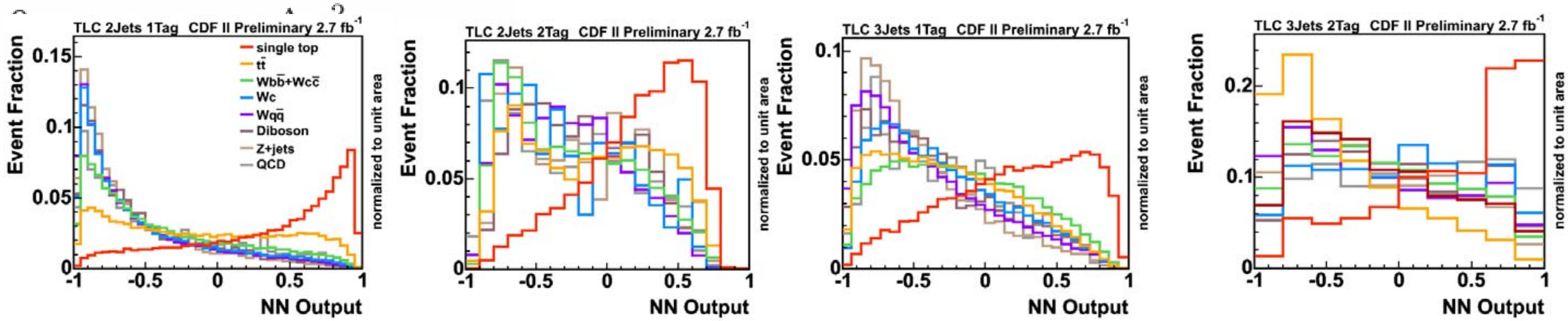
Position	Variable
1	NN b tag
2	$M_{l\nu b}$
3	M_{j_1,j_2}
4	$Q \times \eta$
5	# loose jets
6	H_T
7	$cos\Theta(\mathrm{lep, quark})$
8	$\eta(W)$

Separate tight lepton (TLC) networks trained on four samples:

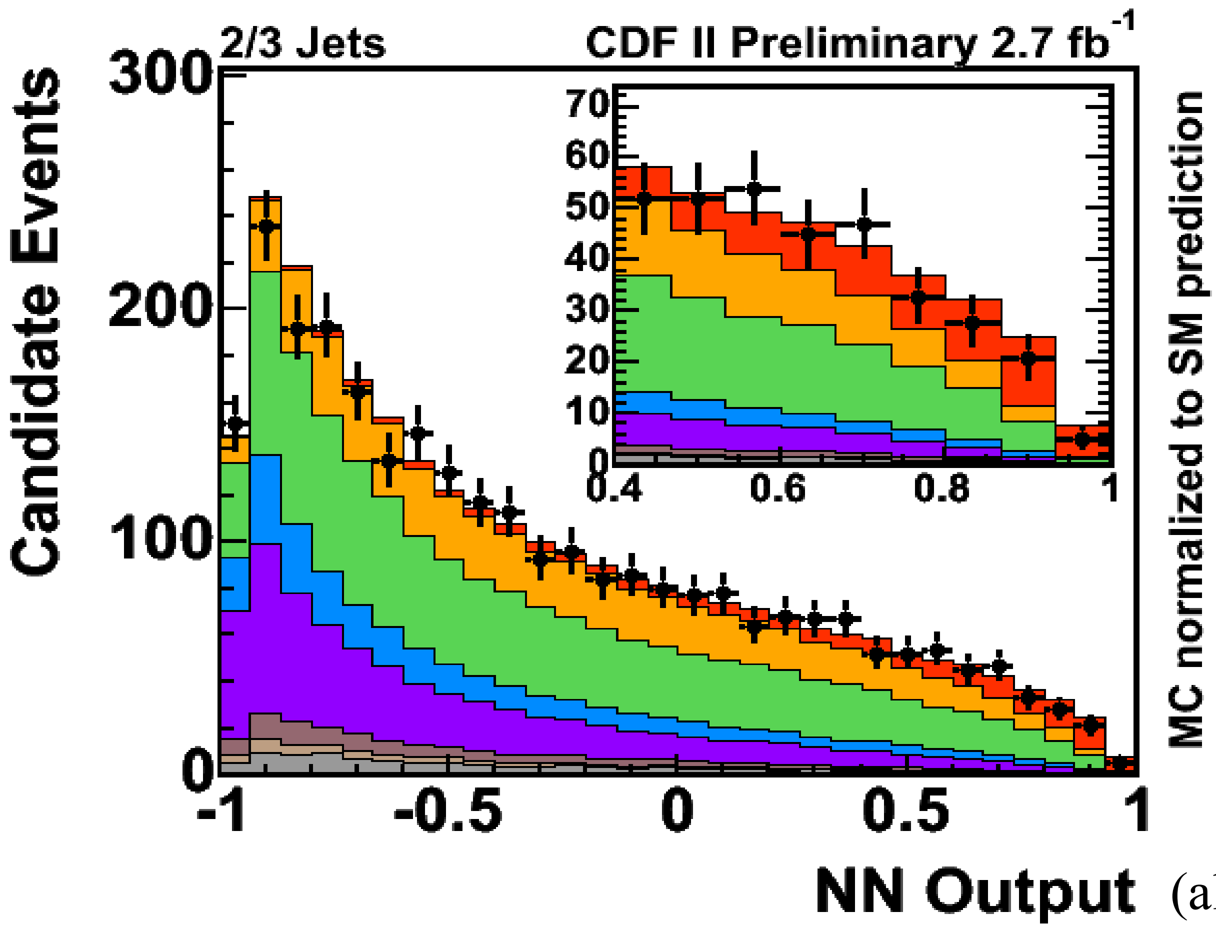
- 2 jets, 1 B-tag : Trained on *t*-channel signal
- 2 jets, 2 B-tags : Trained on *s*-channel signal
- 3 jets, 1 B-tag : Trained on *t*-channel signal
- 3 jets, 2 B-tags : Ttrained on *t*-channel signal

Similar for extended muon coverage (EMC) events (accepted trough MET+2j trigger). Total: 8 ANN's

The output distributions for the 4 TLC networks



Comparison to Data



(all channels)

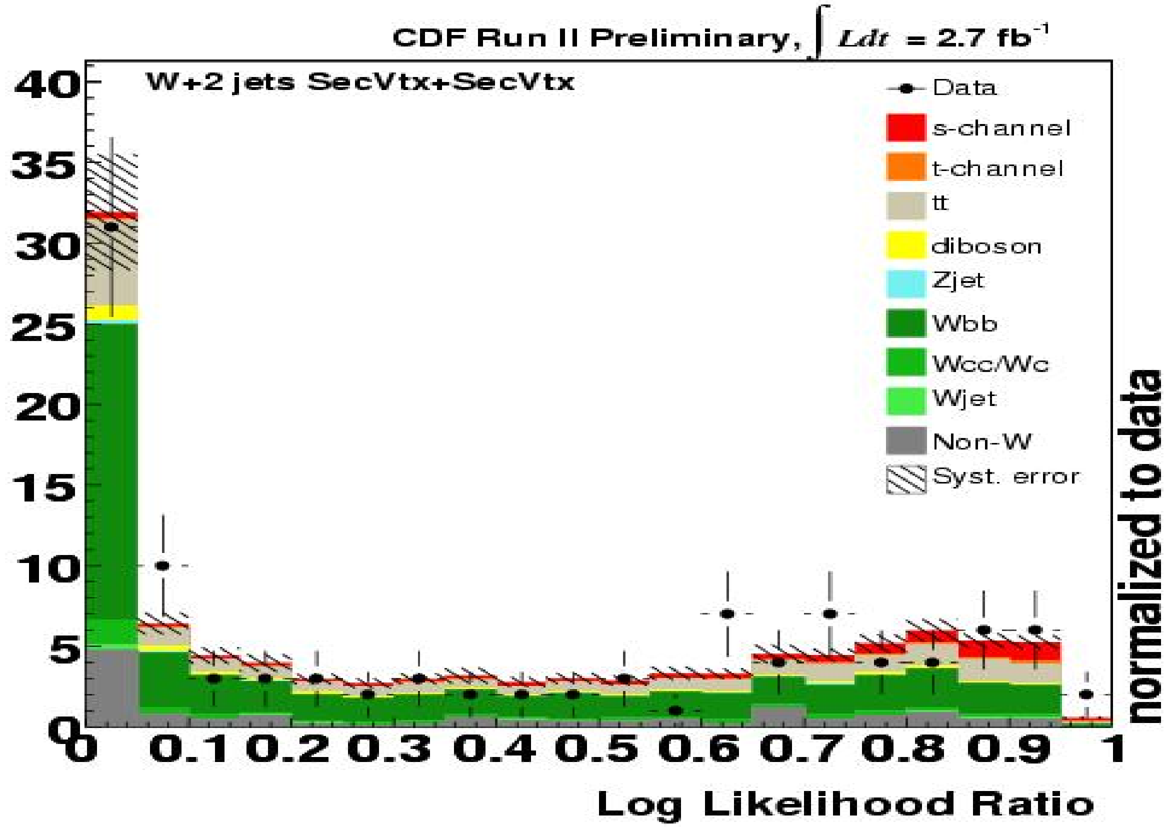
3.7σ obs

5.0σ median expected

s-channel likelihood function search

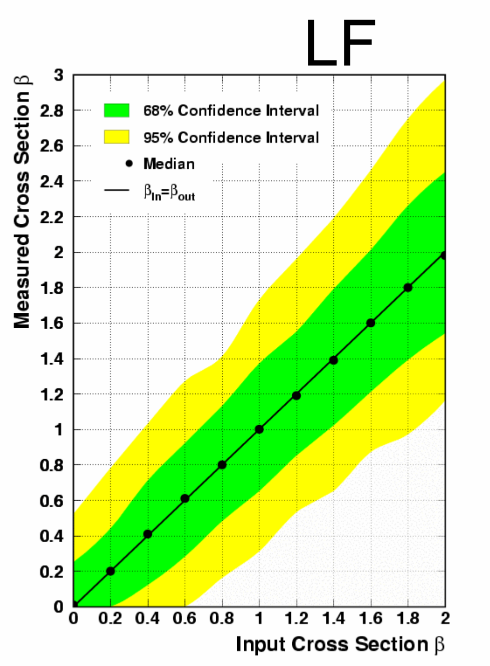
- More challenging (less distinct) than t-channel
- Also smaller rate (1pb)
- Likelihood-type analysis. W+2j double tagged sample

Best Fit Cross Section : $\sigma_s = 0.9$ pb, $\sigma_t = 1.2$ pb.

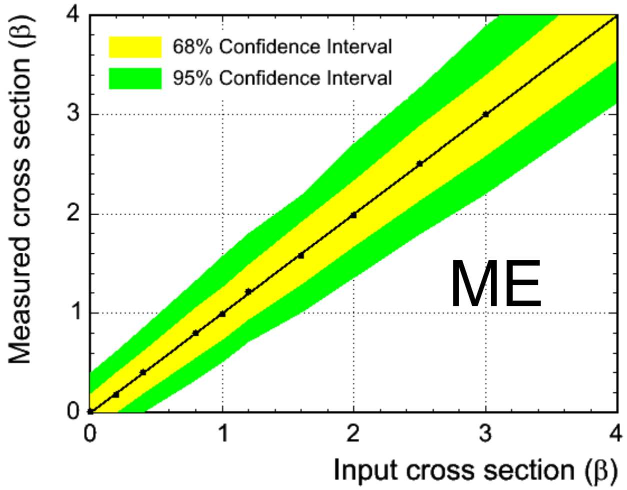


Cross Section Measurements

- Bayesian Technique selected
  - Flat prior in signal cross section σ_{s+t}
  - Integrate out rate and shape uncertainties
  - Check biases with pseudoexperiments with systematics fluctuated.
  - m_{top}=175 GeV assumed.



Linearity checked with systematically varied pseudoexp.

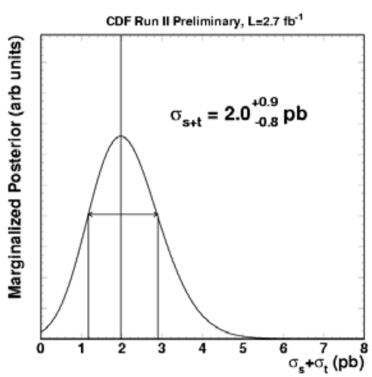


Systematic Uncertainties

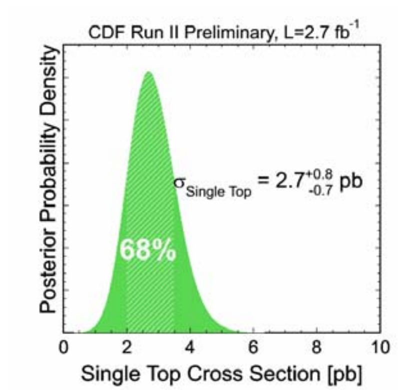
Source of Uncertainty	Rate	Shape
Jet Energy Scale	0...16%	✓
Initial State Radiation	0...11%	✓
Final State Radiation	0...15%	✓
Parton Distribution Functions	2...3%	✓
Monte Carlo Generator	1...5%	
Event Detection Efficiency	0...9%	
Luminosity	6%	
Neural Net B-tagger		✓
Mistag Model		✓
Q^2 scale in ALPGEN MC		✓
Input variable mismodeling		✓
Wbb+Wcc normalization	30%	
Wc normalization	30%	
Mistag normalization	17...29%	
ttbar normalization & m_{top}	23%	✓
Non-W Normalization	40%	
Non-W Flavor Model		✓

Cross Section Measurements

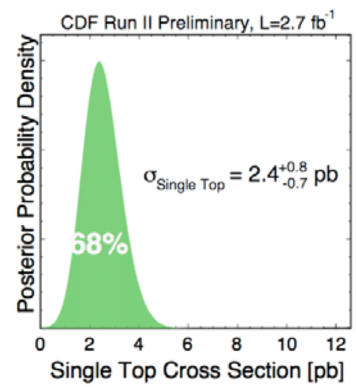
- Bayesian posterior marginalized over uncertain nuisance parameters
- Flat prior taken in $\sigma_s+\sigma_t$



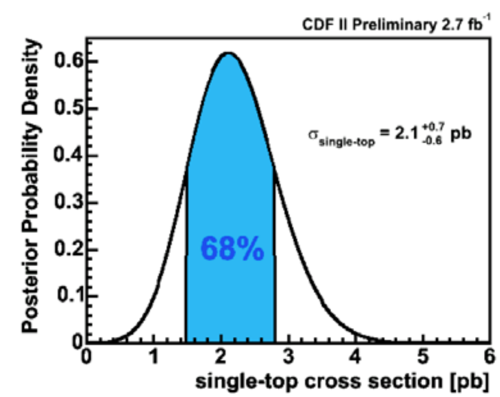
Likelihood Function



Matrix Element



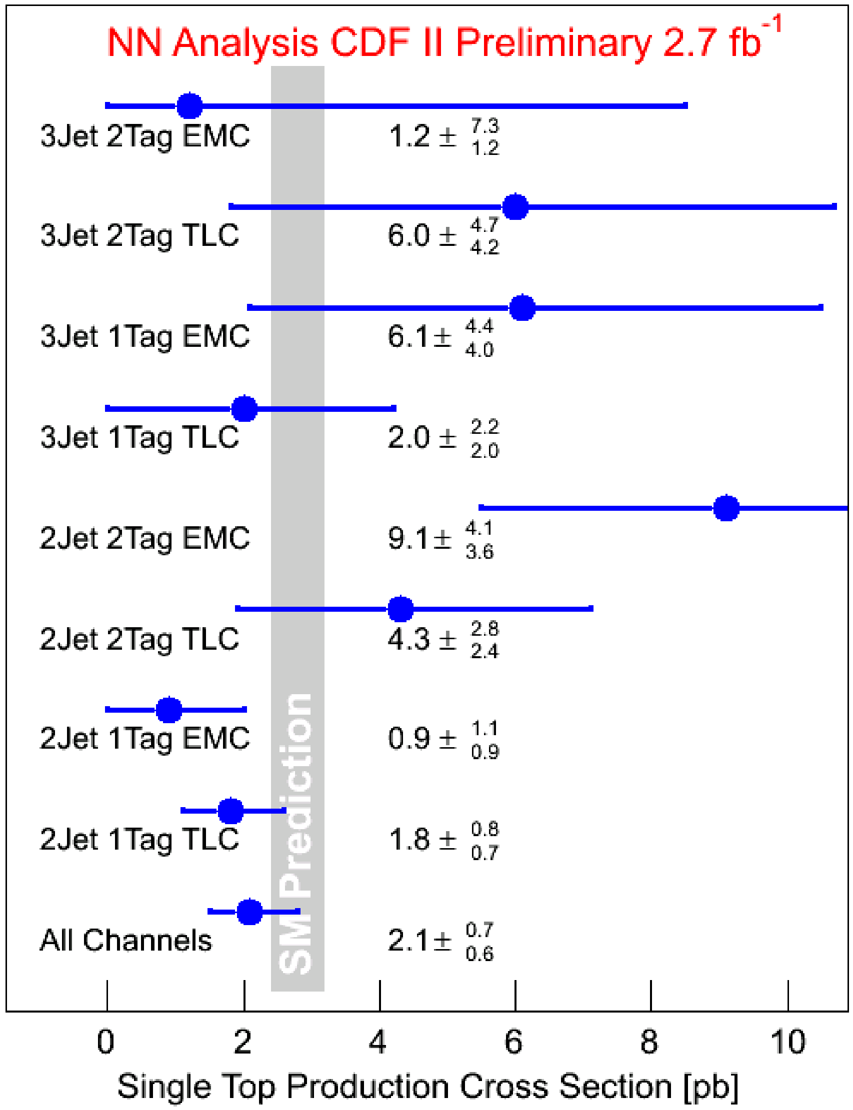
Decision Trees



Neural Networks

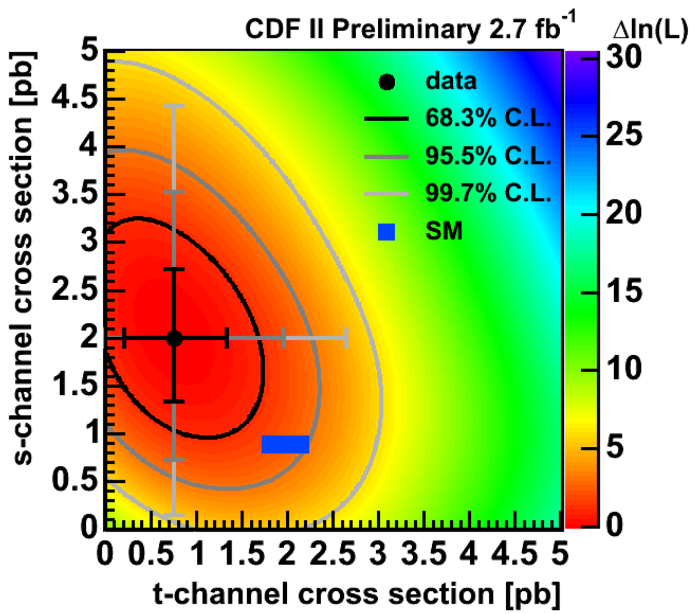
All Assuming m_t=175 GeV

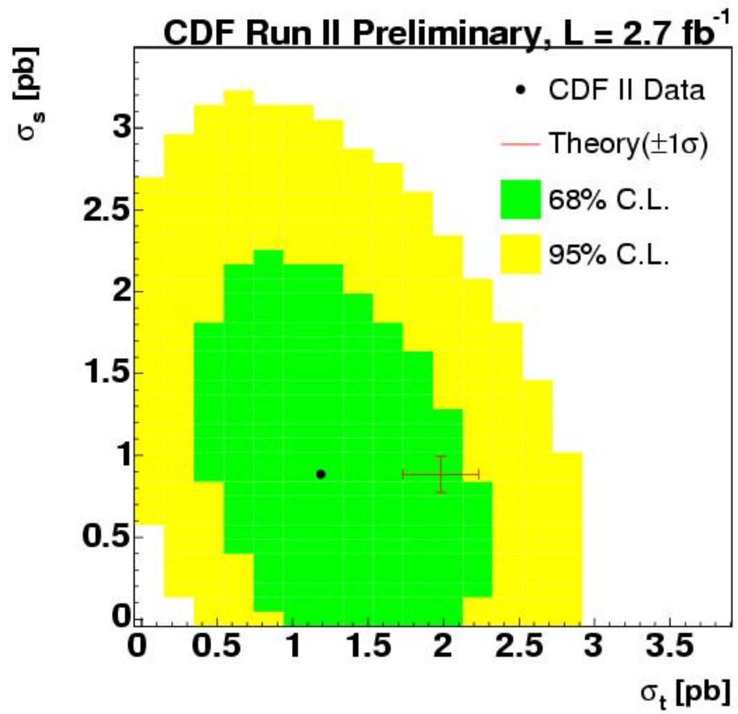
NN cross section



2D measurements

Template fit (marginalization) is done in 2D. Flat priors taken in the (σ_s,σ_t) plane.

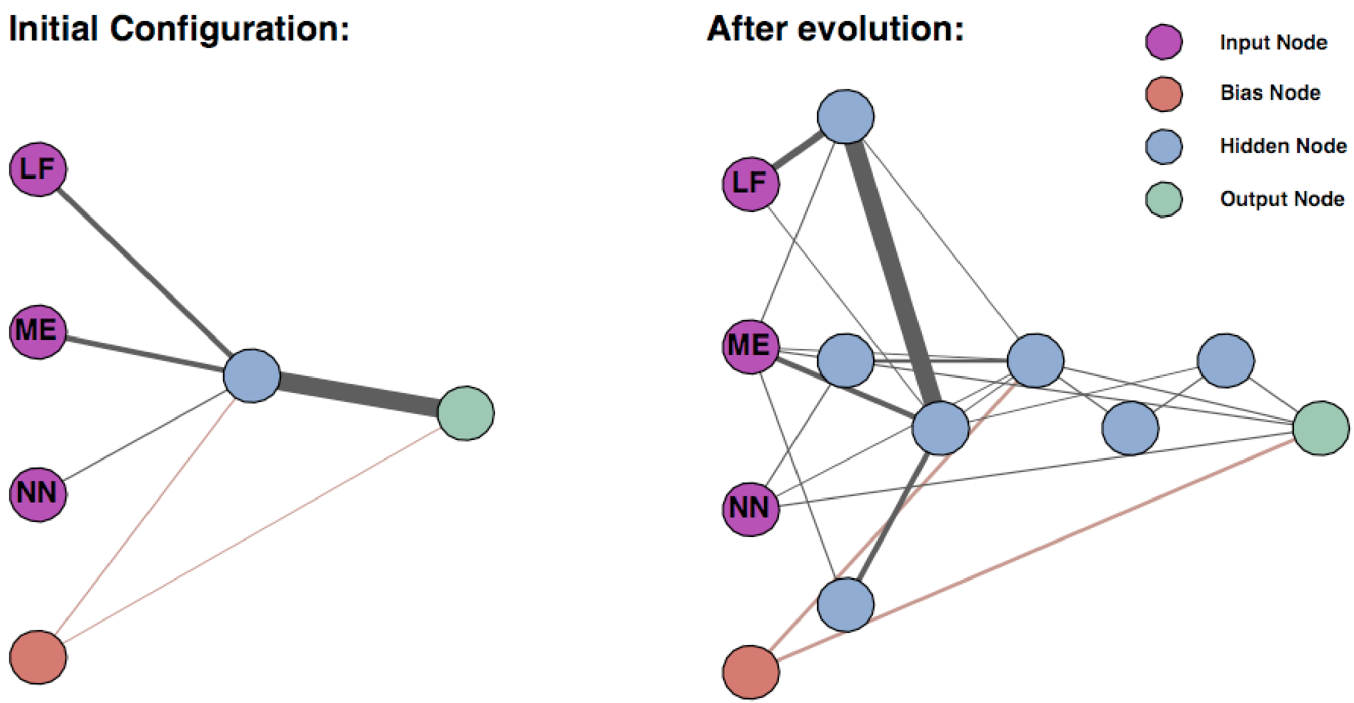




Analysis Combination

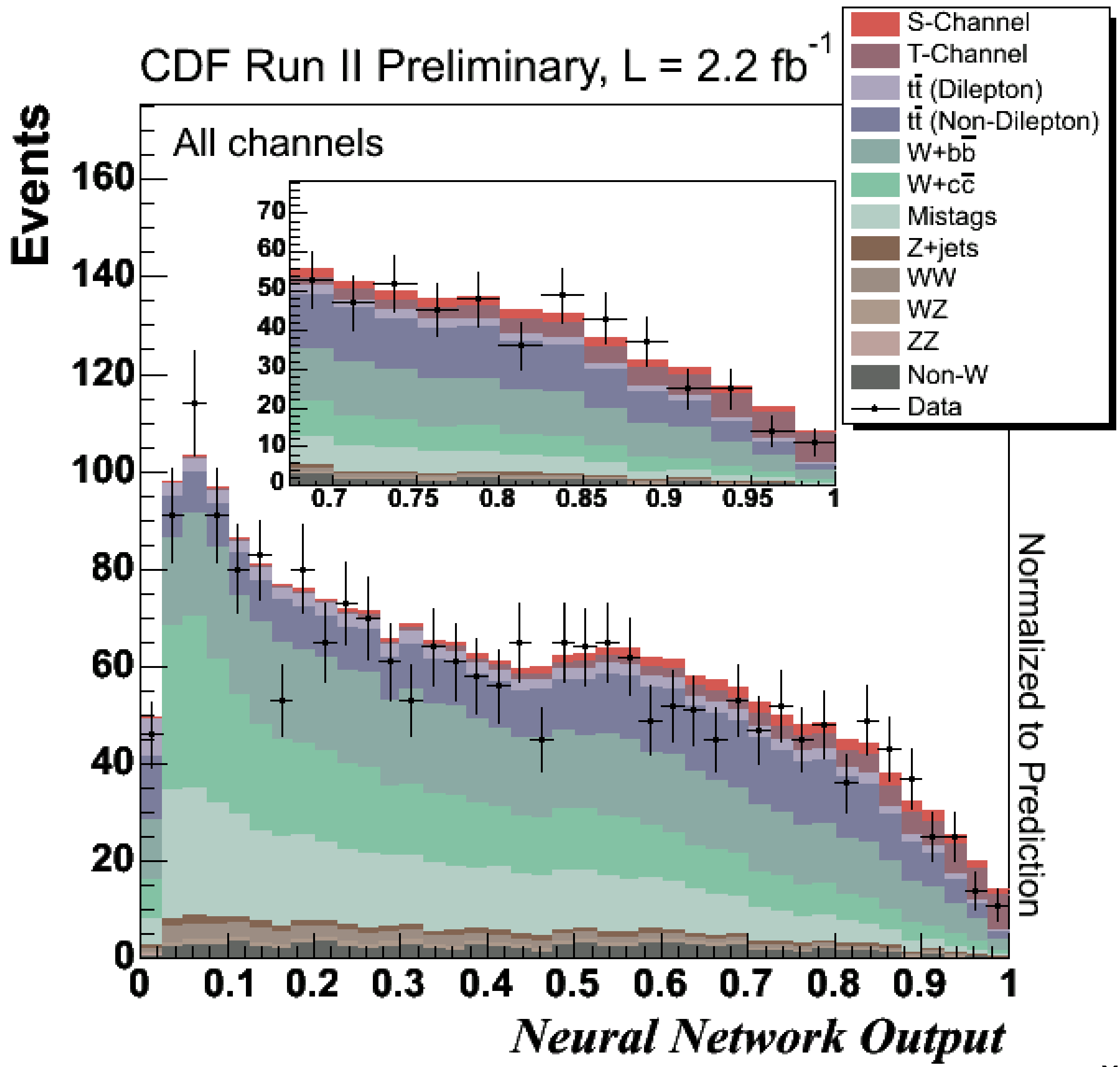
- Have 4 different results – what do the data actually say?
- Same dataset:
  - Combine analyses rather than results

- NEAT ("Neuro-Evolution of Augmenting Topologies"):
  - is **designed to optimize the expected *p*-value** (discovery significance).



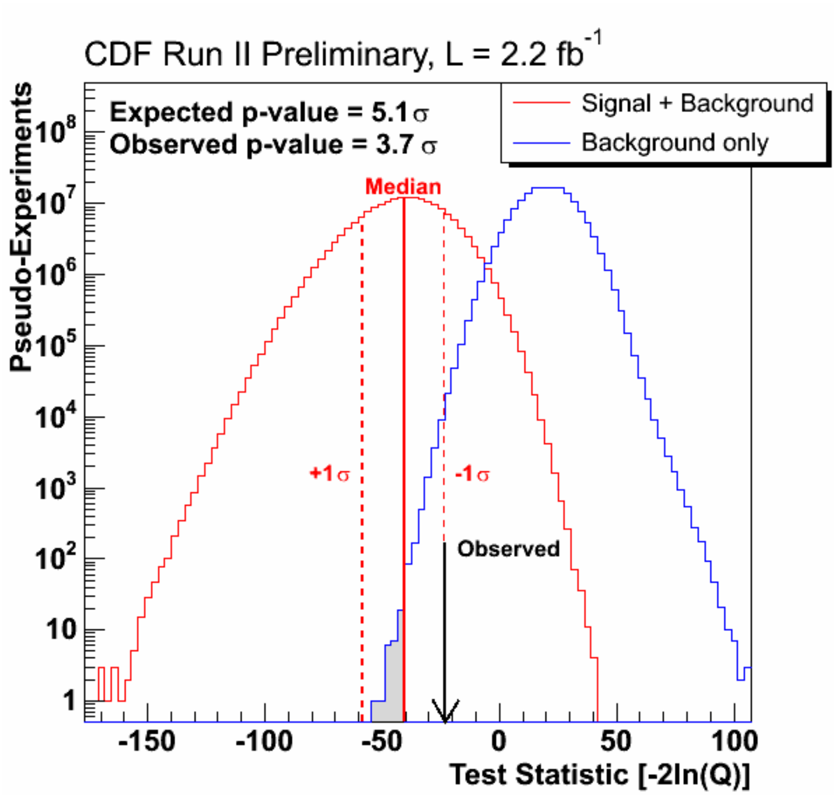
Data Result

2-jet, 3-jet data summed, all lepton categories and n_{tags} summed.

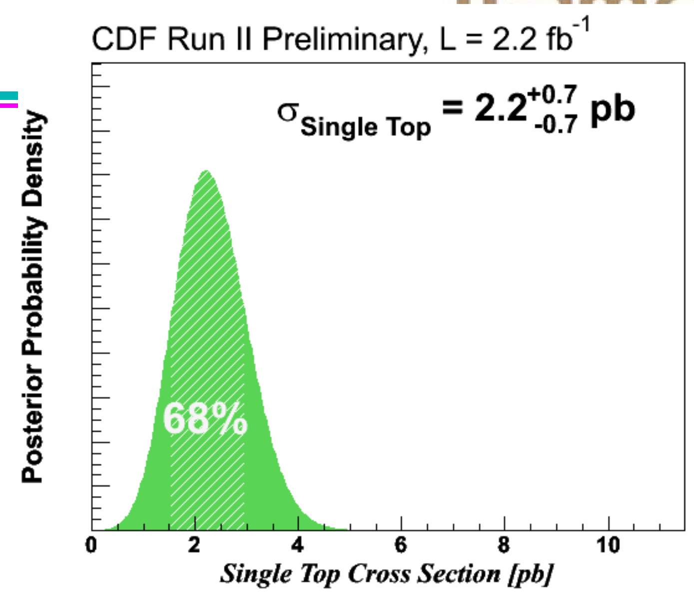


Super-Discriminant

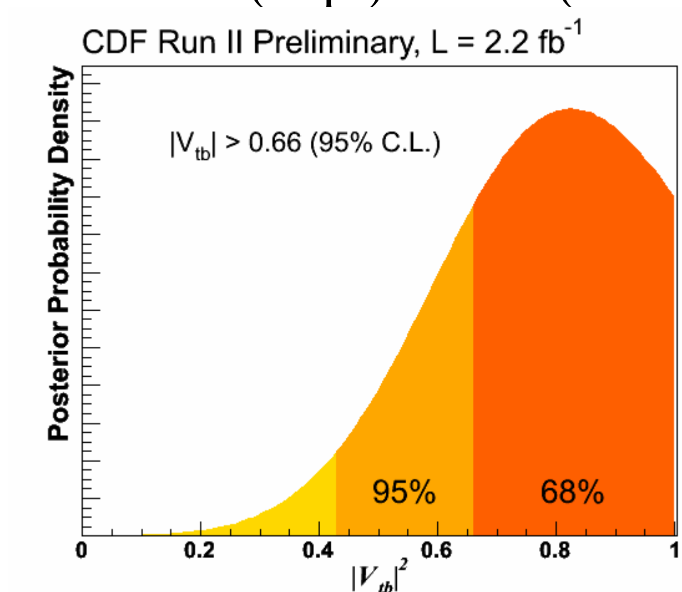
Observed p-value: 3.7σ
Expected: 5.1σ



- NEAT gives us 13% better performance in the expected significance with respect to the best analysis.

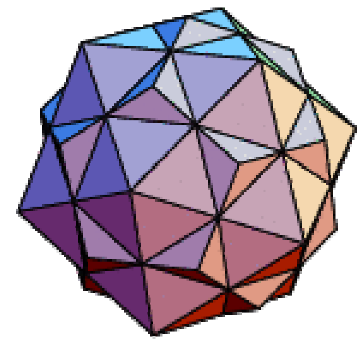


$$|V_{tb}| = 0.88 \pm 0.14 \text{ (exp.)} \pm 0.07 \text{ (theory)}$$



W' -> tb Search

- Search for heavy resonances in W+jets events
- Heavy W' bosons appear in many theories:
  - Additional $SU(2)_L$ sector
  - Or lowest KK mode of the W boson
  - Or left-right symmetric model: broken $SU(2)_L$ x $SU(2)_R$
  - Or little Higgs, supersymmetry etc



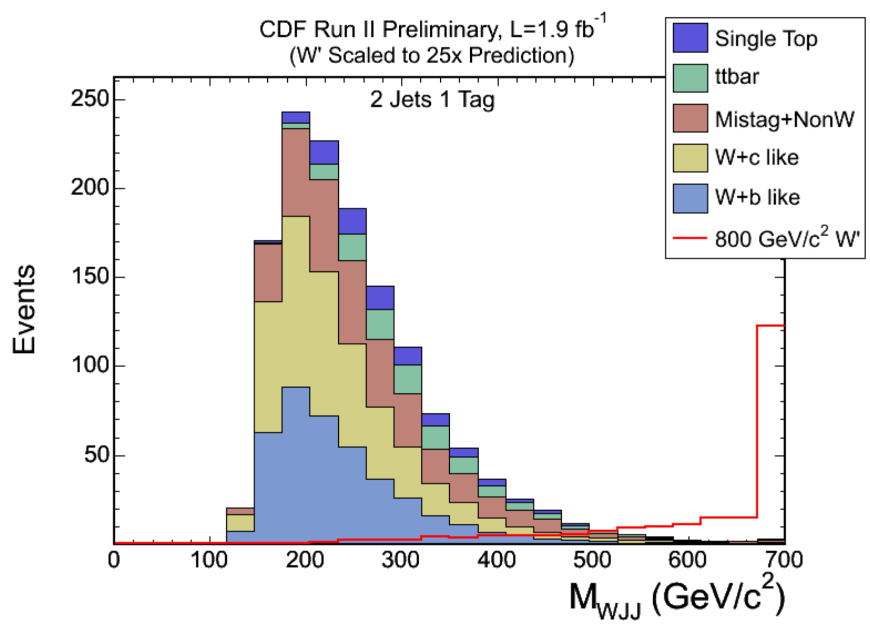
- Lagrangian:

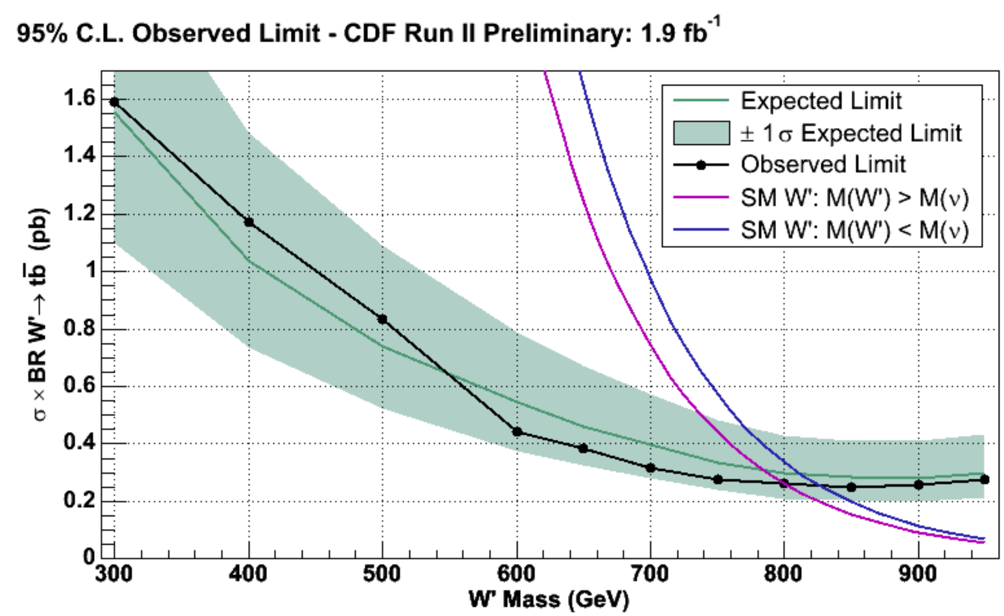
$$\mathcal{L} = \frac{g}{\sqrt{2}} \bar{f}_i \gamma_\mu (C^R_{f_i f_j} P_R + C^L_{f_i f_j} P_L) W' f_j + \mathrm{H.c.},$$

- Will be looking for W'->tb decays (single-top selection!)
  - Complimentary to the W'->eν, μν searches

W' -> tb Search

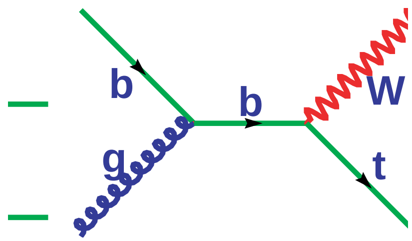
- Invariant mass of the W+jet1+jet2 system and E_T(jet1) provide most sensitivity
- 95%C.L. W' mass limits: 800 GeV and 825 GeV
- $g>0.4g_{SM}$ for the range if masses considered
- D0 limits comparable (740-770 GeV) in PRL 100, 211803 (2008)



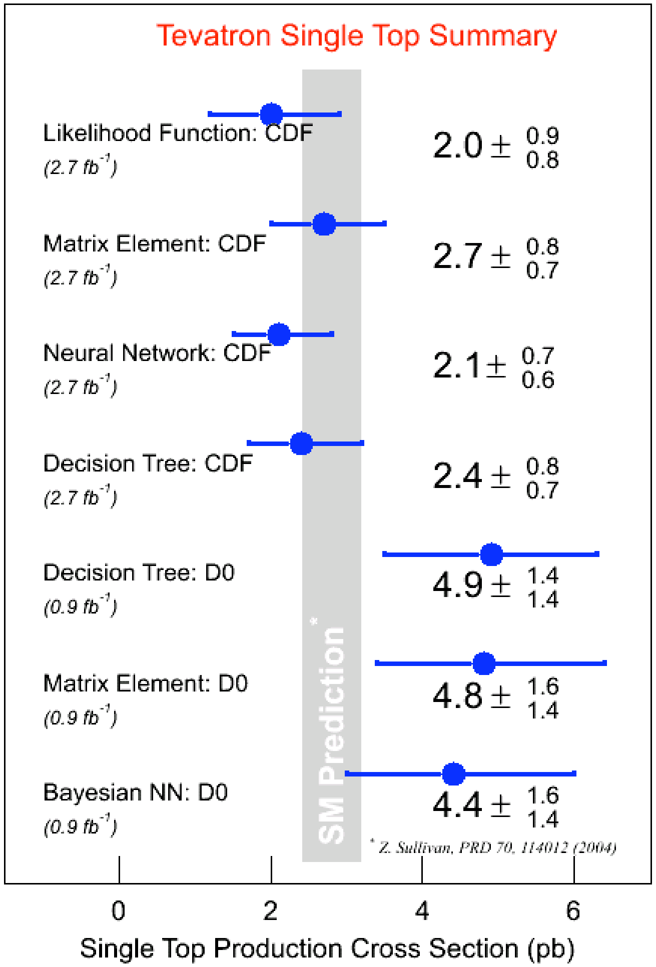


Beyond the Tevatron

- LHC = top quark factory:
  - 8 million top pairs per experiment per year (10 fb^{-1} / year)
  - Some cross section values for $\sqrt{s}$ = 14 TeV:
    - top pair production: ~ 800 pb (mostly via gluon-gluon fusion)
    - t-channel single top: 153 (top) and 90 (antitop) = 243 pb
      - **e.g. per day ~6000 events, at $10^{33} cm^{-2} s^{-1}$**
    - s-channel single top: 6.6 (top) and 4.8 (antitop) = 11 pb
    - associated Wt production: 50-60 pb
      - **Negligible at the Tevatron**
- With 10 fb^{-1}, both experiments should be able to see evidence of t-channel (and Wt?) single top processes



Summary

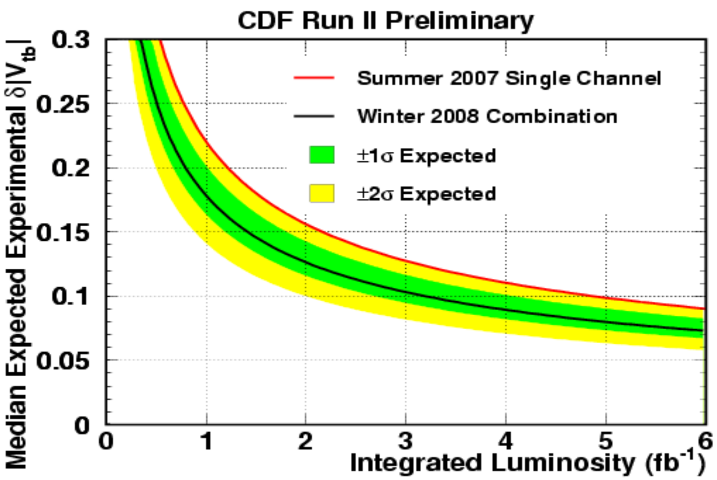


Artwork credit: Jan Lück

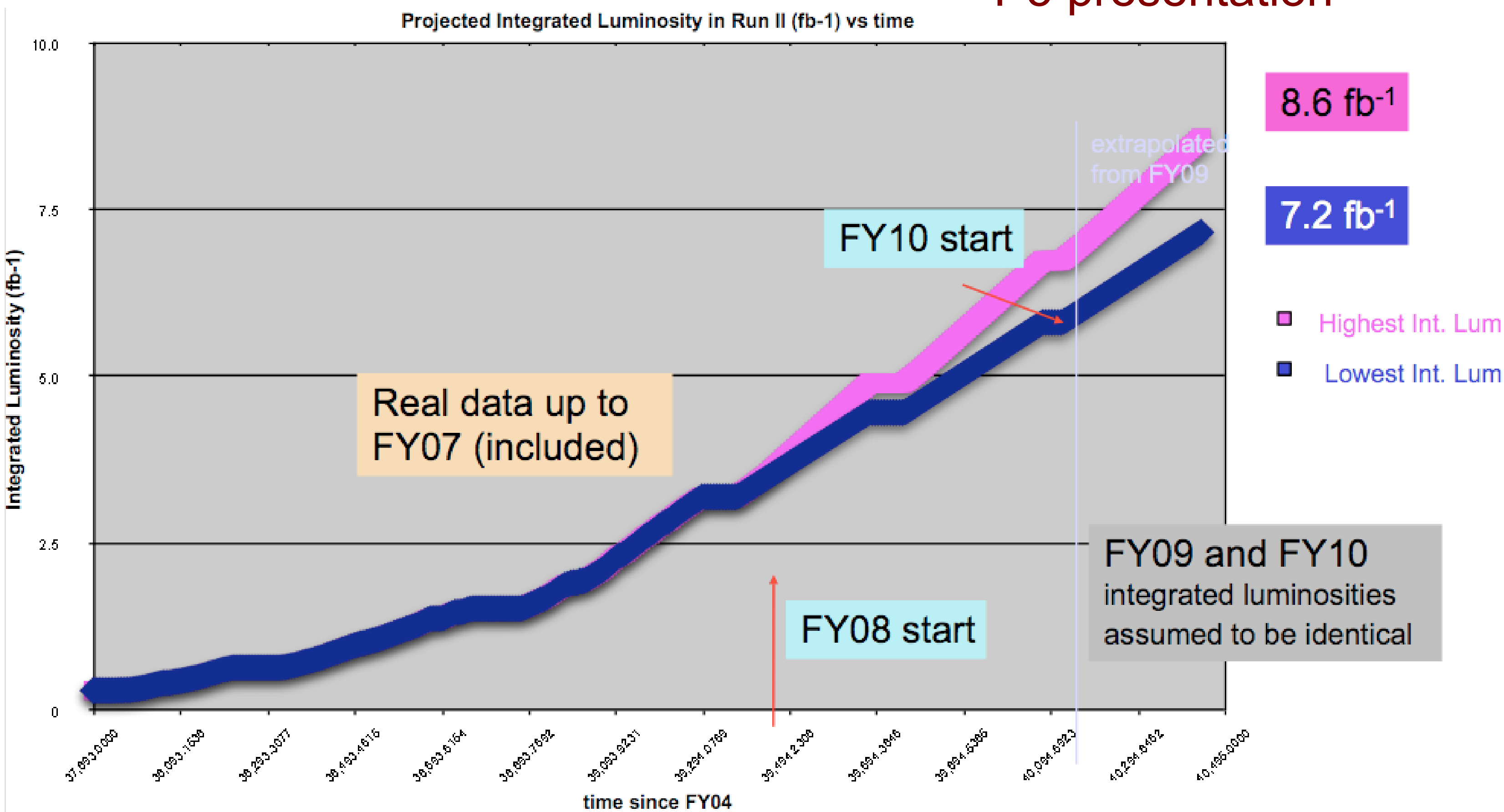
- A taste of LHC physics!
  - Challenging backgrounds
  - Pushing the limits on MC modeling (multiple analyses on the same dataset).

Thanks to the CDF single-toppers!

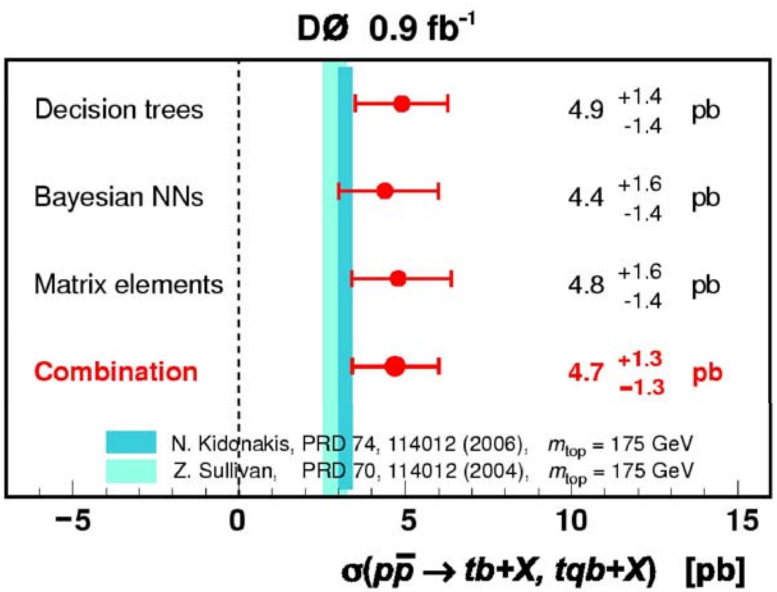
Future



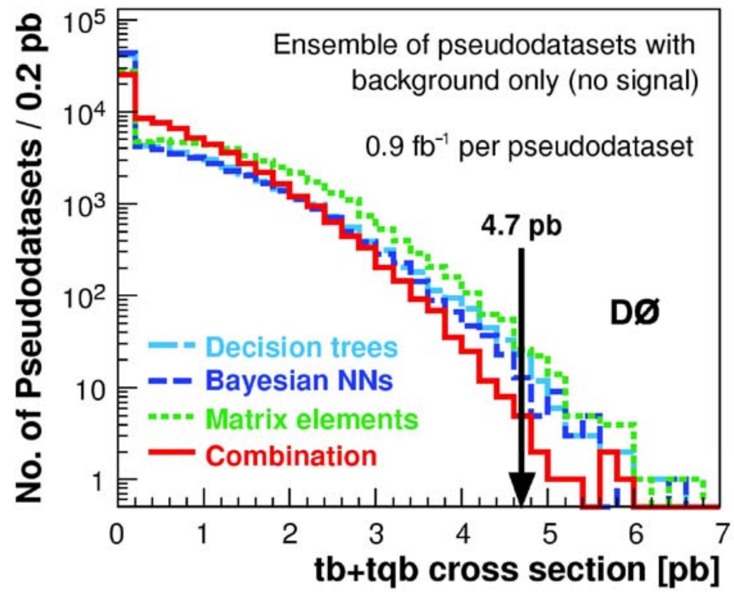
R. Dixon, Feb. 2008
P5 presentation



D0



Cross Section measurements combined with BLUE (Best Linear Unbiased Estimate)



Combined cross section measurement used as a test statistic. How many background-only pseudoexperiments would fake a signal this large?

A: 1.4×10^{-4} of them. $\rightarrow$ 3.6σ evidence.

Expected in SM: 2.3σ