Observation of Electroweak Single Top Quark Production

(submitted to Phys. Rev. Lett. March 4th, 2009 arXiv0903:0885)

Rainer Wallny
on behalf of
the CDF collaboration

Fermilab Joint Theoretical and Experimental Physics Seminar

March 10th, 2009

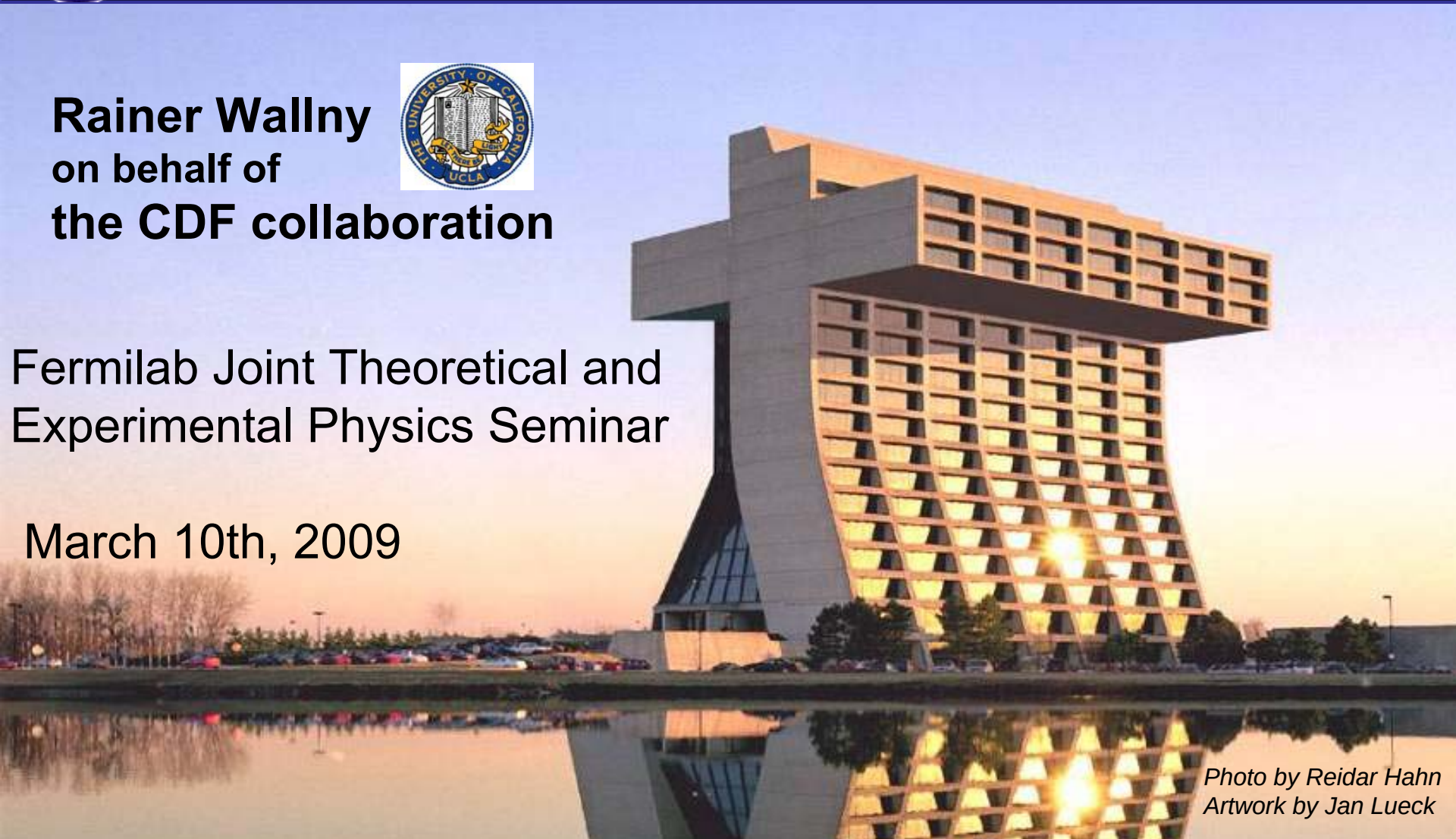
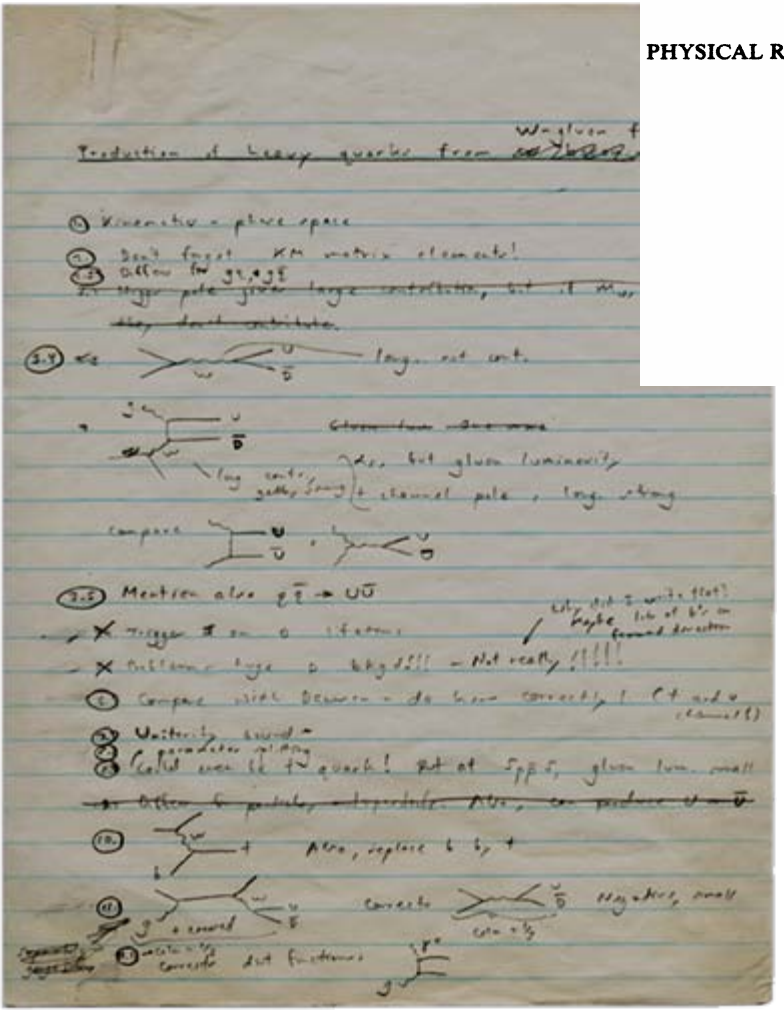


Photo by Reidar Hahn
Artwork by Jan Lueck

A single top quark is born ….



Symmetry magazine Jan./Feb. 2007

PHYSICAL REVIEW D VOLUME 34, NUMBER 1 1 JULY 1986

Production of heavy quarks from *W*-gluon fusion

Scott S. D. Willenbrock and Duane A. Dicus
Theory Group and Center for Particle Theory, University of Texas, Austin, Texas 78712
(Received 3 February 1986)

We show that heavy-quark production via W-gluon fusion in high-energy pp and $\bar{p}p$ collisions is an important source of the heavier member of an $SU(2)_L$ doublet of quarks if the mass splitting within the doublet is large. W-gluon fusion exceeds the strong production of heavy quarks for mass splittings greater than 300–350 GeV at $\sqrt{s}=10$ TeV and 400–450 GeV at $\sqrt{s}=40$ TeV. An al-

Scott Willenbrock, D. Dicus, Phys. Rev. **D34**, 155 (1986).

High Five !

Aged ~15 years!

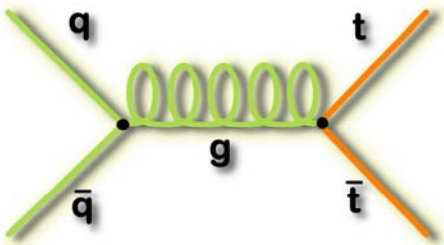
Now 5 sigma significance…

....Discovery!

Top Quark Production at the Tevatron

- The search for the top quark lasted almost two decades

  The big surprise was the huge mass!



Discovered March 1995!

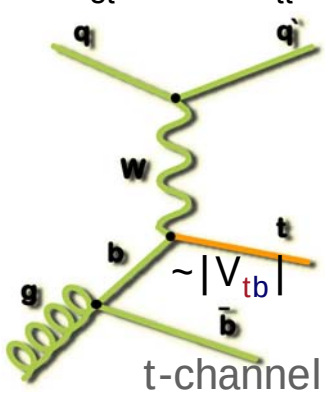
σ_{NLO} = 6.7±0.8pb (m_t=175GeV/c^2)

VOLUME 74, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1995

Observation of Top Quark Production in $\bar{p}p$ Collisions with the Collider Detector at Fermilab

F. Abe,[14] H. Akimoto,[32] A. Akopian,[27] M. G. Albrow,[7] S. R. Amendolia,[24] D. Amidei,[17] J. Antos,[29] C. Anway-Wiese,[4] S. Aota,[32] G. Apollinari,[27] T. Asakawa,[32] W. Ashmanskas,[15] M. Atac,[7] P. Auchincloss,[26] F. Azfar,[22] P. Azzi-Bacchetta,[21] N. Bacchetta,[21] W. Badgett,[17] S. Bagdasarov,[27] M. W. Bailey,[19] J. Bao,[35] P. de Barbaro,[26] A. Barbaro-Galtieri,[15] V. E. Barnes,[25] B. A. Barnett,[13] P. Bartalini,[24] G. Bauer,[16] T. Baumann,[9] F. Bedeschi,[24] S. Behrends,[3] S. Belforte,[24] G. Bellettini,[24] J. Bellinger,[34] D. Benjamin,[31] J. Benlloch,[16] J. Bensinger,[3] D. Benton,[22] A. Beretvas,[7] J. P. Berge,[7] S. Bertolucci,[8] A. Bhatti,[27] K. Biery,[12] M. Binkley,[7] D. Bisello,[21] R. E. Blair,[1] C. Blocker,[3] A. Bodek,[26] W. Bokhari,[16] V. Bolognesi,[24] D. Bortoletto,[25] J. Boudreau,[23] G. Brandenburg,[9] L. Breccia,[2] C. Bromberg,[18] E. Buckley-Geer,[7] H. S. Budd,[26] K. Burkett,[17] G. Busetto,[21] A. Byon-Wagner,[7] K. L. Byrum,[1] J. Cammerata,[13] C. Campagnari,[7] M. Campbell,[17] A. Caner,[7] W. Carithers,[15] D. Carlsmith,[34] A. Castro,[21] G. Cauz,[24] Y. Cen,[26] F. Cervelli,[24] H. Y. Chao,[29] J. Chapman,[17] M.-T. Cheng,[29] G. Chiarelli,[24] T. Chikamatsu,[32] C. N. Chiou,[29] L. Christofek,[11] S. Cihangir,[7] A. G. Clark,[24] M. Cobal,[24] M. Contreras,[5] J. Conway,[28] J. Cooper,[7] M. Cordelli,[8] C. Couyoumtzelis,[24] D. Crane,[1] D. Cronin-Hennessy,[6] R. Culbertson,[5] J. D. Cunningham,[3] T. Daniels,[16] F. DeJongh,[7] S. Delchamps,[7] S. Dell'Agnello,[24] M. Dell'Orso,[24] L. Demortier,[27] B. Denby,[24] M. Deninno,[2] P. F. Derwent,[17] T. Devlin,[28] M. Dickson,[26] J. R. Dittmann,[6] S. Donati,[24] R. B. Drucker,[15] A. Dunn,[17] N. Eddy,[17] K. Einsweiler,[15] J. E. Elias,[7] R. Ely,[15] E. Engels, Jr.,[23] D. Errede,[11] S. Errede,[11] Q. Fan,[26] I. Fiori,[2] B. Flaugher,[7]

- Single top quark production also predicted by the SM through an electroweak vertex ($\sigma_{st} \sim 0.4\ \sigma_{tt}$)



t-channel

σ_{NLO} = 1.98±0.21pb

(m_t=175 GeV/c^2)

Discovered March 2009!

s-channel

σ_{NLO} = 0.88±0.07pb

First Observation of Electroweak Single Top Quark Production

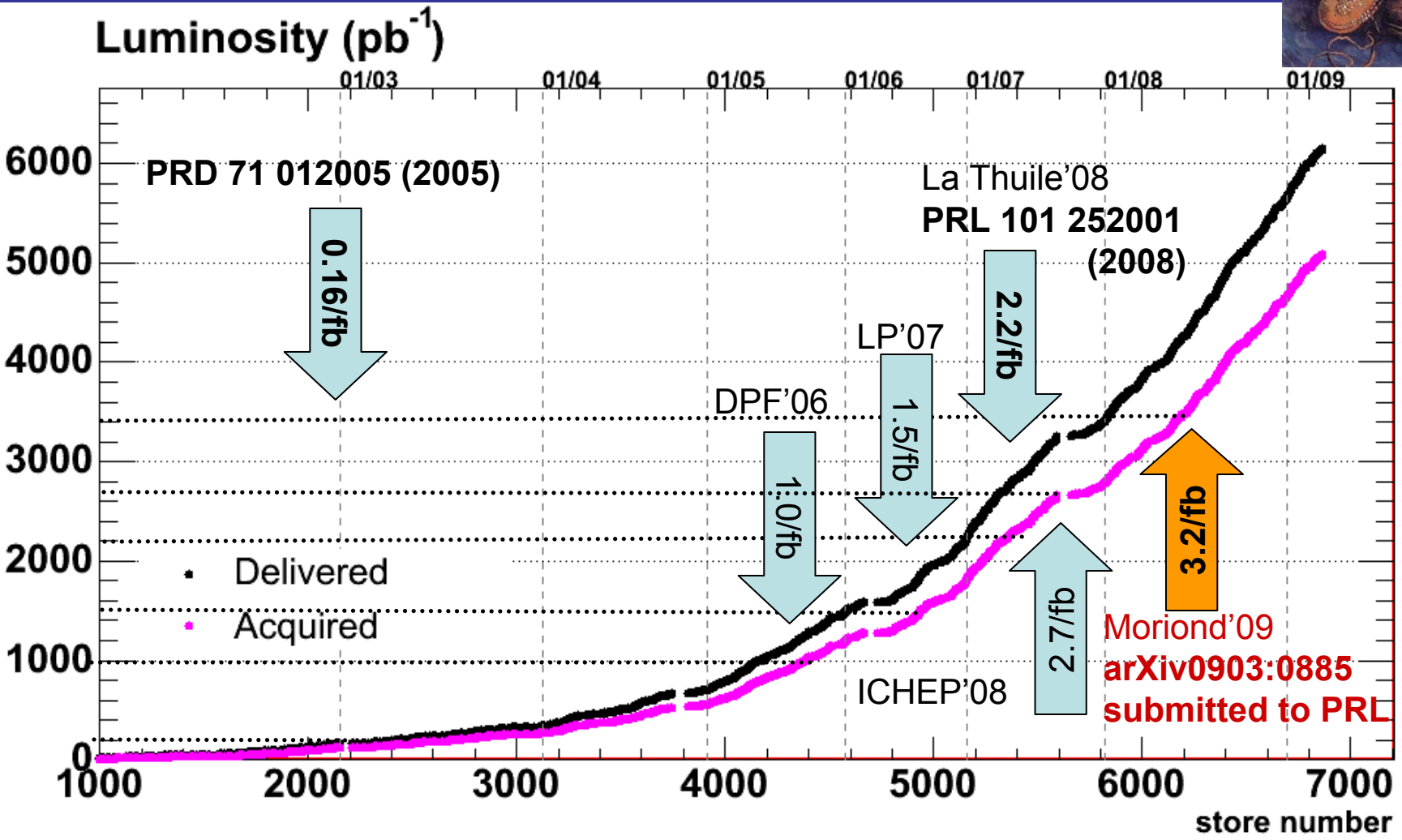
T. Aaltonen,[24] J. Adelman,[14] T. Akimoto,[56] B. Álvarez González[s],[12] S. Amerio[y],[44] D. Amidei,[35] A. Anastassov,[39] A. Annovi,[20] J. Antos,[15] G. Apollinari,[18] A. Apresyan,[49] T. Arisawa,[58] A. Artikov,[16] W. Ashmanskas,[18] A. Attal,[4] A. Aurisano,[54] F. Azfar,[43] W. Badgett,[18] A. Barbaro-Galtieri,[29] V.E. Barnes,[49] B.A. Barnett,[26] P. Barria[aa],[47] V. Bartsch,[31] G. Bauer,[33] P.-H. Beauchemin,[34] F. Bedeschi,[47] D. Beecher,[31] S. Behari,[26] G. Bellettini[z],[47] J. Bellinger,[60] D. Benjamin,[17] A. Beretvas,[18] J. Beringer,[29] A. Bhatti,[51] M. Binkley,[18] D. Bisello[y],[44] I. Bizjak[ee],[31] R.E. Blair,[2] C. Blocker,[7] B. Blumenfeld,[26] A. Bocci,[17] A. Bodek,[50] V. Boisvert,[50] G. Bolla,[49] D. Bortoletto,[49] J. Boudreau,[48] A. Boveia,[11] B. Brau[a],[11] A. Bridgeman,[25] L. Brigliadori[x],[6] C. Bromberg,[36] E. Brubaker,[14] J. Budagov,[16] H.S. Budd,[50] S. Budd,[25] S. Burke,[18] K. Burkett,[18] G. Busetto[y],[44] P. Bussey,[22] A. Buzatu,[34] K. L. Byrum,[2] S. Cabrera[u],[17] C. Calancha,[32] M. Campanelli,[36] M. Campbell,[35] F. Canelli[14],[18] A. Canepa,[46] B. Carls,[25] D. Carlsmith,[60] R. Carosi,[47] S. Carrillo[n],[19] S. Carron,[34] B. Casal,[12] M. Casarsa,[18] A. Castro[x],[6] P. Catastini[aa],[47] D. Cauz[dd],[55] V. Cavaliere[aa],[47] M. Cavalli-Sforza,[4] A. Cerri,[29] L. Cerrito[o],[31] S.H. Chang,[28] Y.C. Chen,[1] M. Chertok,[8] G. Chiarelli,[47] G. Chlachidze,[18] F. Chlebana,[18] K. Cho,[28] D. Chokheli,[16] J.P. Chou,[23] G. Choudalakis,[33] S.H. Chuang,[53] K. Chung,[13] W.H. Chung,[60] Y.S. Chung,[50] T. Chwalek,[27] C.I. Ciobanu,[45] M.A. Ciocci[aa],[47] A. Clark,[21] D. Clark,[7] G. Compostella,[44] M.E. Convery,[18] J. Conway,[8] M. Cordelli,[20] G. Cortiana[y],[44] C.A. Cox,[8] D.J. Cox,[8] F. Crescioli[z],[47] C. Cuenca Almenar[u],[8] J. Cuevas[s],[12] R. Culbertson,[18] J.C. Cully,[35] D. Dagenhart,[18] M. Datta,[18] T. Davies,[22] P. de Barbaro,[50] S. De Cecco,[52] A. Deisher,[29] G. De Lorenzo,[4] M. Dell'Orso[z],[47] C. Deluca,[4] L. Demortier,[51] J. Deng,[17] M. Deninno,[6] P.F. Derwent,[18]

σ_{NLO} = 1.98±0.21pb

(m_t=175 GeV/c^2)

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

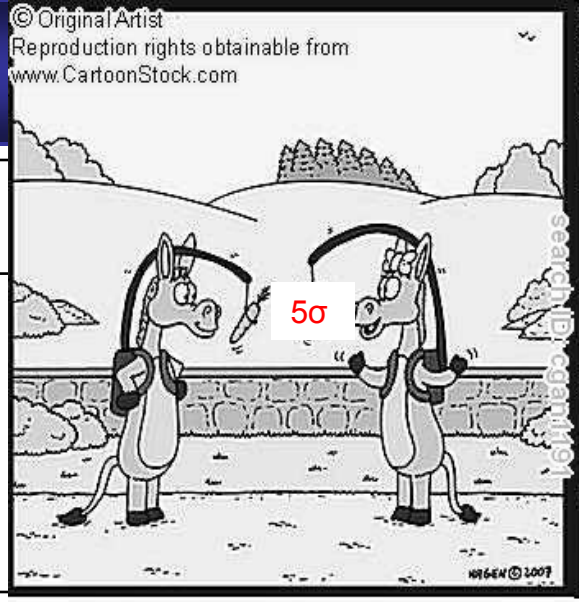
A long way …



Many thanks to the accelerator division for a fantastic job !!

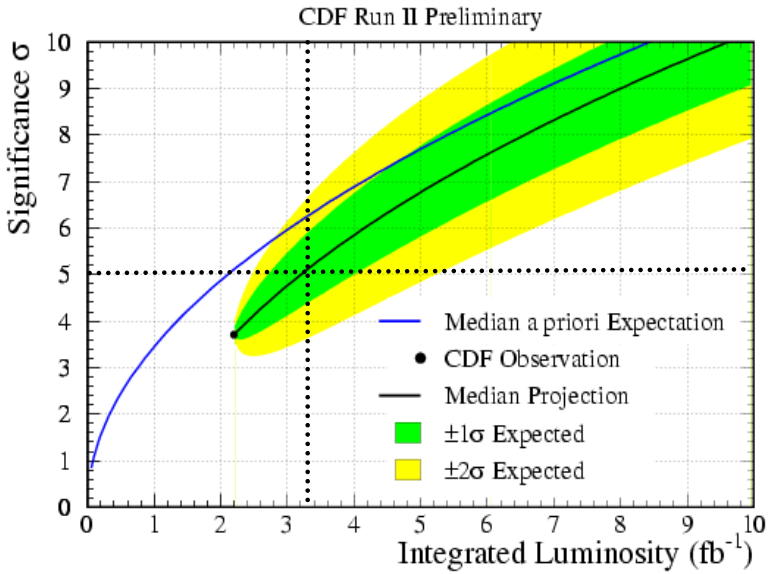
Milestones

Result	Lumi fb^{-1}	Expected signal sensitivity (σ)	Observed signal significance (σ)
PRD 71 012005 (2005)	0.16	limit	limit
DPF '06 *(best analysis)*	1.0	2.5	2.3
LP '07 *(best analysis)*	**1.5**	**3.1**	**3.0**
PRL 101 252001 (2008)	2.2	4.9	3.7
ICHEP '07 *(best analysis)*	2.7	5.0	3.8
This publication	**3.2**	**5.9**	**5.0**



Improvements since ICHEP '08:

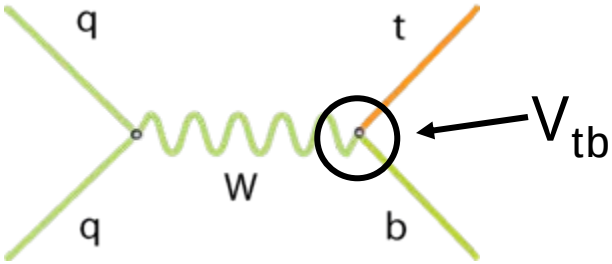
- Three new analyses
- Additional orthogonal event selection
- Improved combination



T. Junk, JETP Seminar March 28th, 2008

Why measure Single Top Production ?

- Access to the W-t-b vertex
  - V-A structure
  - access to top quark spin



- Allows measurement of CKM matrix element $|V_{tb}|$:
  - Is this Matrix 3x3 ?
    Is there a 4th generation ?
  - Does unitarity hold ?

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

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{uX}? \\ V_{cd} & V_{cs} & V_{cb} & V_{cX}? \\ V_{td} & V_{ts} & V_{tb} & V_{tX}? \\ V_{Yd}? & V_{Ys}? & V_{Yt}? & V_{YX}? \end{pmatrix}$$

  - "simple" 4th generation ruled out by EW fits but see e.g.
    J. Alwall et. al., "Is $|V_{tb}|$~1?"
    Eur. Phys. J. C49 791-801 (2007).

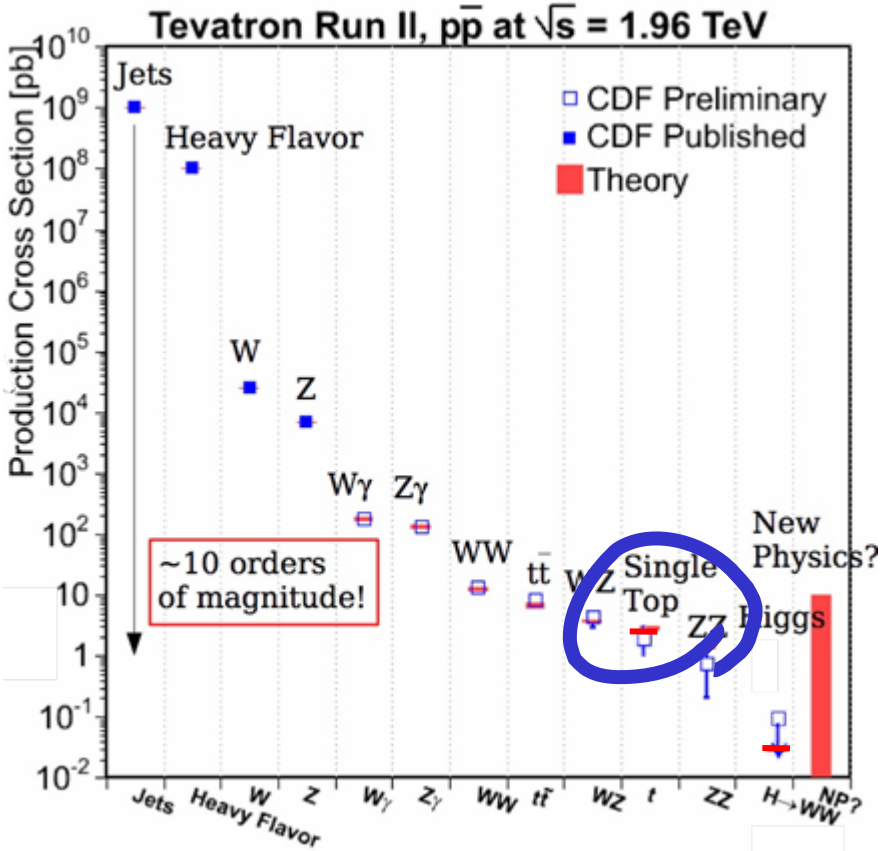
- t- and s-channel sensitive to (different) BSM physics
  - FCNC
  - Anomalous W-t-b couplings
  - Extra gauge bosons (W', W_{kk})

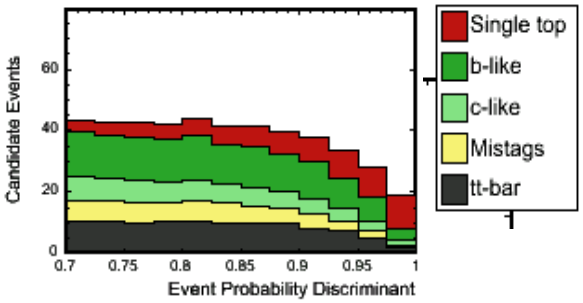
- Benchmark to WH Higgs search - $\sigma_{WH} \sim 1/10\ \sigma_{Singletop}$

The Challenge

Analysis Outline

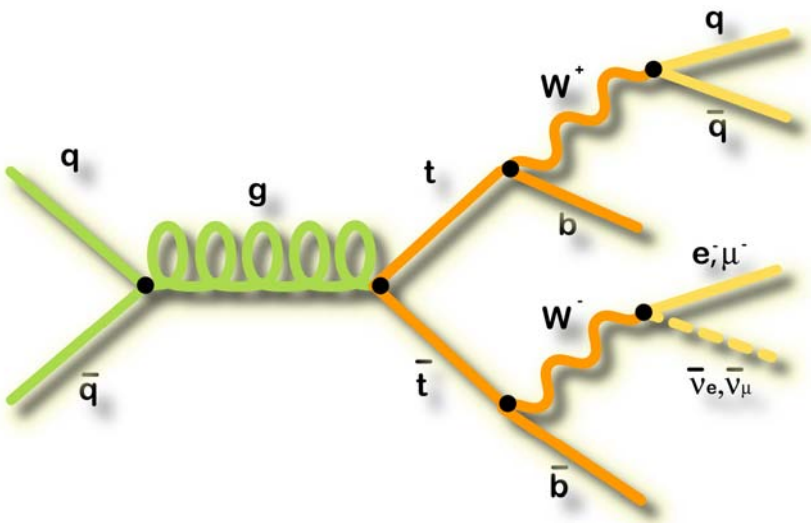
- Single Top production is a rare process at the Tevatron
  - Signal:Background (S:B) ~ 1:10^9 before doing anything
- First step:
  - Trigger and ID clean leptons/MET improves S:B by a factor ~10^6
  - High p_T lepton triggers (e,μ)
  - MET + jets triggers (recover non-fiducial leptons + hadronic τ decays)
- Second step:
  - Topological event selection
  - Efficient *b*-tagging
  - Careful background estimates
- Third step:
  - Advanced analysis techniques to separate signal from background using discriminants
  - S:B > 1:1 in most significant bins

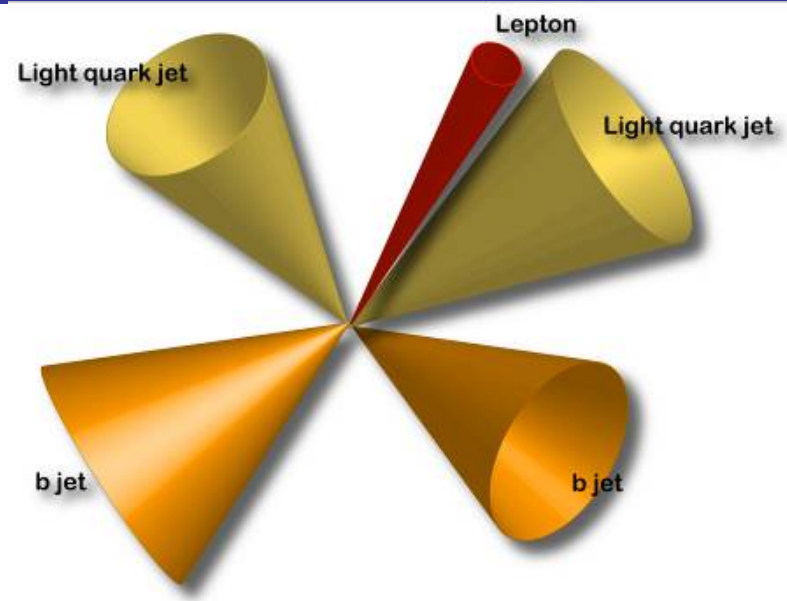




Event Signatures

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





Event Signatures

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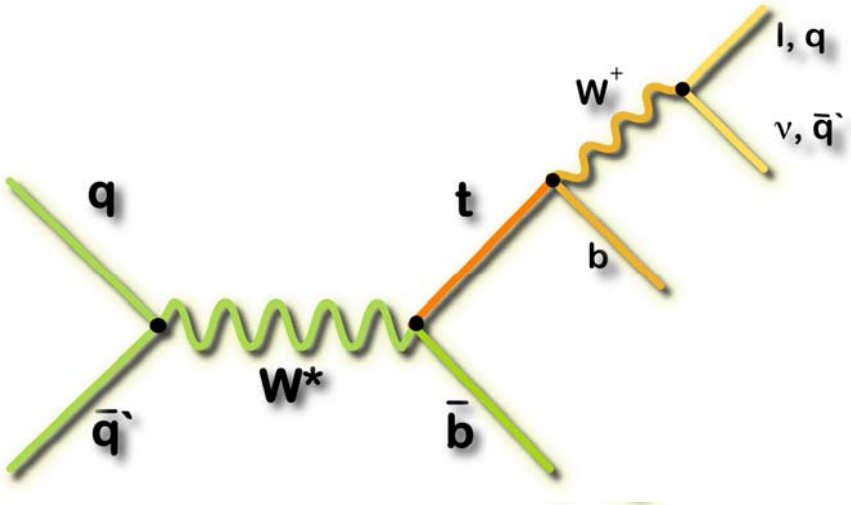
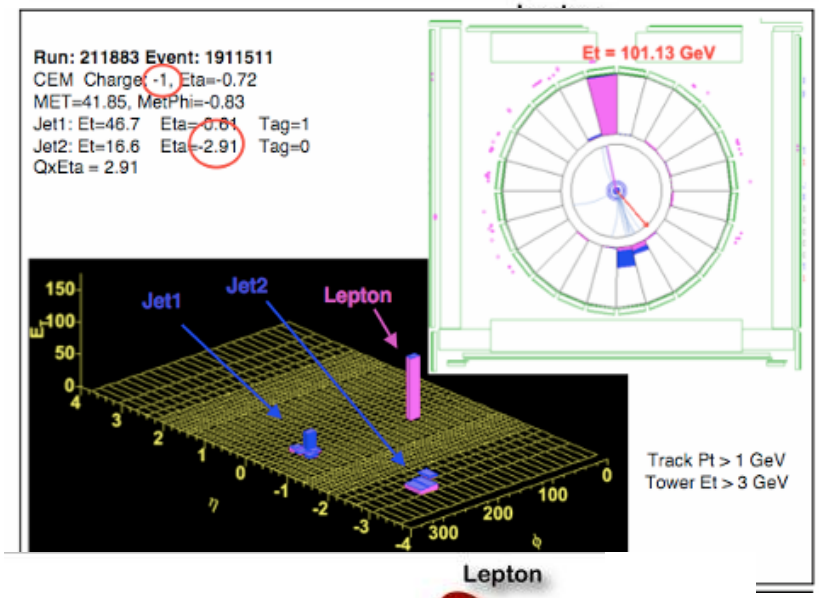
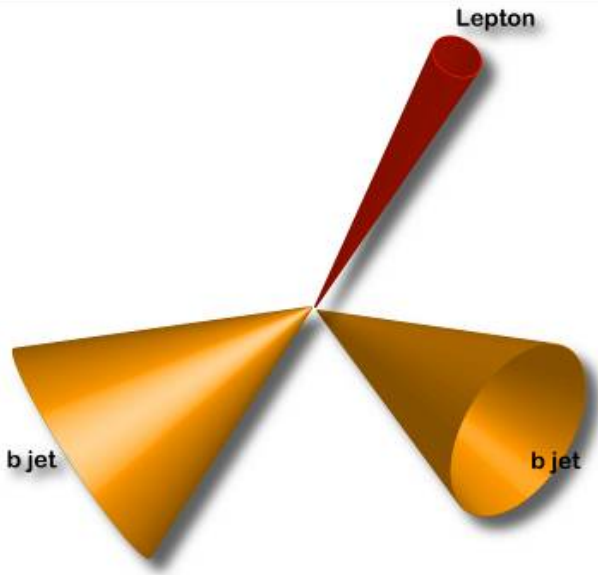




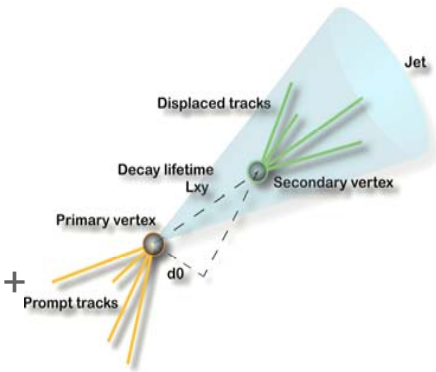
Single top Production with decay Into Lepton + 2 Jets final state is less distinct!



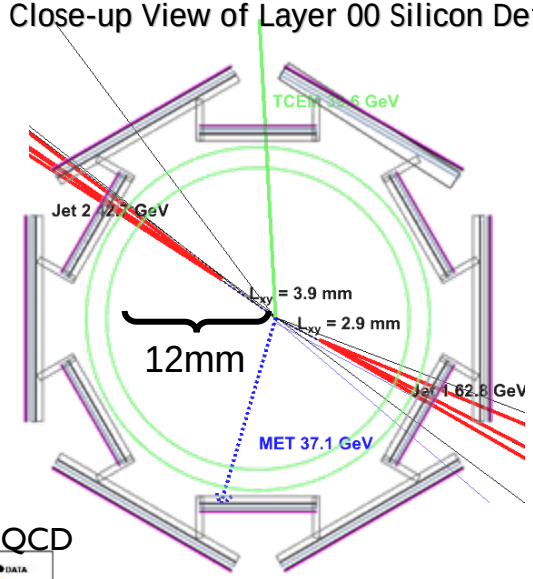
Single Top Candidate Selection

(1) High p_T lepton + MET + jets Selection:

- 1 Lepton, E_T >20 GeV, $|\eta_{e(\mu)}|$< 1.6
- Missing E_T, (MET) > 25 GeV
- 2 Jets, E_T > 20 GeV, $|\eta|$< 2.8
- Veto "non-W", Z, Dileptons, Conversions, Cosmics
- At least one *b*-tagged jet (displaced secondary vertex tag + optional jet probability tag)



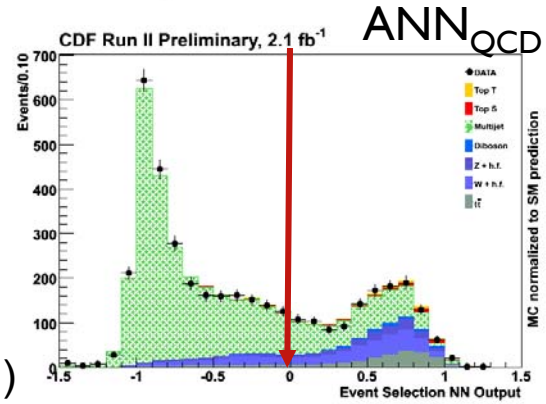
CDF W(lν) + 2 jets Candidate Event:
Close-up View of Layer 00 Silicon Detector



Run: 205964, Event: 337705
Jet 1: E_T = 62.8 GeV, L_{xy} = 2.9mm
Jet 2: E_T = 42.7 GeV, L_{xy} = 3.9mm

(2) MET + jets Selection:

- MET > 50 GeV
- Veto leptons
- E_T> 35 GeV (1st jet) and E_T> 25 GeV (2nd jet)
- Same *b*-tag requirements as (1)
- Neural Network to suppress QCD background

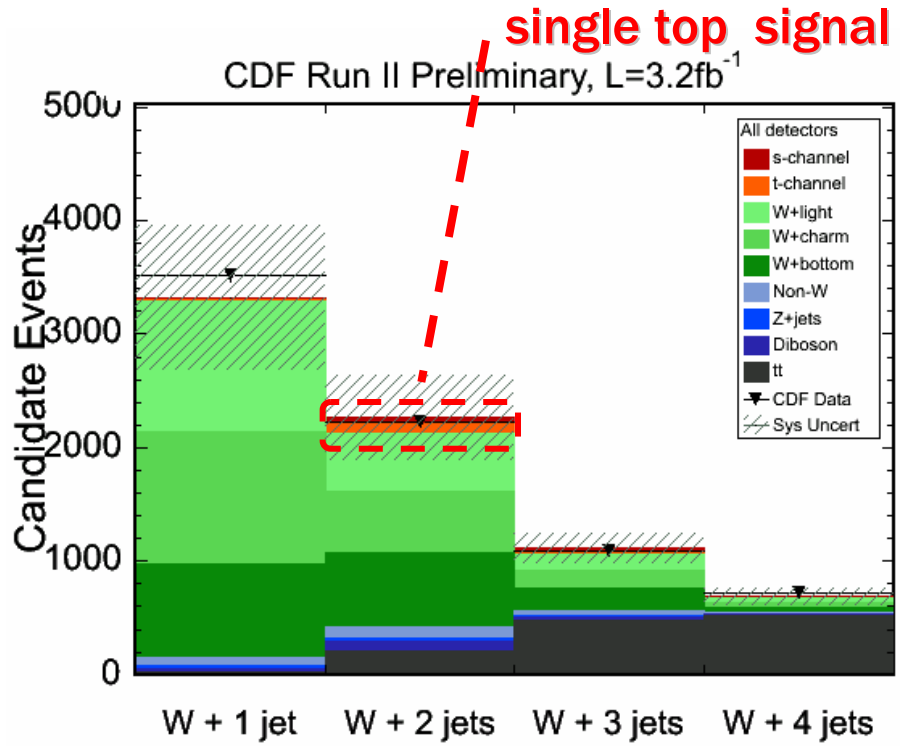


=> Orthogonal Event Selections: (2) adds 33% acceptance to (1)

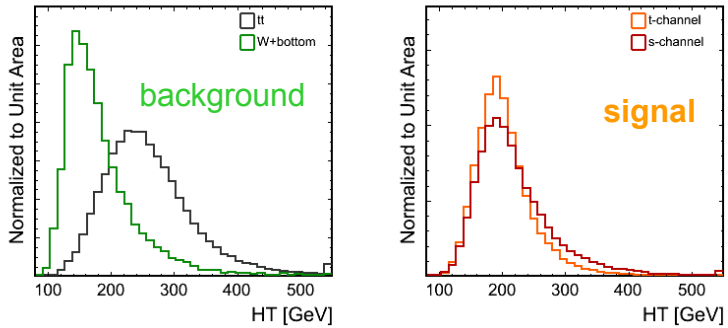
The Challenge

- "W+2 jet" topology not very distinct
  - Signal/Background W+2jet+btag ~ 1:17
  - Counting experiment impossible
- Many sources of background
  - Only a few directly estimated from (~NLO) MC
  - Data driven and "hybrid" (data+MC)

    → large syst.uncertainties!
- No "golden" variable
  - Signal distributions and background distributions look similar



$H_T = \Sigma E_T$(lepton, Missing Energy, Jets)

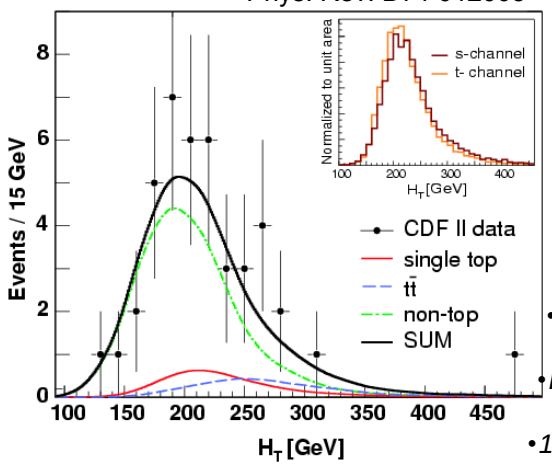


Need multivariate techniques to exploit all available information

CDF Single Top History

2004: Simple analysis while refining Monte Carlo samples and analysis tools

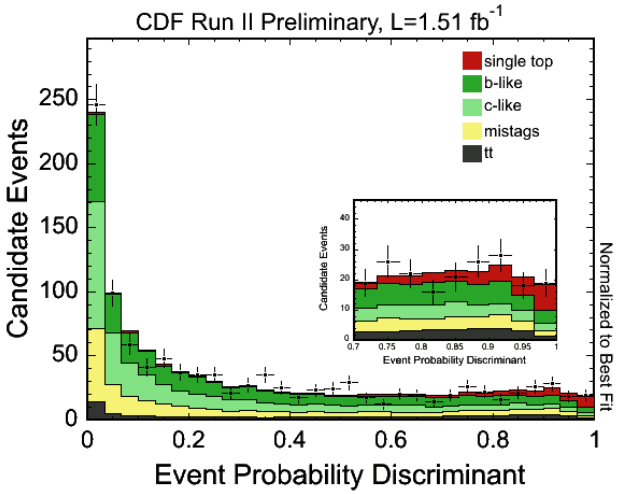
Phys. Rev. D71 012005



2 Years

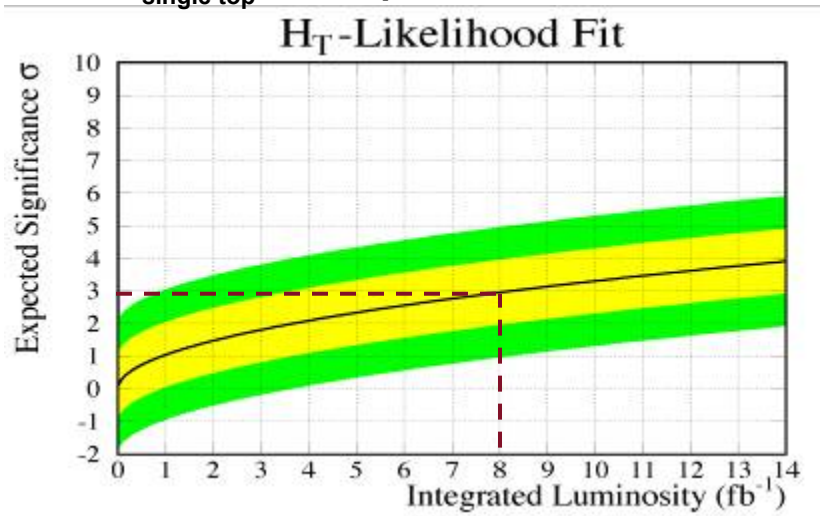
- *Development of powerful analysis techniques (Matrix Element, NN, Likelihood Discriminant)*
- *NN Jet-Flavor Separator to purify sample*
- *Refined background estimates and modeling*
- *Increase acceptance (forward electrons)*
- *10x more data*

2006: Established sophisticated analyses
Check robustness in data control samples

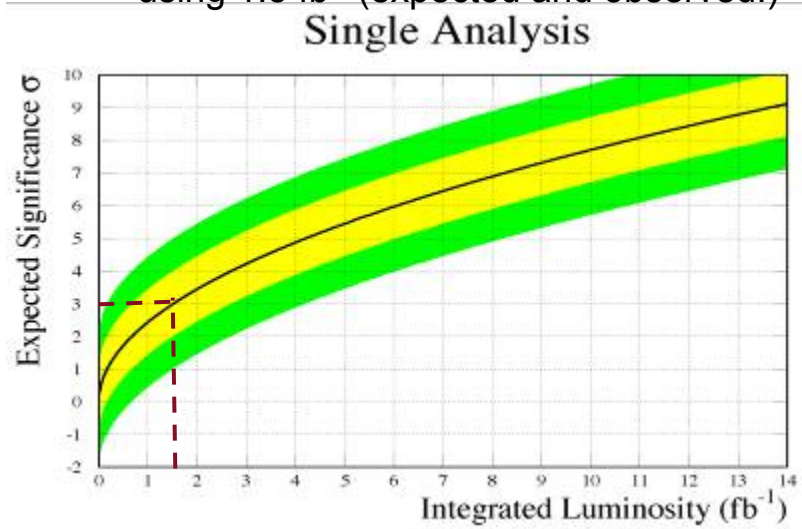


First Tevatron Run II result using 162 pb^{-1}

$\sigma_{\text{single top}}$ **< 17.5 pb at 95 % C.L.**



2007: Evidence for single top quark production using 1.5 fb^{-1} (expected and observed!)



The Experimental Tools

CDF II Detector

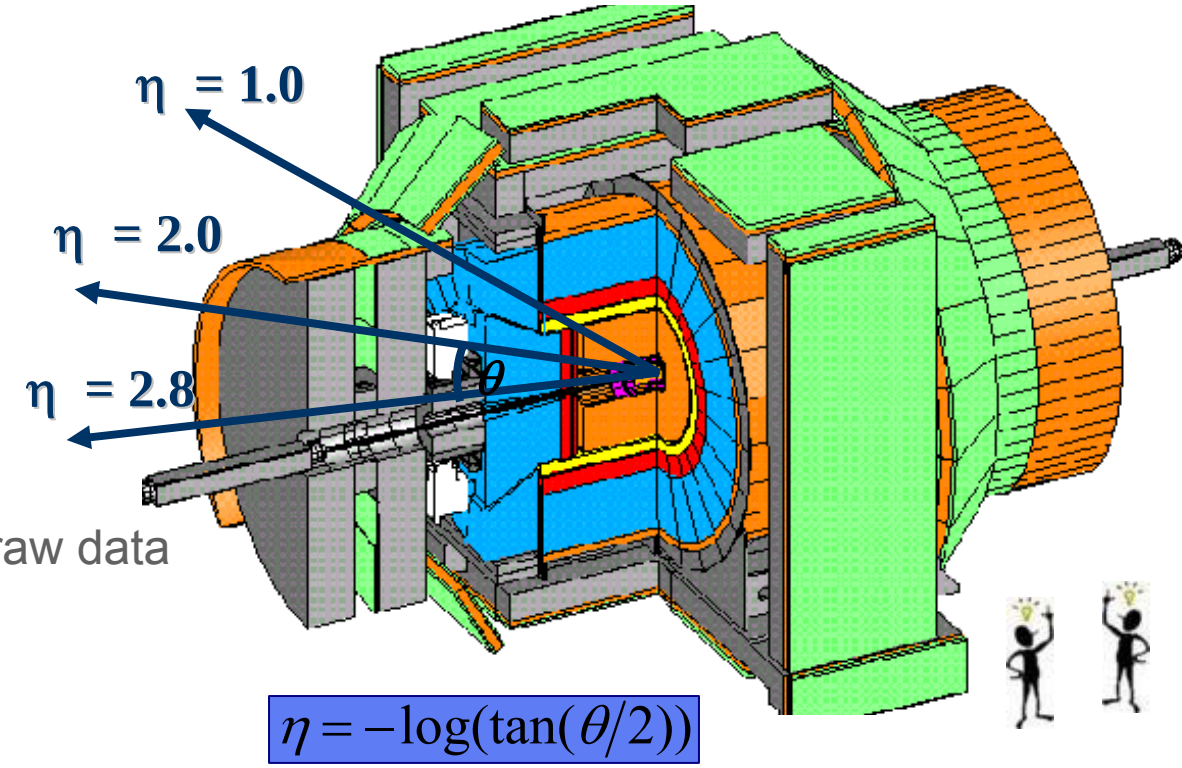
CDF is working well

- integrated 5 fb^{-1} on tape
- The analyses in this paper use 3.2 fb^{-1}

(All detector components ON)

CDF is getting fast

- 6 weeks turnaround time to calibrate, validate and process raw data



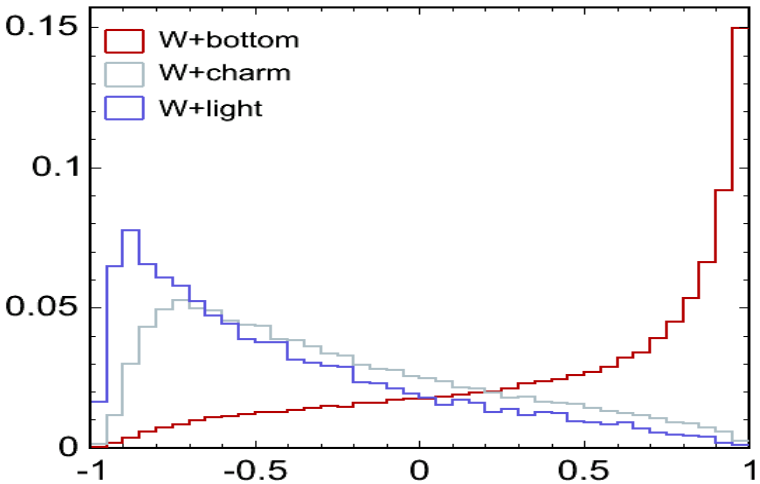
Making use of our detector at its best!

- Silicon tracking detectors
- Central drift chambers (COT)
- Solenoid Coil
- EM calorimeter
- Hadronic calorimeter
- Muon scintillator counters
- Muon drift chambers
- Steel shielding

B-tagging and Jet Flavor Separation

- Even with a fully reconstructed secondary vertex required, ~50% of the background in the W + 2 jets sample do NOT contain bottom quarks
- Train Neural Network with secondary vertex tracking information (25 input variables) for bottom/charm/light flavor separation
  - L_{xy}, vertex mass, track multiplicity, impact parameter, semi-leptonic decay information, etc...
- Replaces Yes-No tag decision by a continuous variable *(0<b<1)* - used in all lepton + jets analyses
- Improves sensitivity by ~10-15%!

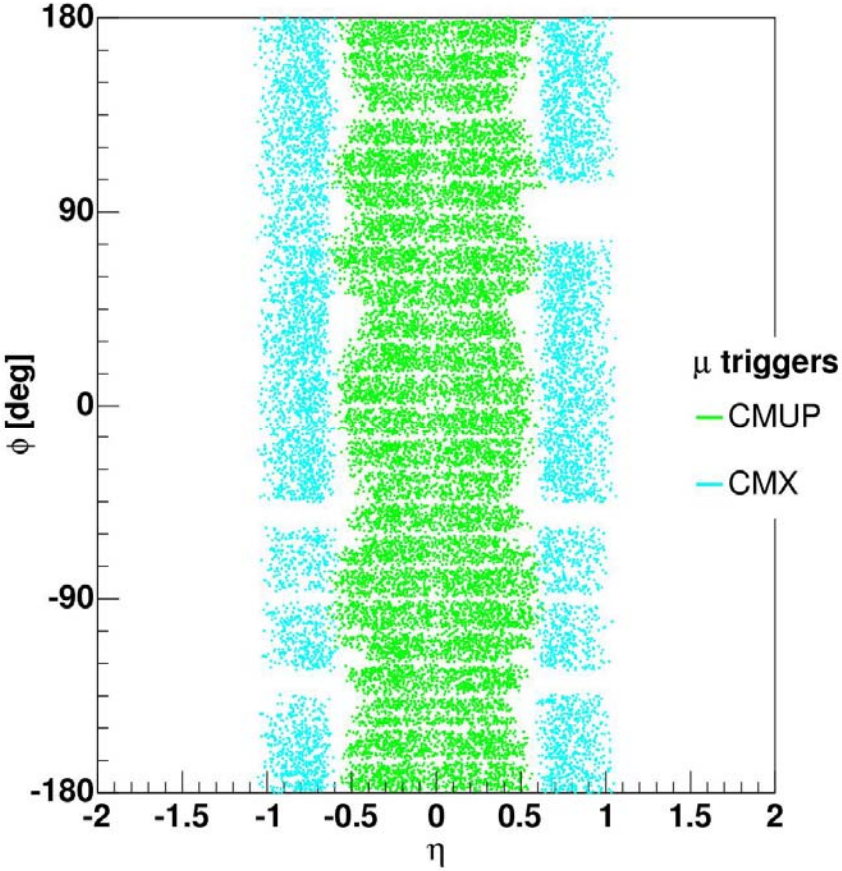
SecVtx tagging rates:
- Bottom ~50%
- Charm ~9%
- Mistag ~ 0.5-1%



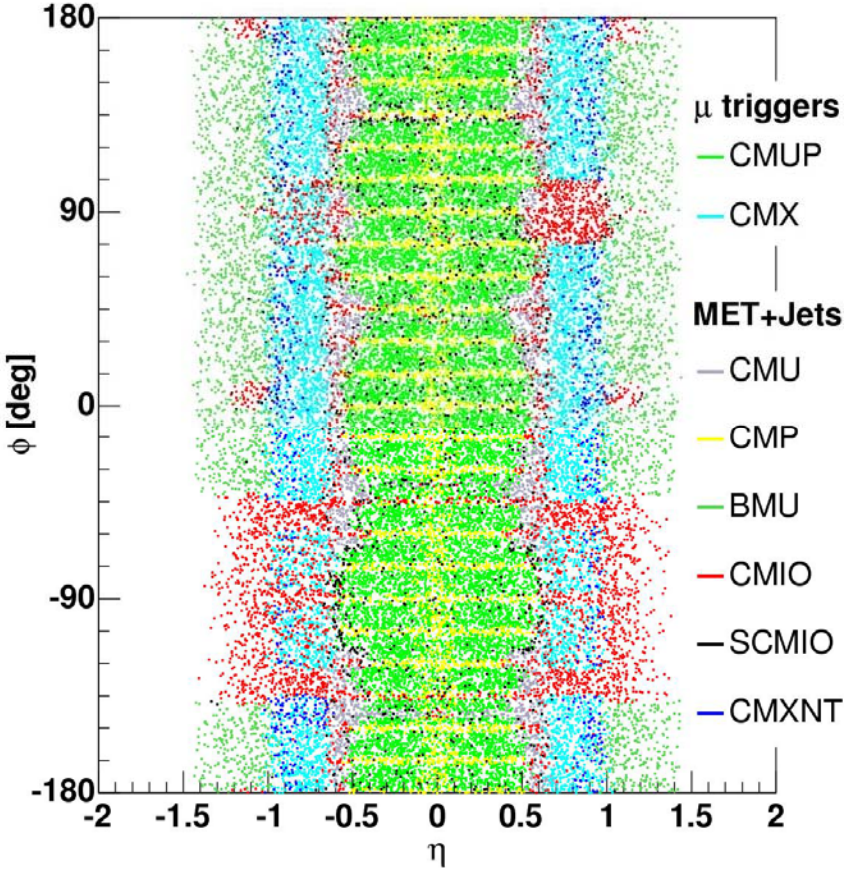
mistags / charm ..... bottom

Filling the CDF Cracks ….

Muons from High pT Muon Trigger



Muons from MET+jets trigger



Gain from MET+jets triggered events:

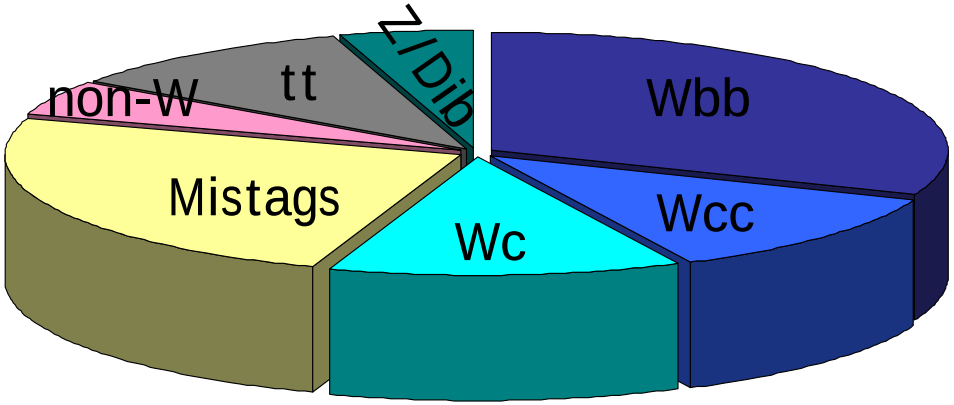
- ~30% gain in muon acceptance
- ~10-14% gain in sensitivity

Single Top Background Estimate

Top/EWK (WW/WZ/Z→ττ, ttbar)

- MC normalized to theoretical cross-section
- Modeled by Pythia Monte Carlo

MC driven



Single Top Background Estimate

Top/EWK (WW/WZ/Z→ττ, ttbar)

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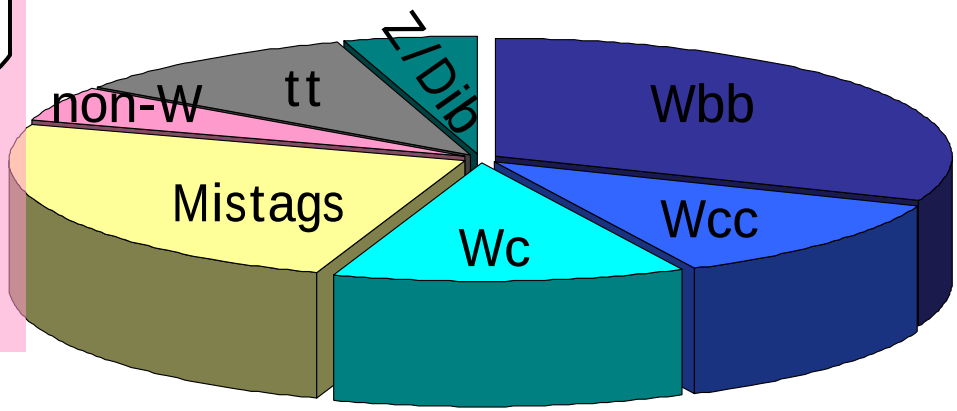
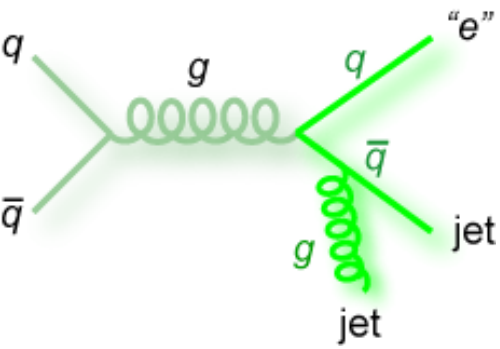
MC driven

Non-*W (QCD)*

- Multijet events with semileptonic *b*-decays or mismeasured jets
- Fit low MET data and extrapolate into signal region
- Modeled by 'Anti/Jet-electons'

Data driven





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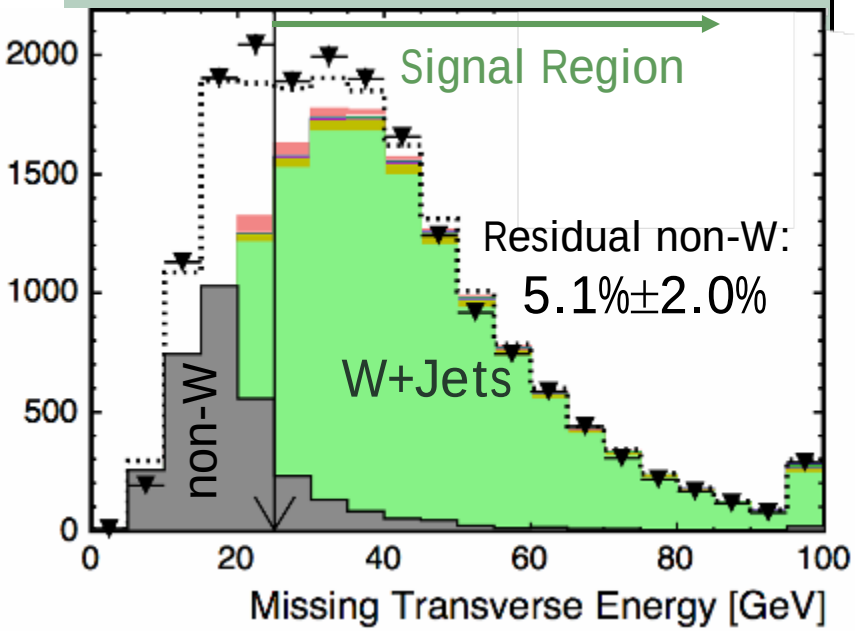

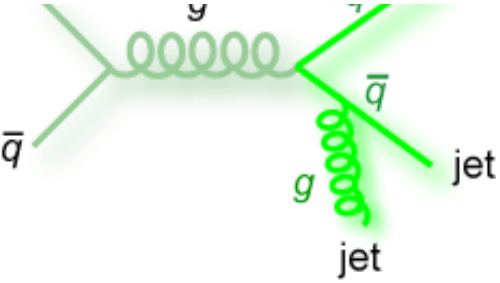

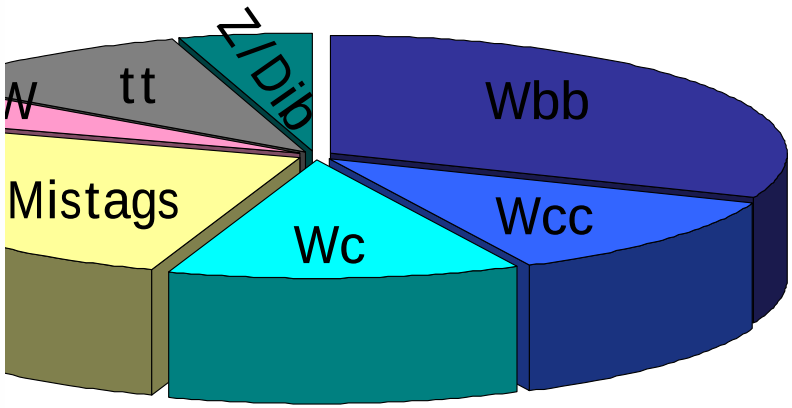

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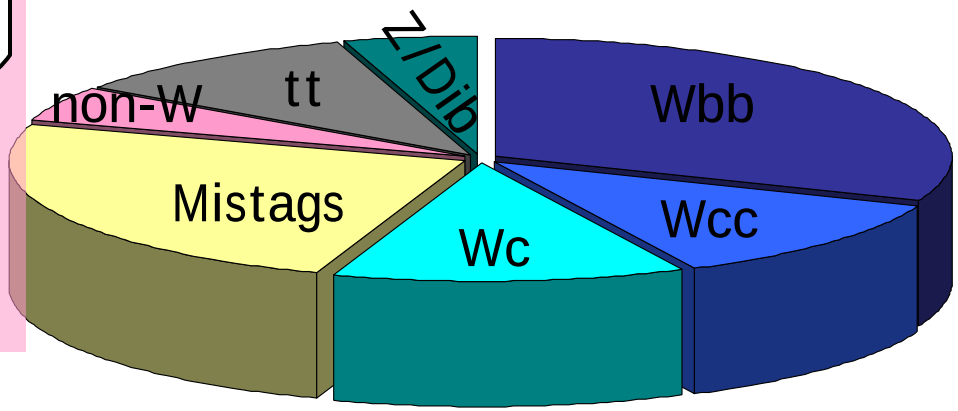

Mistags (W+2jets)

- Falsely tagged light quark or gluon jets
- Mistag probability parameterization obtained from inclusive jet data
- Apply mistag probability to generic W+jets sample

data driven

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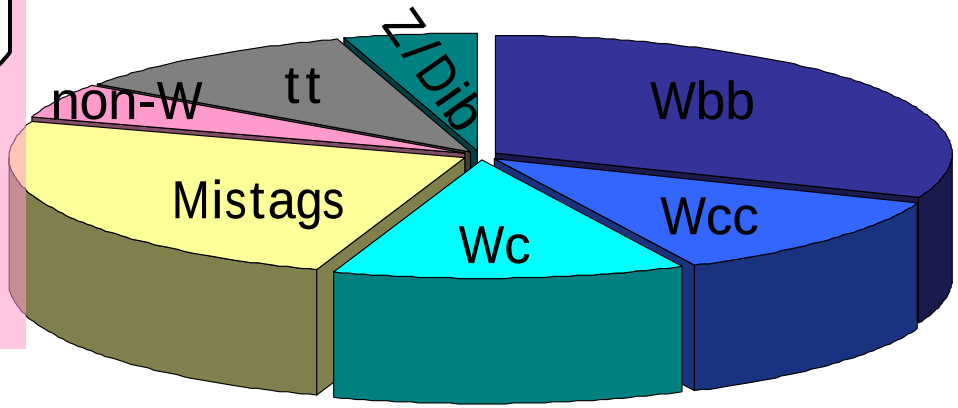

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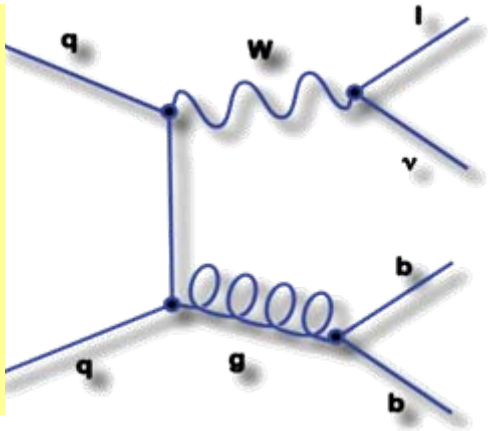

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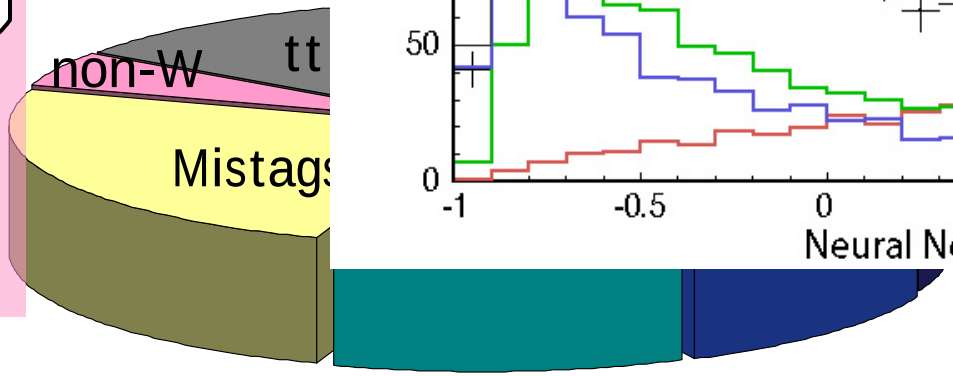

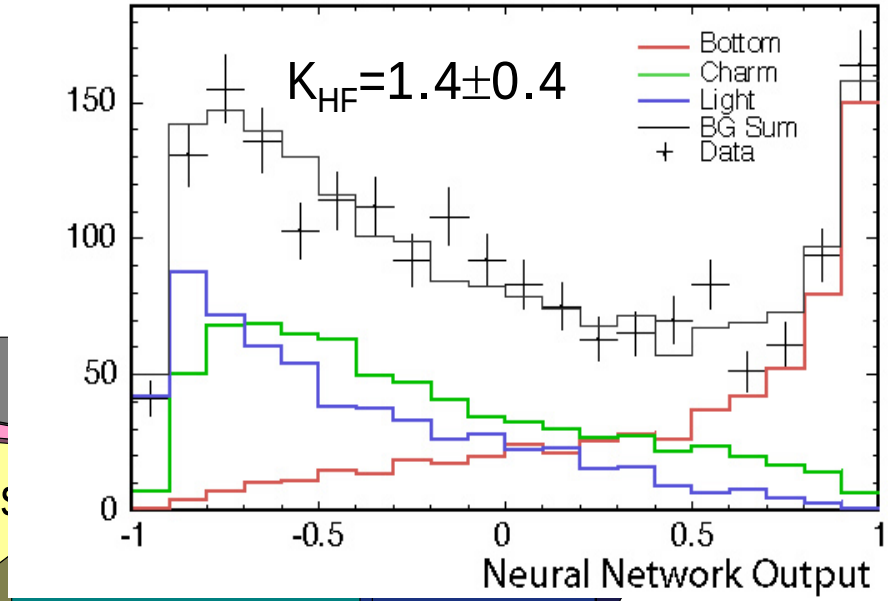

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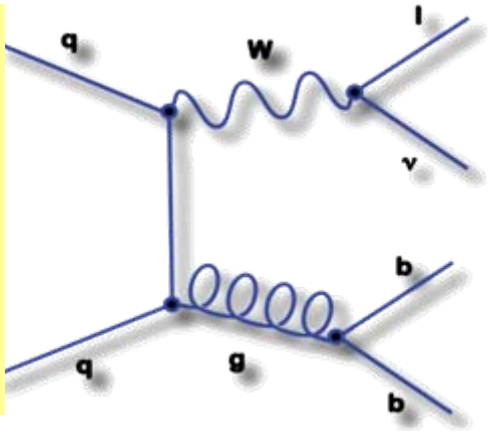

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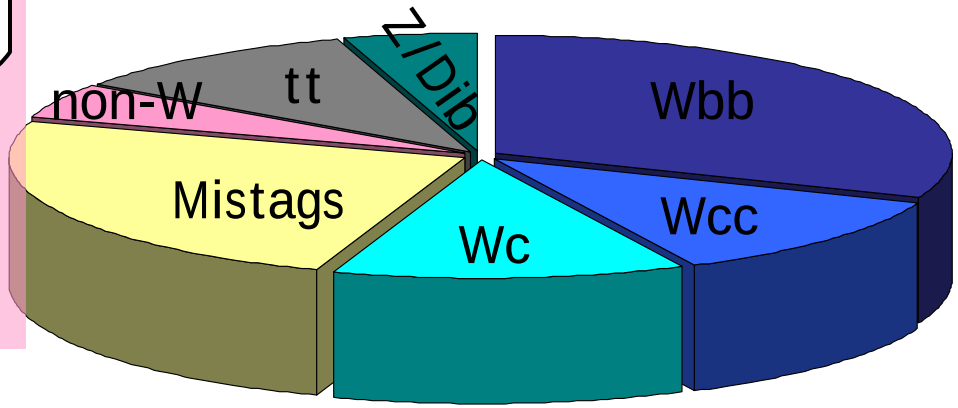

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- Apply mistag probability to generic W+jets sample

data driven

Background estimate in 3.2/2.1 fb^{-1}

MET + high p_T lepton + 2 jets 3.2 fb^{-1}
(single + double SECVTX tag)

s-channel	58.1 ± 8.4
t-channel	87.6 ± 13.0
Single top	145.7 ± 21.4
tt	204.1 ± 29.6
Dibosons	88.3 ± 9.1
Z + jets	36.5 ± 5.6
W + bb	656.9 ± 198.0
W + cc	292.2 ± 90.1
W + cj	250.4 ± 77.2
W + light flavor	501.3 ± 69.6
Non-*W*	89.6 ± 35.8
Total background	2119.3 ± 350.9
Total prediction	2265.0 ± 375.4
Observed	**2229**

~30%

MET+ ≥2 jets 2.1 fb^{-1}
(single + double SECVTX tag, SECVTX + JetProb.)

s-channel	29.6 ± 2.7
t-channel	34.5 ± 6.1
Single top	64.1 ± 8.8
tt	184.5 ± 30.2
Diboson	42.1 ± 6.7
W + HF	304.4 ± 115.5
QCD multijet	679.4 ± 27.9
Total background	1339.9 ± 170
Total prediction	1404 ± 172
Observed	**1411**

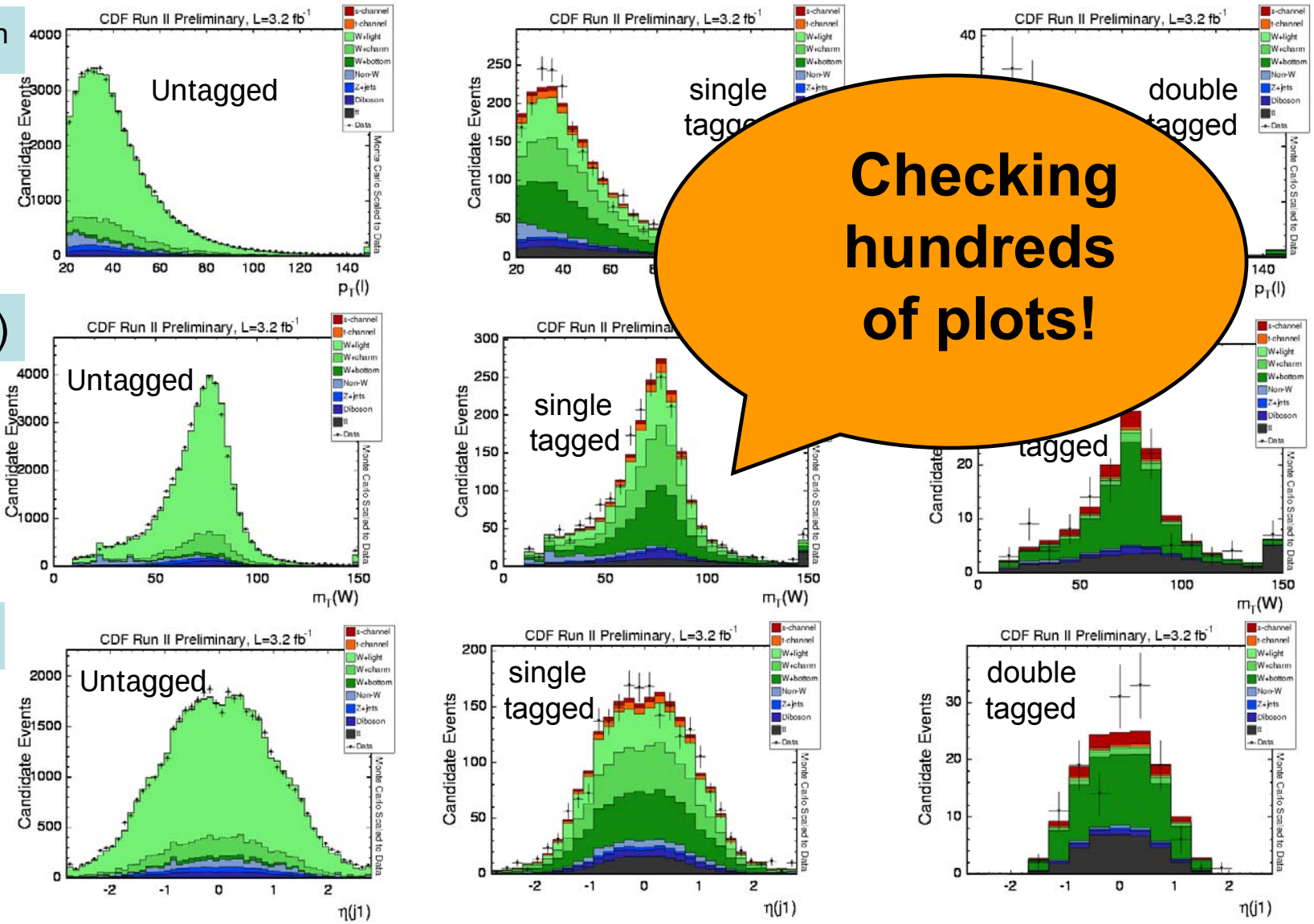
Predicted total backgrounds known to 13-17%

Input Variables: Data versus MC Agreement

P_T^{lepton}

$M_T(W)$

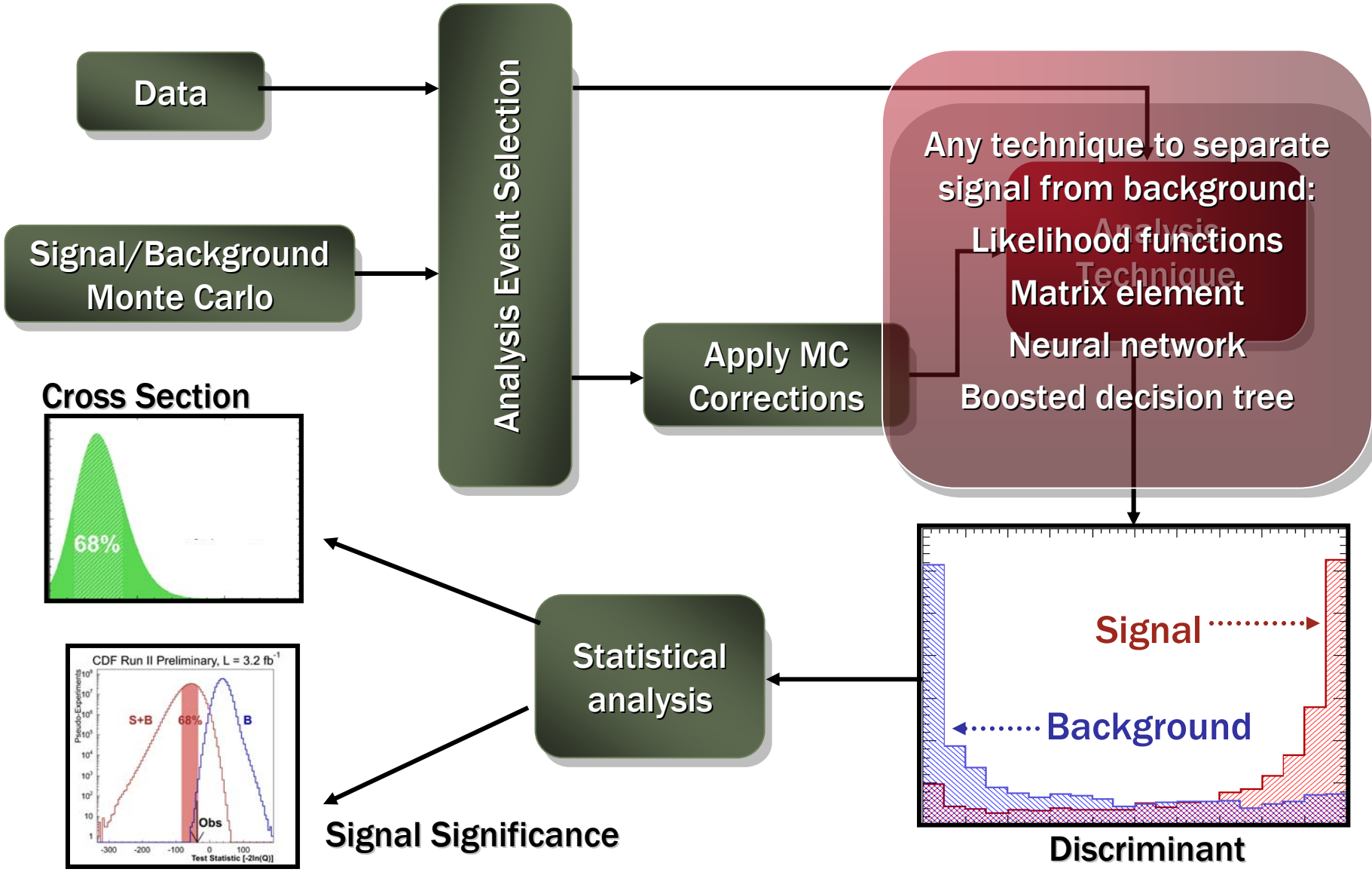
$J_1(\eta)$



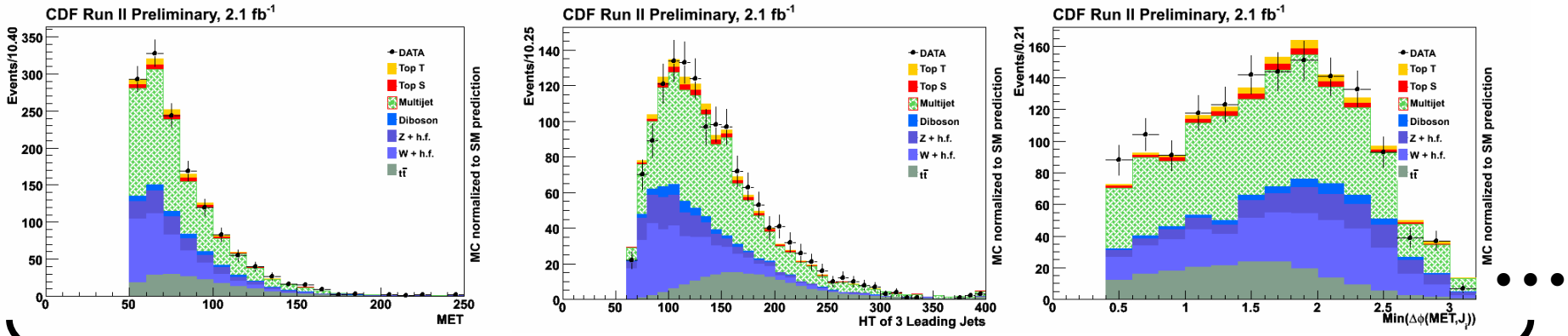
Checking hundreds of plots!

The Analyses

General analysis method



Multivariate Analyses



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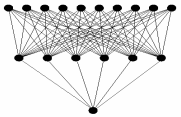

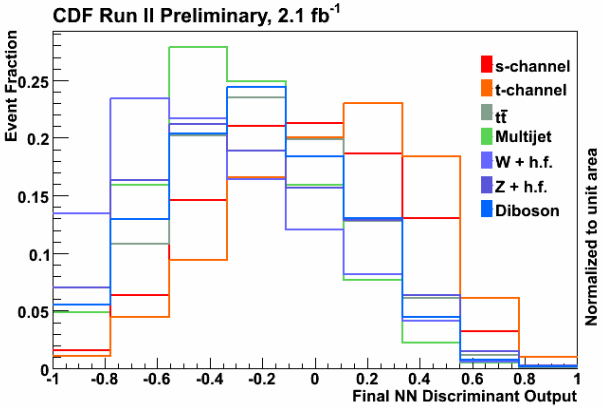

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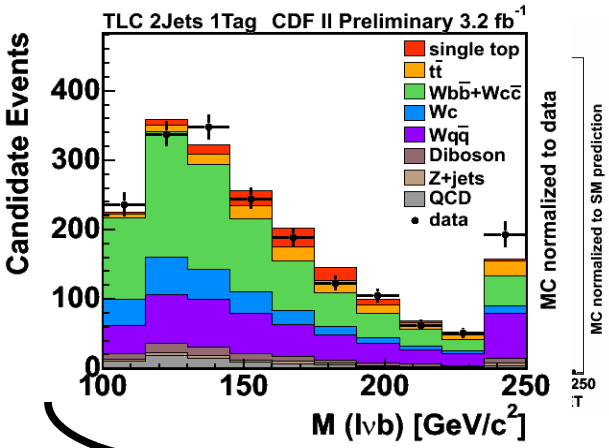

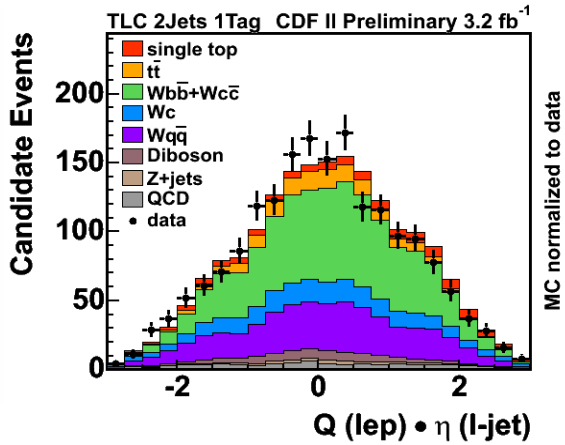

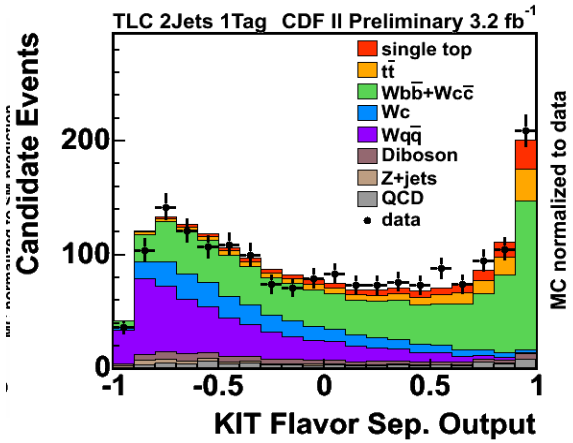

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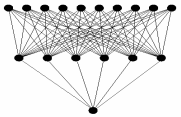

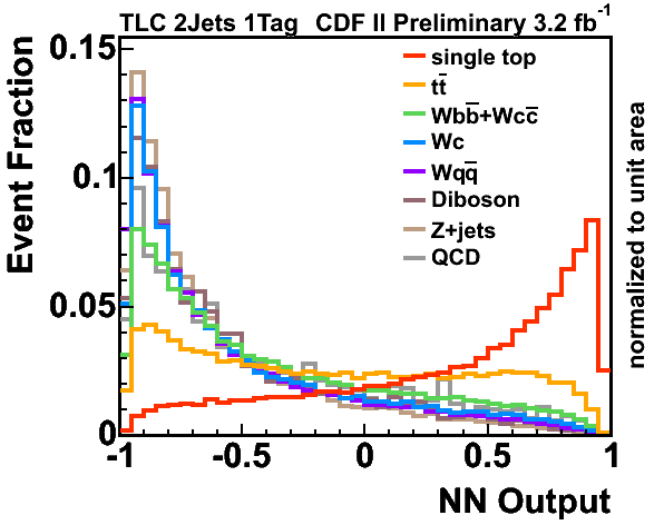

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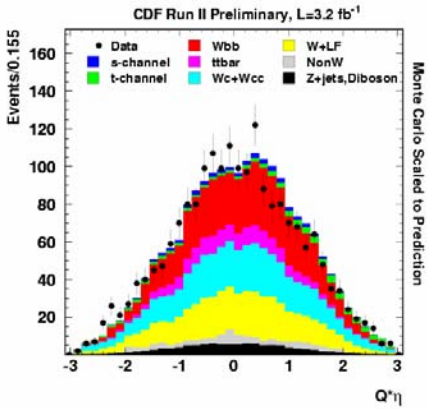

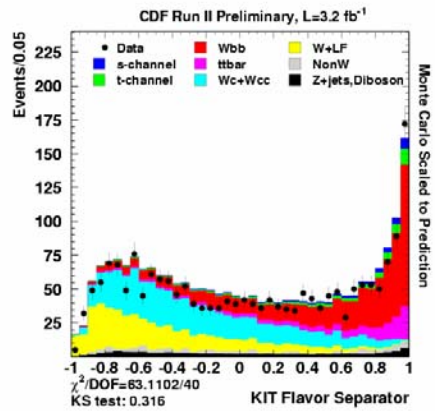

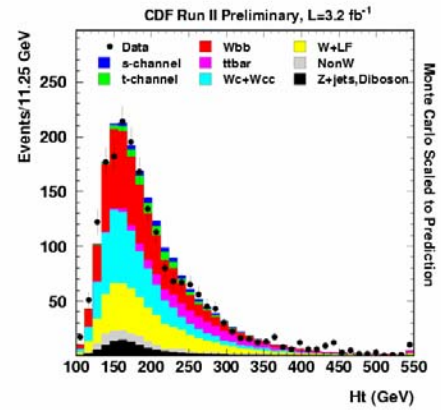

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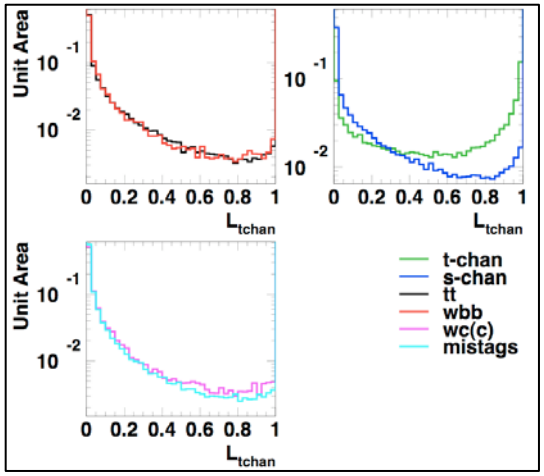
$$\mathcal{L}^{signal} = \frac{\prod_{i=1}^{n_{val}} P_i^{\text{signal}}}{\prod_{i=1}^{n_{val}} P_i^{\text{signal}} + \sum_{m=1}^{n_{bkg}} \prod_{i=1}^{n_{val}} P_i^m \times \alpha^m}$$



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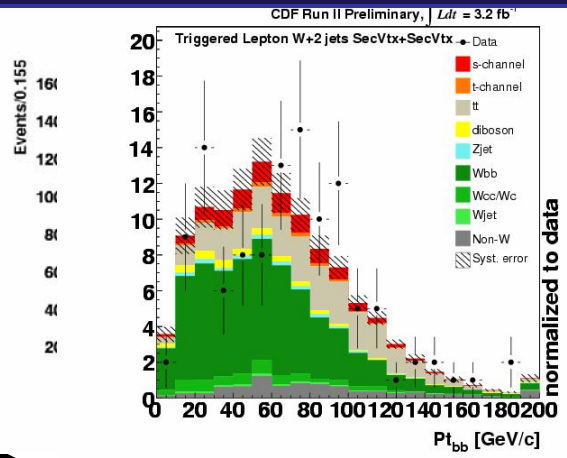

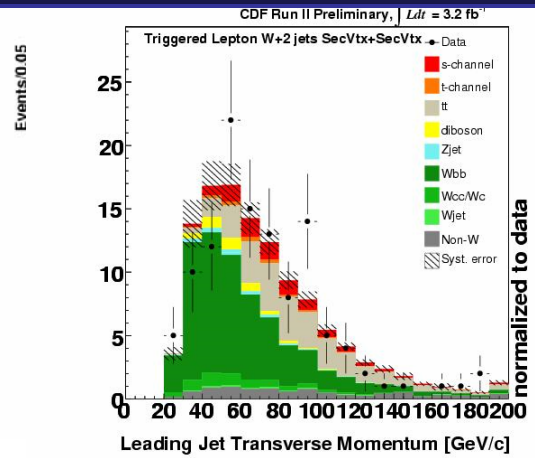

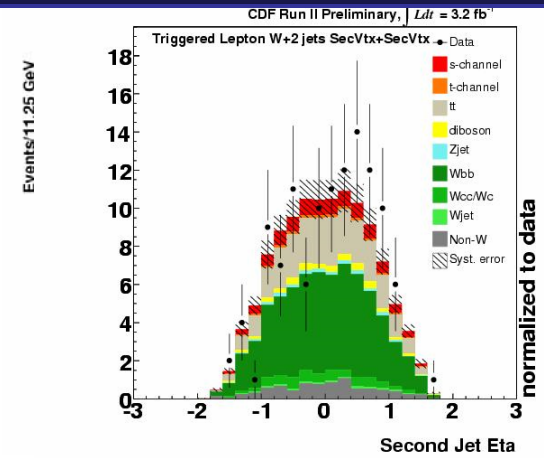

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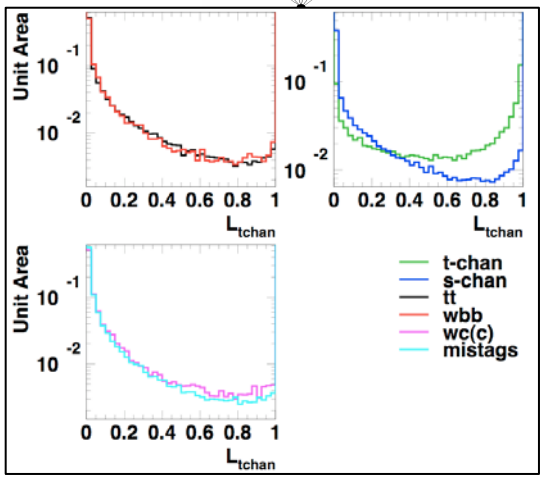

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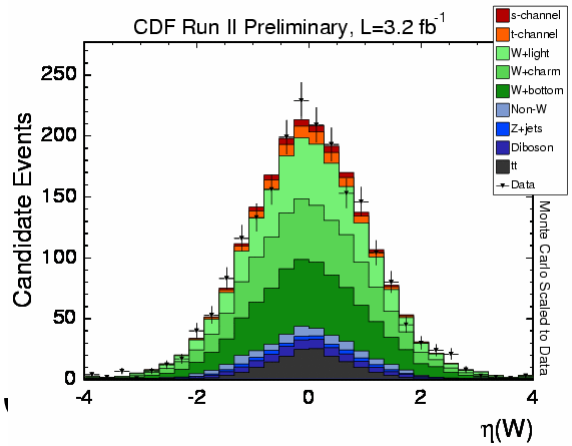

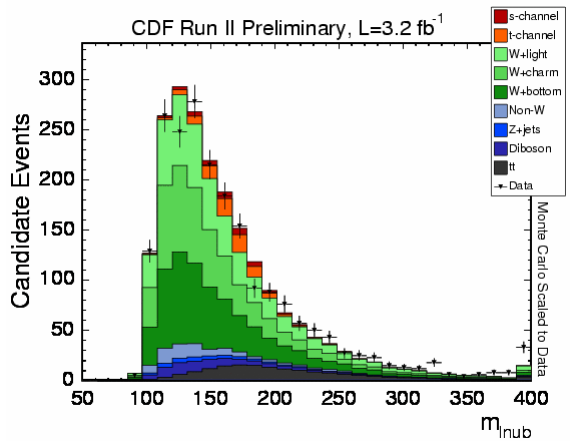

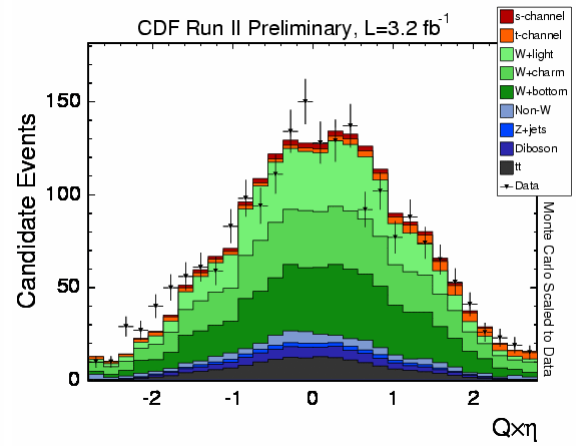

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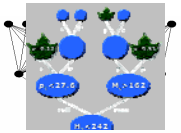

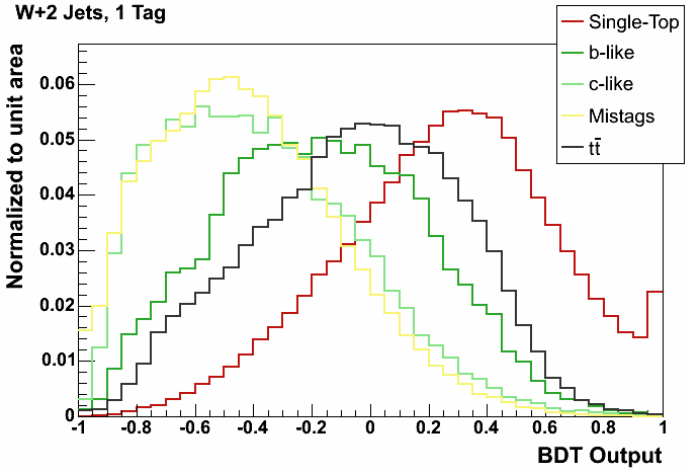

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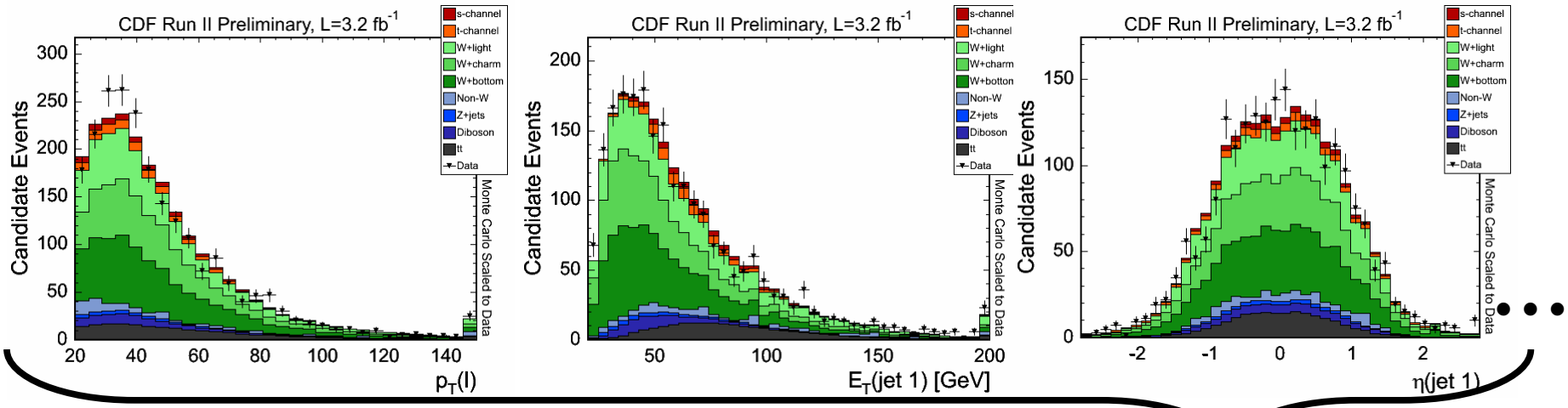

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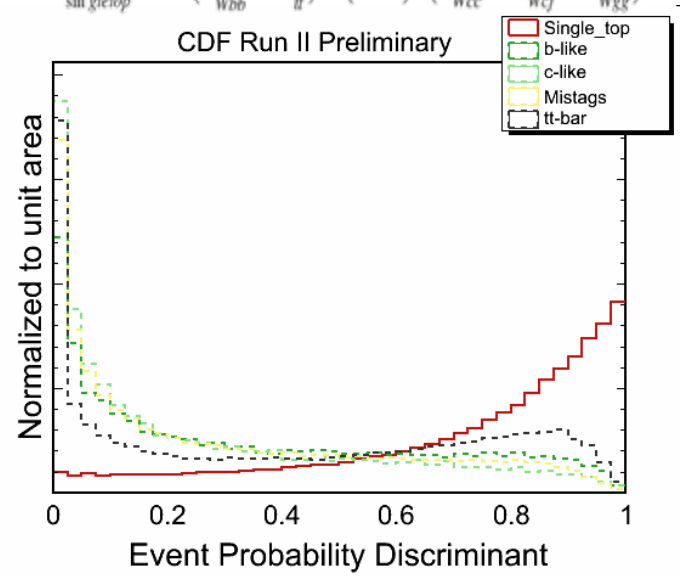
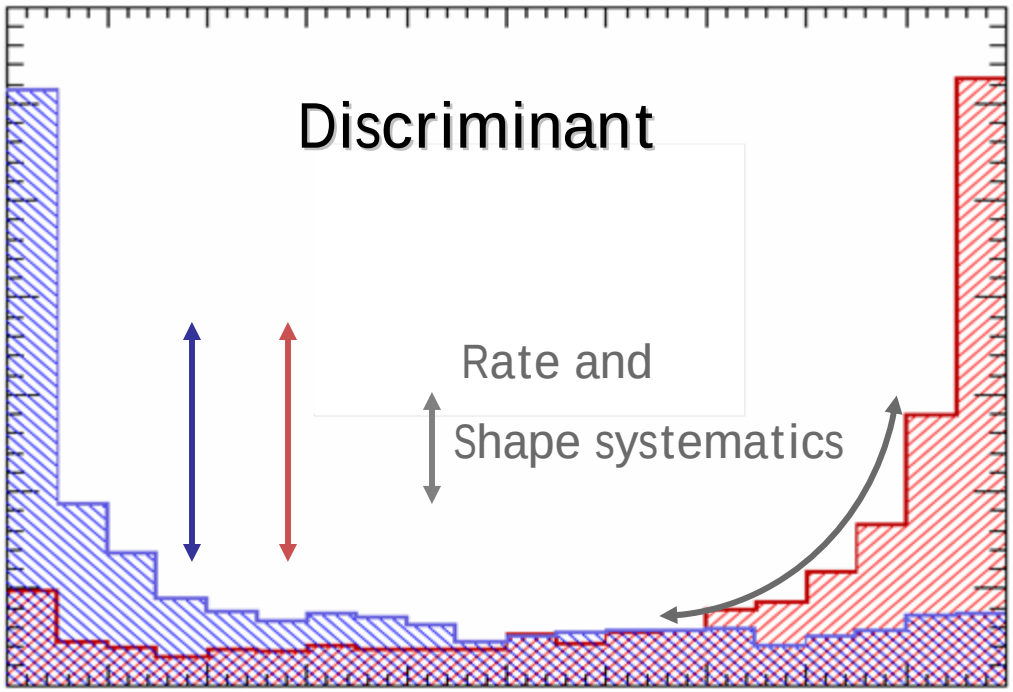


Binned Maximum Likelihood Fit

We perform binned maximum likelihood fit of templates to the data:

$$L(signal, bkg1..bkg4) = \prod_{k=1}^{B} \frac{e^{-\mu_k} \mu_k^{n_k}}{n_k!} \prod_{j=1}^{4} G(bkg_j \mid 1, \Delta_j)$$

Support wheels!



Systematic uncertainties can affect rate and template shape and are taken into account:

- Rate systematics give fit templates freedom to move vertically only
- Shape systematics allow templates to ‘slide horizontally’ (bin by bin)

Sources of Systematic Uncertainties

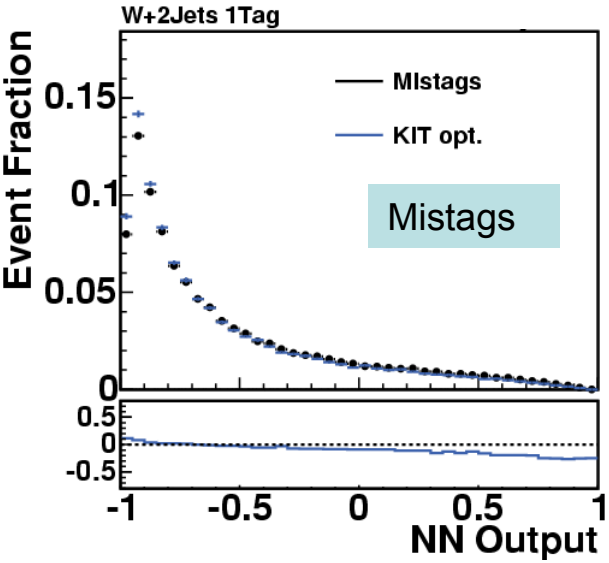
Systematic Uncertainty	Rate	Shape
Jet Energy Scale	0...10%	✓
Initial + Final State Radiation	0...15%	✓
Parton Distribution Functions	2...3%	✓
Monte Carlo Generator	1...5%	
Event Detection Efficiency	0...9%	
Luminosity	6%	
Neural Net B-tagger		✓
Mistag Model		✓
Q^2 scale in ALPGEN MC		✓
Input variable mismodeling		✓
Wbb+Wcc normalization	30%	
Wc normalization	30%	
Mistag normalization	17...29%	
ttbar normalization & m_{top}	23%	✓

Also, MC statistics treated as a source of systematic uncertainty in each bin independently

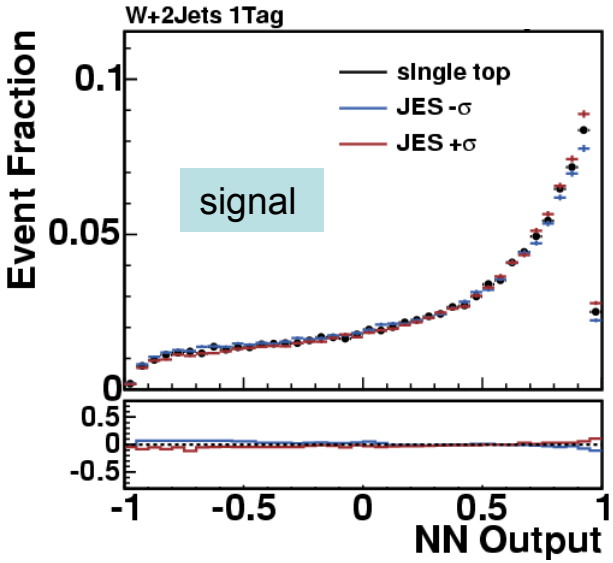
Largest uncertainty on background normalization

Template Shape Uncertainties

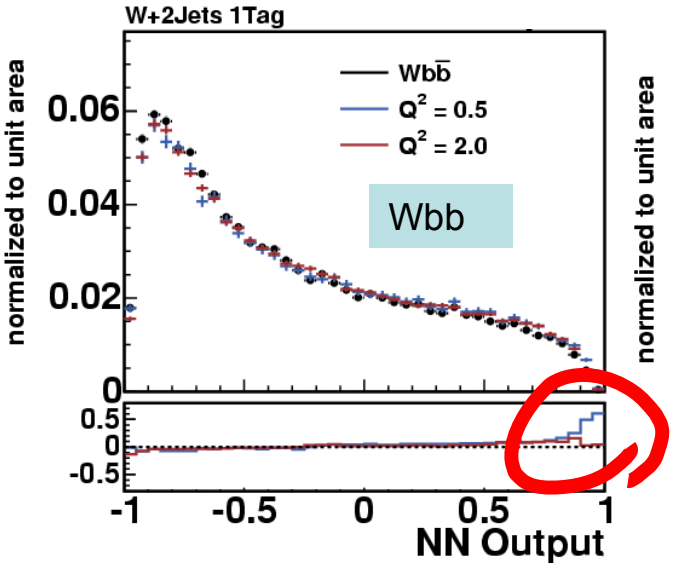
Flavor Separator



Jet energy scale



Factorization and renormalization scale



- A total of 370 shape uncertainties evaluated!
- Each template, each source of shape error, each channel (#tags, #jets, extended muon coverage)
- Shape uncertainties affect sensitivity - most are quite small but some appreciable

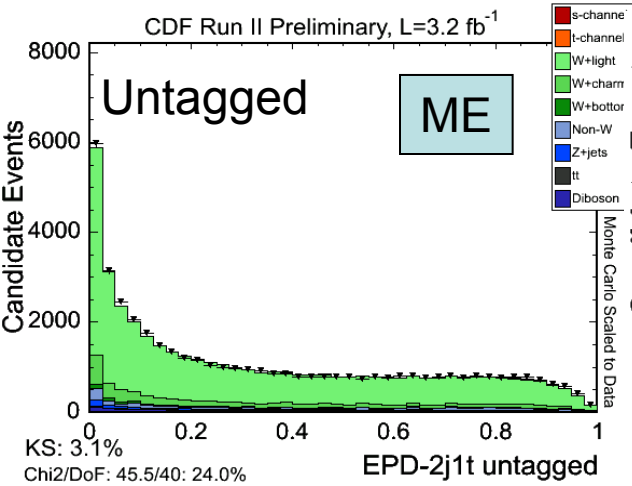
Blind Analysis

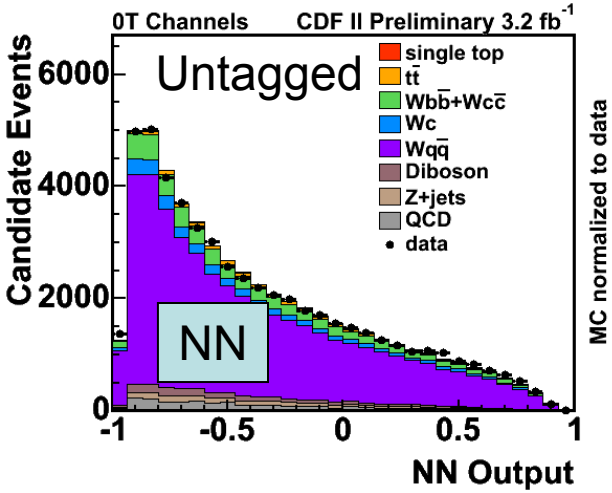
Note:

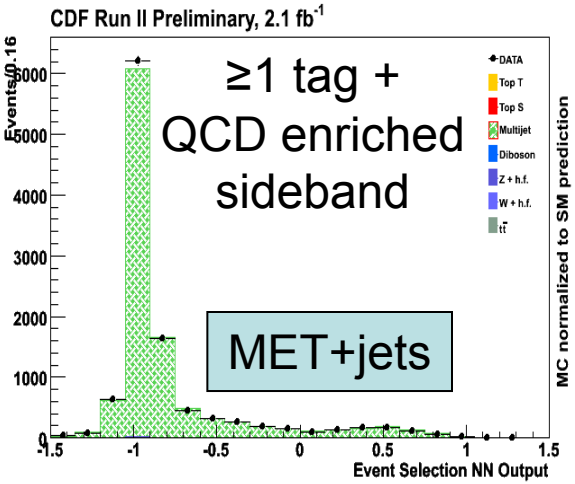
All measurements were performed with the discriminant distributions "blinded" until all aspects of the analysis were under control

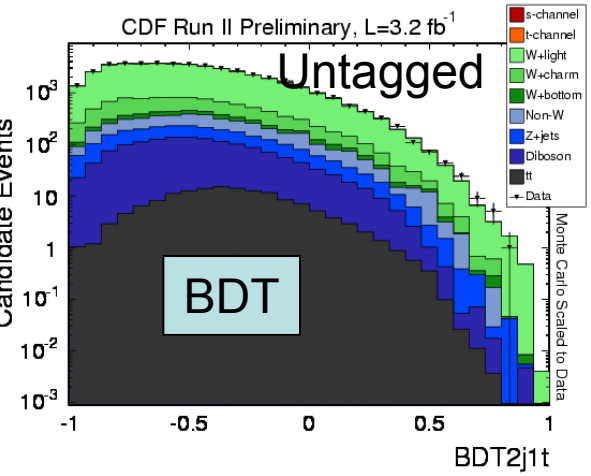
Sideband Cross Checks (many…)

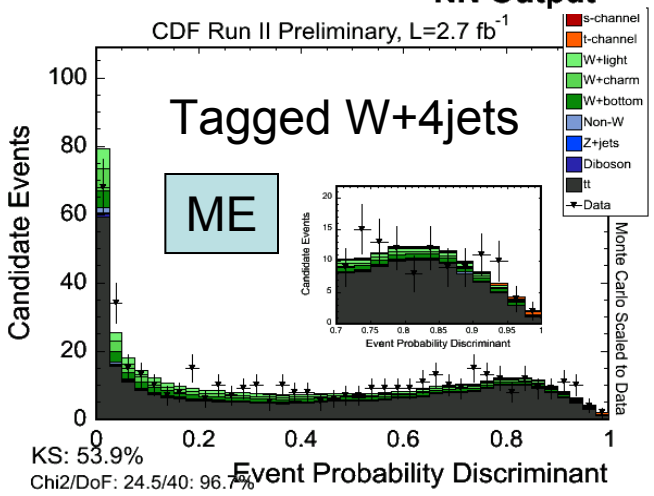
Extensive side band cross checks performed to check modeling before unblinding the signal region.

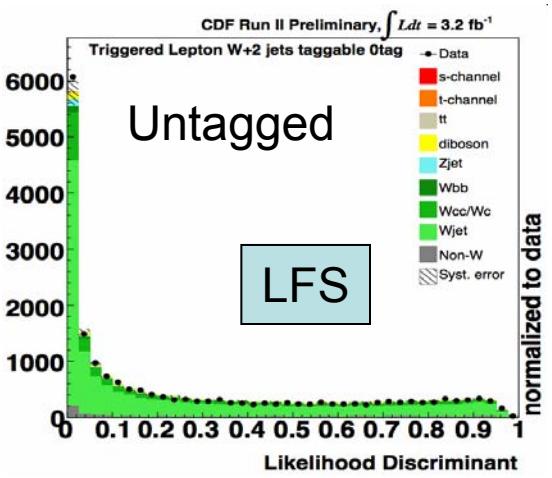










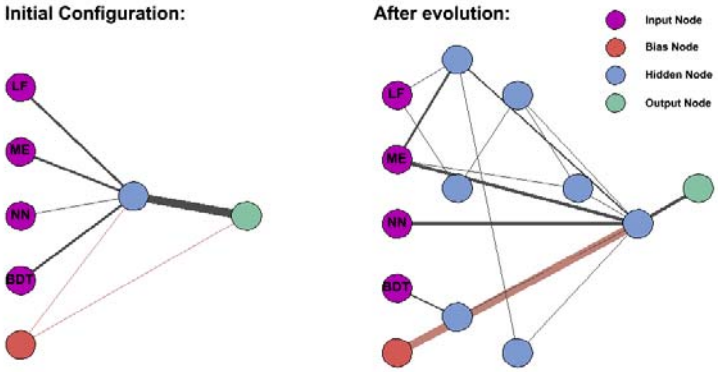


The Combination

Combine and conquer…

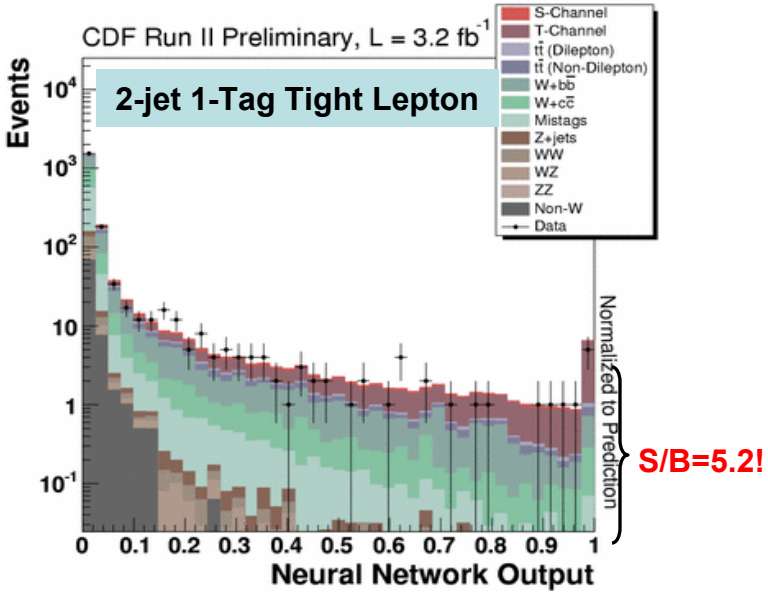
Combination Strategy

- Combination using "Super Discriminant" (SD)
  - Combine individual analyses into one, more powerful - use discriminant outputs as input to NN
  - Evolutionary neural networks trained to give the **best expected p-value**, not classification error function
  - Candidate networks compete with each other
  - Gained 13% over most sensitive input



Neuro-Evolution of Augmenting Topologies (NEAT)
K O. Stanley and R. Miikkulainen, Evolutionary Computation **10 (2)** 99-127(2002)

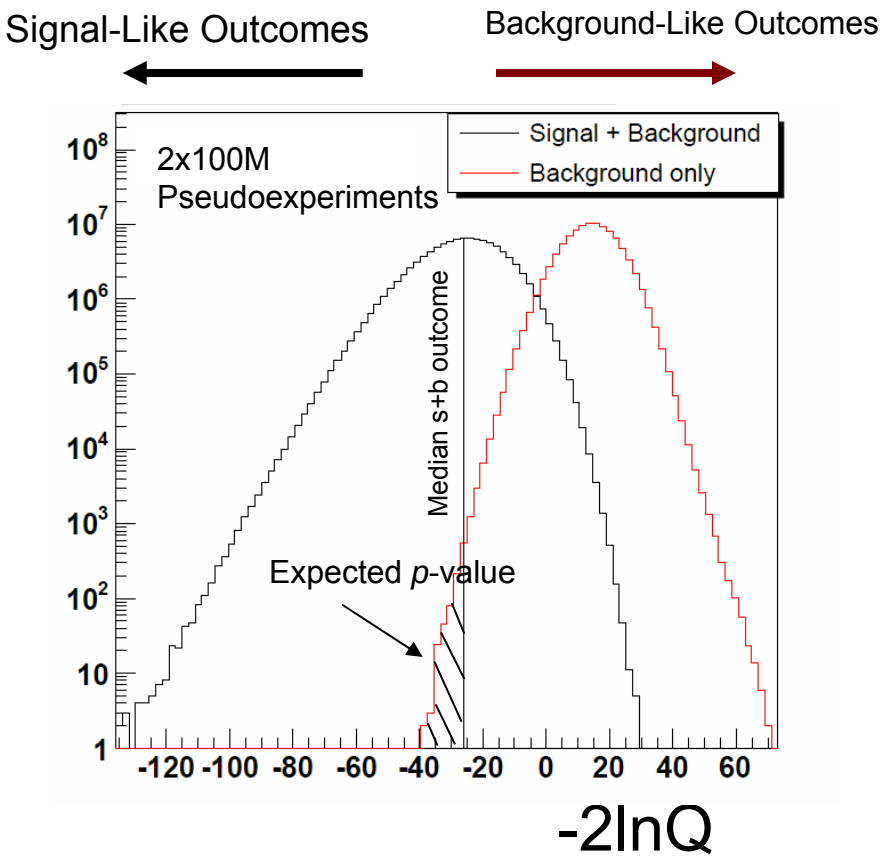
- Optimization of
  - Network topology
  - Inter-node weights
  - Output histogram binning



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

Hypothesis Testing: p-values

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



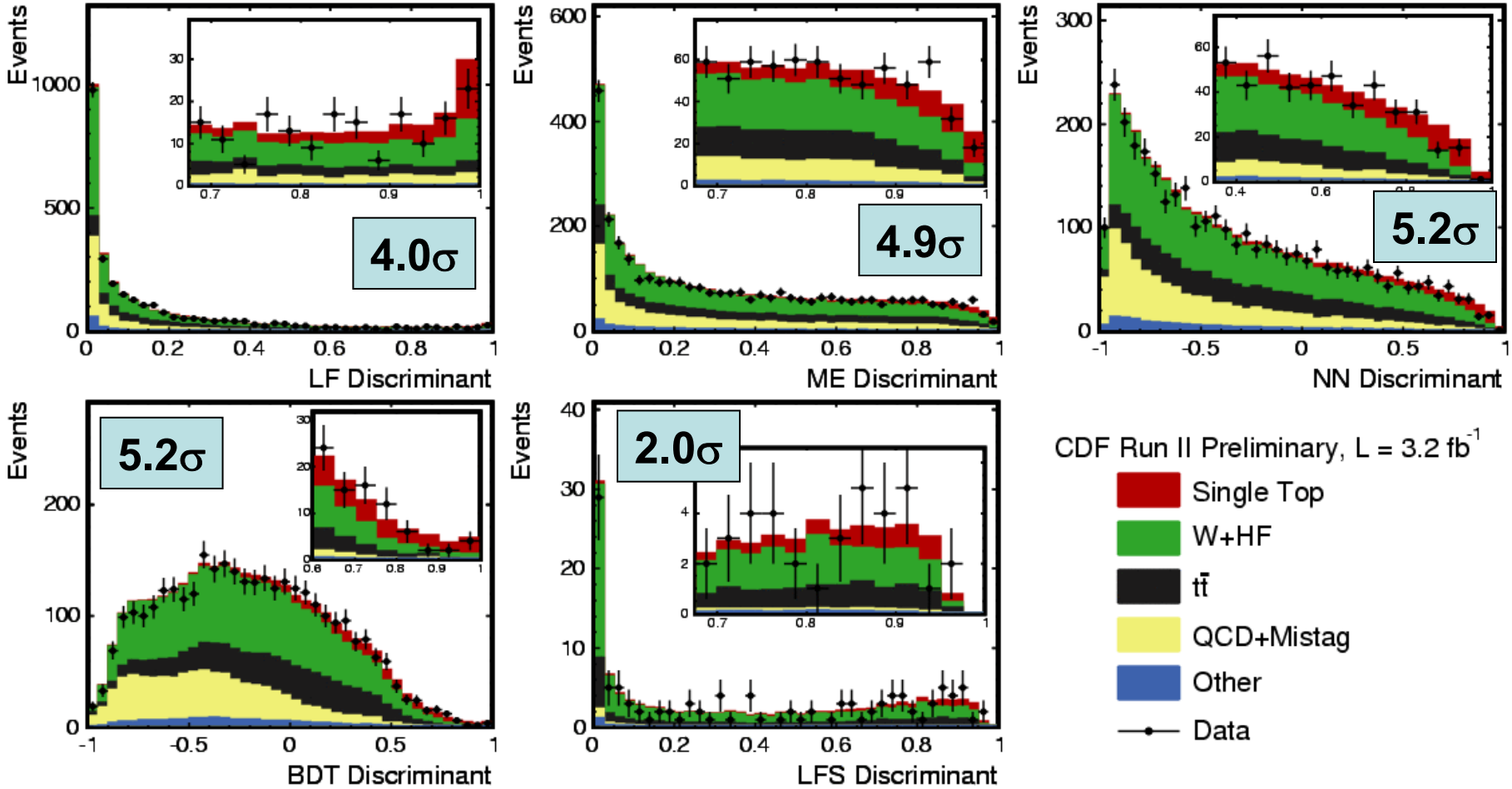
$$Q = \frac{P(\text{data} \mid s+b, \hat{\theta})}{P(\text{data} \mid b, \hat{\hat{\theta}})}$$

θ=nuisance parameters

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

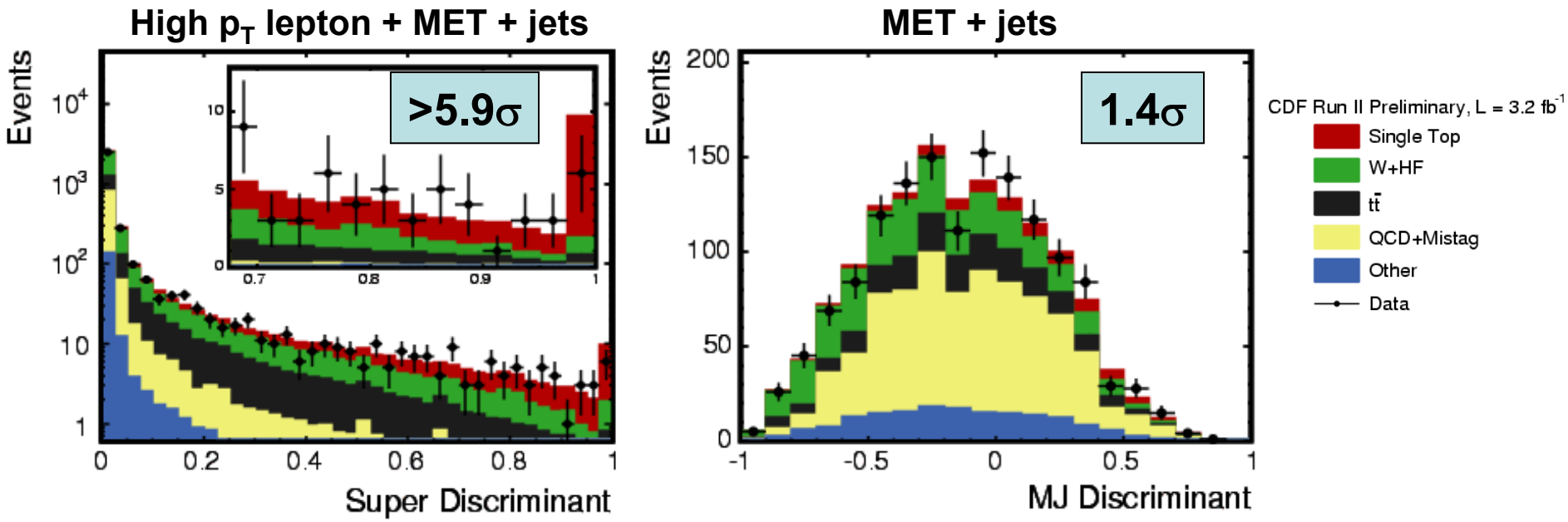
Fit for W+LF and W+HF scale factors. Fluctuate **all** nuisance parameters in Pseudo-experiments

Discriminants and expected Sensitivity



Discriminants normalized to prediction

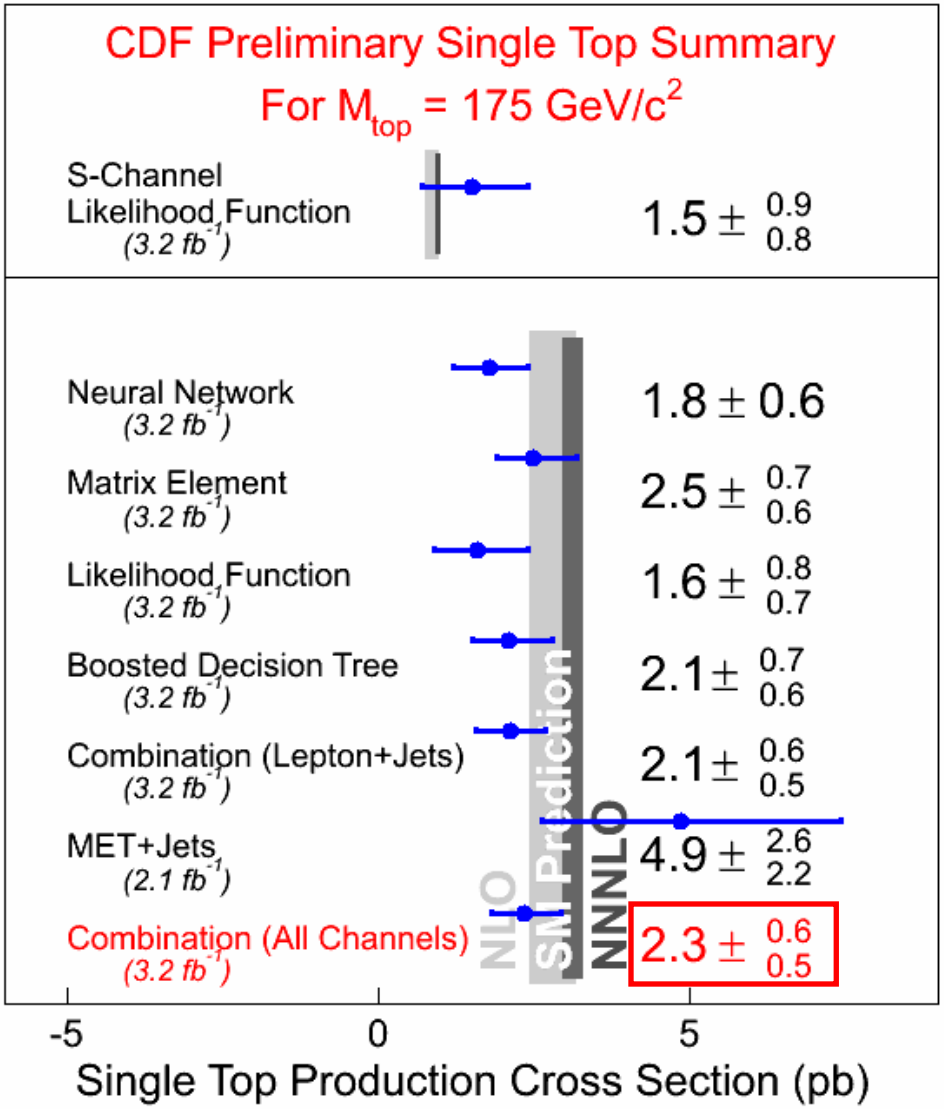
Combination



Perform combined cross section fit over the two orthogonal analyses (SD + MJ)

The Results

Cross Section

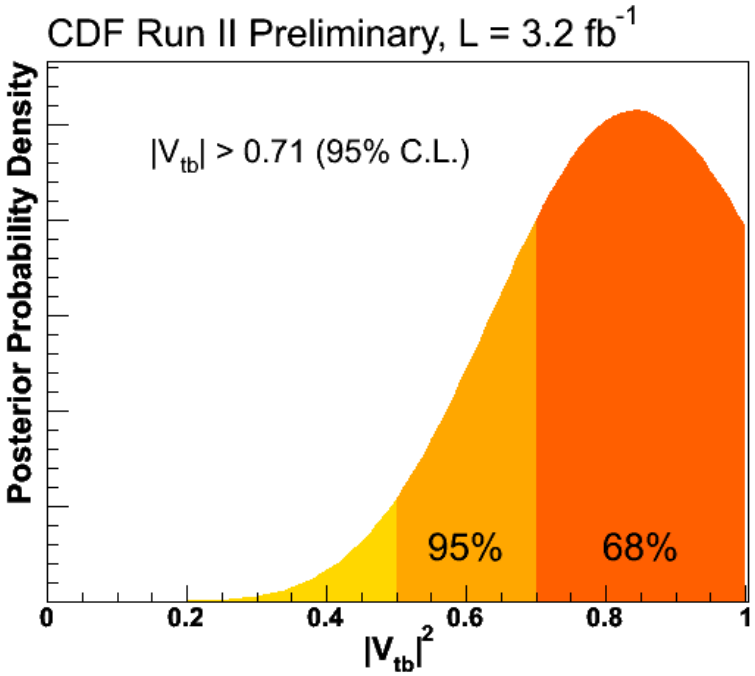


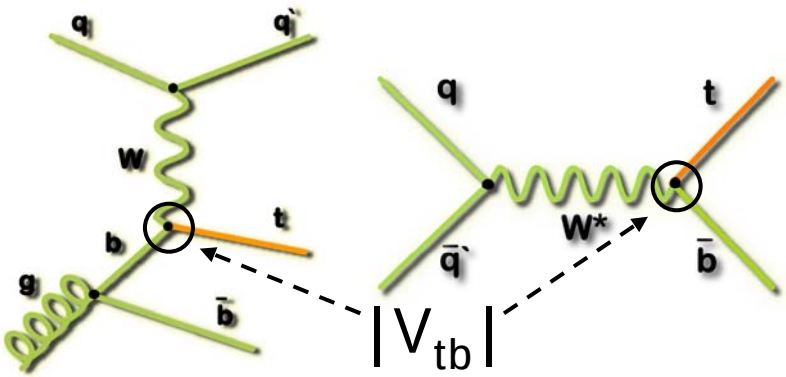
also recently NLO t-channel 2→3
Campbell et. al. hep-ph 0903.0005

Direct $|V_{tb}|$ Measurement

- Using cross section result measure $|V_{tb}|$
- Assume Standard Model (V-A) coupling and $|V_{tb}| >> |V_{ts}|, |V_{td}|$ (from BR(t →Wb) measurements)

$$|V_{tb,meas}|^2 = \frac{\sigma_{meas}}{\sigma_{SM}} \cdot |V_{tb,SM}|^2$$





CDF combined fit:

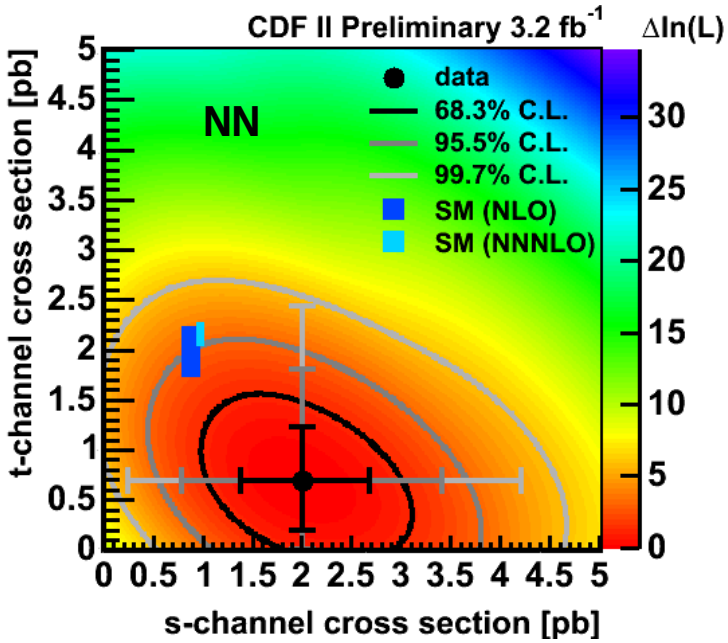
$|V_{tb}|>0.71$ at 95% C.L.

Z. Sullivan, Phys.Rev. D70 (2004) 114012

$|V_{tb}| = 0.91 \pm 0.11$ (stat+syst) ± 0.07 (theory)

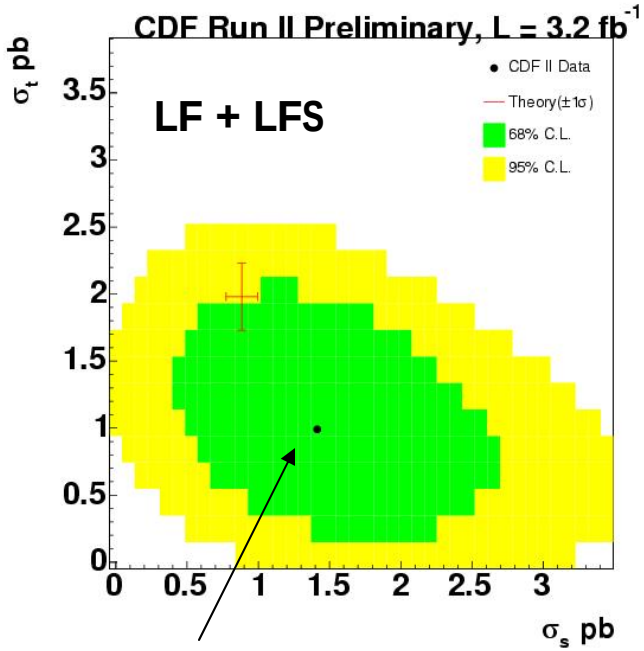
Two Dimensional Interpretation

- Measure σ_s and σ_t separately
- Interesting because s- and t-channels have different sensitivity to BSM models
- Train dedicated s-channel and t-channel discriminants and fit 2D



$$\sigma_s = 2.0^{+0.7}_{-0.6}\ \text{pb}$$

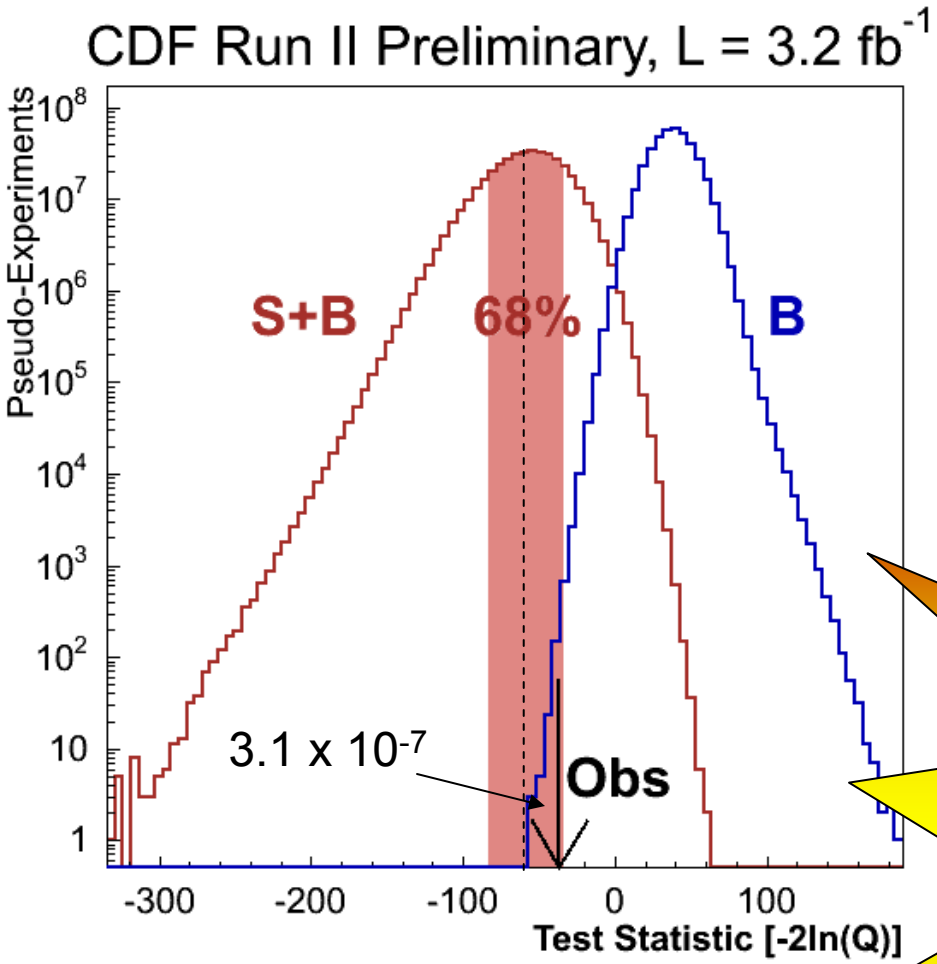
$$\sigma_t = 0.7^{+0.5}_{-0.5}\ \text{pb}$$



σ_s= 1.4 pb

σ_t= 0.98 pb

Significance



Analysis	Significance Std.Dev. (σ)	Sensitivity Std.Dev. (σ)
NN	3.5	5.2
ME	4.3	4.9
LF	2.4	4.0
LFS	2.0	1.1
BDT	3.5	5.2
SD	4.8	>5.9
[illegible]	2[illegible]	[illegible]4
Com[illegible]		[illegible]5.9

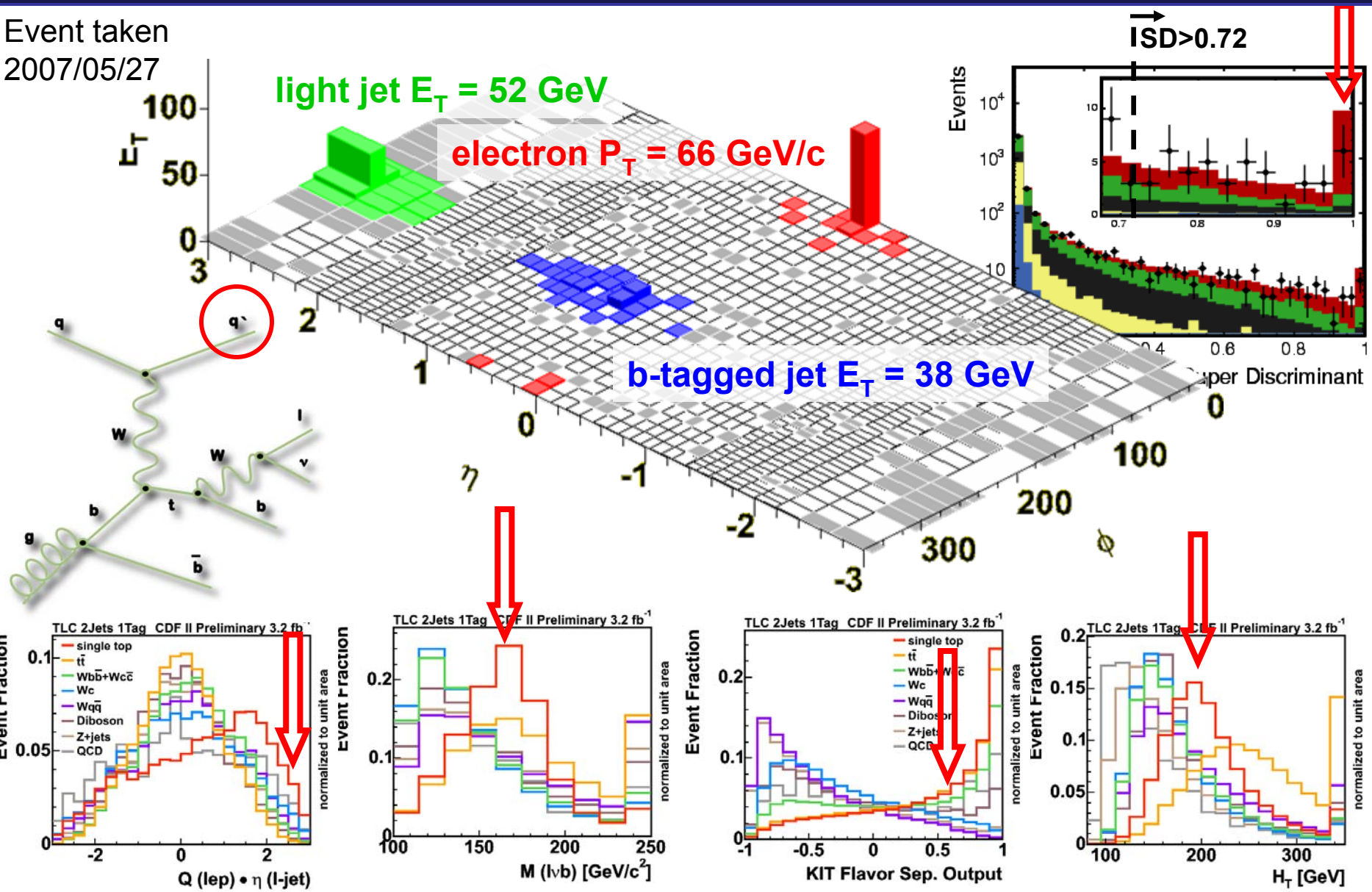
5σ Observation!

Expected p-value : xxx x10 $^{-10}$: >5.9σ
Observed p-value: 3.1 x10^{-7} : 5.0σ

400 Mio pseu[illegible]nts
(130,0[illegible] CPU

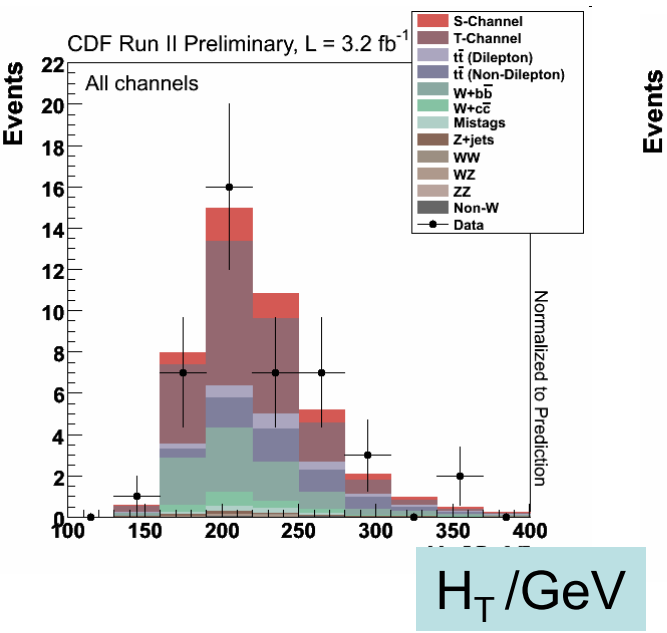
A Golden Event

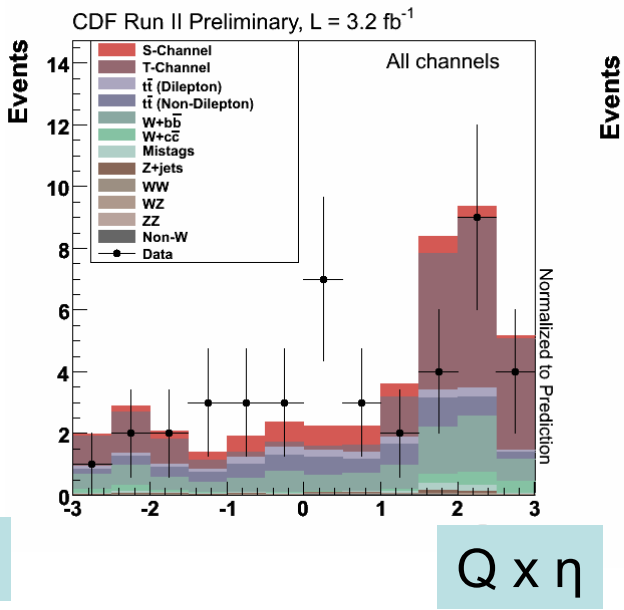
Event taken
2007/05/27

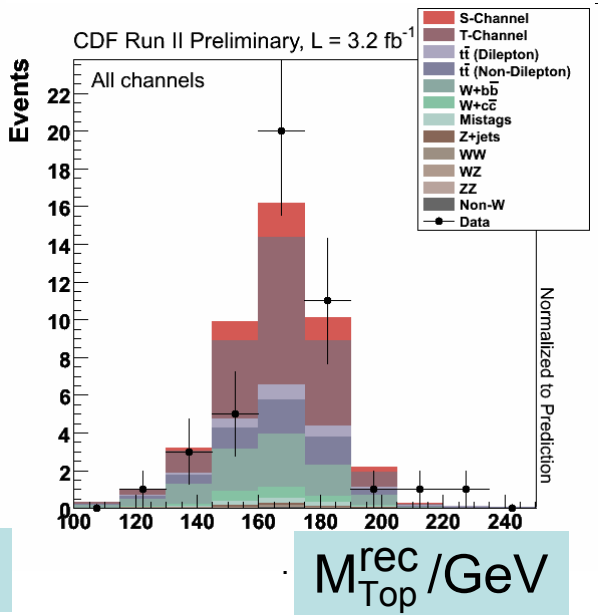


Signal Features

SD>0.72







Purity S/B ~ 1.2

The Conclusions

The Tevatron, 14 years after the top-quark discovery,
has again …

...reached to the...

..with another...
...discovery!
Artwork by Jan Lueck

Conclusions

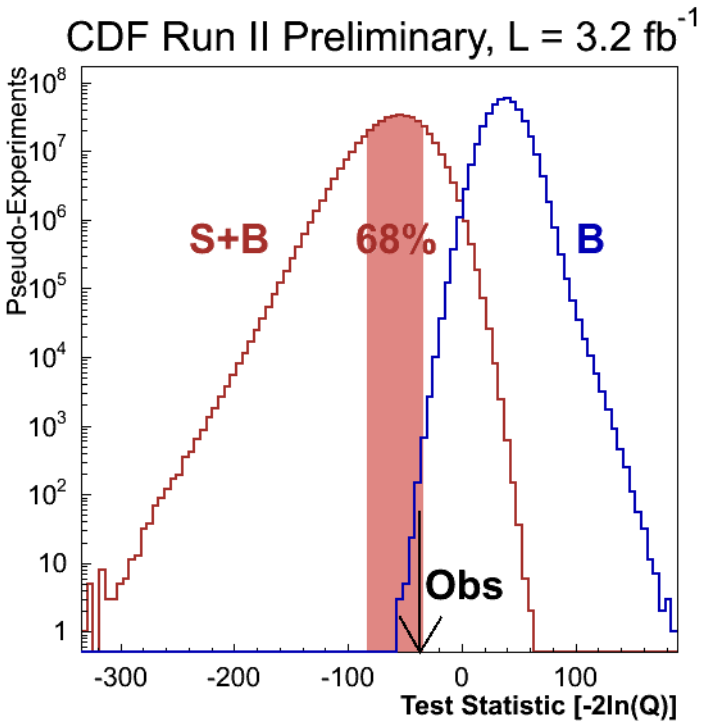
- We report Observation (5σ) for electroweak single top quark production at CDF
  - Important Milestone in Run II
  - direct measurement of the CKM matrix element
    $|V_{tb}|=0.91 \pm 0.11$ (stat+syst) ± 0.07 (theory)
- Advanced analysis tools essential to establish small signals buried underneath large backgrounds
  - We developed and applied new experimental tools
- Future of this measurement:
  - top polarization
  - precise measurements of σ_t and σ_s
  - $\delta|V_{tb}|$(experimental) ~ $\delta|V_{tb}|$(theory) feasible in Run II
- Important milestone along the way to the Higgs!
  - All Standard Model backgrounds for Higgs searches are now firmly established

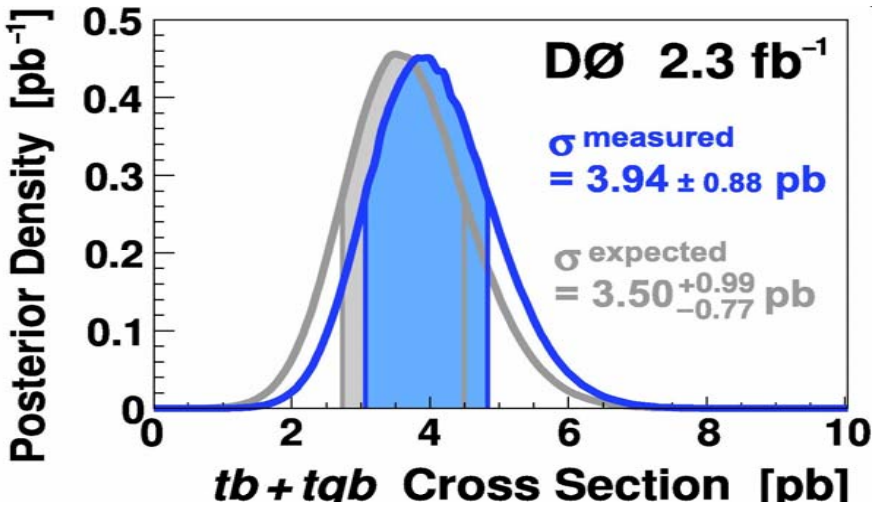
Exciting times! The race for the Higgs Boson is on!

Party at User's Center
at 5pm by invitation
of the CDF and D0 top
groups!
Thank you, Fermilab!
Artwork by Jan Lueck

Backup

Tevatron Results





The measured cross section is

$$\sigma(p\bar{p} \to tb + X, tqb + X) = 3.94 \pm 0.88 \text{ pb}$$

The most probable value of the combined s-channel and t-channel cross sections is $2.3^{+0.6}_{-0.5}$ pb assuming a top quark mass of 175 GeV/c^2. The dependence on the top quark mass is +0.02 pb/(GeV/c^2). From the cross

M_{top}= 170 GeV/c^2