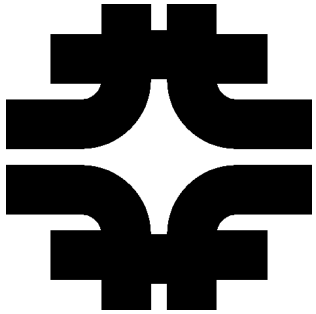
Measurement of Single Top Quark Production with CDF



Thomas Junk

Fermilab

On behalf of the CDF Collaboration

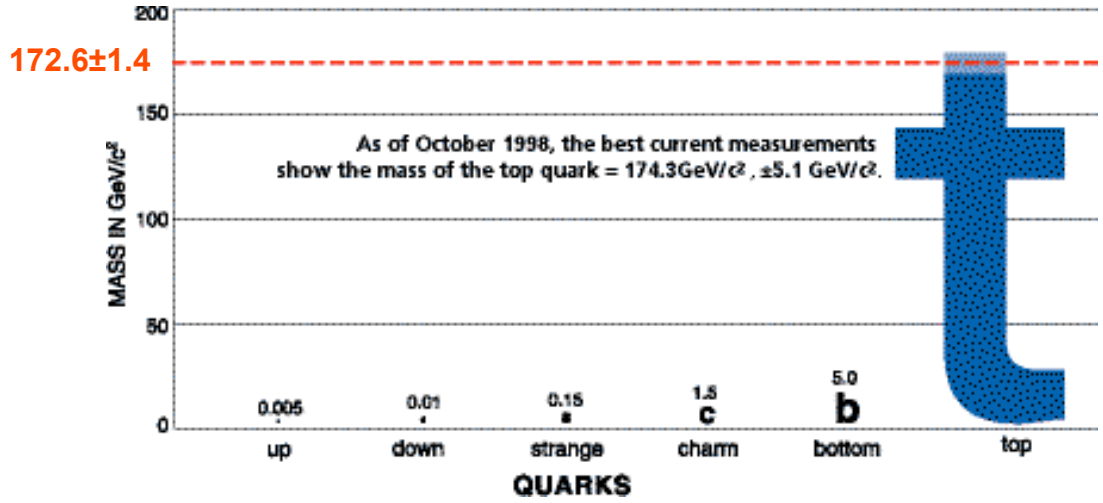
Fermilab Joint Theoretical and Experimental Physics Seminar, March 28, 2008

Outline

- Why Single Top?
- Status as of Lepton-Photon '07
- Summary of Improvements
- Signal and Background Estimation
- Search Techniques
- Results and Prospects

Is the Top Quark Trying To Tell Us Something?

- The top quark is very heavy! $m_t = 172.6 \pm 1.4$ GeV/c^2
  Why?
- Higgs Yukawa coupling ~1
- Why are other quarks so light?
- Alternative Higgs model – t-tbar condensate?
- One of the main ingredients of the radiative corrections to m_H is the top loop
- Is there more out there we cannot yet see?



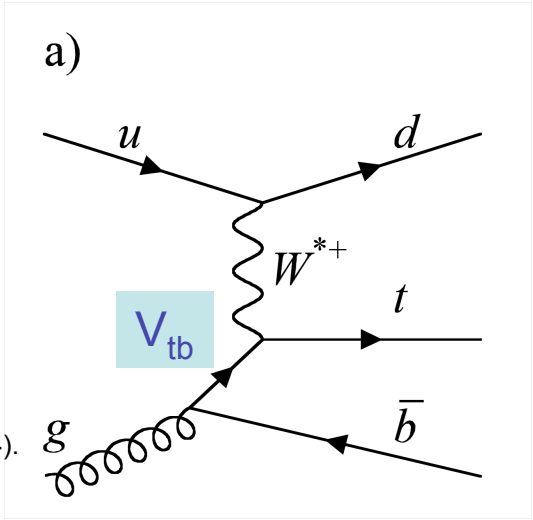
Motivation for Searching for Single Top

Production rate is proportional to $|V_{tb}|^2$

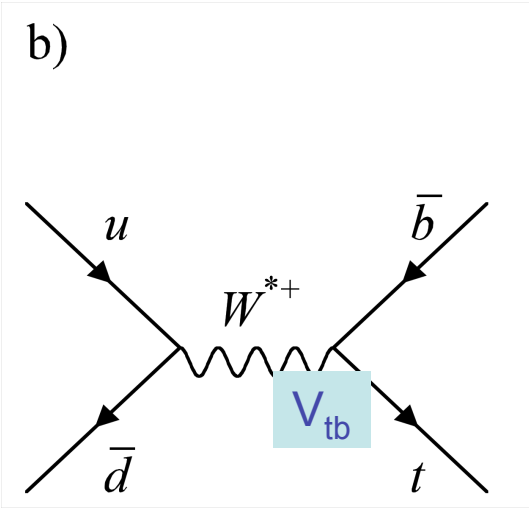
$$\sigma_s = (0.88 \pm 0.11)\,|V_{tb}|^2 \text{ pb}$$

$$\sigma_t = (1.98 \pm 0.25)\,|V_{tb}|^2 \text{ pb}$$

B.W. Harris et al., Phys. Rev. D66, 054024 (2002).
Z. Sullivan, Phys. Rev. D70, 114012 (2004).
Compatible Results;
Campbell/Ellis/Tramontano, Phys. Rev. D70, 094012 (2004).
N. Kidonakis, Phys. Rev. D74, 114012 (2006).

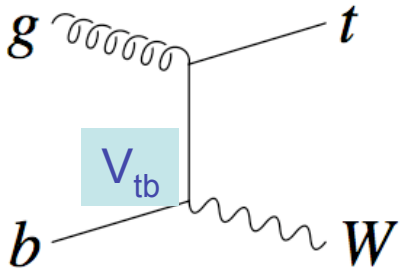


t-channel production



s-channel production

$$g + b \rightarrow W^- + t$$



Associated production
(small, ~ 0.3 pb)
-- neglected here.

Status of the CKM Matrix

From the PDG review 2006 (Ceccucci, Ligeti, Sakai)

$$V_{\rm CKM} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$V_{\rm CKM} = \begin{pmatrix} 0.97383^{+0.00024}_{-0.00023} & 0.2272^{+0.0010}_{-0.0010} & (3.96^{+0.09}_{-0.09}) \times 10^{-3} \\ 0.2271^{+0.0010}_{-0.0010} & 0.97296^{+0.00024}_{-0.00024} & (42.21^{+0.10}_{-0.80}) \times 10^{-3} \\ (8.14^{+0.32}_{-0.64}) \times 10^{-3} & (41.61^{+0.12}_{-0.78}) \times 10^{-3} & 0.999100^{+0.000034}_{-0.000004} \end{pmatrix}$$

Rigid SM prediction →
Measurement of $|V_{tb}|$ is a solid test of assumptions

- **Magnitudes only**
- **3x3 Unitarity enforced**

What Can Affect $|V_{tb}|$?

- 3x3 Unitarity is not true if the matrix is 4x4 (or more..)

$$V_{CKM} = \begin{vmatrix} V_{ud} & V_{us} & V_{ub} & V_{uX}\,? \\ V_{cd} & V_{cs} & V_{cb} & V_{cX}\,? \\ V_{td} & V_{ts} & V_{tb} & V_{tX}\,? \\ V_{Yd}\,? & V_{Ys}\,? & V_{Yb}\,? & V_{YX}\,? \end{vmatrix}$$

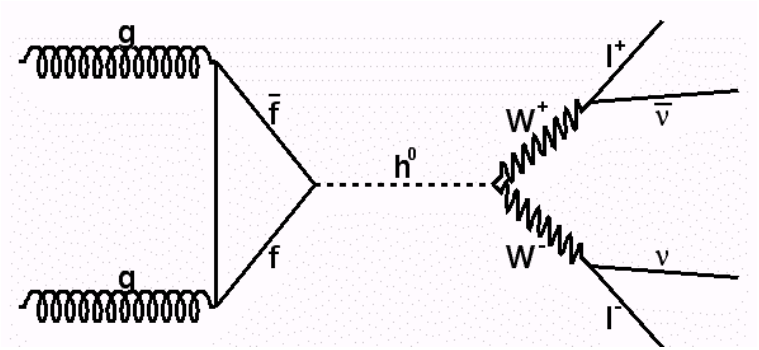
- Vector t' quark is also a possibility

J. Alwall et. al., "Is $|V_{tb}|$~1?"
Eur. Phys. J. C49 791-801 (2007).

Interesting constraints from precision EW measurements.

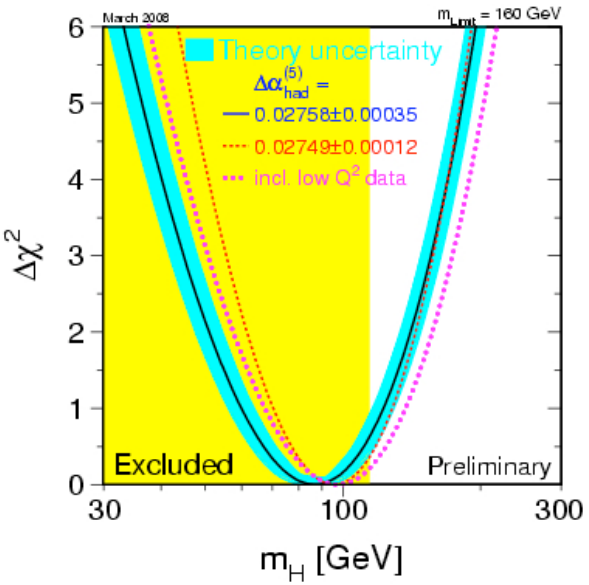
It's Not Looking Good For a Fourth Generation, However!

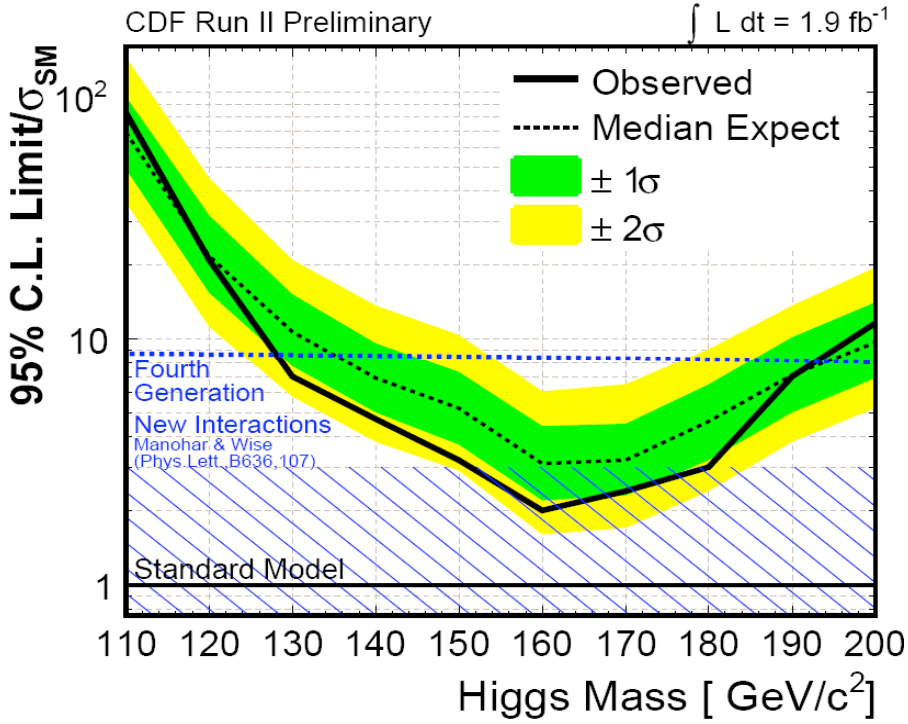
Higgs production via gluon-gluon fusion proceeds mostly via a top loop in a 3-gen model, and gets a boost from heavier quarks if they exist.



Propagators and vertex mass dependencies cancel in the triangle diagram.

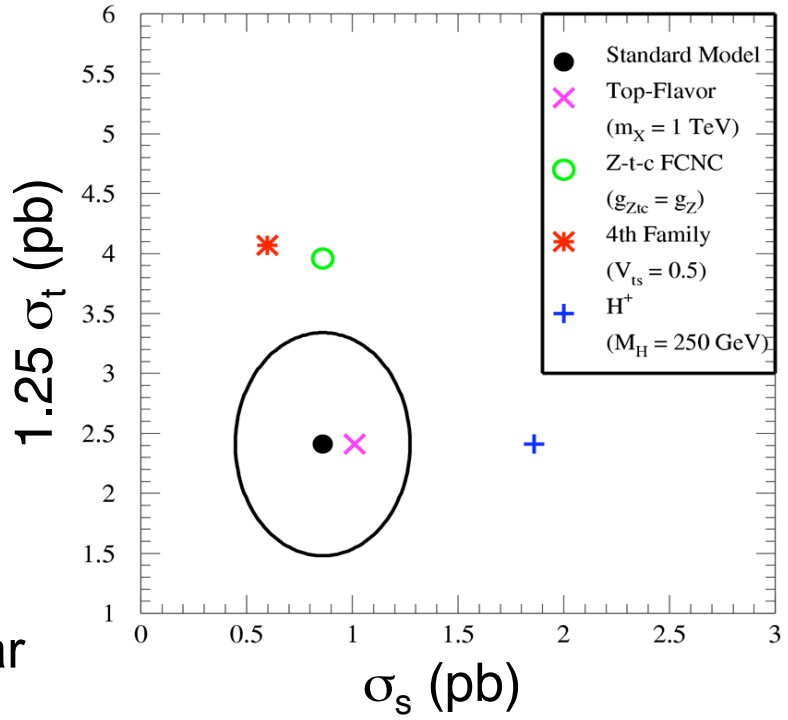
$$m_{\mathrm{H}}^{\mathrm{EW-fit}} = 87^{+36}_{-27}\ \mathrm{GeV}$$





Physics Motivations for Seeking Single Top

- Interesting signal -- *s* and *t*-channel rates are differently sensitive to new interactions
- Can search for FCNC's involving top quarks
- Single top quarks are ~100% polarized in the SM
  - Can test this with angular distributions of decay products
- Can test CP-violation -- single t vs. single tbar
- A check of the b PDF of the proton
- Can search for heavy W′ bosons (L or R-handed), contributing to s- and t-channel production modes

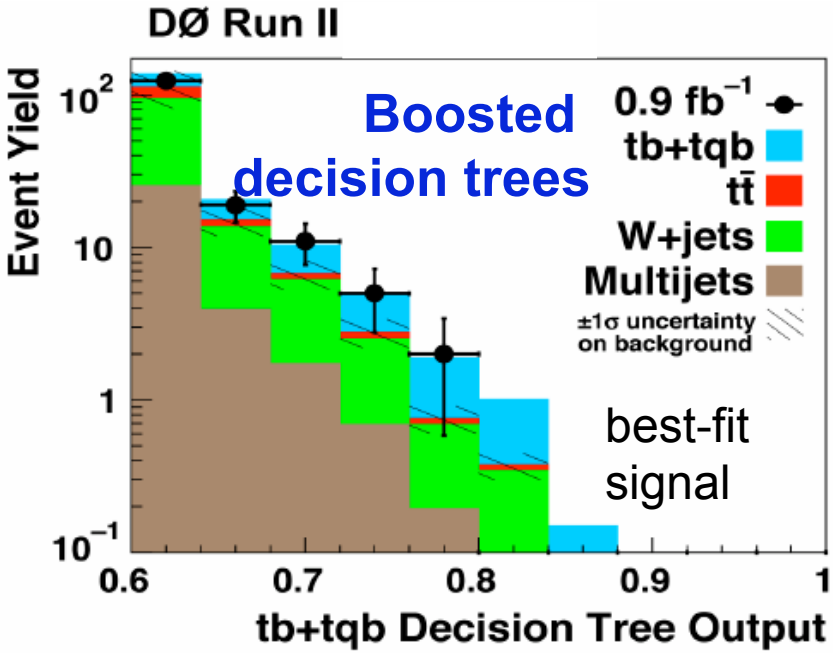


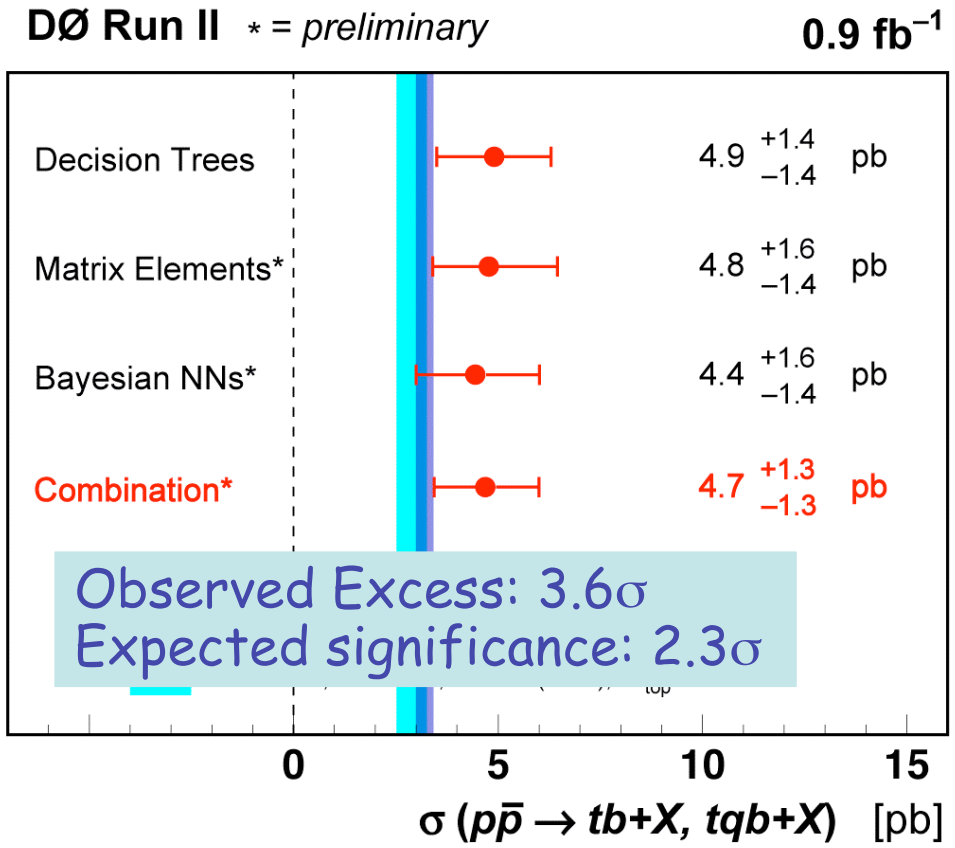
T. Tait and C. P. Yuan, Phys.Rev.**D63**:014018 (2001)

Technical Motivations for Seeking Single Top

- Single top is a background to WH→lνbb
  Measurements are preferable to MC predictions
- Its backgrounds are backgrounds to WH→lνbb
  (W+jets, ttbar, QCD, dibosons)
- We need to observe it on our way to observing a light Higgs boson
  - It has a larger cross section than WH→lνbb (order of magnitude)
  - The kinematic signature is more distinct than WH→lνbb
  - It's a great testing ground for making a discovery using advanced signal/background separation techniques

DØ Evidence for Single Top in December 2006

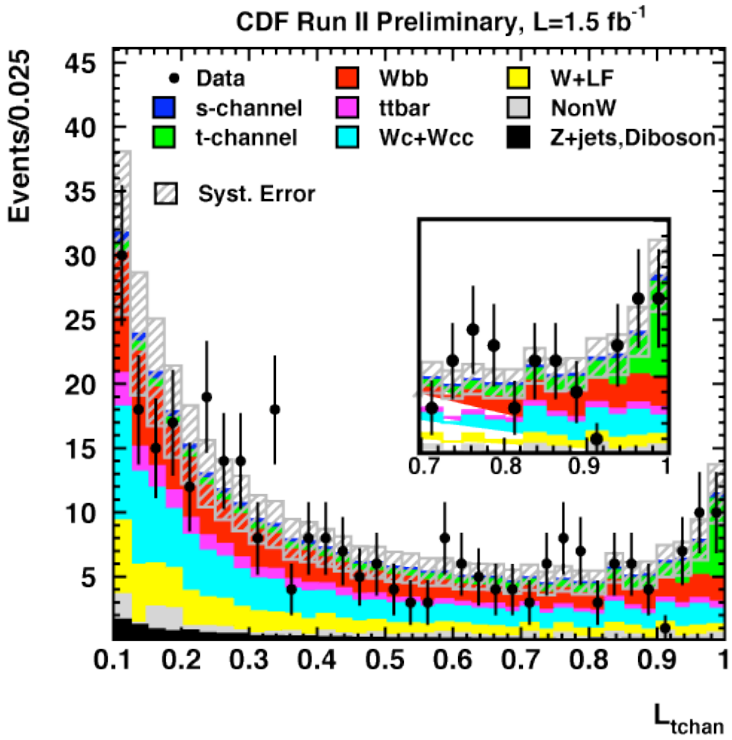


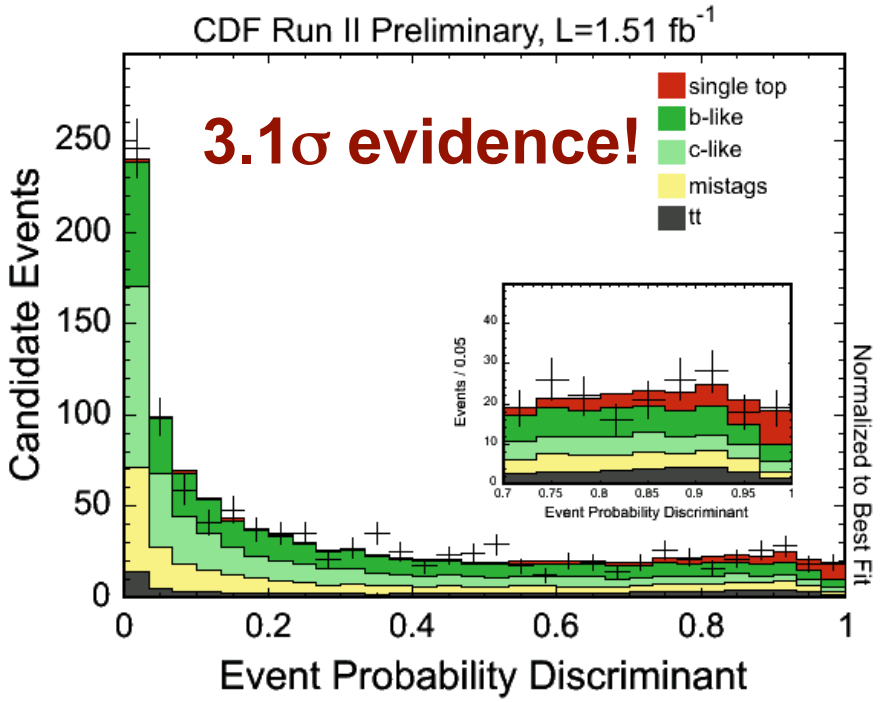


PRL 98 18102 (2007),
PRD article available at
arXiv:0803.0739 [hep-ex]

First direct measurement of V_{tb}:
$0.68 < |V_{tb}| < 1$ @ 95%CL or
$|V_{tb}| = 1.3 \pm 0.2$

CDF's Evidence with 1.5 fb^{-1}





σ_{s+t}= 2.7 ± 1.2 pb

Expected sensitivity: 2.9σ
Observed significance: 2.7σ

σ_{s+t}= 3.0 ± 1.2 pb

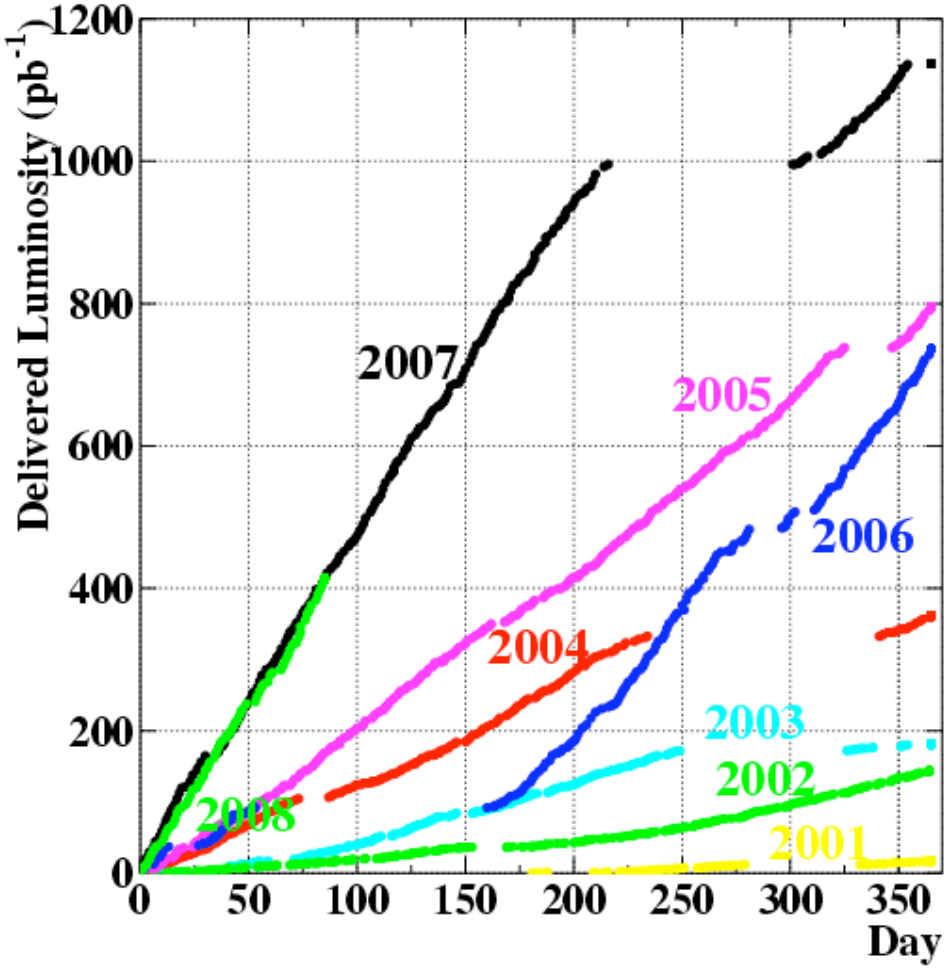
Expected sensitivity: 3.0σ
Observed significance: 3.1σ

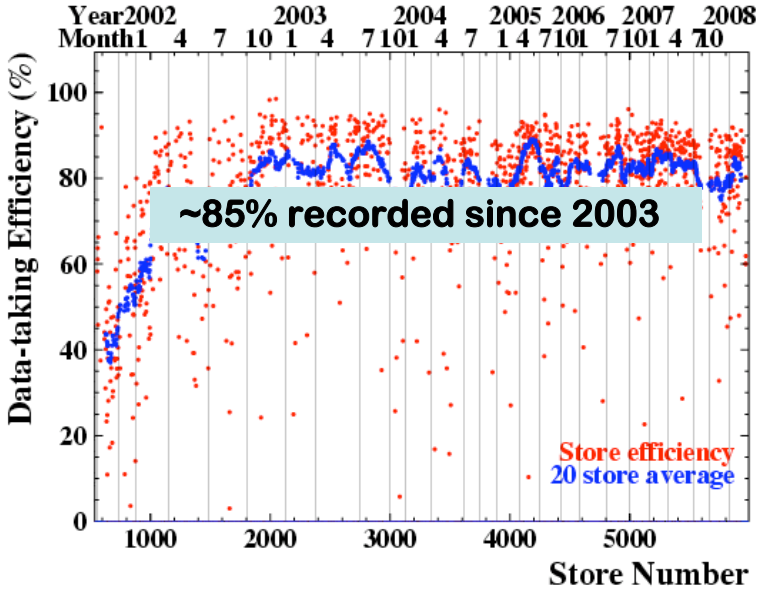
Improvements Made Since Lepton-Photon '07

Thanks to CDF and the Accelerator Division!

- More Data! Tevatron has been running very well.
  LP07: 1.5 fb^{-1} analyzed
  Now: 2.2 fb^{-1} analyzed
- Neural Network analysis updated
- Additional muon acceptance on Missing-E_T+jets trigger
  12% more signal acceptance
- 1-Btag and 2-Btag samples analyzed separately
- W+3 jet channels analyzed and combined with W+2 jet channels
- Improved discriminants
- Innovative combination techniques developed

Delivered and Collected Integrated Luminosity

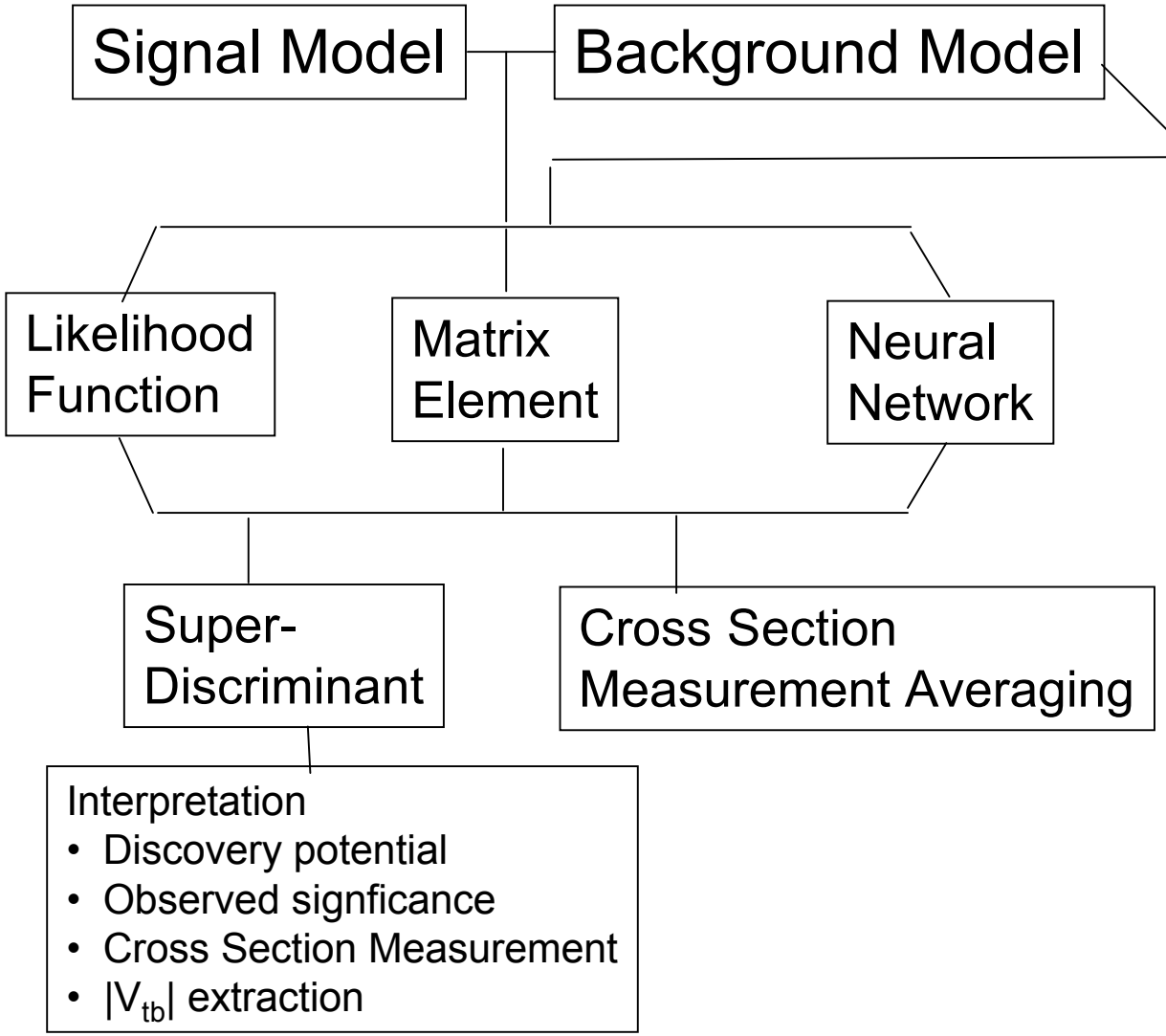




Data up to 2007 shutdown included in these analyses

2.2 fb^{-1} of data with all subdetectors used.

Analysis Roadmap

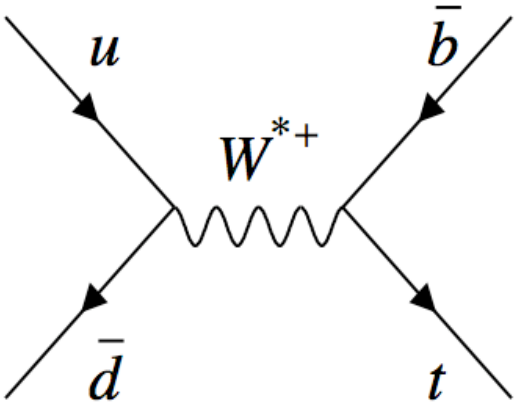


Nearly 100% overlap in selected events

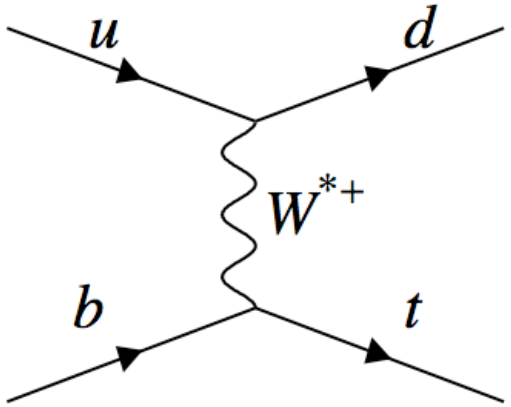
Optimization choices guided by best expected performance

Blind!

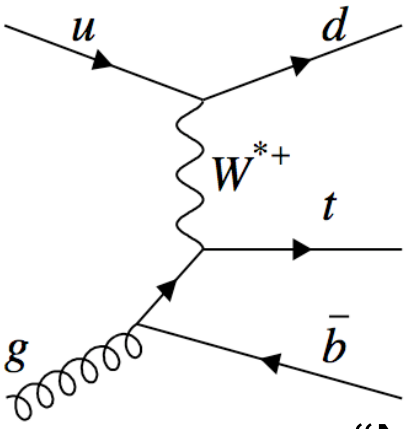
Single Top Production Mechanisms

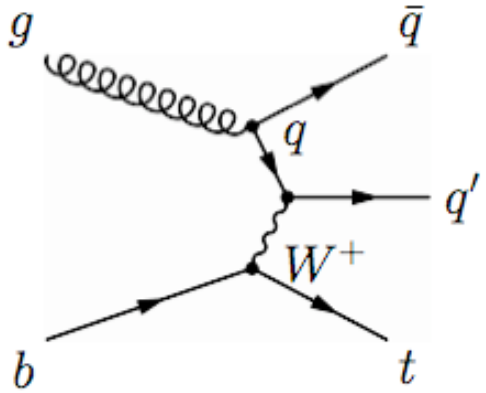


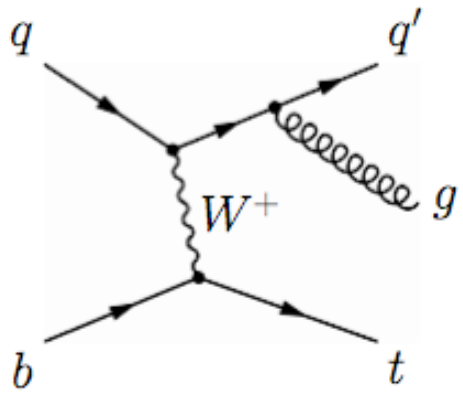
"*s*-Channel"



"*t*-Channel"







"NLO Contributions to *t*-Channel Production"

Single Top Signal Model

- Pythia model inadequate -- Pythia's single top quarks are unpolarized

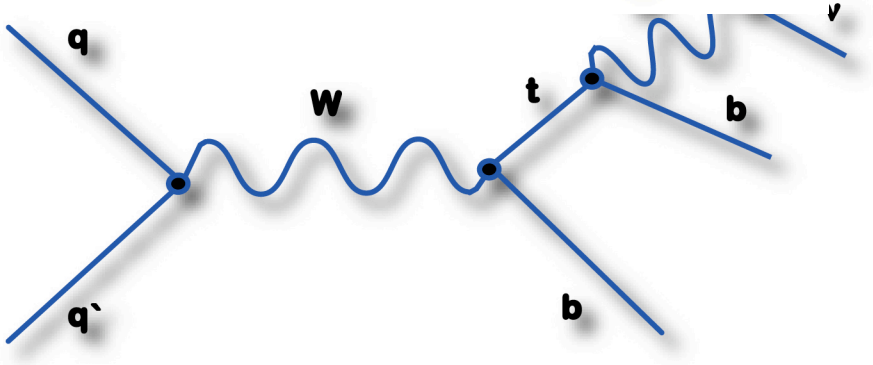
- Use MADEVENT + PYTHIA for showering
  MADEVENT: JHEP 0709:028 (2007) arXiv:0706.2334

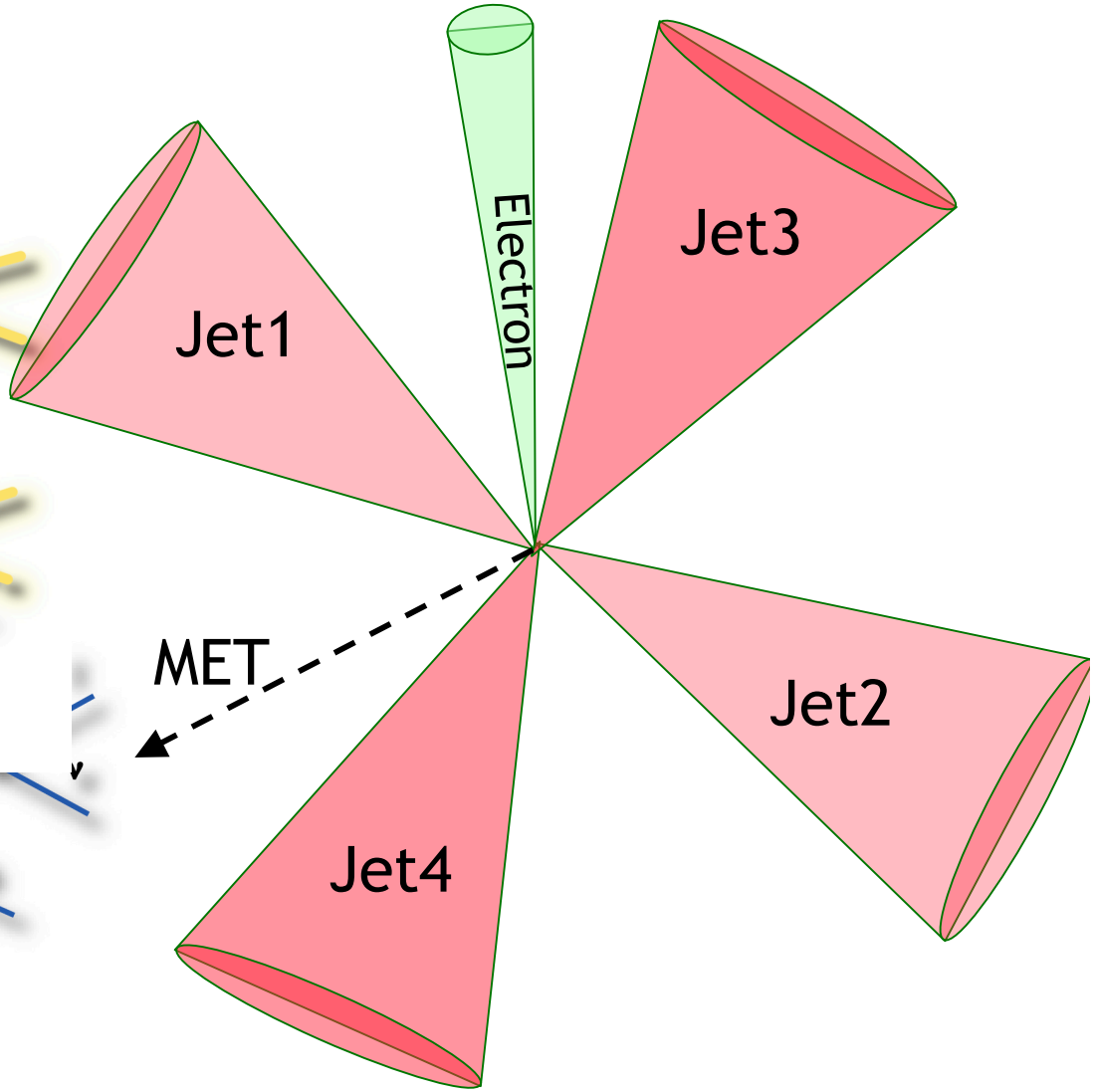
- W-b fusion and W-g fusion processes generated separately and matched in b p_T to match NLO differential prediction

B.W. Harris et al., Phys. Rev. **D66**:054024 (2002).
Thanks Z. Sullivan for ZTOP

Event Signatures

Top Pair Production with decay
Into Lepton + 4 Jets final state
are very striking signatures!





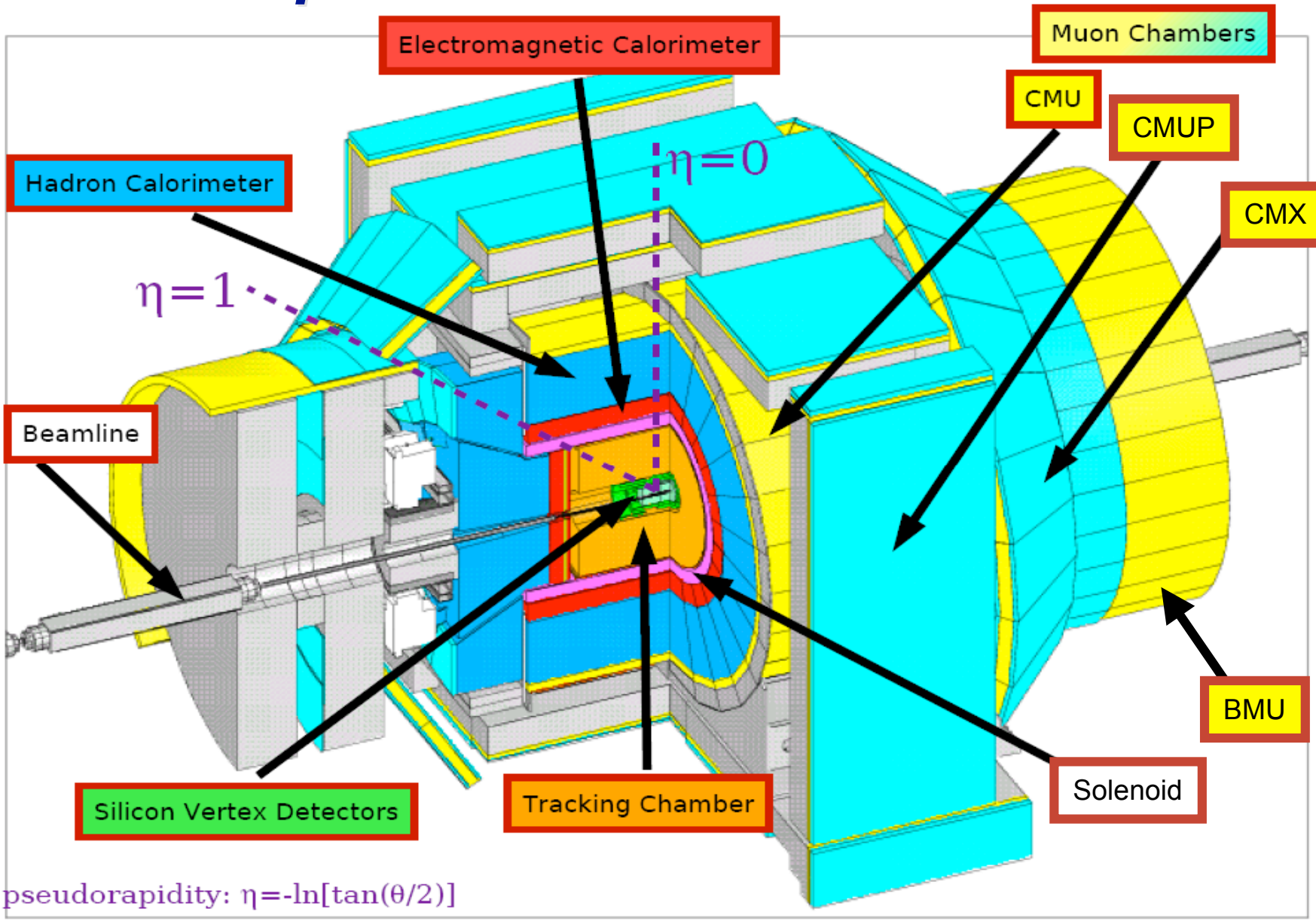
B. Stelzer, Dec. 2006 W+C

Event Selection

- Main Triggers: Electron or muon with p_T> 18 GeV

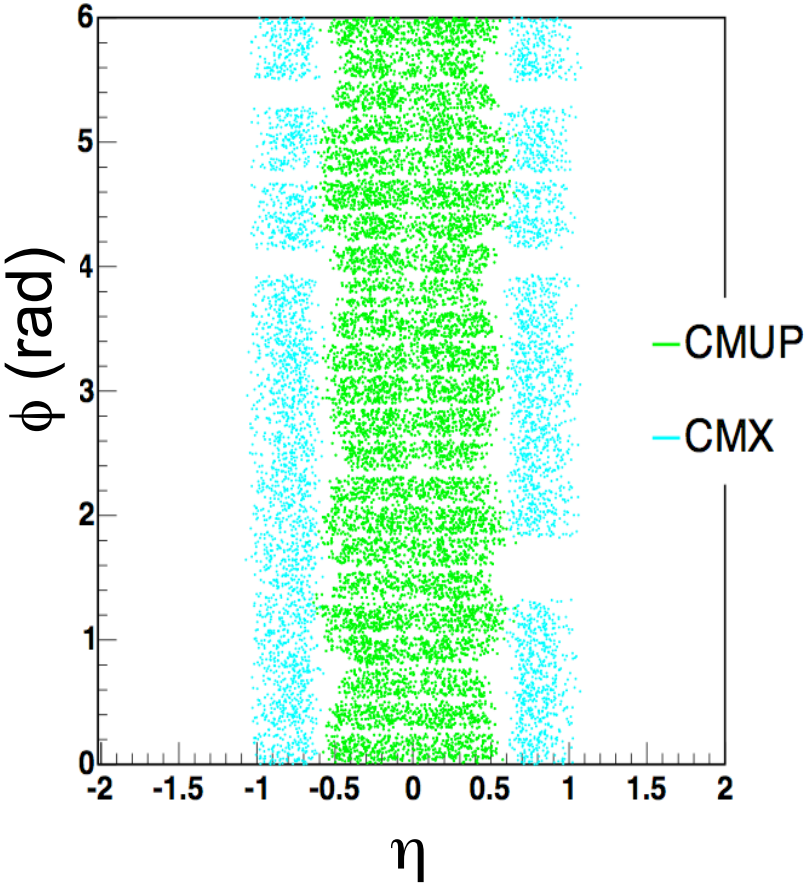
- A lepton (e or μ) with p_T>20 GeV, $|\eta|$<1.6
- Two jets or three jets
  - Jet E_T > 20 GeV
  - $|\eta_{jet}|$ < 2.8 (much wider angular acceptance than other CDF analyses!)
- At least one displaced vertex b-tag
- MET > 25 GeV
- Vetoes:
  - Dilepton (rejects $Z \rightarrow \ell\ell$ and some ttbar)
  - Cosmics
  - Conversions
  - Anti-QCD veto -- triangle cuts

CDF Components

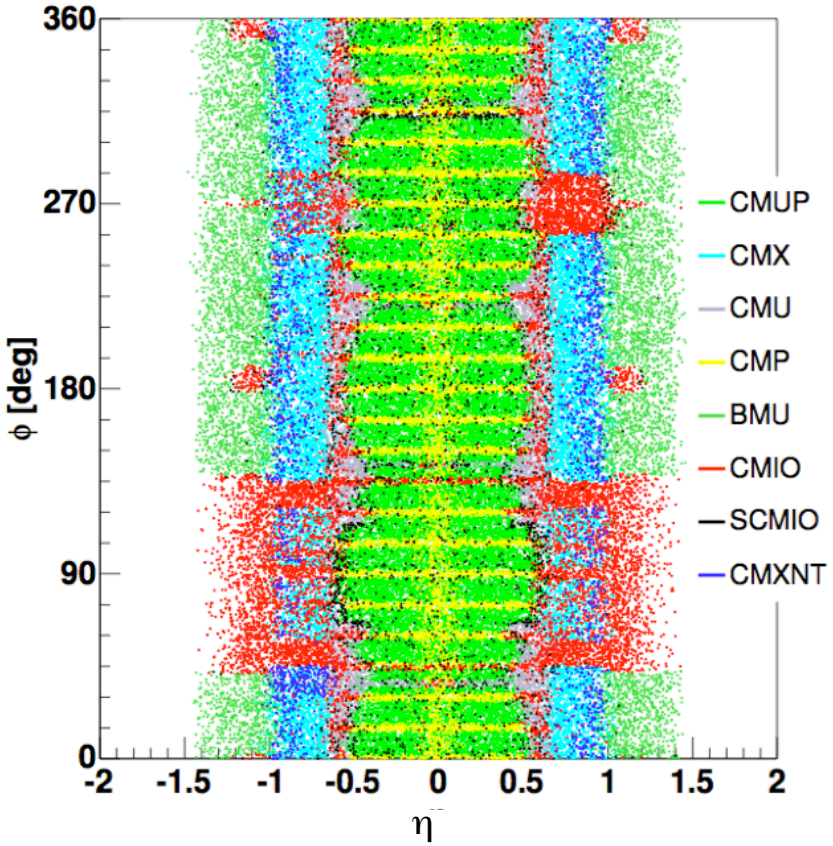


Finding More Muons in CDF

Muon coverage used for LP07



Gains from Missing-E_T+jets triggered events

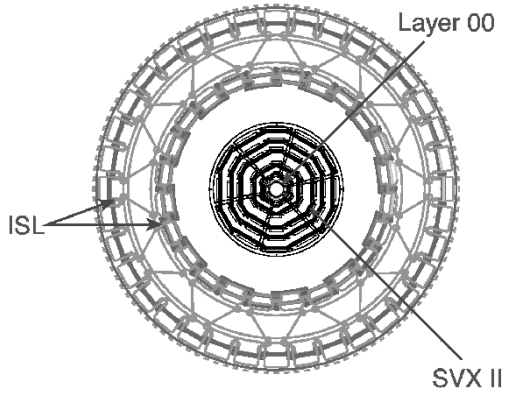


Additional requirement:
$\Delta R_{jj}>1.0$

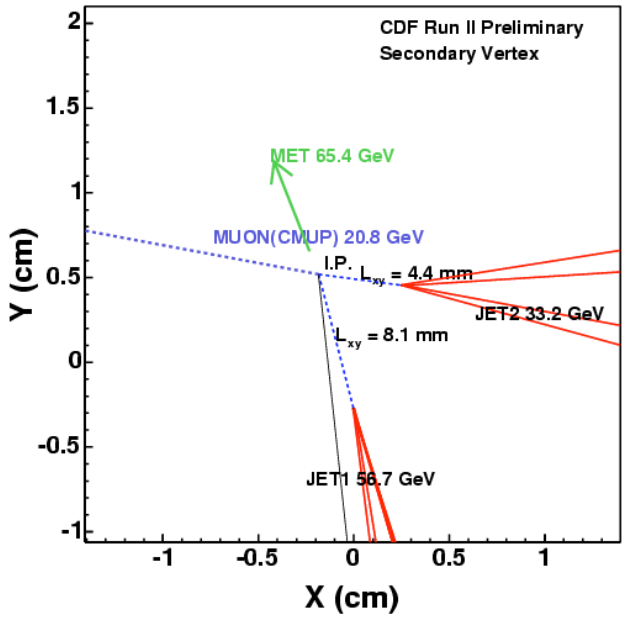
~30% gain in muon acceptance,
~20% gain in total signal acceptance (incl. electrons)

B-Tagging at CDF

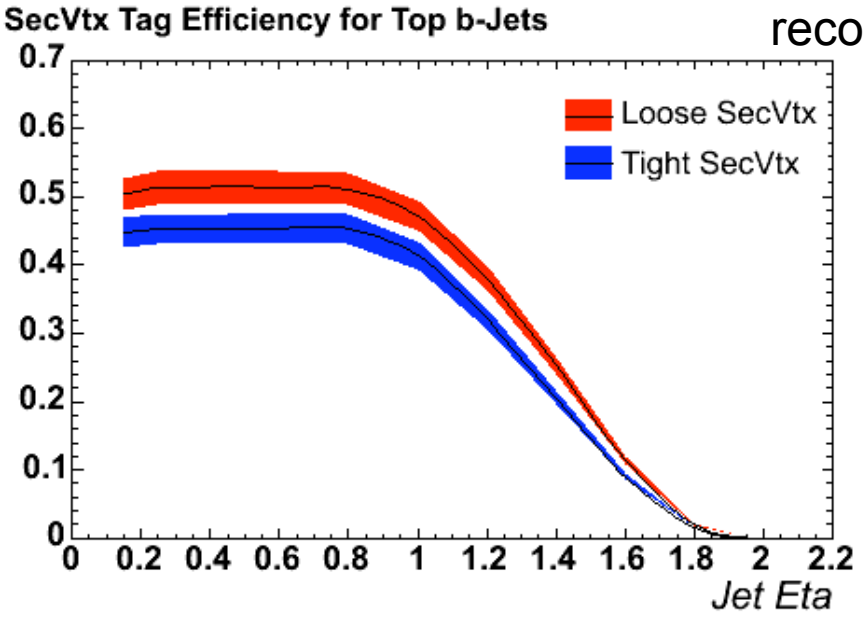
L00 single-sided silicon +
5-layer double-sided silicon+
2-layer ISL



Impact parameter resolution for high-p_T tracks ~18μm



B-tagging relies on displaced vertex reconstruction



Mistag rates typically ~1% for light-flavor jets

Example candidate event

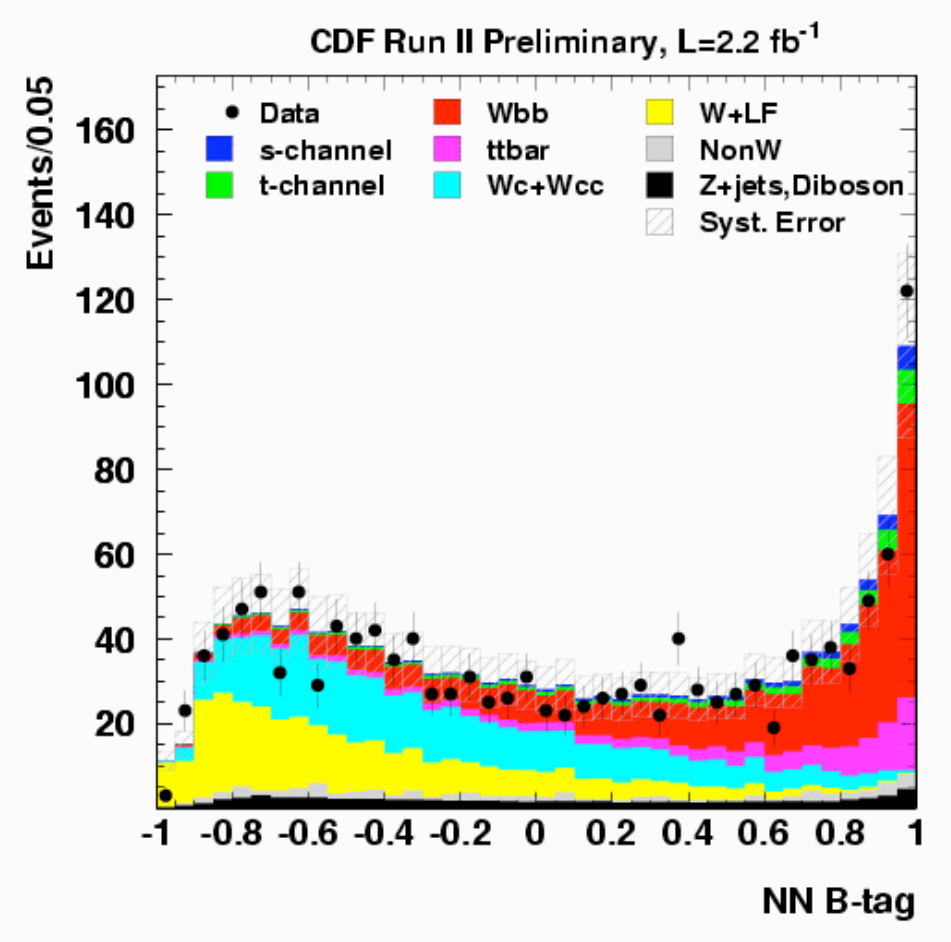
A Neural-Net B-tagging Tool

Identified secondary-vertex tags have a significant charm and mistag contamination.

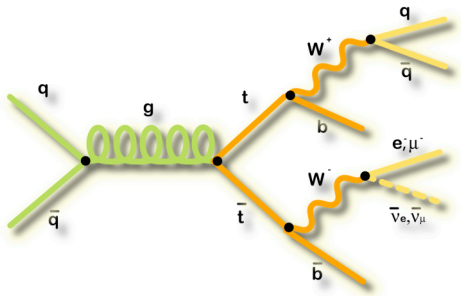
➔Train a NN to separate b, c, LF in the vertex-tagged samples.

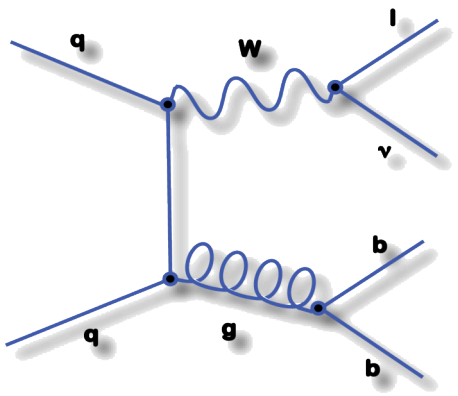
Some of the Inputs:

- Displaced vertex mass
- # tracks in displaced vertex
- Decay flight distance and significance
- Identified leptons in and near jets
- Secondary vertex fit χ^2
- Jet E_T



Background Modeling



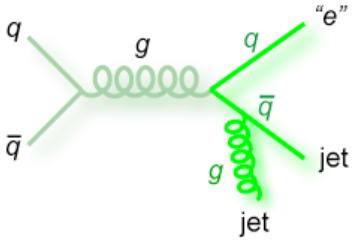


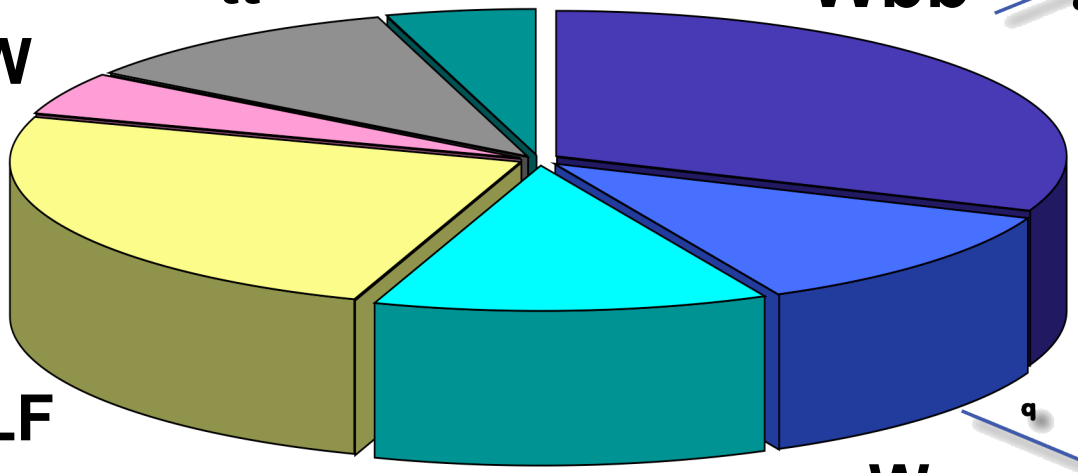
tt

Z/Dib

Wbb

Non-W

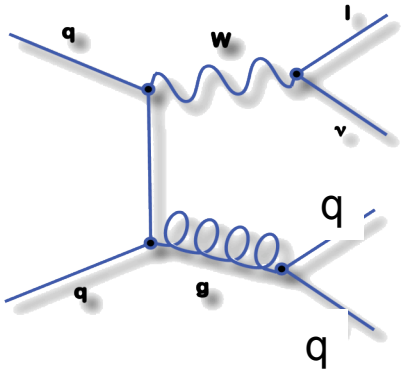


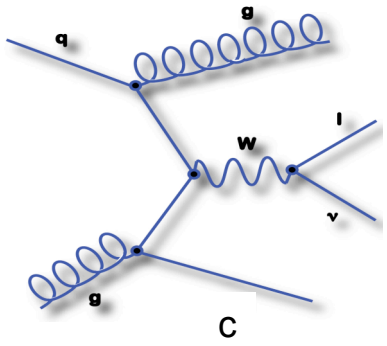


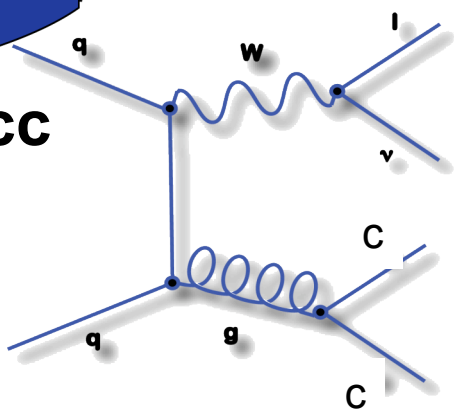
W+LF

Wc

Wcc

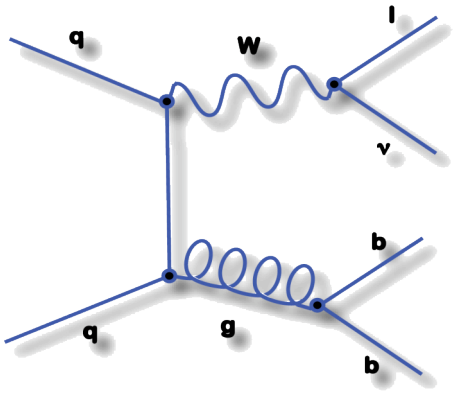




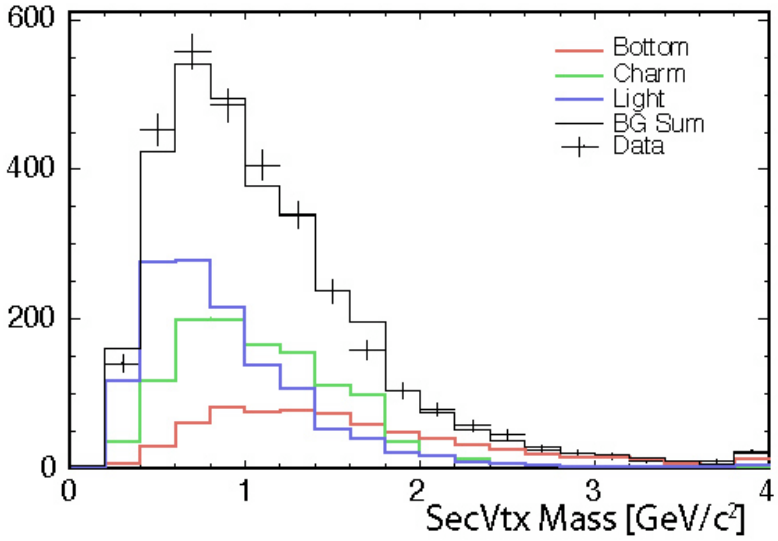


Background Estimate I: W+Heavy-Flavor Jets

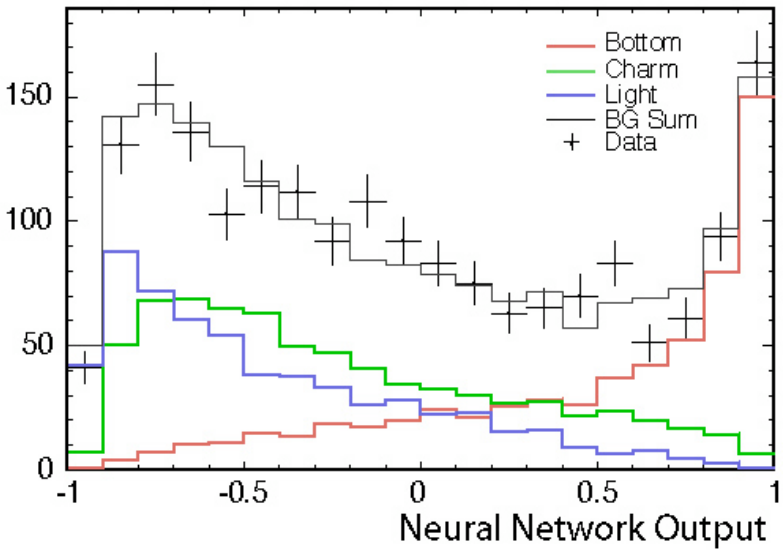
- General Strategy
  - Use ALPGEN predictions of kinematic distributions
  - We Mistrust ALPGEN rates:
    - Scale ALPGEN to pre-tagged W+jets
    - HF fraction in ALPGEN is also too low.
  - Use Displaced Vertex Mass and NN b-tag output distributions in W+1-jet events
  - Fit the b, charm and LF components
  - Apply a factor of 1.4±0.4 on ALPGEN's HF fractions, Wbb and Wcc



CDF Run II Preliminary, L=1.5 fb^{-1}

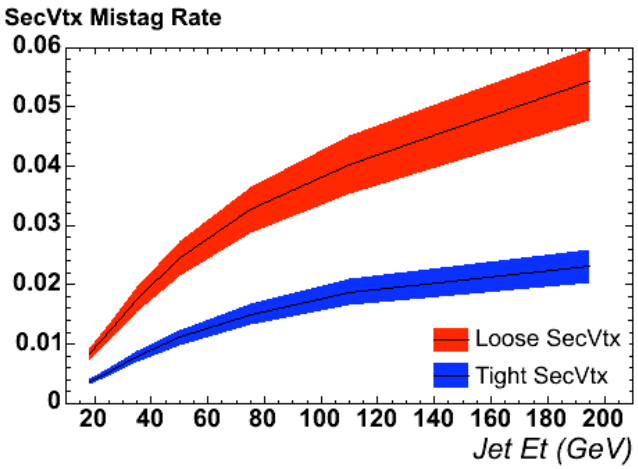


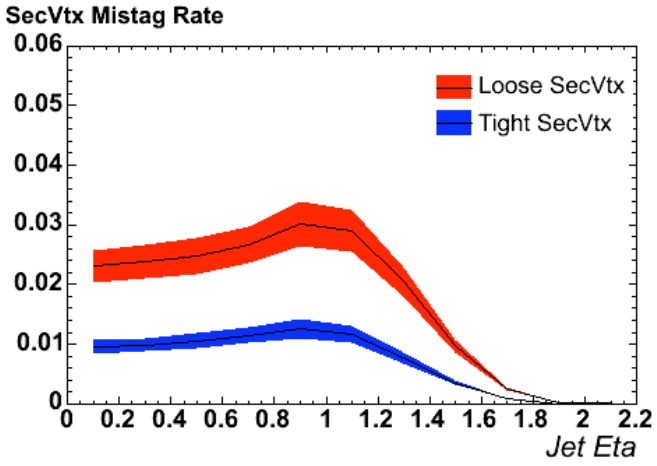
CDF Run II Preliminary, L=1.5 fb^{-1}



Background Estimate II: W+Light-Flavor Jets

- ALPGEN W+LF used to predict kinematic distributions
- Fake b-tag fractions measured in inclusive multijet data samples using negative-tag rates (asymmetry corrected)
  - Parameterized as a function of
    $n_{trks,jet}$, $E_{T,jet}$, $|\eta_{jet}|$, $n_{primary\text{-}vertices}$, $SumE_T(event)$, $z_{primary}$

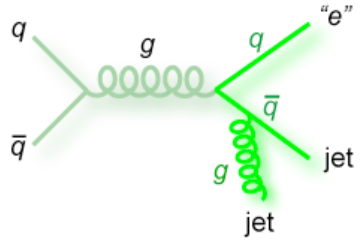




We use the "tight" (blue) tag.

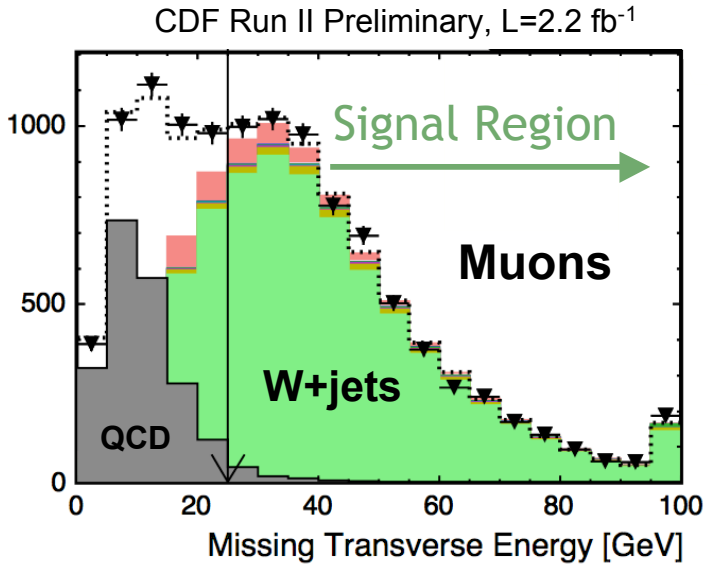
- Apply fake b-tag fraction to W+LF MC
- Alternate kinematic model: use the untagged, selected data, with fake-tag probabilities applied
  - Trades MC mismodeling for contamination

Background Estimate III: Non-W ("QCD") ("Multijets") ("Instrumental")

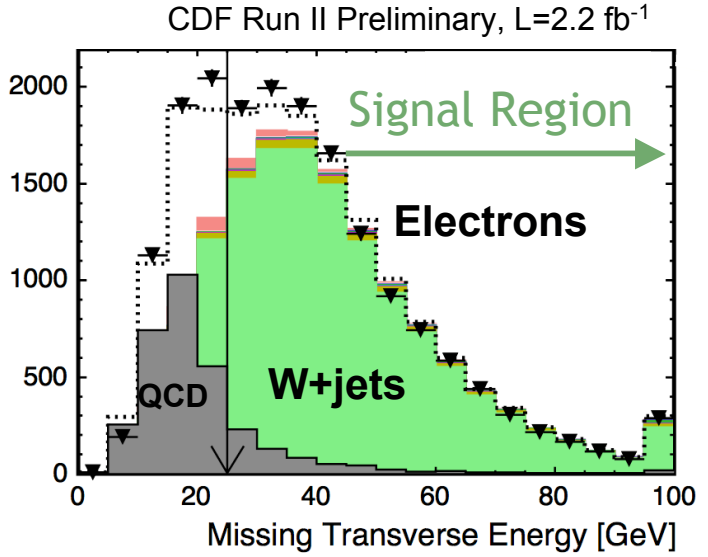


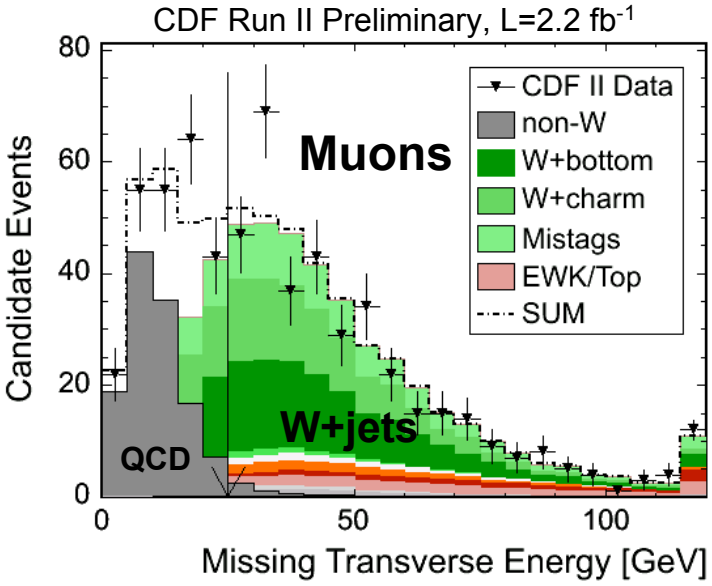
- Monte Carlo models of inclusive jet+MET production are not precise enough
- Use data samples to model kinematics of non-W events
  - Two independent samples:
    Electron candidates which fail some selection requirements
- Loosen up the MET cut and fit the MET distribution.
- Apply same anti-QCD cuts used in the selection -- reduces QCD by a factor of 3.
- Use kinematic model to extrapolate the Non-W fit into the signal sample
- Assign a 40% uncertainty on non-W rate

Background Estimate III: Non-W ("QCD")

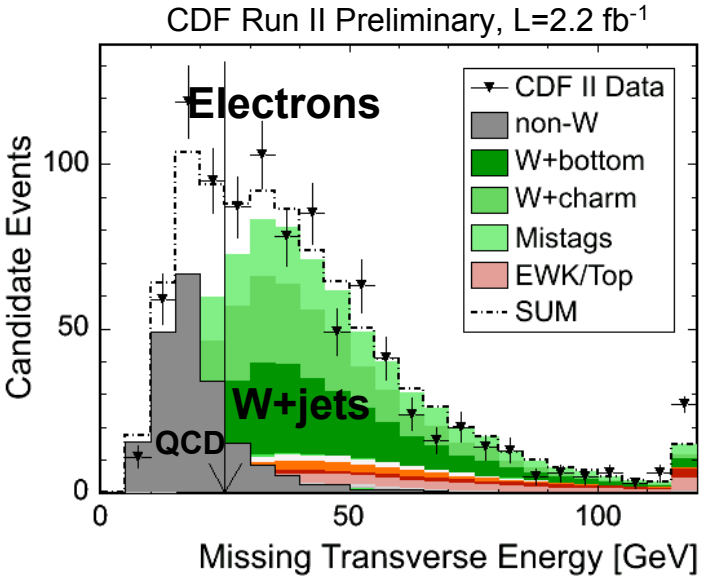


No B-tag





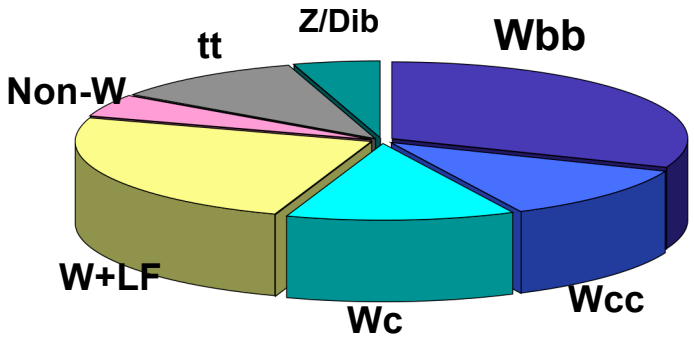
B-tagged



Background Estimate IV: MC-Based Backgrounds

- Diboson: WW + WZ + ZZ
- top-pair production
  - ℓ+jets and dilepton assigned own systematic errors
- Z+jets background estimated with ALPGEN Z+np samples with W+HF scale factors applied (small background)

Background Estimate Summary



2-jet Background composition

3-jet sample has more ttbar

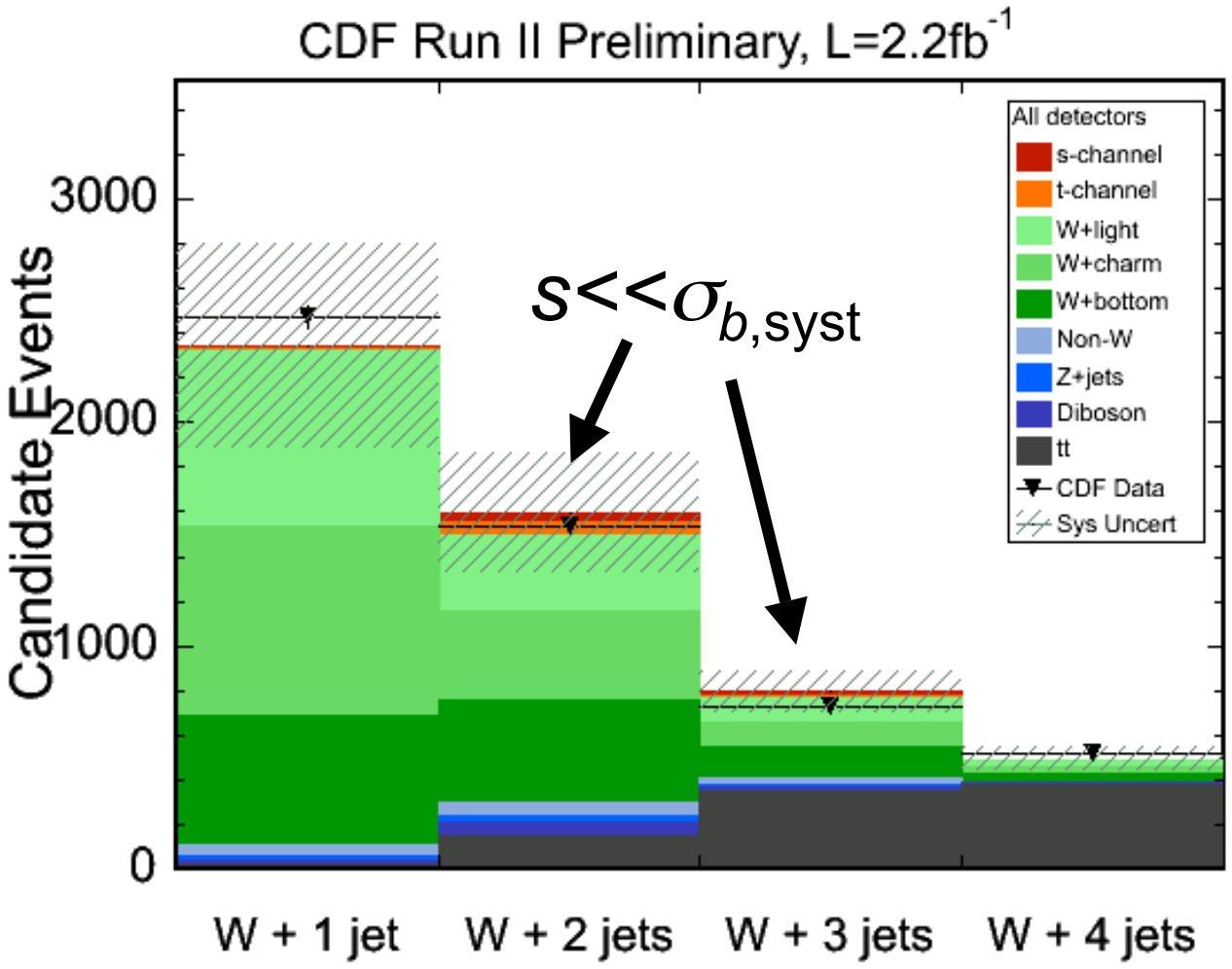
2-Jet Event Yields

s-channel	41.2 ± 5.9
t-channel	62.1 ± 9.1
Single top	103.3 ± 15.0
tt	146.0 ± 20.9
Diboson	63.2 ± 6.3
Z + jets	26.7 ± 3.9
W + bottom	461.6 ± 139.1
W + charm	395.0 ± 121.8
W + light	339.8 ± 56.1
Non-*W*	59.5 ± 23.8
Total bckgd	1491.8 ± 268.6
Total prediction	1595.1 ± 269.0
Observed	1535

3-Jet Event Yields

s-channel	13.5 ± 1.9
t-channel	18.3 ± 2.7
Single top	31.8 ± 4.6
tt	338.7 ± 48.2
Diboson	21.5 ± 2.2
Z + jets	11.0 ± 1.6
W + bottom	141.1 ± 42.6
W + charm	108.8 ± 33.5
W + light	101.8 ± 16.9
Non-*W*	21.3 ± 8.5
Total bckgd	744.8 ± 91.3
Total prediction	776.6 ± 91.4
Observed	712

Signal and Background By Jet Count



Counting selected events won't allow us to see single top.

$$s/\sqrt{b}$$

is an inadequate estimate of sensitivity

We need a more pure sample of signal! Let's leverage its features.

Reconstruction Ambiguities

- Ambiguities in the 2-jet channel
  - **Which jet is the b from top decay?**
    t-channel signal – only one b in the detector (usually, but sometimes the other one's there) pick the b-tagged jet. Gets it right 95% of the time.
    s-channel signal – Use a linear combination of the $\Delta\chi^2$ (kinematic fit) and $Q_l \times \eta_{jet}$. Gets the b right 81% of the time.
  - **Quadratic ambiguity in solving for $p_{z,\nu}$.** Pick smaller $|p_{z,\nu}|$. Gets it right 75% of the time (including cases where both pz,v solutions are the same)
- More choices for b-jets in the 3-jet channel

Likelihood and Neural Network analyses: Assign a single reconstruction choice for each event
Matrix element analysis: Integrate over possible reconstructions

Consequences of Imprecise Jet Measurement

- Lepton energy resolution is quite good $\sigma_{E_T} = 14\% / \sqrt{E_T} \oplus 1.5\%$

  for central electrons (using the electromagnetic calorimeter), and

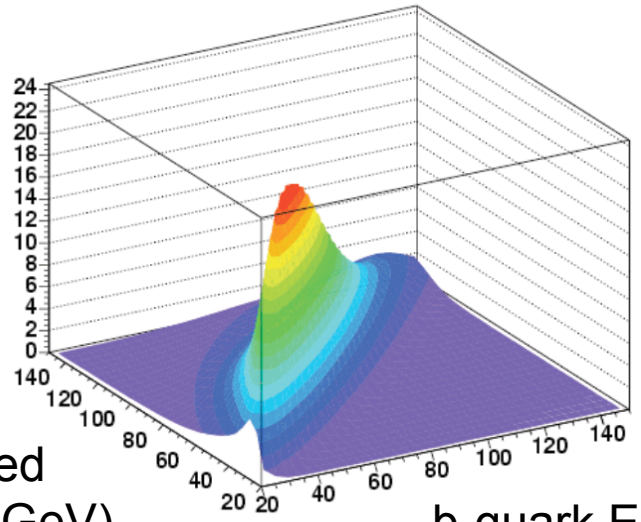
  $$\sigma(p_T) / p_T^2 = 0.0017\ c / \mathrm{GeV}$$

  for muons (using tracking chamber).

- B-jet energy is much more poorly measured. Core resolutions around 10%, but with long tails
  - >50% of b-jets have neutrinos, sometimes more than one, and sometimes very energetic.
- Badly measured b-jet energy impacts Missing-E_T measurement

- Matrix Element analysis takes a different approach than LF and NN analyses -- integrates instead of fits

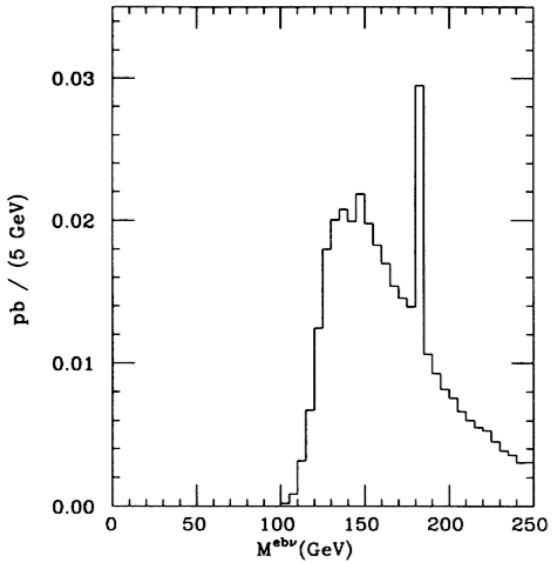
Fully simulated MC b-jets



Measured b-jet E (GeV)

b-quark E (GeV)

A Powerful Separation Variable -- Invariant Mass

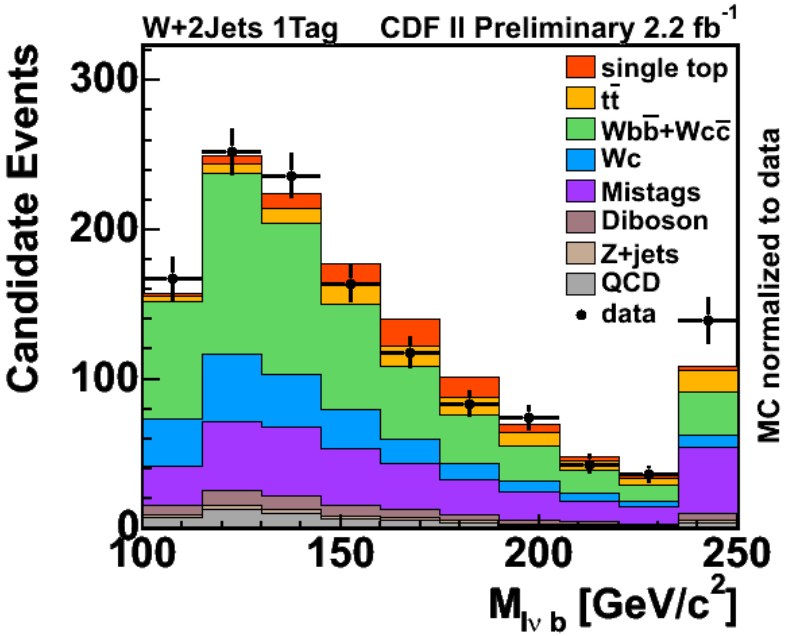


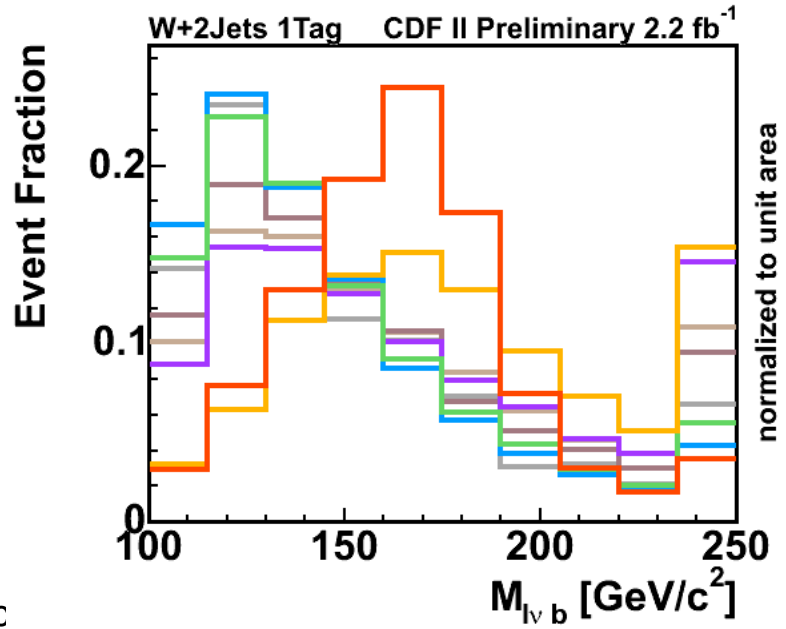
Well, maybe a little too powerful!

C.P. Yuan
Phys. Rev. **D41**, 42 (1990)

No experimental resolution effects taken into account.

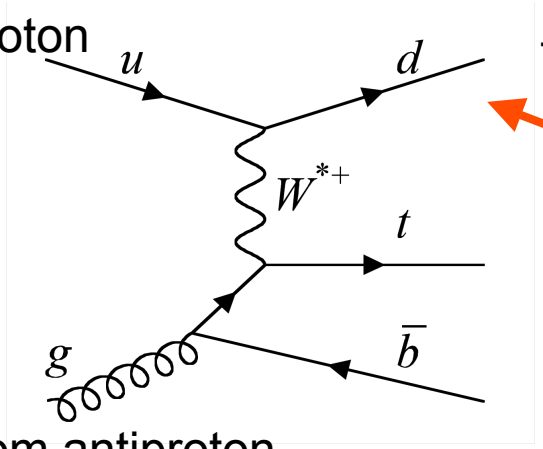
Reality sets in: MET and jet resolution, wrong jet assignment, wrong $p_{z,\nu}$ choice all degrade signal peak

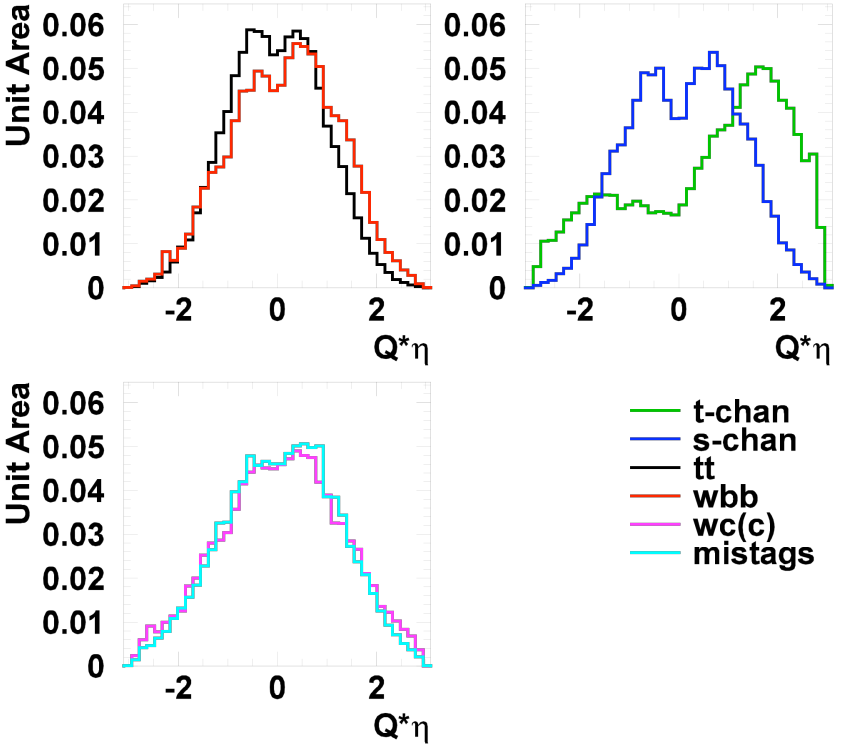


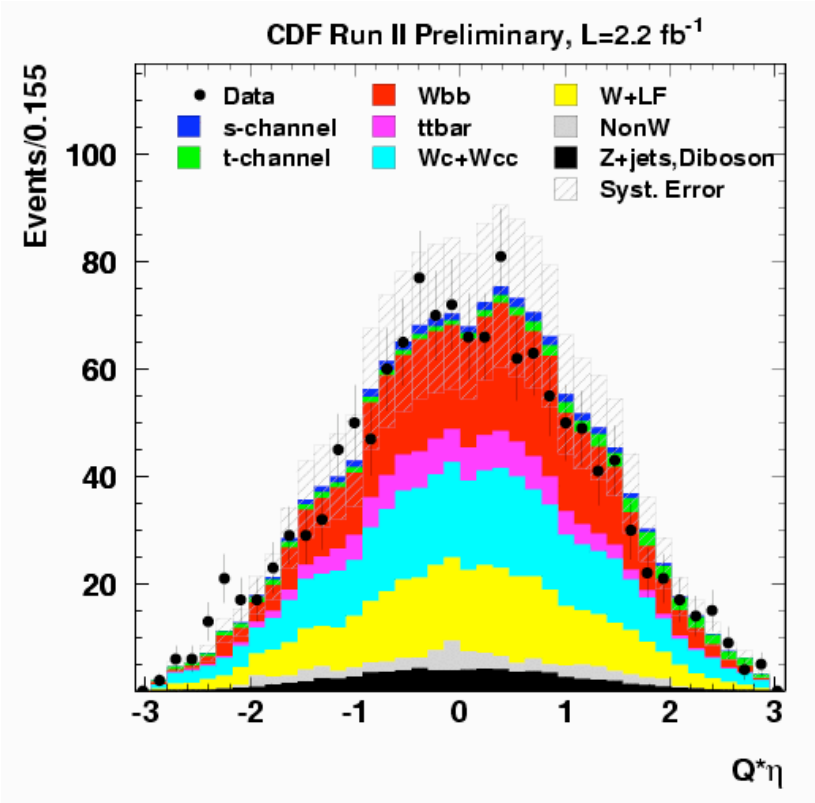


Q×η

Excellent t-channel signal/background separator Yuan, 1990.

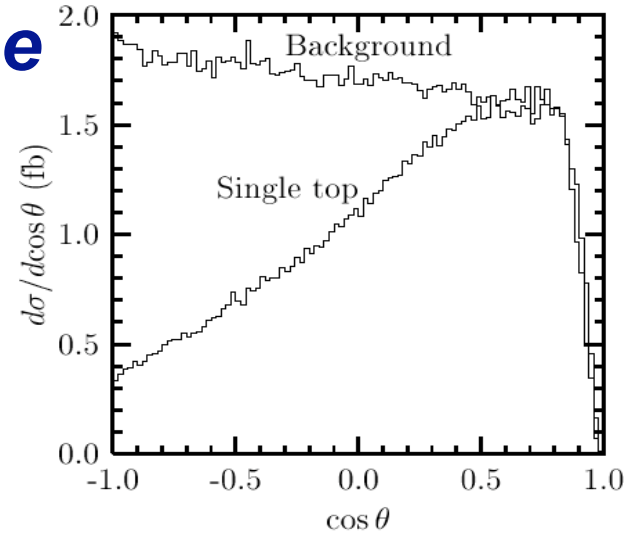




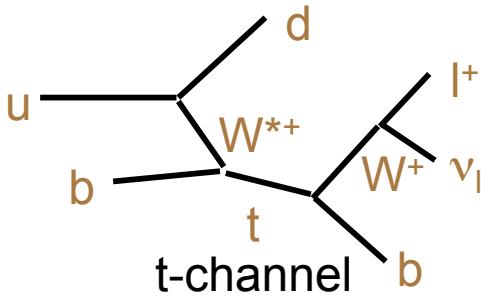


$\cos\theta_{l,\text{other jet}}$ in Top Decay Frame

- Relies on top polarization (we are trying to observe single top, assuming SM properties. To measure polarization, we'd have to have a more inclusive selection)
- Shape affected by lepton isolation requirement -- high s/b region next to a cut!

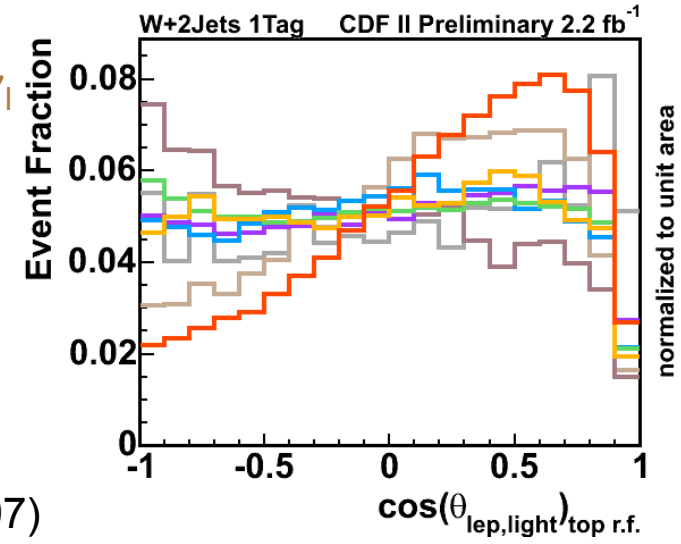


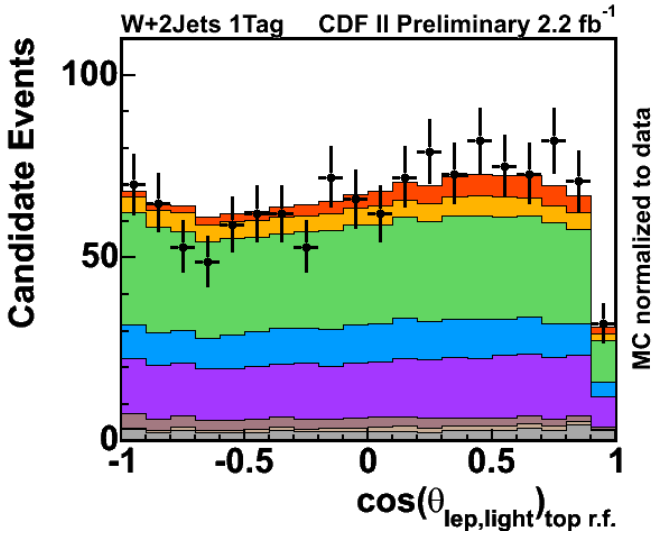
Stelzer, Sullivan, Willenbrock
Phys.Rev.D58:094021,1998.



Optimal spin basis:

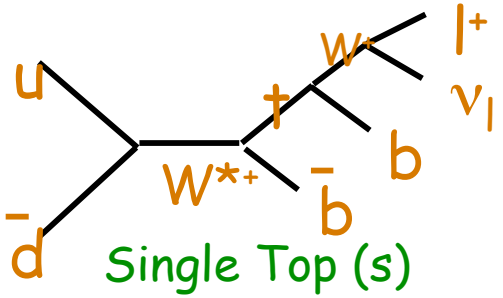
G. Mahlon and S. Parke,
Phys. Rev. D55, 7249 (1997)

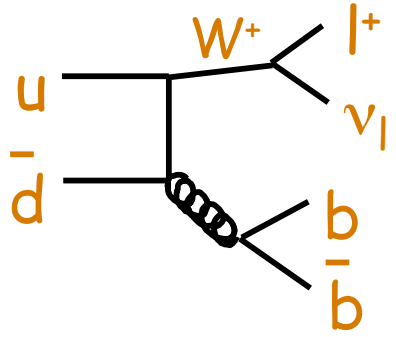


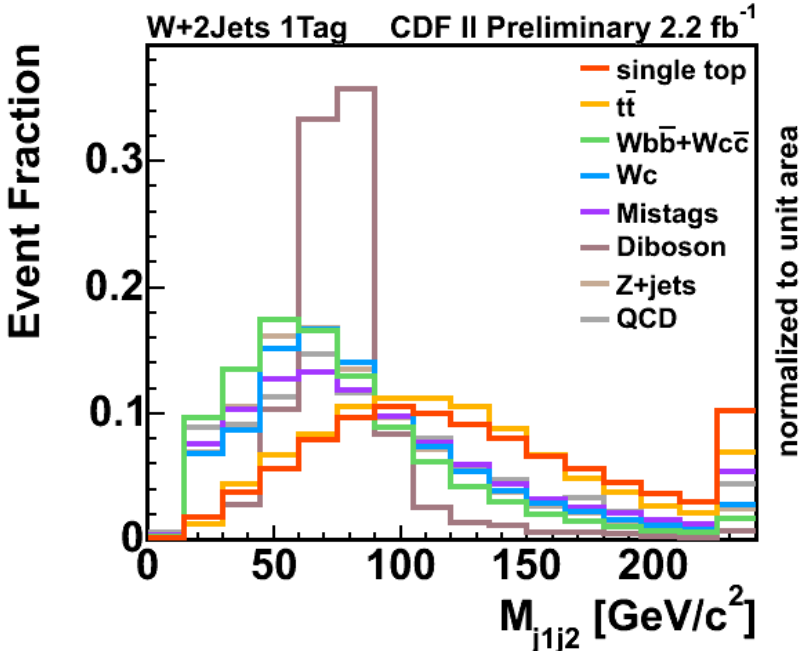


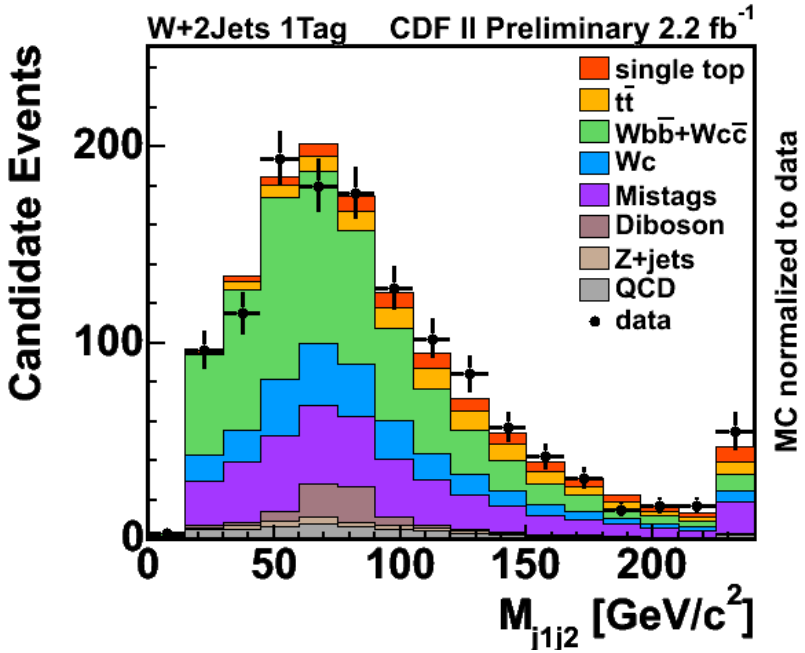
Exploiting Background Signatures

- Example: m_{jj} -- Wbb and Wcc background tend to have lower m_{jj} on average (gluon splitting to bb/cc is peaked towards low invariant mass)









Analysis I: LEP-Style Likelihood Discriminant

- Bayesian-motivated combination of information of several input variables.
- Two- and Three-Jet bins analyzed separately
- Does not take advantage of correlations between variables -- all separation information is in projected templates
- Available as an option in TMVA, R
- Need to choose a b from top decay, and also a $p_{z,\nu}$ solution

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

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

i=variable index
k=sample index (signal, Wbb, W+charm, W+LF, ttbar)
m=sum over samples
j_i= template histogram bin

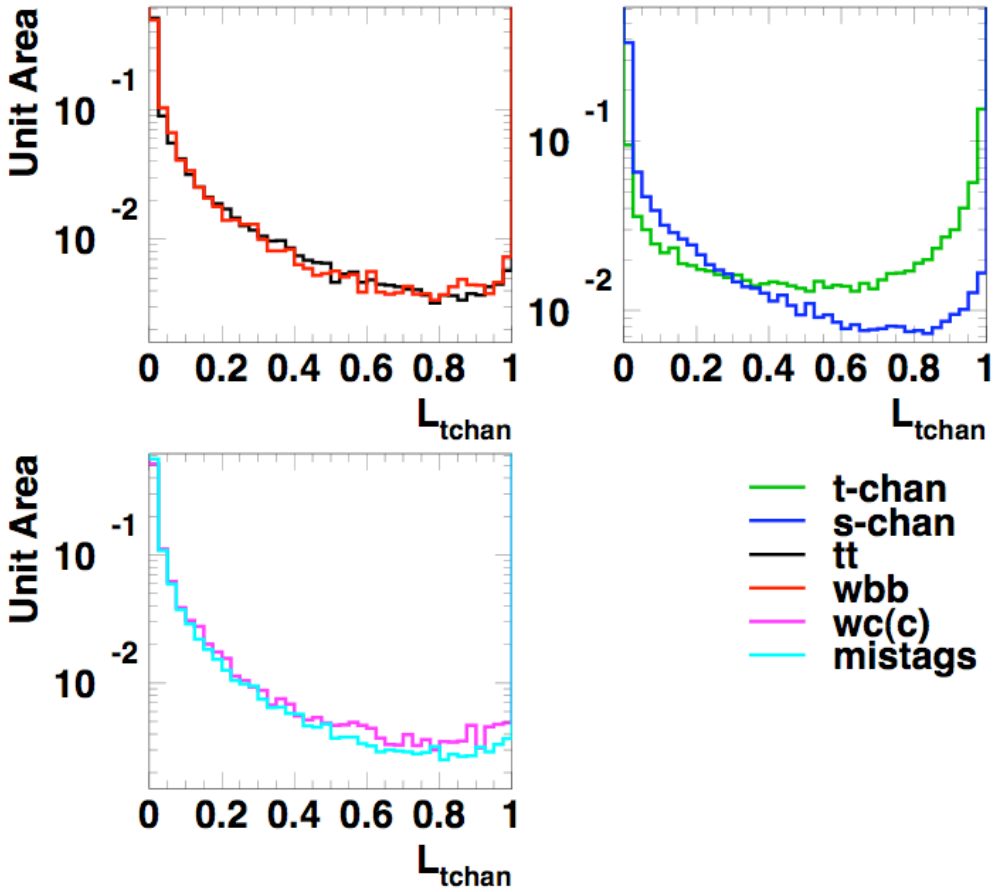
Likelihood Input Variables and Discriminant

2-jet bin input variables:

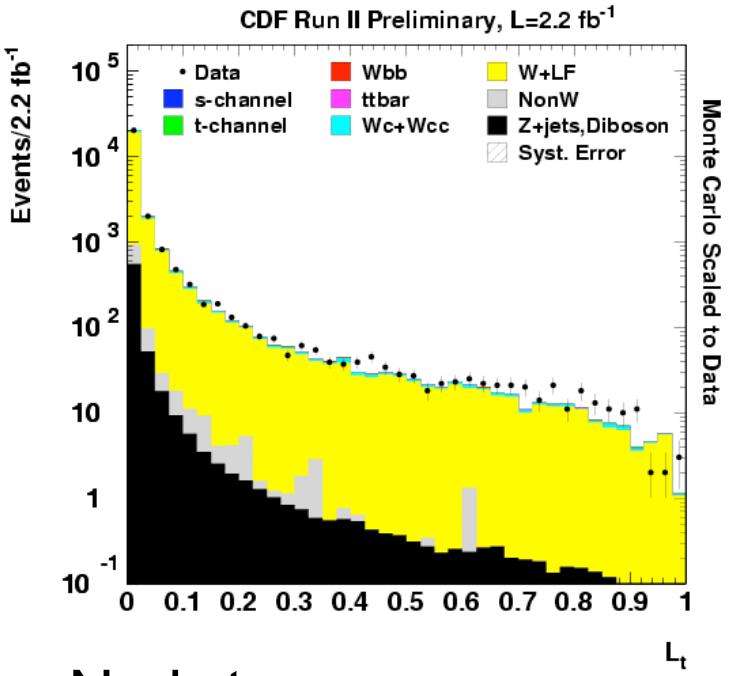
- H_T
- $\cos\theta_{\text{lepton, other jet}}$
- $Q\times\eta$
- M_{jj}
- $\log(ME_{\text{t-chan}})$ from MADGRAPH (Stelzer and Willenbrock)
- ANN b-tag output
- χ^2(t-channel) (replaces m_{lvb})

3-jet variables similar

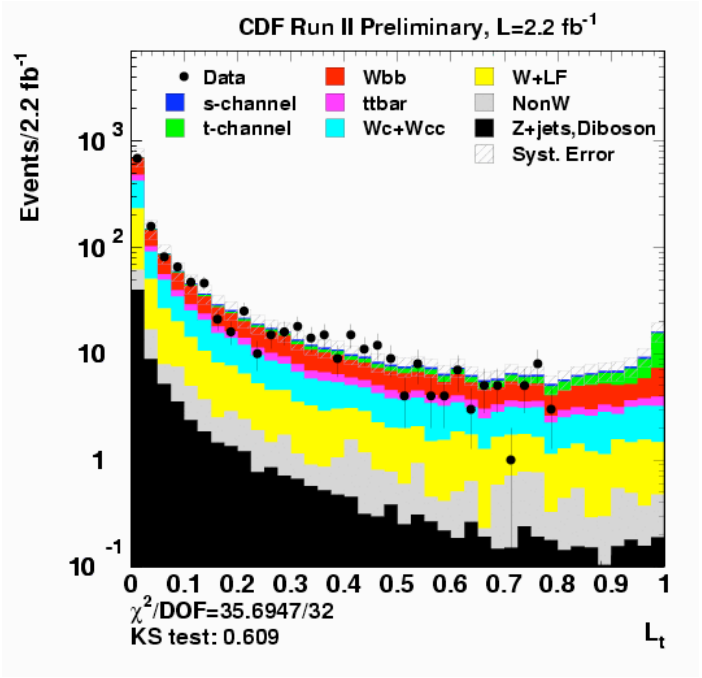
Predicted shapes



Checking the Control Samples



No b-tags



b-tagged, signal blinded

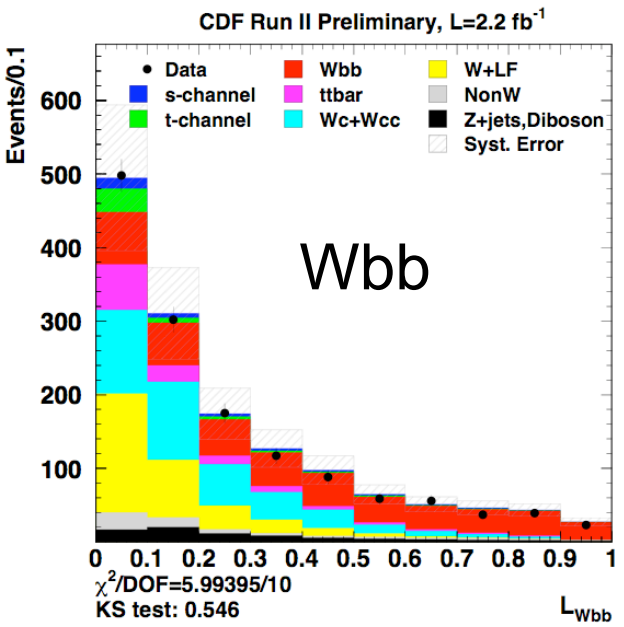
Blind studies slicing and dicing control samples

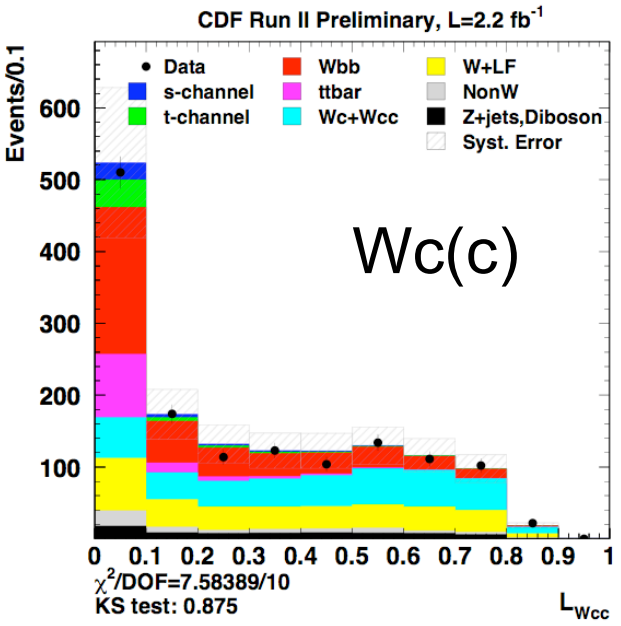
+,- leptons

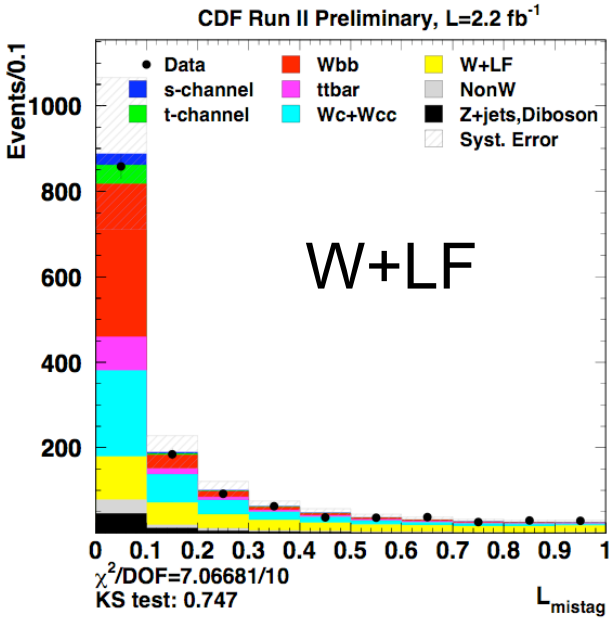
+.- η_{lepton}, +,-$\eta_{j1,2}$, high-H_T/low-H_t, high MET/low MET

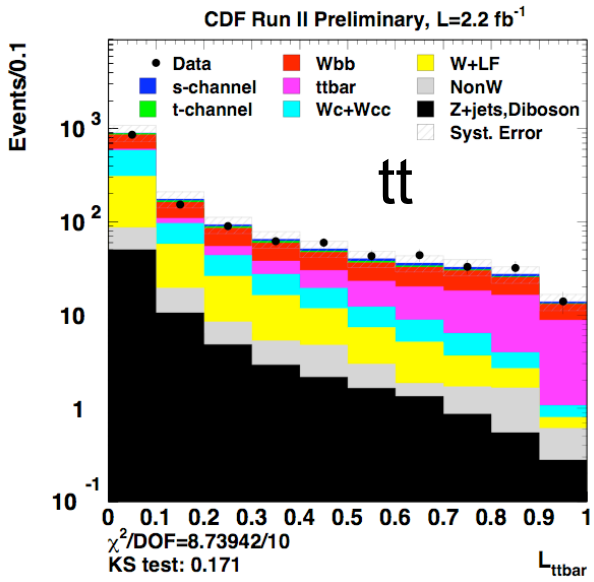
electrons and muons separately

Likelihood Functions Trained to Identify Each Background







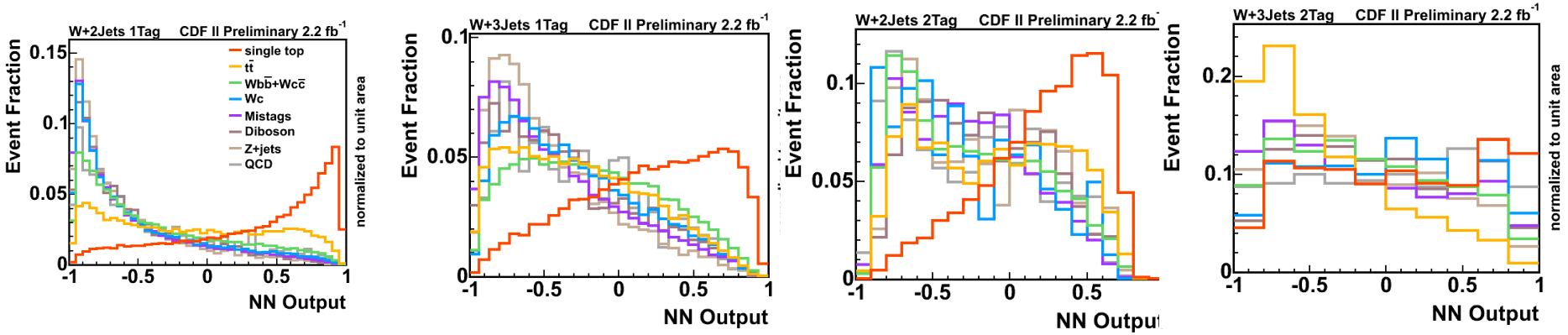


Invert the roles of signal and background templates to get new discriminants

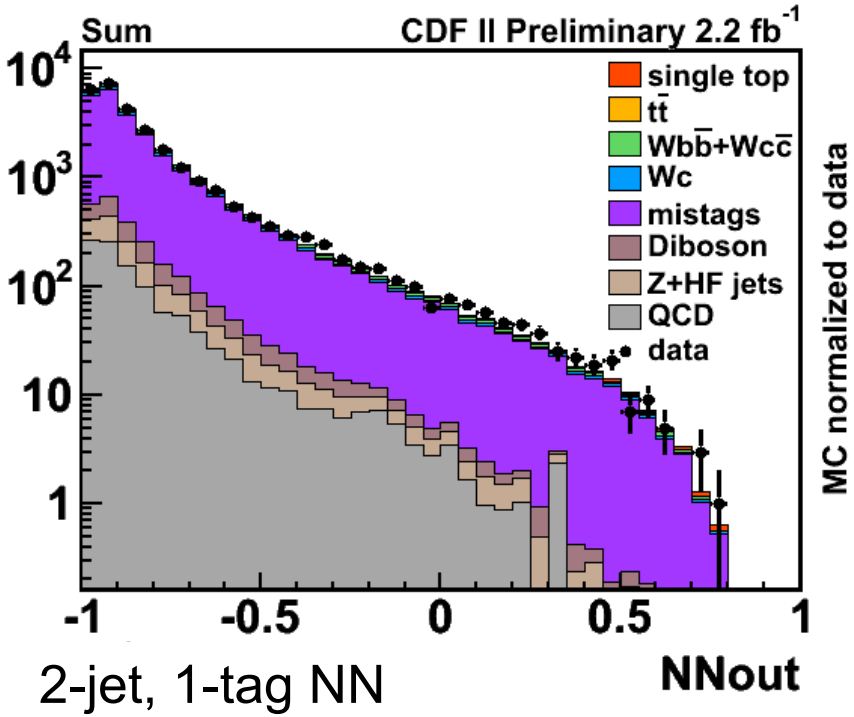
Analysis II: Neural Network Discriminants

- NeuroBayes is used to separate signal from background
- Separate 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
- Variable list similar to LF's -- 10-15 variables per channel

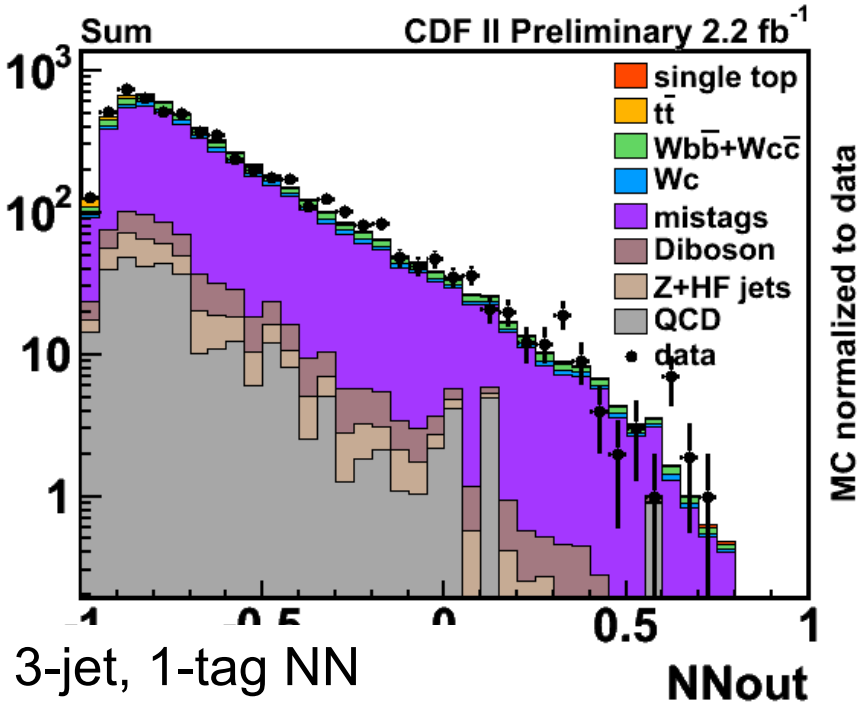
Templates normalized to unit area



Neural Net Checks in Control Samples



2-jet, 1-tag NN
with untagged data



3-jet, 1-tag NN
with untagged data

Analysis III: Matrix-Element Discriminant

- Calculate probability density of an event resulting from a given process

Phase space factor: Integrate over unknown or poorly measured quantities

Parton distribution functions

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

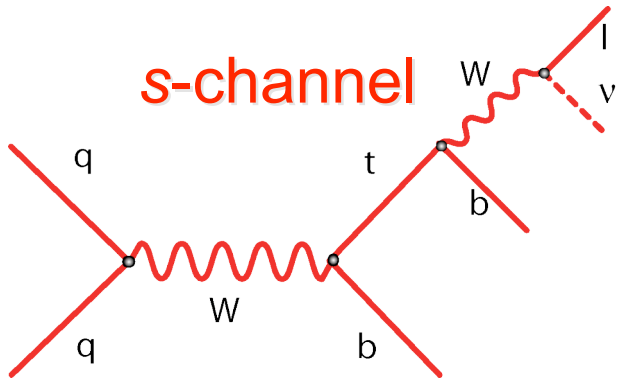
Inputs: lepton and jet 4-vectors – no other information needed!

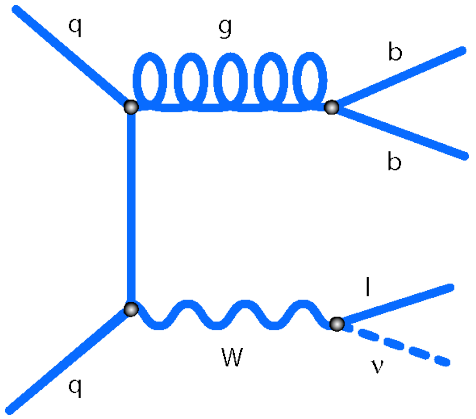
Matrix element: Different for each process. Leading order, obtained from MadGraph

Transfer functions: Account for detector effects in measurement of jet energy

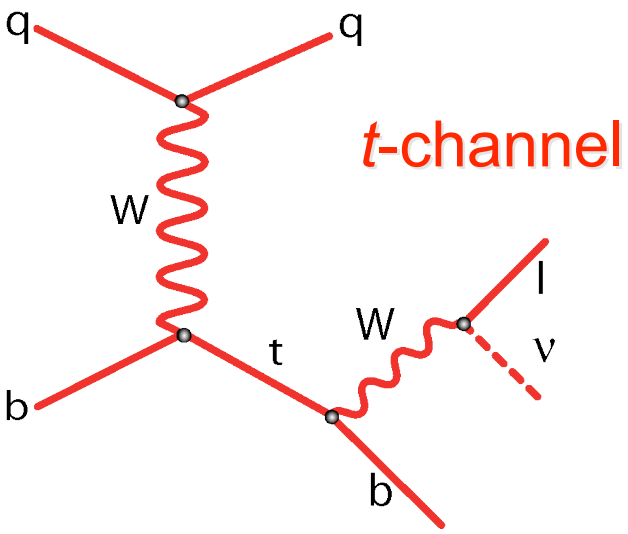
- The input variables are the same for all matrix elements – adding a new matrix element requires more calculation but does not use any different information from the data

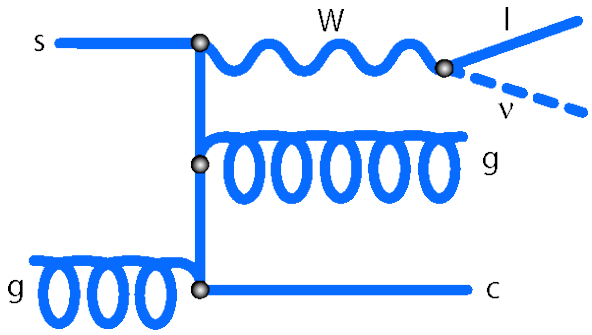
Matrix elements used





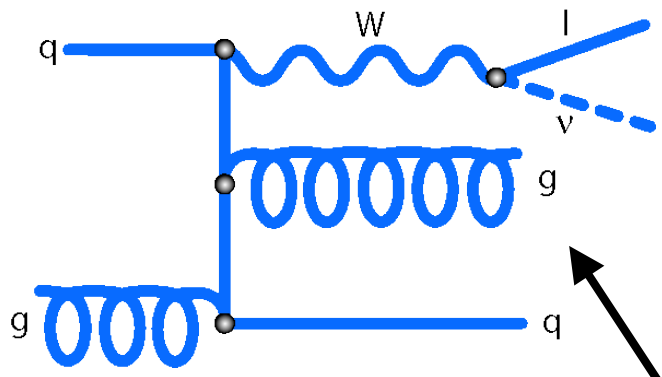
Wbb



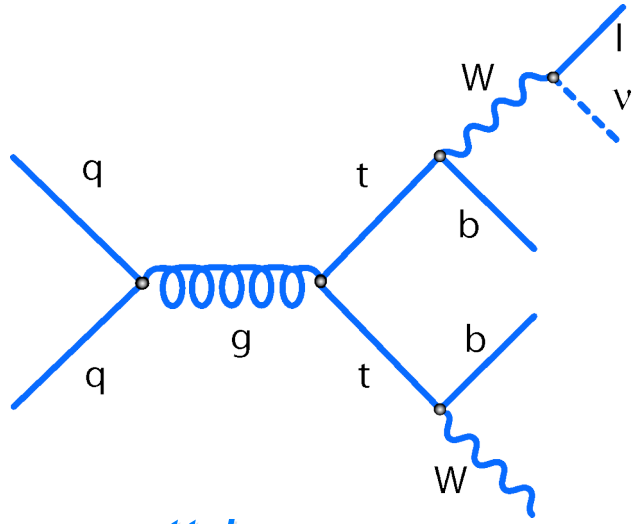


Wc+jet

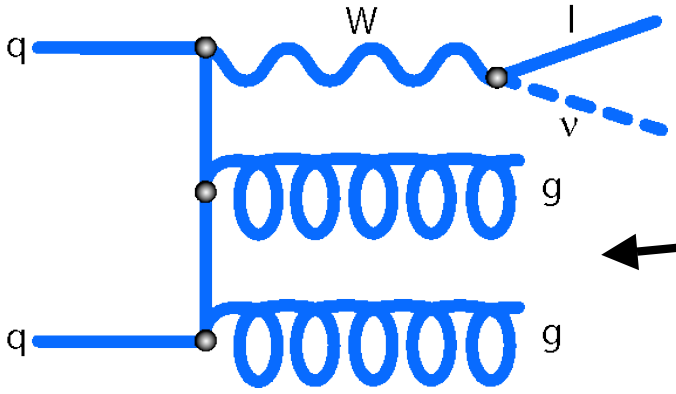
Additional 2-jet Matrix Elements



Wjg



tt-bar



Wgg

Special gluon transfer functions developed.

Constructing the Discriminant

- Matrix elements know only about 4-vectors, not about b-tagging quantities.
- Need to include information from signal and background matrix elements.

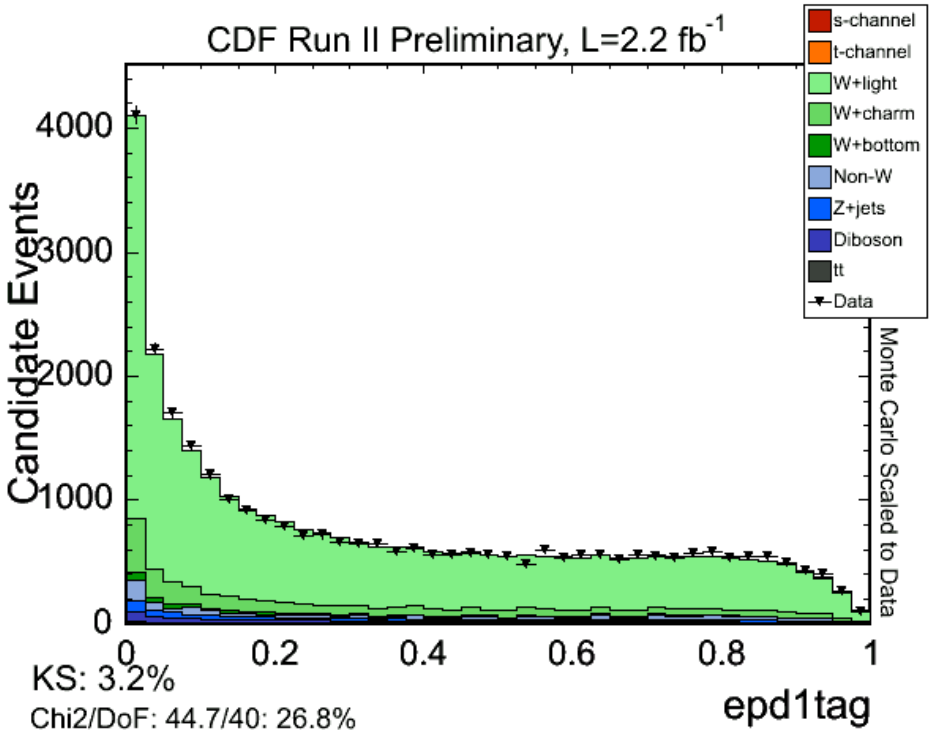
$$EPD = \frac{b \cdot P_{\text{singletop}}}{b \cdot P_{\text{singletop}} + b \cdot \left(P_{Wb\bar{b}} + P_{t\bar{t}} \right) + (1-b) \cdot \left(P_{Wc\bar{c}} + P_{Wcj} + P_{Wgg} \right)}$$

b is the NN B-tag output

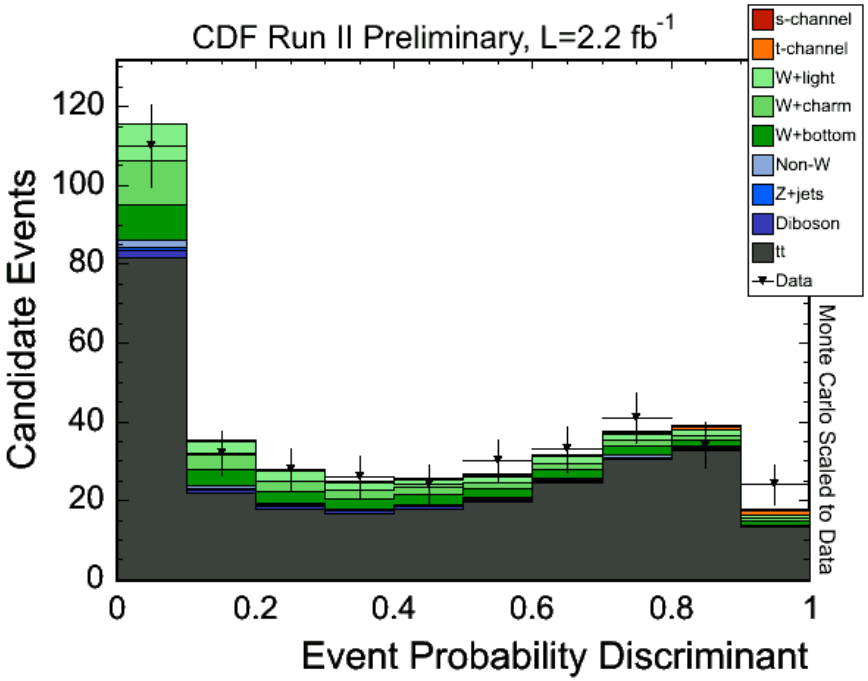
- Not every process has a matrix element (non-W for example), so this is not a probability, just a good separation variable, use in template fits like other variables

Matrix Element Analysis Blind Checks

Events with no B-tag,2-jet bin



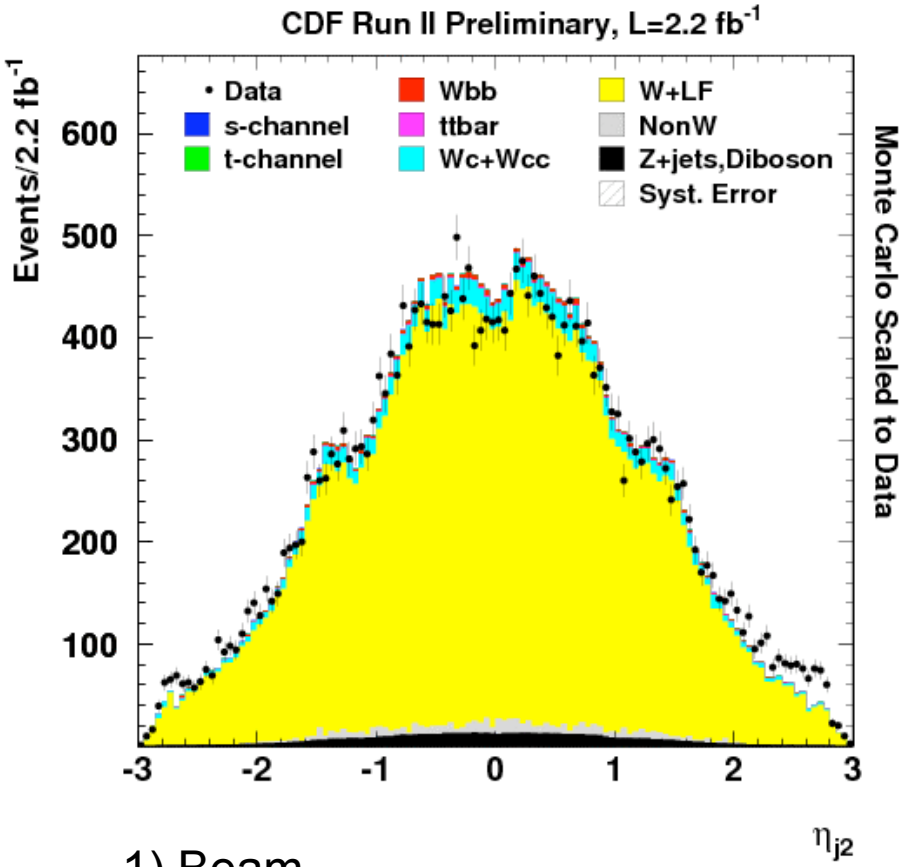
4-jet bin check of ttbar modeling

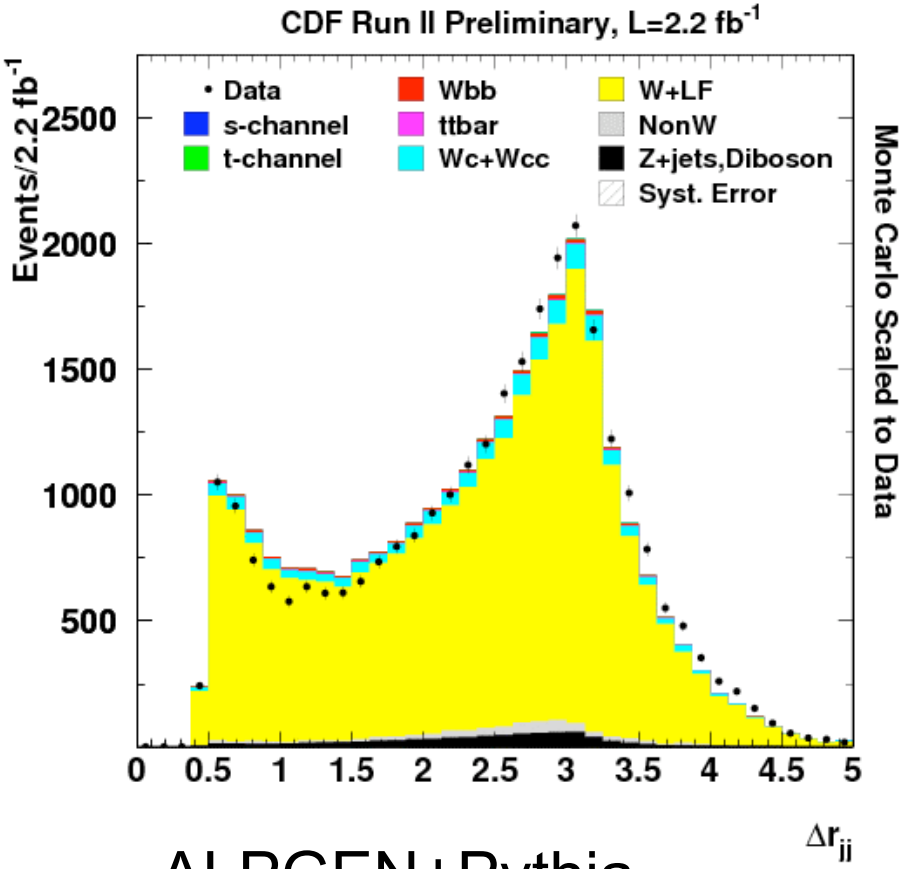


Systematic Uncertainty	Rate	Shape
Jet Energy Scale	0...16%	✓
Initial State Radiation	0...11%	✓
Final State Radiation	0...15%	✓
Parton Distribution Functions	2...3%	✓
Monte Carlo Generator	1...5%	
Event Detection Efficiency	0...9%	
Luminosity	6%	
Neural Net B-tagger		✓
Mistag Model		✓
Q^2 scale in ALPGEN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

Also:
MC Stats
in each
bin
independently

Input Variable Modeling Uncertainties





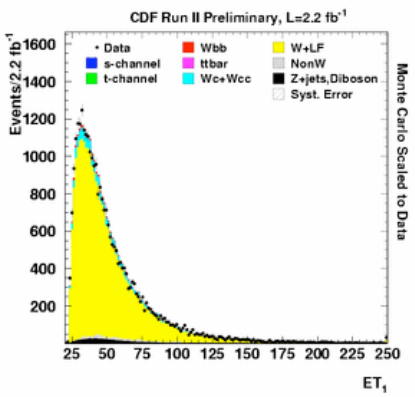
1) Beam splash?

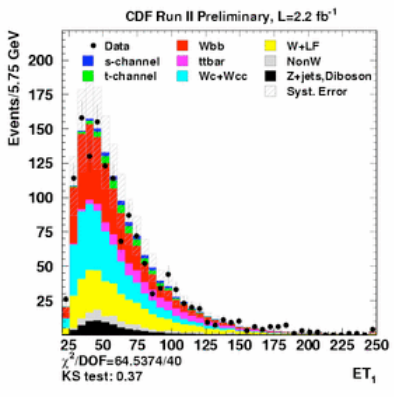
ALPGEN+Pythia mismodeling

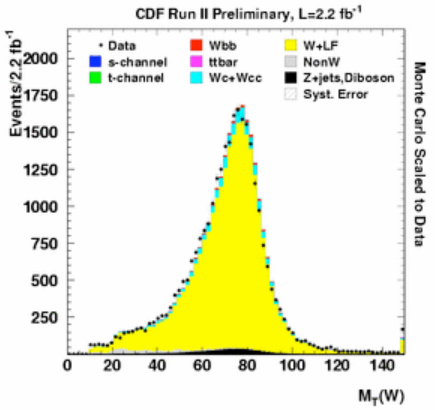
2) Jet energy scale in plug?

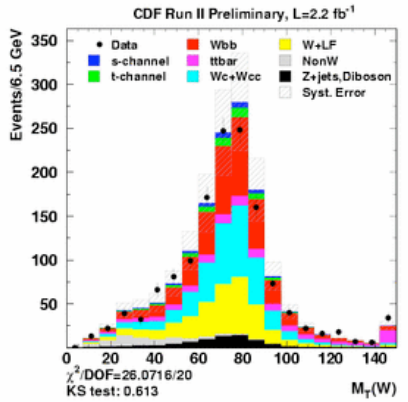
MC predictions reweighted to match the data as the systematic alternative sample.

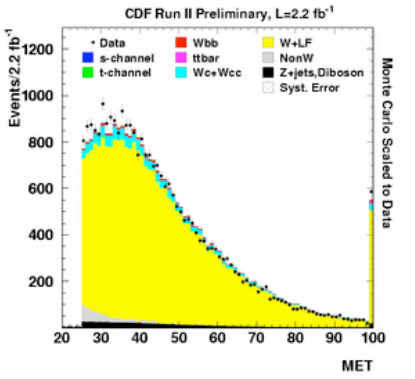
Just Some of the Other Distributions Checked

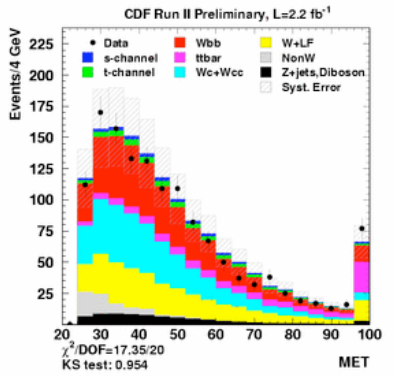


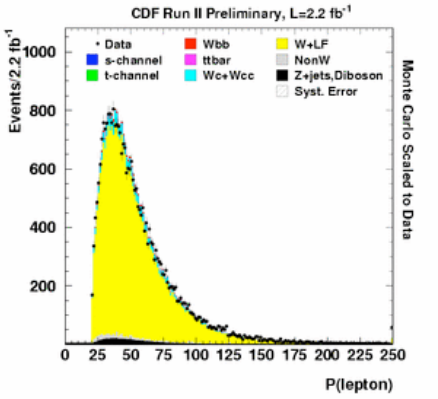


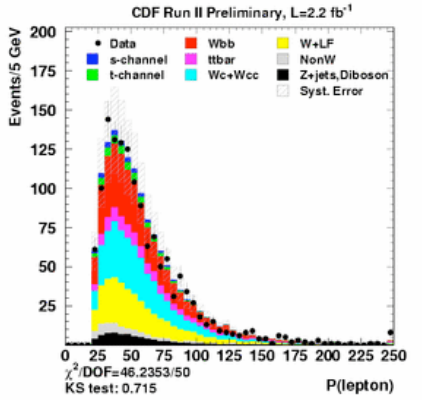


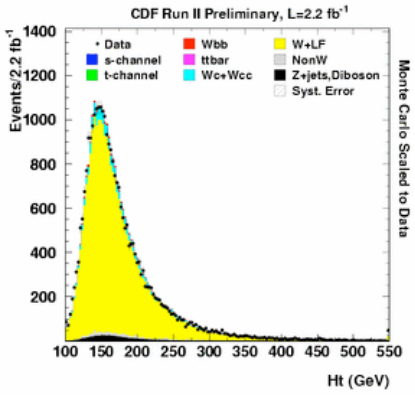


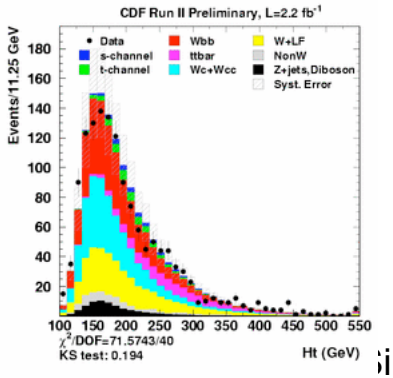


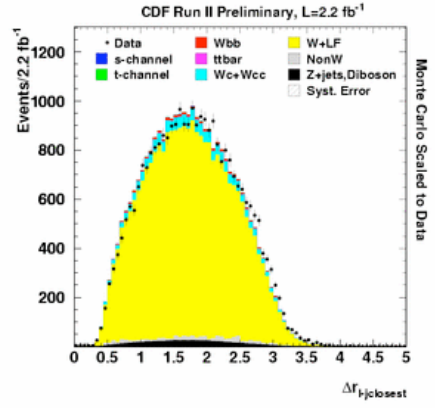


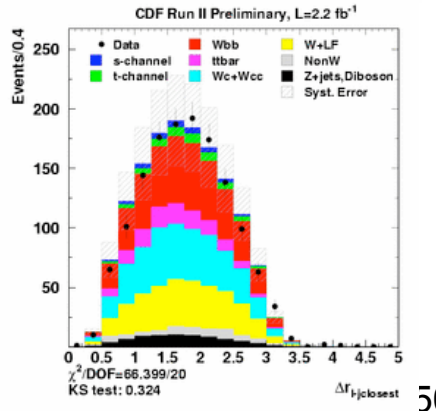












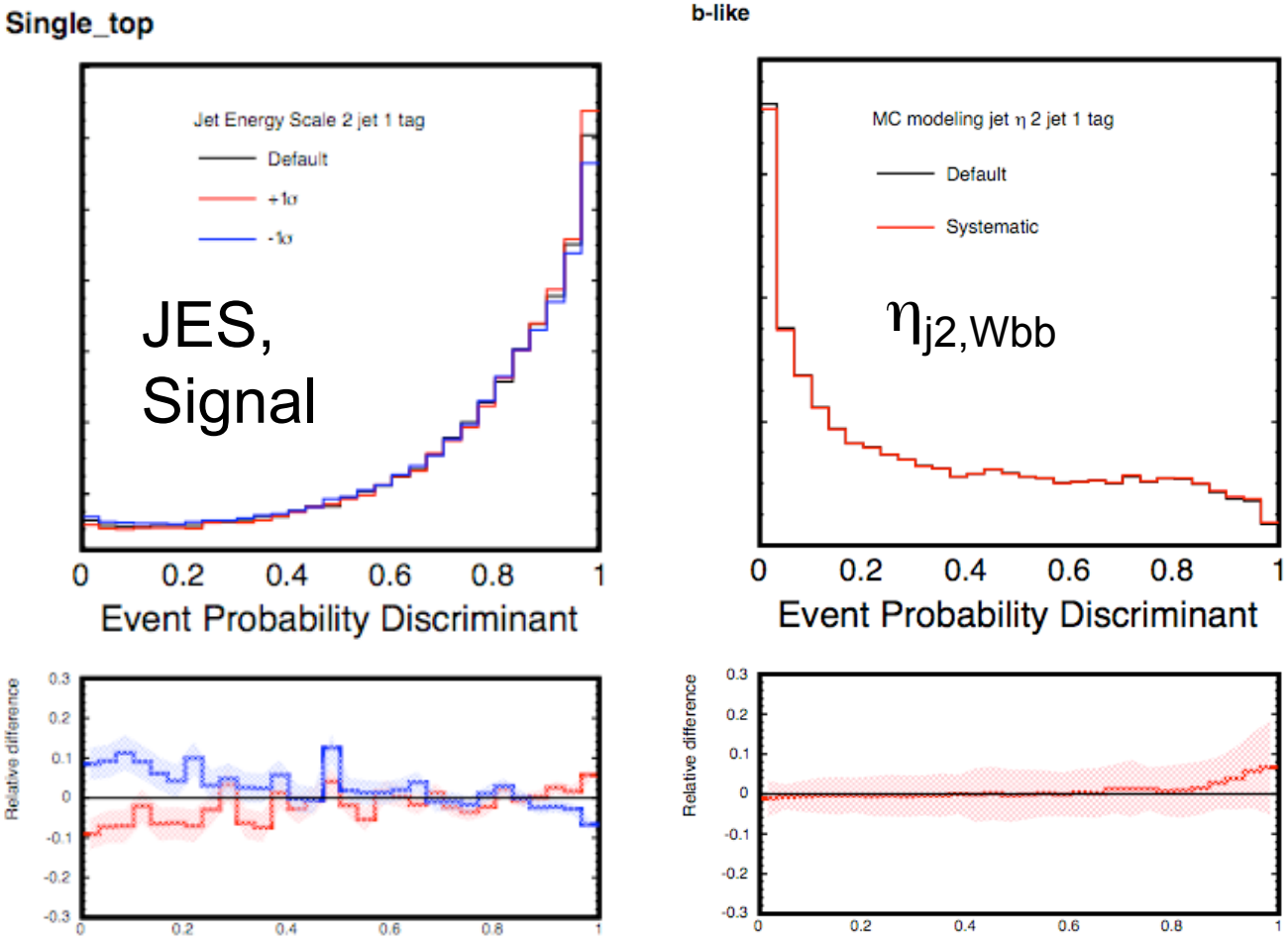
Systematic Shape Uncertainties

A total of 370 shape uncertainties evaluated!

Most are quite small

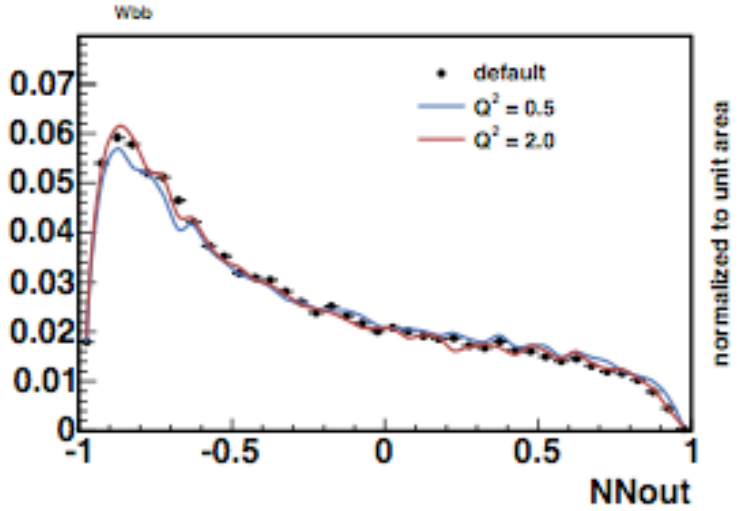
Each template, each source of shape error, each channel (#tags, #jets, extra muons)

Two exmples from the ME analysis

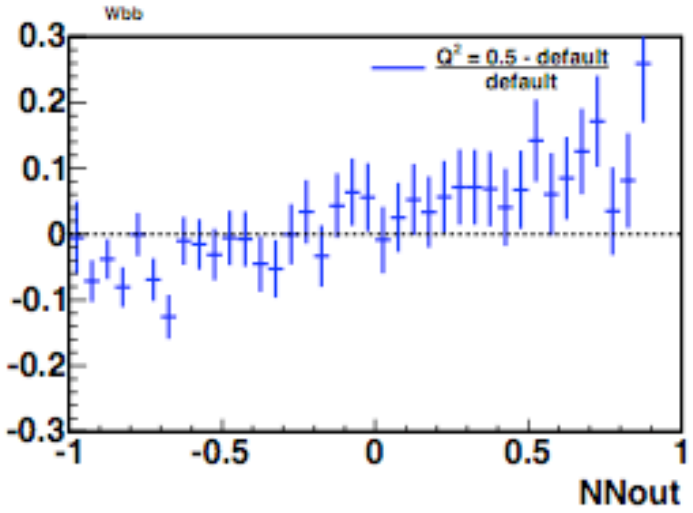


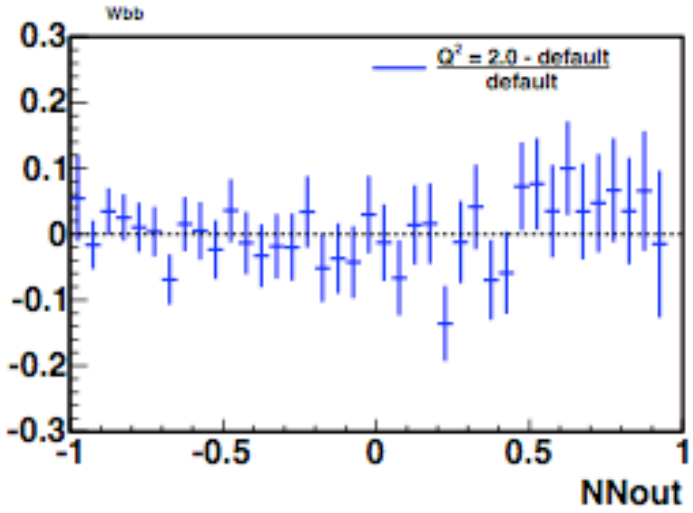
ALPGEN Wbb Template Shape Uncertainty Due to Renormalization/Factorization Scale

Vary Q^2 scale by a factor of 2 in each direction



NN analysis





Combination I: Super-Discriminant

- Combine all analyses into one by using ME, NN, LF discriminants as inputs to a neural net. Just like having a fourth analysis; same procedures to extract physics quantities as a single analysis.

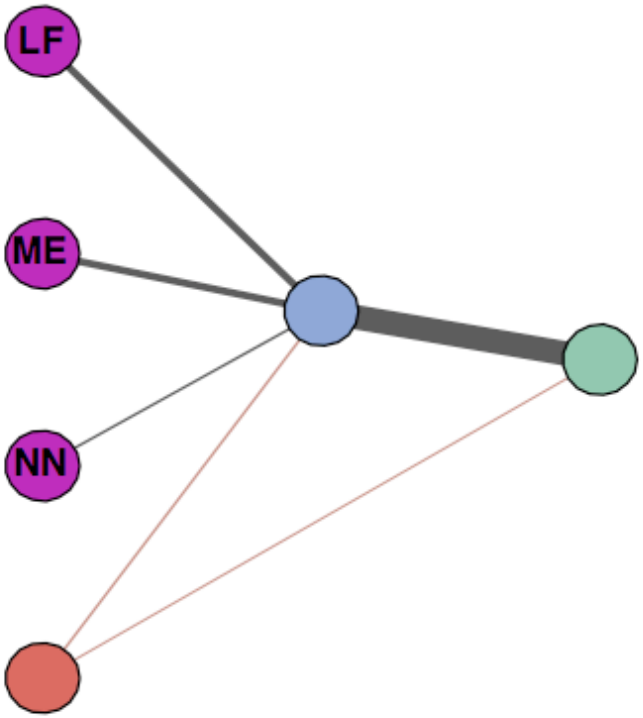
- NEAT ("Neuro-Evolution of Augmenting Topologies") is **designed to optimize the expected *p*-value** (discovery significance). Most NN's optimize something else (classificiation error -- weights wrong kinds of information) **Back-Propagation is impossible.** Instead candidate networks compete against each other.

- Automatically optimizes
  - **Network topology** -- number of nodes and their connections
  - **Inter-node weights**
  - **Output histogram binning** (expected p-value has MC stats accounted for in each bin)
- Systematic errors included in optimization procedure

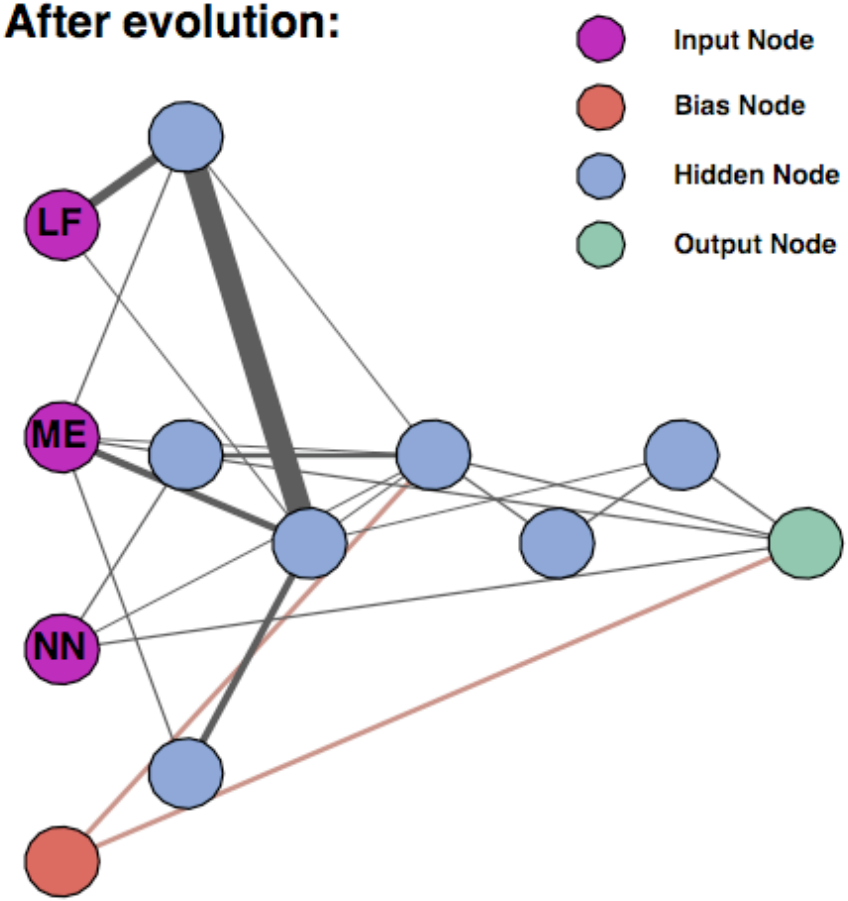
- Channels are divided up at least as finely as any ingredient analysis (2 jets + 3 jets) x (1 tag + 2 tags) x (2 Lepton Categories) = 8 Channels

Network Topology Optimization

Initial Configuration:

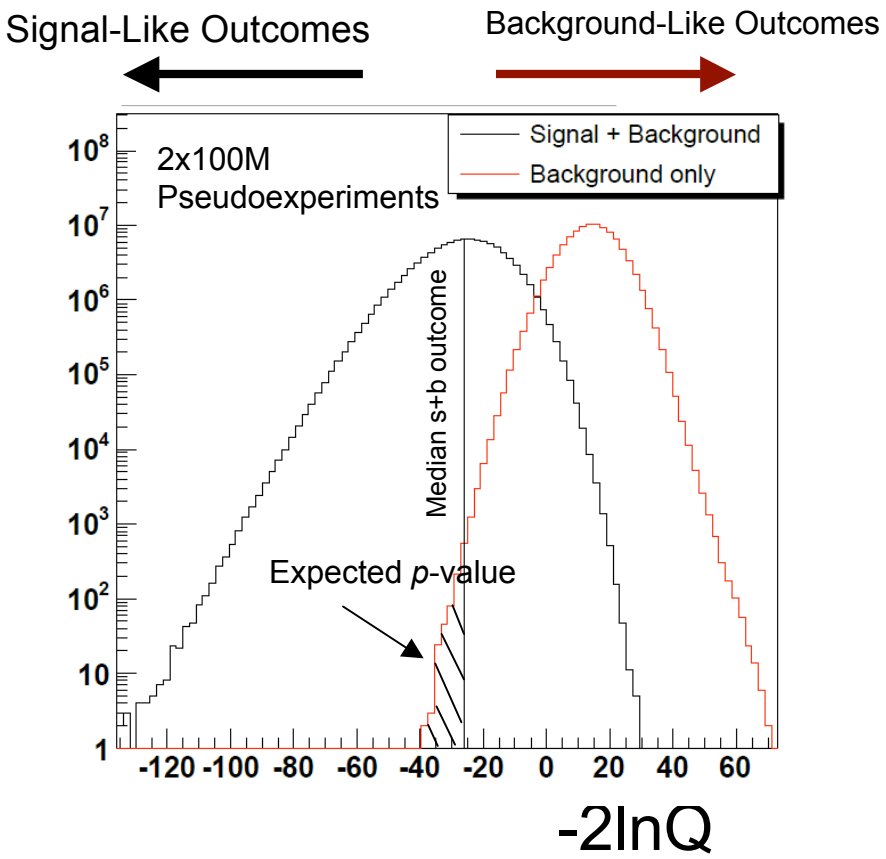


After evolution:



Hypothesis Testing: p-Values

p-value = probability of upward fluctuation of background to the data or something more "signal-like"
Outcomes ranked as signal-like using -2lnQ



$$Q = \frac{P(\text{data} \mid s+b, \hat{\theta})}{P(\text{data} \mid b, \hat{\hat{\theta}})}$$

θ=nuisance parameters

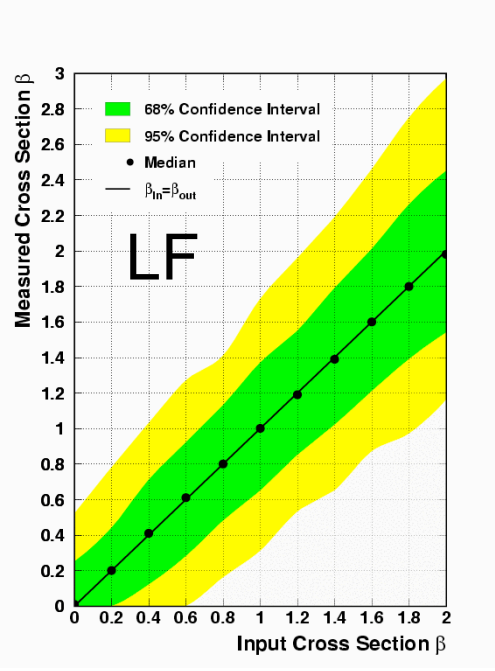
Neyman-Pearson Lemma: Q is the uniformly most powerful t

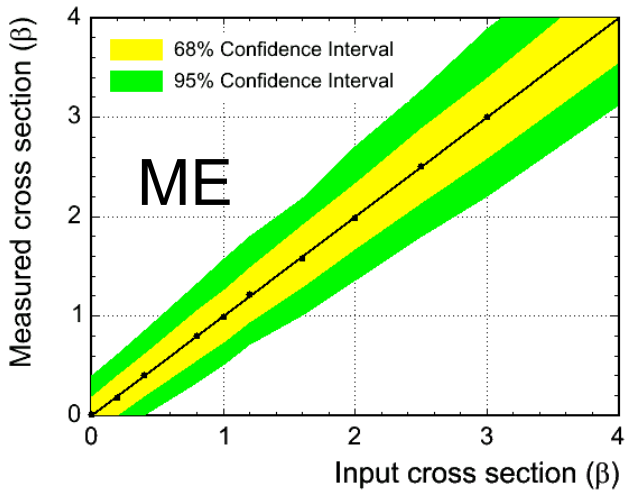
Fit for W+LF and W+HF scale factors. Fluctuate **all** nuisance parameters in pseudoexperiments

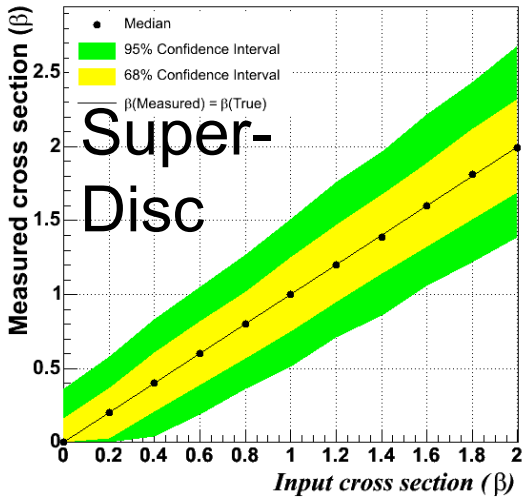
Cross Section Measurements

- 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.

No biases seen in cross-section fit technique.







Combination II: AIB

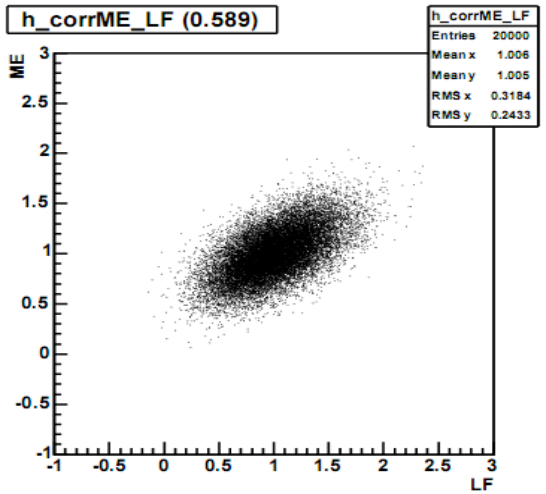
AIB = Asymmetric Iterative **BLUE**

"**B**est
Linear
Unbiased
Estimator"

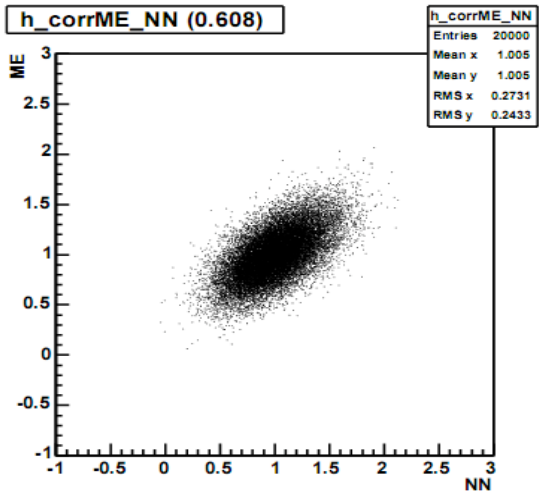
- Designed to handle complex situations with asymmetric uncertainties with correct pull distributions. Iterate to get correct expected errors on inputs.
- Draw pseudoexperiments from fully simulated MC. Important result: shows how correlated single analyses are

Original BLUE: L. Lyons, NIM **A270** 110 (1988)

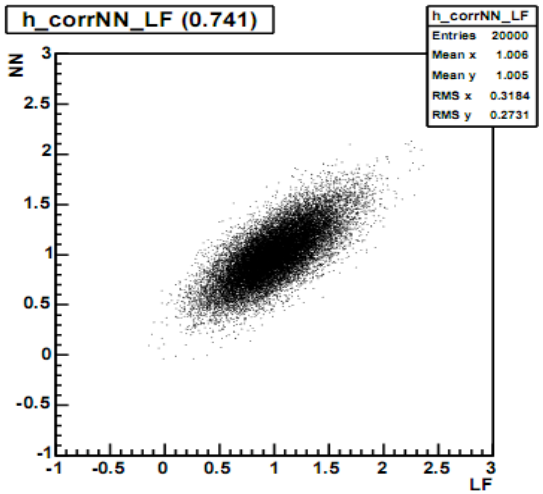
LF-ME 58.9%



ME-NN 60.8%



LF-NN 74.1%



Unblinding

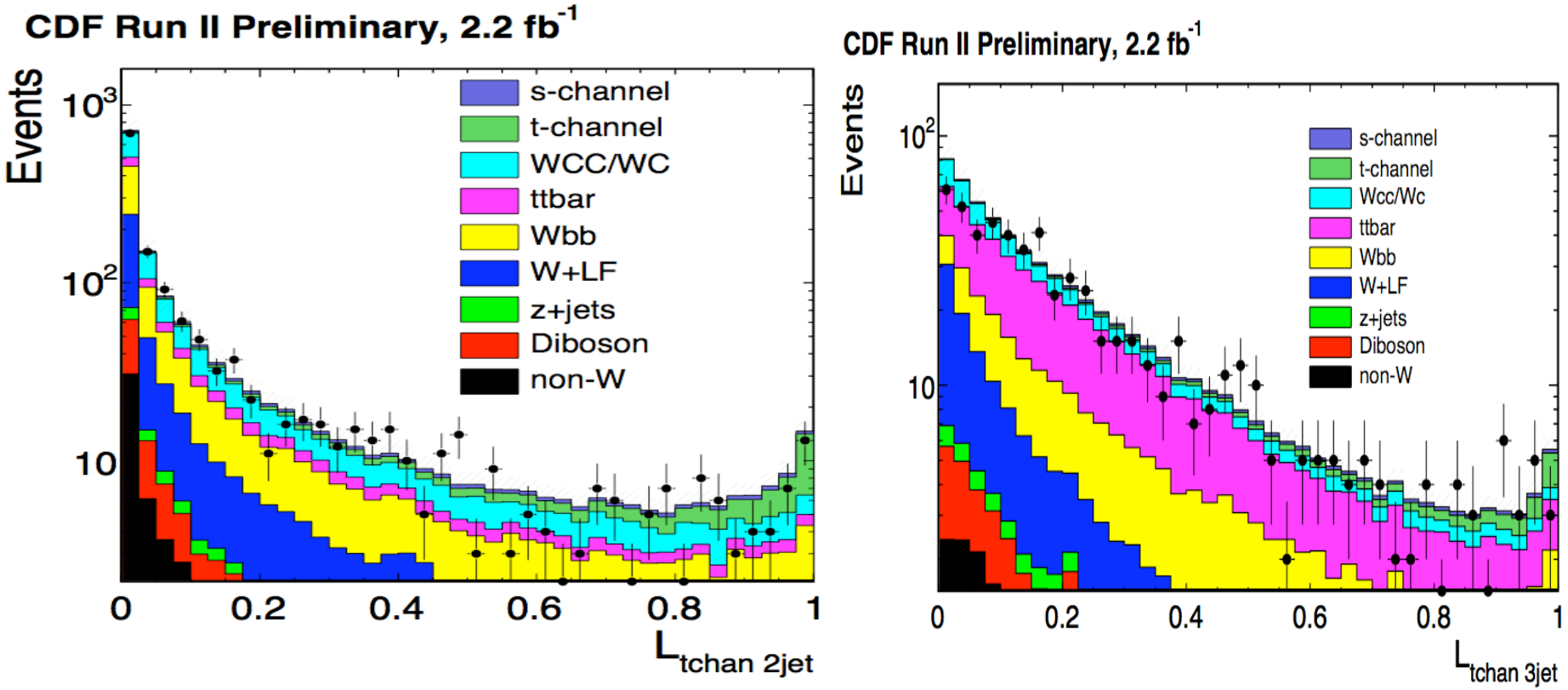
We worked very hard to get our expected sensitivity up -- wanted to have a good chance at observation.

Decided to remain blind until we had at least 4.8σ of expected sensitivity. Did not have that with 1.9 fb^{-1} of analyzed data in December 2007.

Decided to include 0.3 fb^{-1} of data up to the 2007 shutdown.
But
Silicon cooling incident disabled the East half of our innermost layer, and the East half of our two outermost layers for this data (it's all fixed now).

Intense program to calibrate B-tagging in the last batch of data, process it and include in the analysis. It looked good!
Got 5.1σ of expected sensitivity -- **Proceed to unblind!**

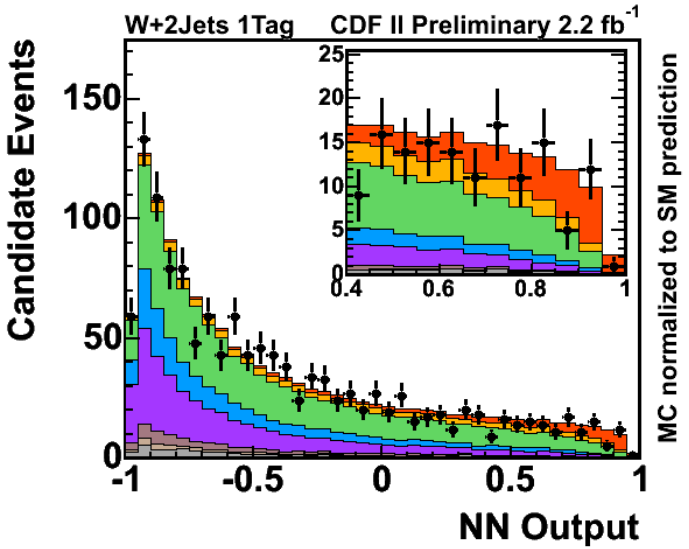
Likelihood Analysis Unblinded Data

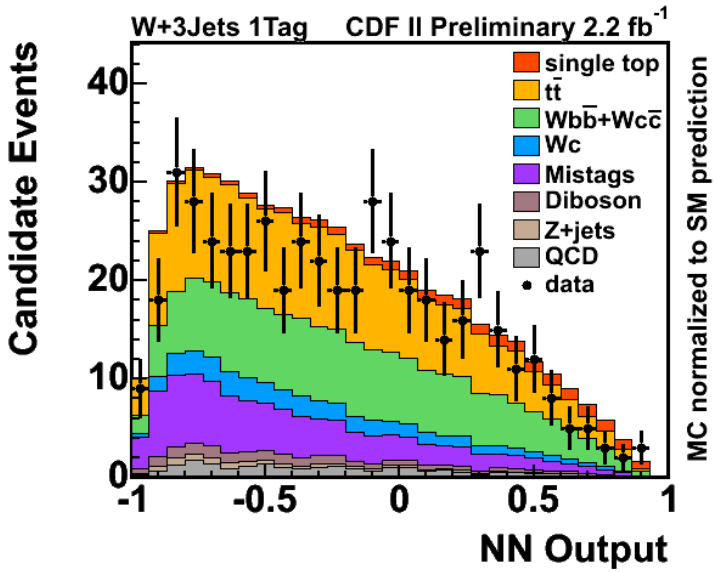


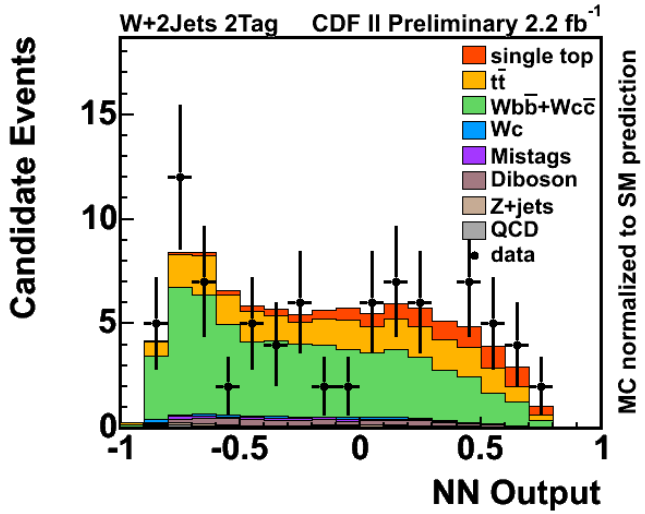
SM predictions shown -- no fitting is done.

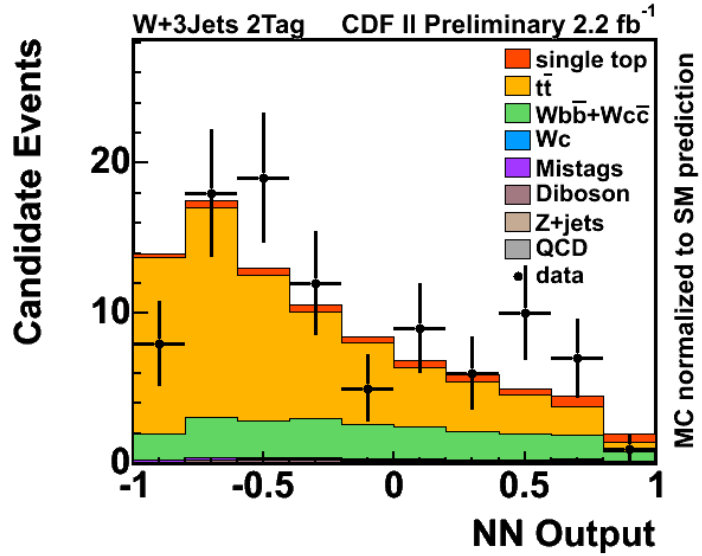
Slight deficit seen in the signal region

NN Output Distributions by Channel

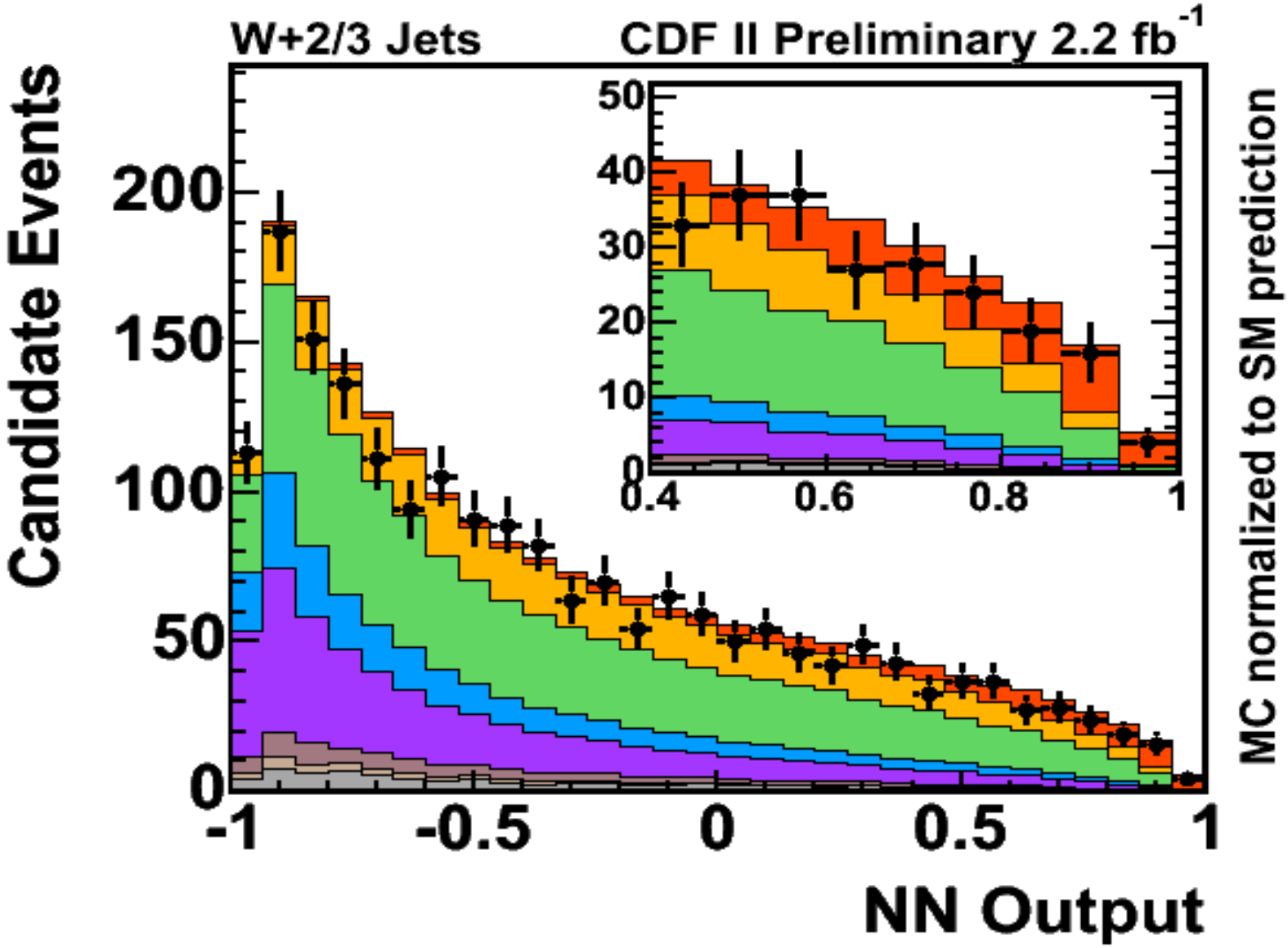




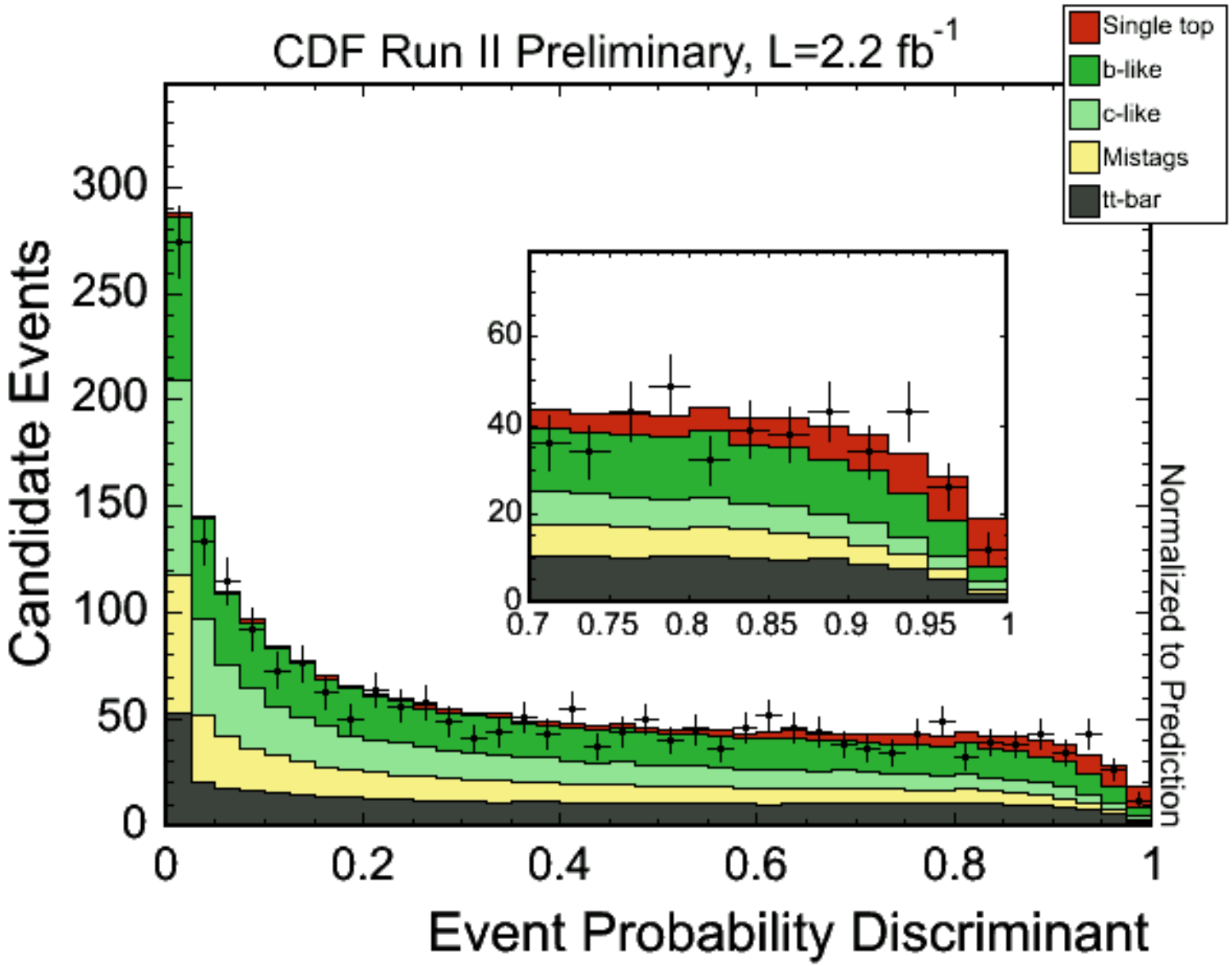




Neural Network Discriminant Unblinded Data

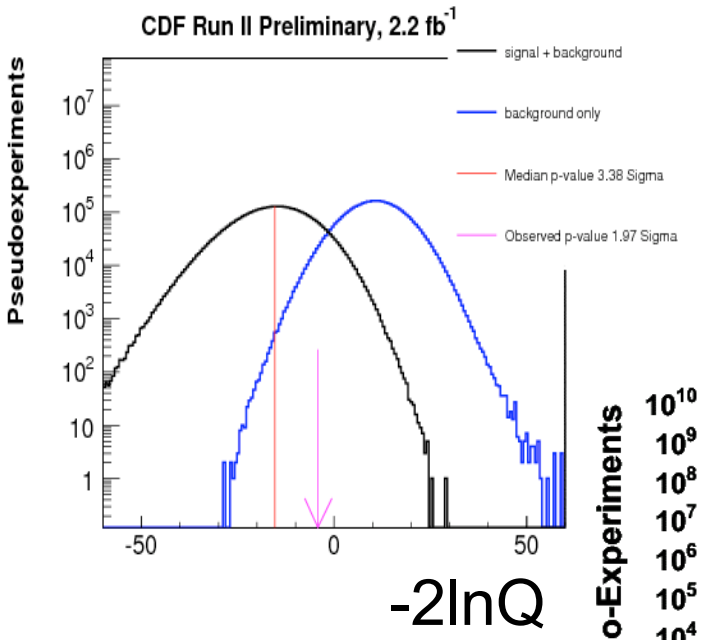


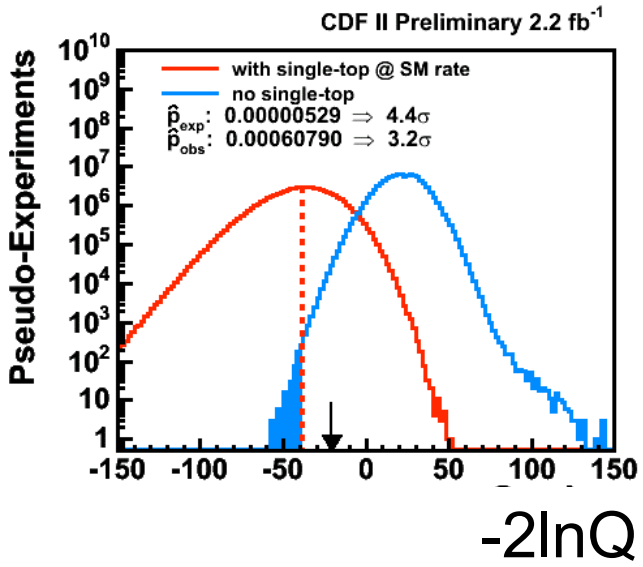
Matrix-Element Analysis Unblinded Data

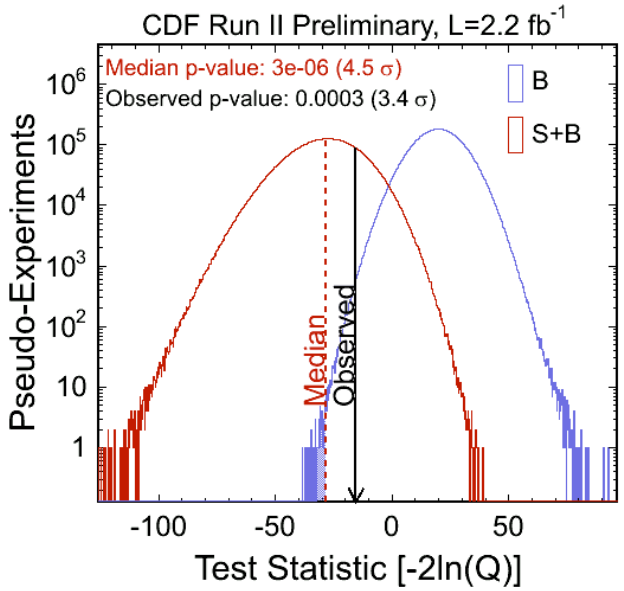


p-Value Results by Analysis

$$Q = \frac{P(\text{data} \mid s+b,\hat{\theta})}{P(\text{data} \mid b,\hat{\hat{\theta}})}$$







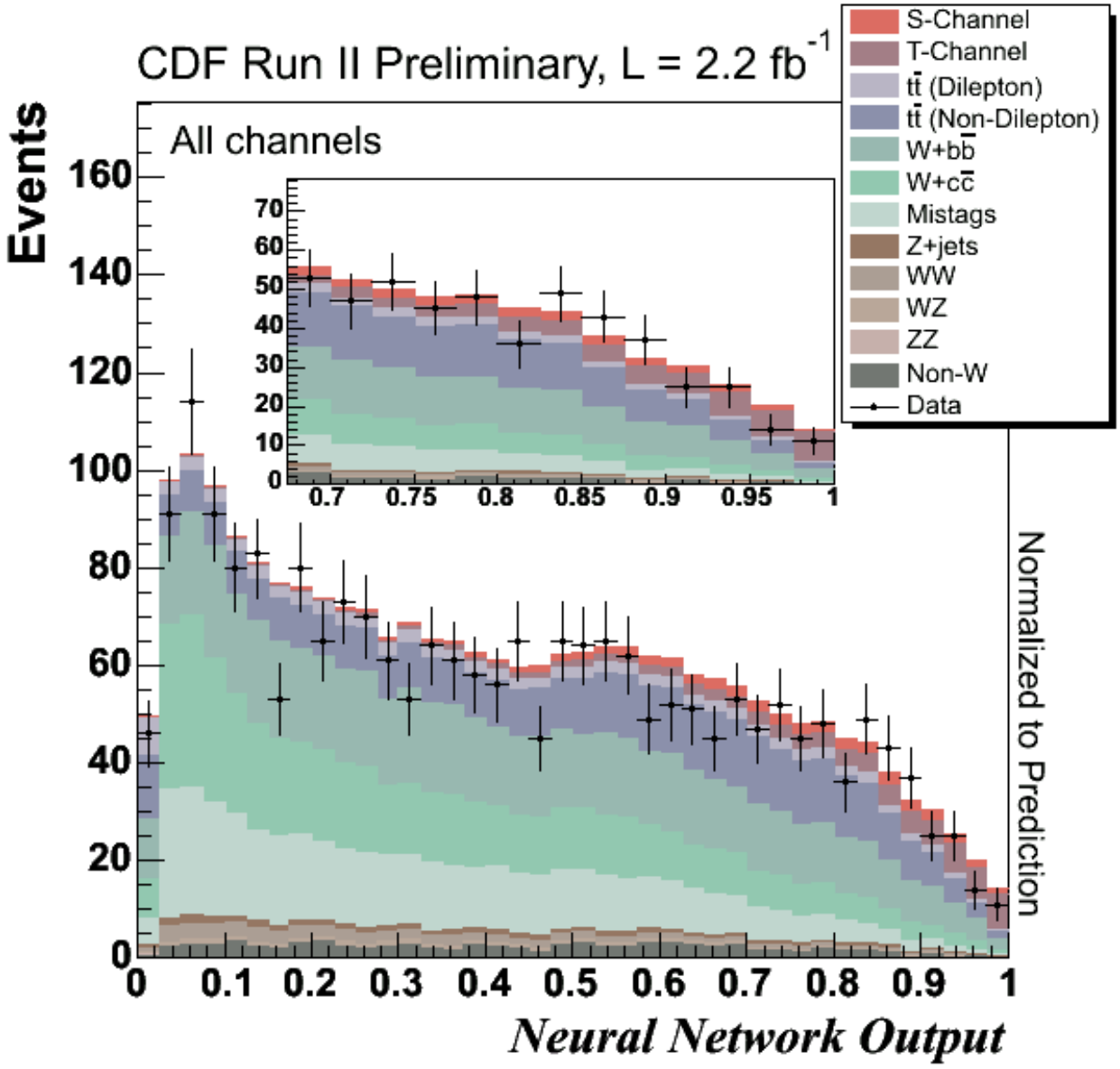
LF: 2.0σ obs
3.4σ median expected

NN: 3.2σ observed
4.4σ expected

ME: 3.4σ observed
4.5σ expected

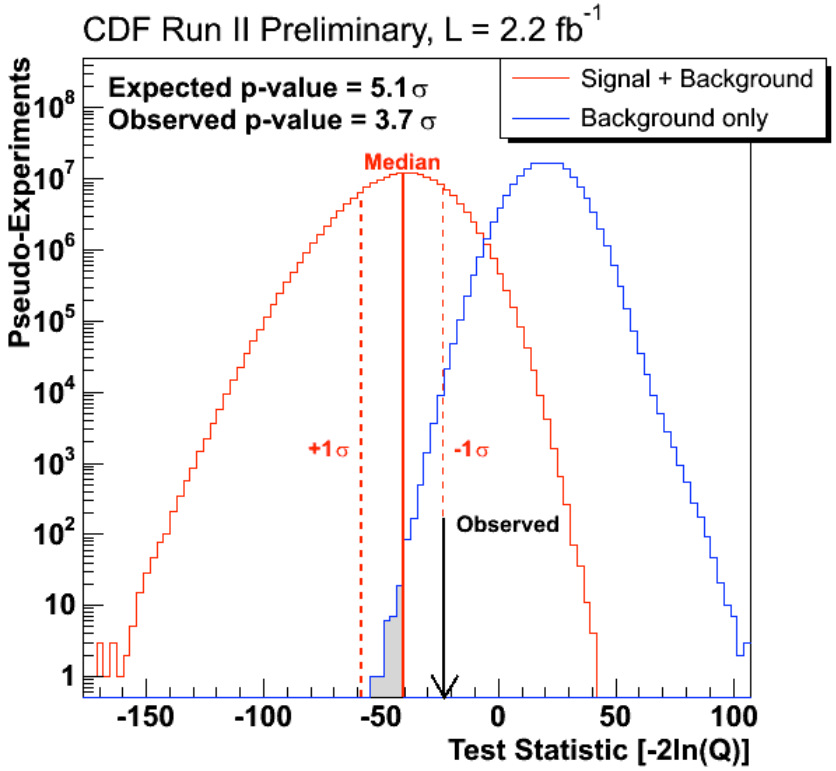
Super-Discriminant Results

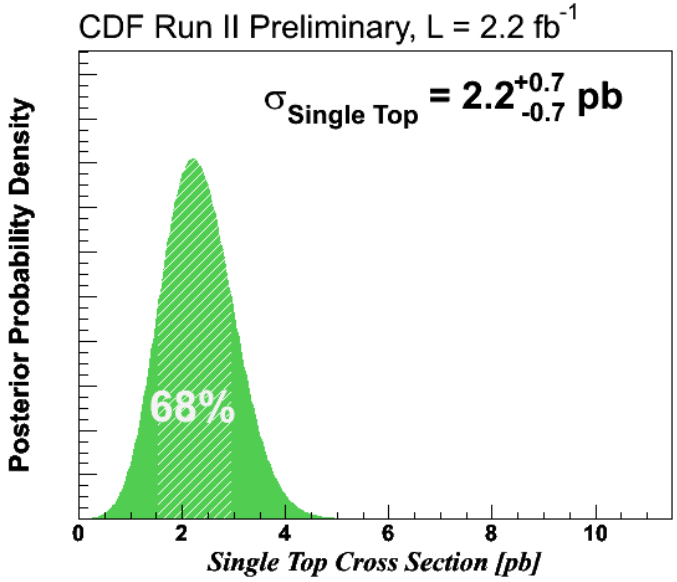
2-jet, 3-jet data summed, all lepton categories and n_{tags} summed.



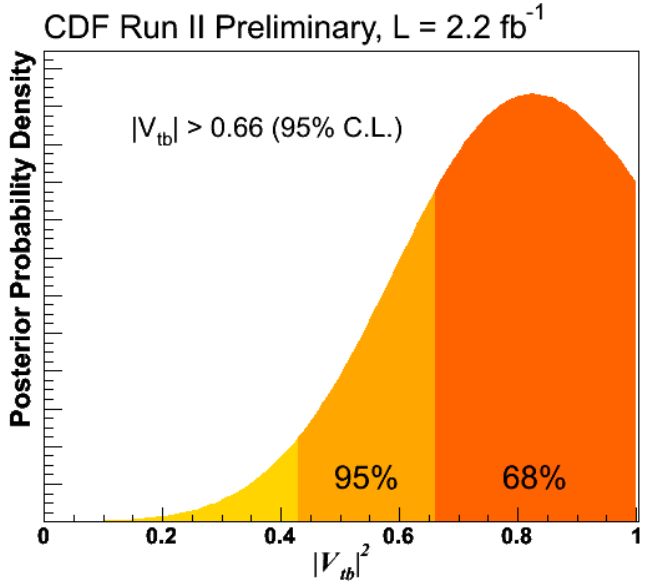
Super-Discriminant Significance, Cross Section and $|V_{tb}|$

Observed p-value: 3.7σ
Expected: 5.1σ



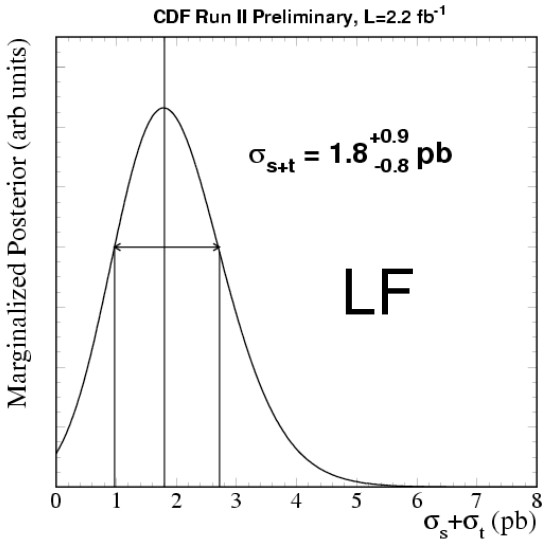


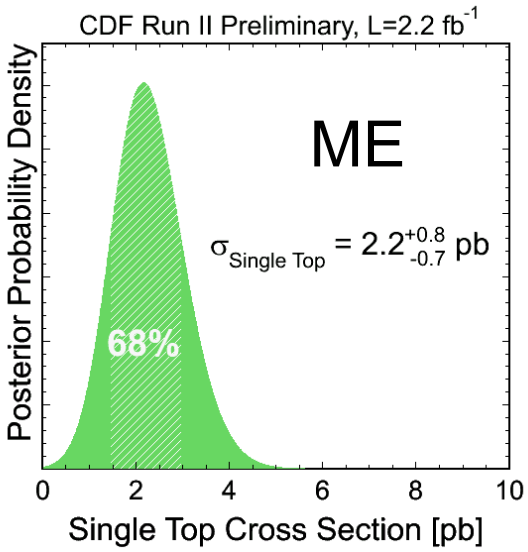
$$|V_{tb}| = 0.88 \pm 0.14\ (\text{exp.}) \pm 0.07\ (\text{theory})$$

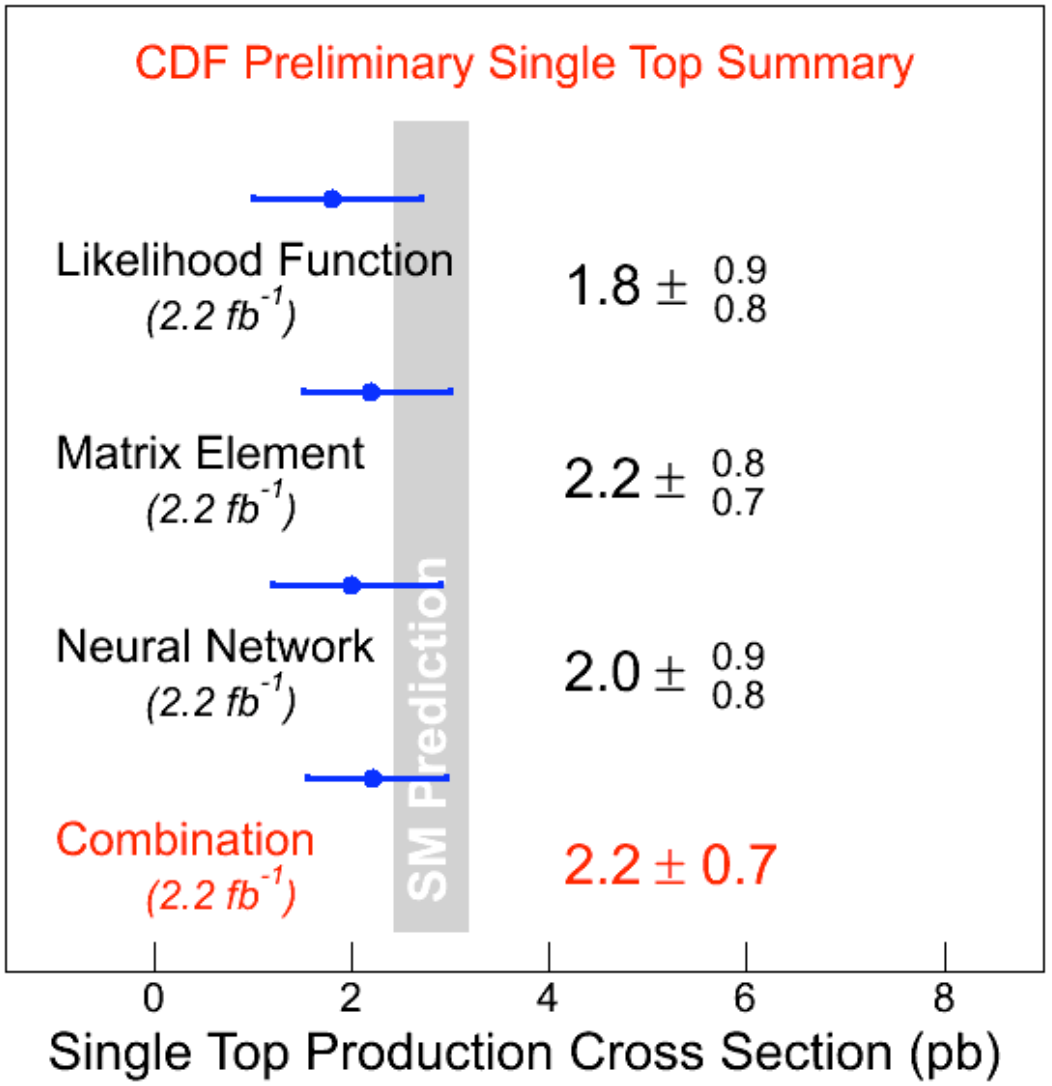


- NEAT gives us 13% better performance in the expected significance with respect to the best analysis.

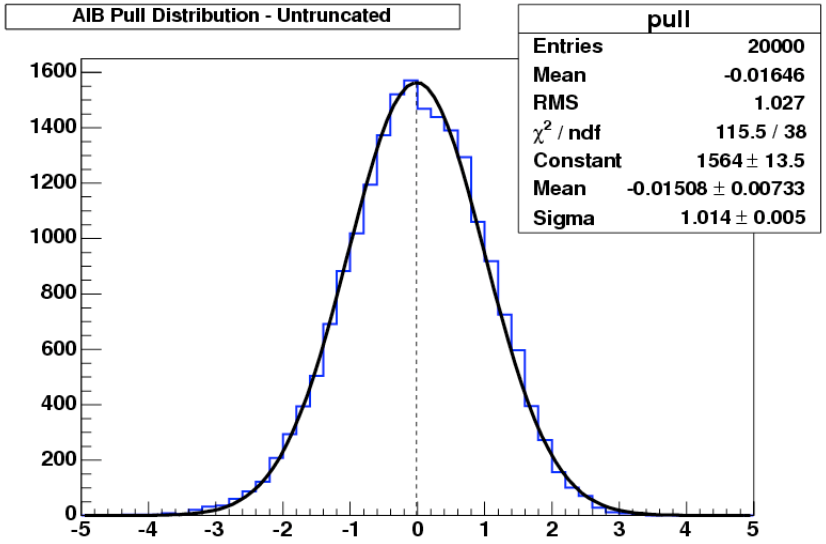
Cross Section Measurements







Combination II: AIB (BLUE)

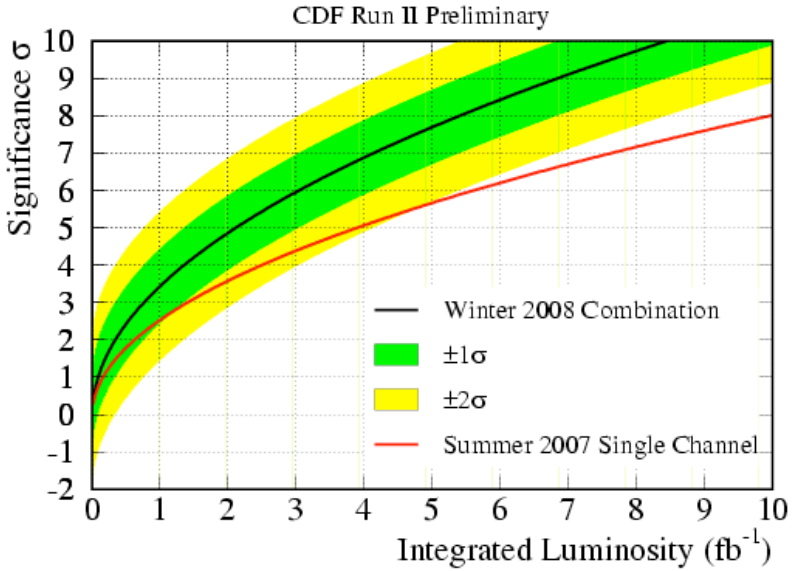


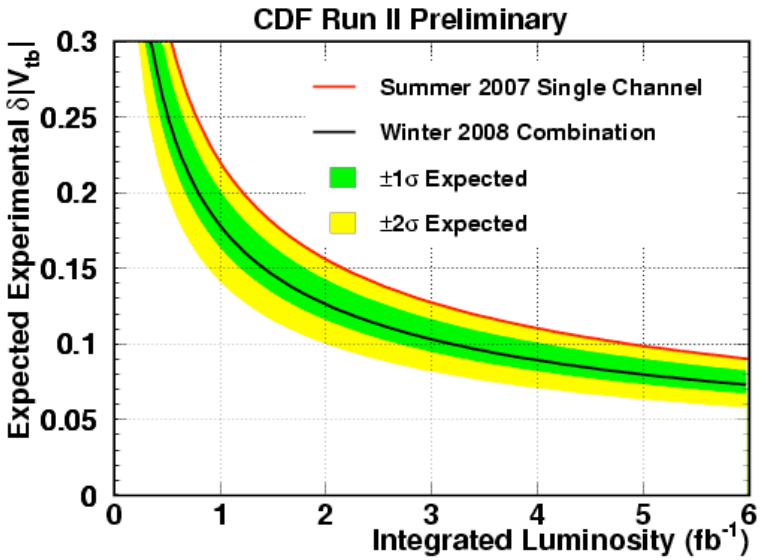
$$\sigma_{\text{single top}} = 2.1\ ^{+0.7}_{-0.6}\ \text{pb}$$

- *Self-consistency of the three measurements:*
  - –PEs generated with $\sigma_{\text{single top}} = 2$ pb with $\chi^2 > \chi^2_{\text{data}}$: **87%**
- *Compatibility with SM expectation:*
  - –PEs generated with $\sigma_{\text{single top}} = 2.9$ pb have $\sigma_{\text{meas}} < 2.13$ pb: **14.8%**

  Discrepancy smaller than 1.1 σ.
- *P-Values:* Expected: 4.7σ, Observed: 3.7σ

Sensitivity Projections



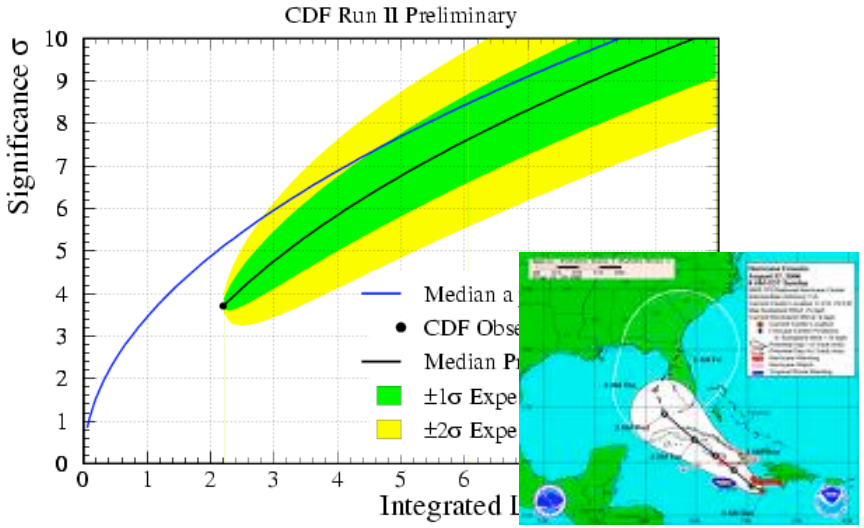


Does not include a ±7% uncertainty due to theory error on cross section

Significance extrapolation assuming $\sqrt{\int Ldt}$ dependence. Gaussian approximations everywhere.

Two effects:

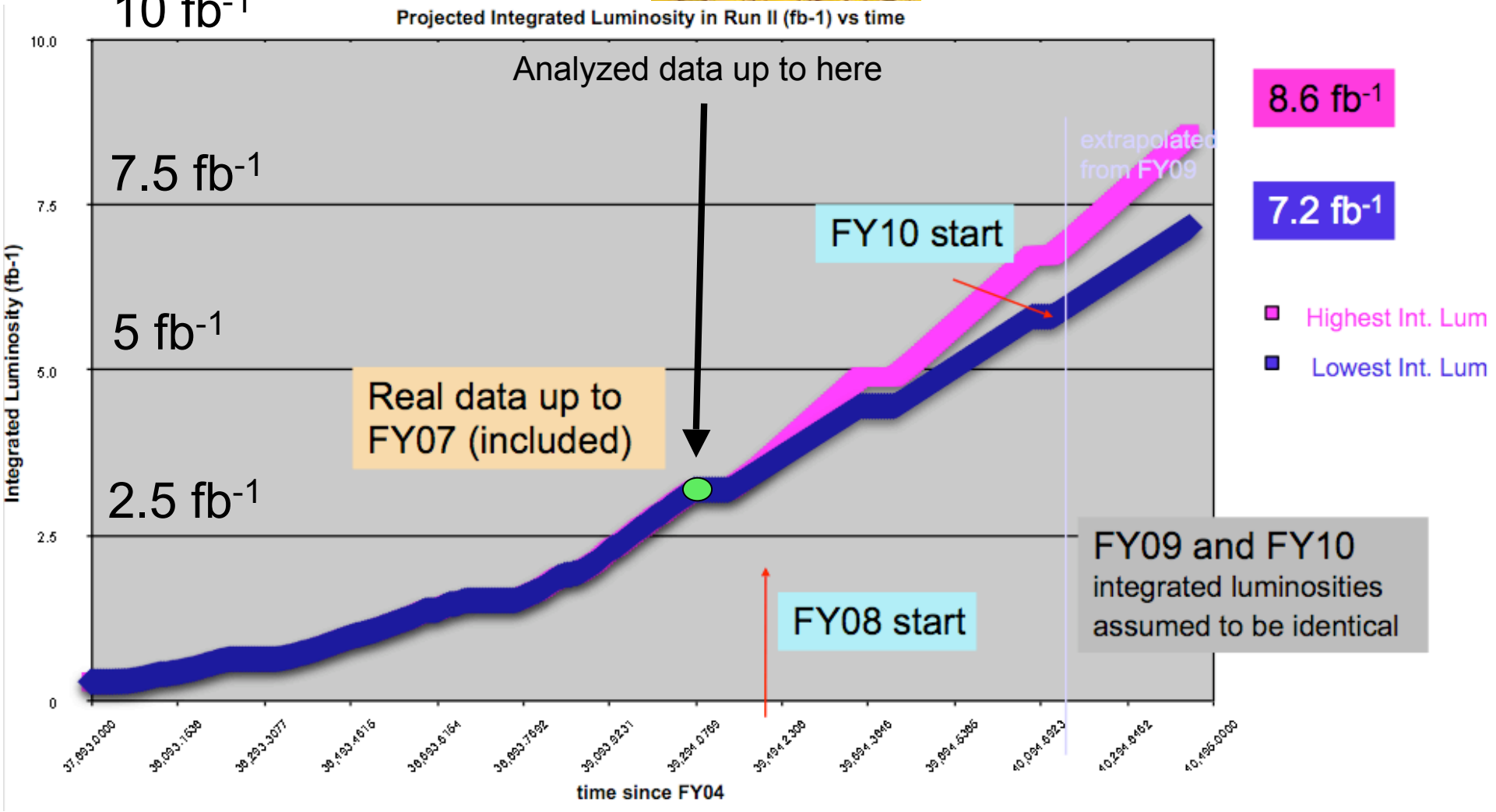
1) We get smarter with time
2) Systematic brick walls?



Integrated Luminosity Projections out to 2010

Banner Week -- 50 pb^{-1} !!!
Peak Lumi >= 3.1E32 !!!

R. Dixon, Feb. 2008
P5 presentation



Summary and Prospects

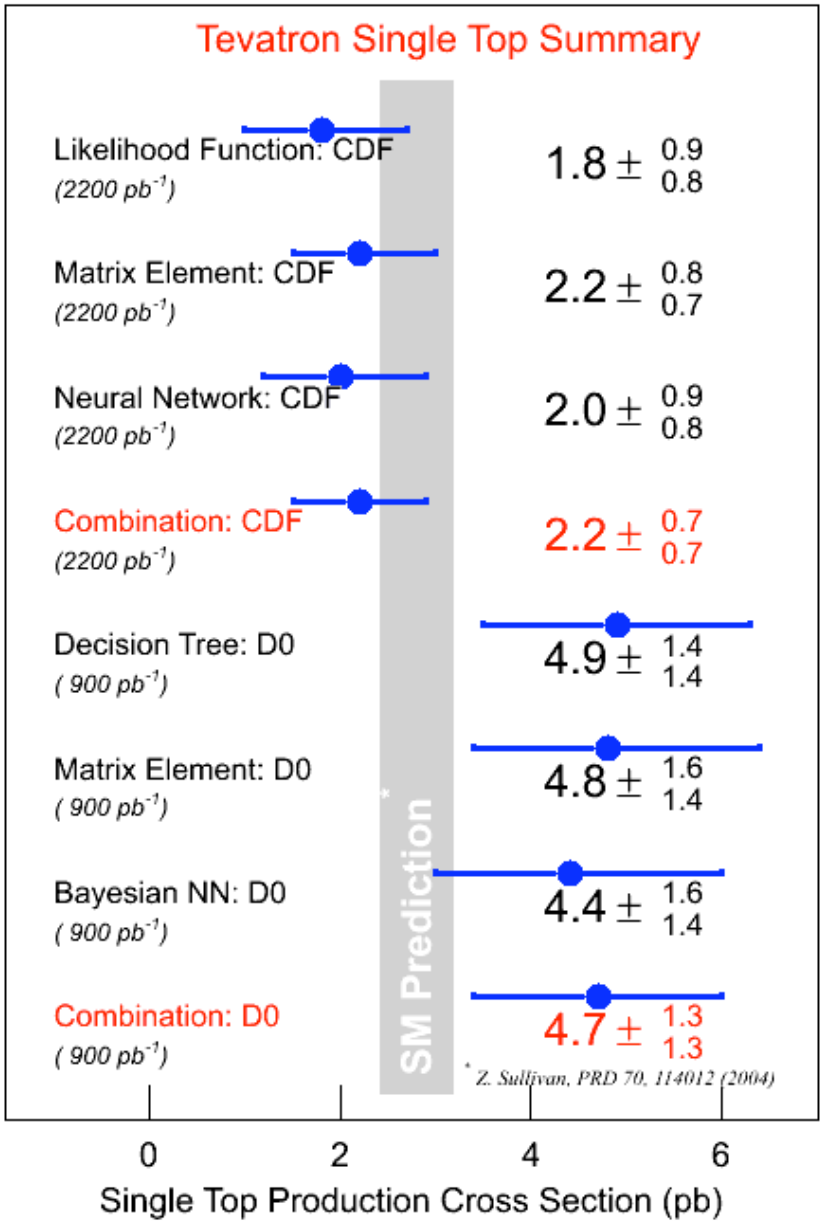
- Thanks to the tireless work of the Accelerator Division and CDF:

- Observation of Single Top quarks was expected
  Observed *p*-value: 3.7σ
  Expected: 5.1σ

- Precise measurement of cross section and $|V_{tb}|$

$\sigma_{\text{Single Top}} = 2.2^{+0.7}_{-0.7}$ pb $\qquad |V_{tb}| = 0.88 \pm 0.14\,(\text{exp.}) \pm 0.07\,(\text{theory})$

- It's time to embark on the future program of single top physics
  - *s*- and *t*-channel separate measurements
  - polarization measurement
  - FCNC search
  - W' search -- Already a nice result with 1.9 fb^{-1} of data.



Artwork credit: Jan Lück