# Single Top Quark Production at CDF

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On behalf of the CDF Collaborations


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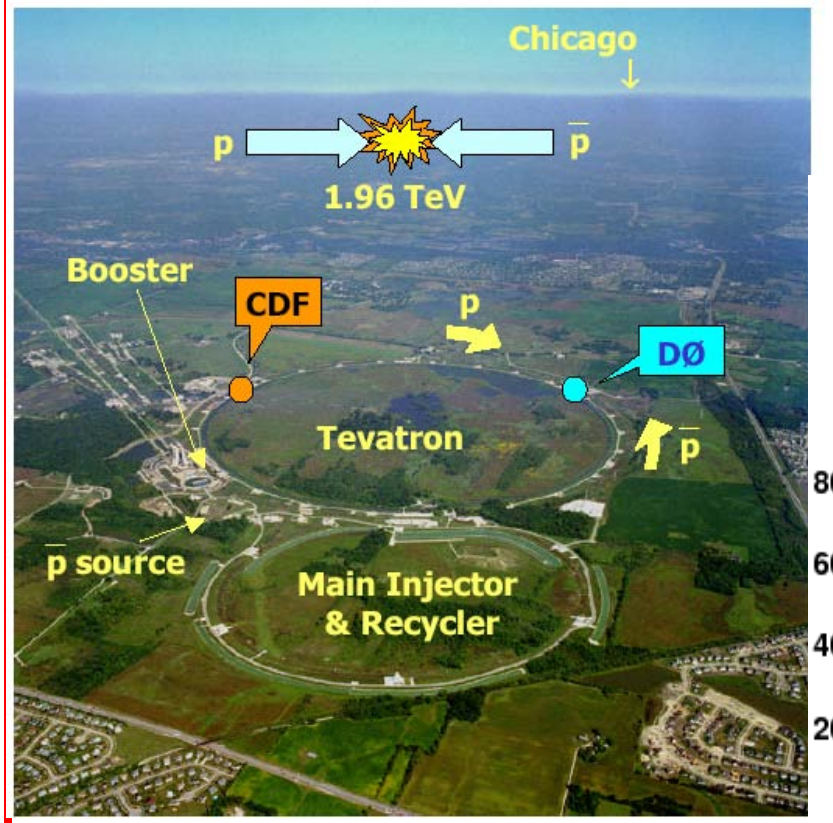
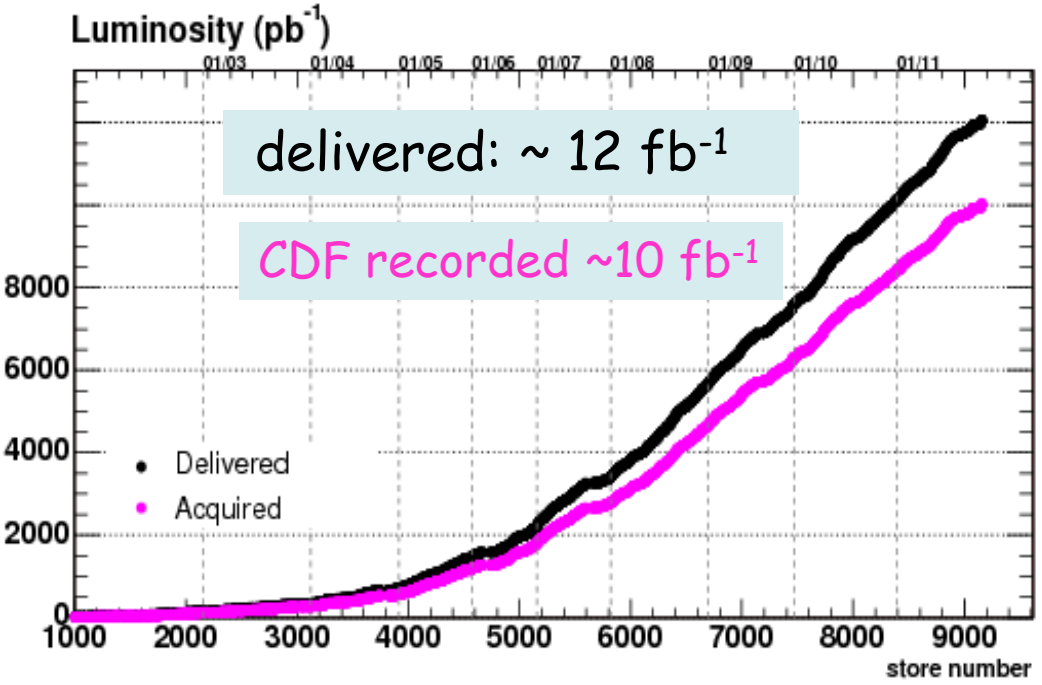
Istituto Nazionale di Fisica Nucleare

# The Tevatron and CDF




**Run II: $\sqrt{s}$ = 1.96 TeV**

Tevatron stopped providing collisions on september 30, 2011




Tevatron was the birthplace of the top quark, observed in 1995 (Tevatron Run I) by CDF and D0

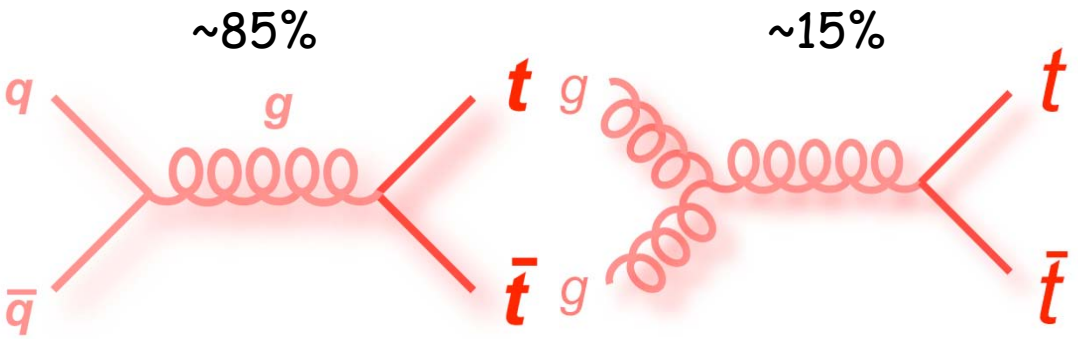
# Top Quark Production at Tevatron

- QCD pair production
- First observed at Tevatron in 1995

PRL 74 2626 (1995) , PRL 74 2632 (1995)

$\sigma_{SM} = 7.35^{+0.28}_{0.33}$ pb

(for $m_{Top}$= 173 GeV)
(PRL 110, 252004 (2003))



# Top Quark Production at Tevatron

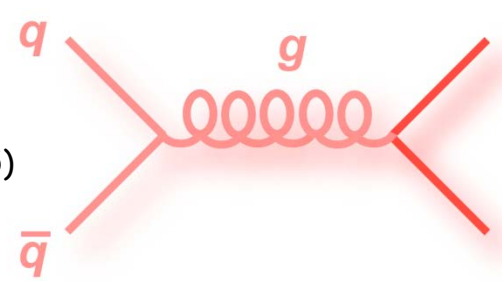
- **QCD pair production**
- First observed at Tevatron in 1995

PRL 74 2626 (1995) , PRL 74 2632 (1995)

$\sigma_{SM} = 7.35^{+0.28}_{0.33}$ pb

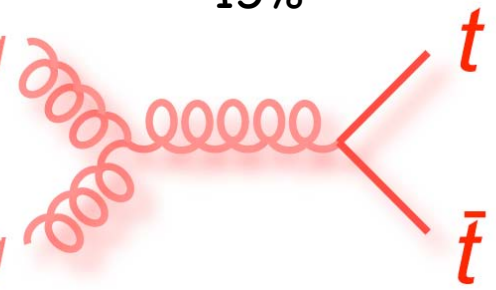
(for $m_{Top}$= 172.5 GeV)
(PRL 110, 252004 (2003))

~85%




Dominant process at Tevatron

~15%




Dominant process at LHC

- **EWK single-top production**
- first observed at Tevatron in 2009

PRL 103 092001 (2009), PRL 103 092002 (2009)

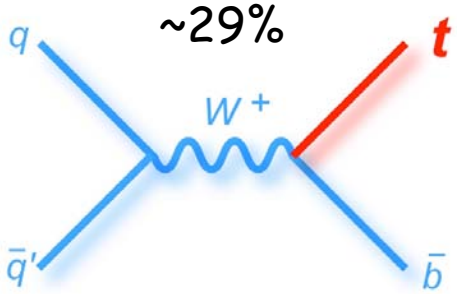
- s-channel: $\sigma_{SM} = 1.06 \pm 0.06$ pb
- t-channel: $\sigma_{SM} = 2.1 \pm 0.1$ pb

(for $m_{Top}$= 172.5 GeV)

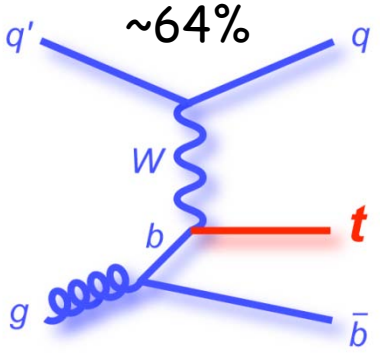
PRD 83, 091503 (2011)
PRD 81, 054028 (2010)
PRD 82, 054018 (2010)
arxiv:1210.7813.

Dominant modes at Tevatron:

s-channel ~29%




t-channel ~64%

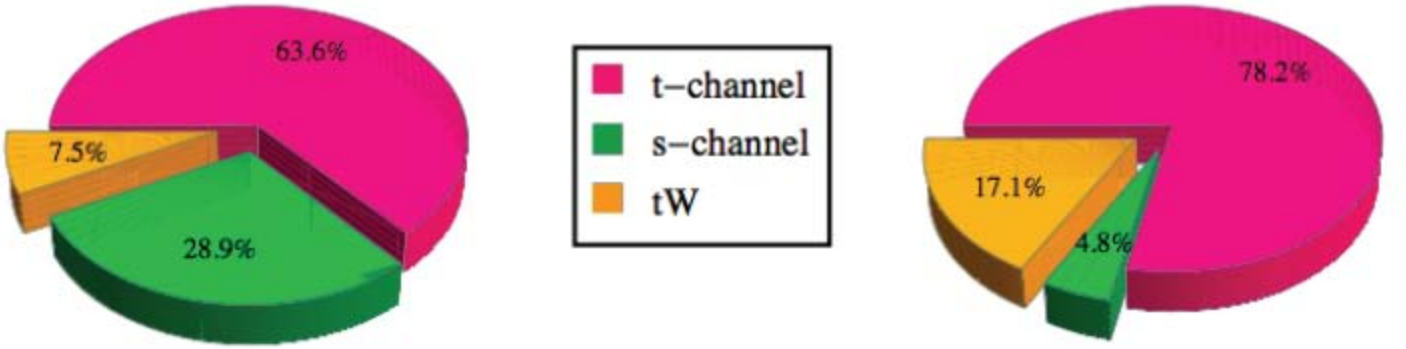



- Single top associated production Wt: $\sigma \sim 0.25$ pb, too small at the Tevatron

# Single top production: Tevatron versus LHC

- Tevatron and LHC are both sensitive to t-channel
- Tevatron is not sensitive to Wt production but has an advantage in s-channel

**Tevatron: $\sigma_{tot}$ = 3 pb** **LHC: $\sigma_{tot}$ = 114 pb @ 8 TeV**

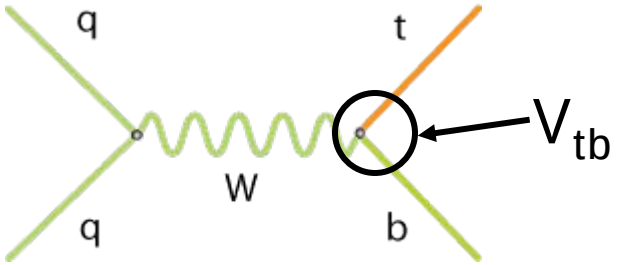



| Cross section(pb) | $t\bar{t}$ | $s$-channel | $t$-channel |
|---|---|---|---|
| Tevatron(1.96 TeV) | 7.08 | 1.05 | 2.08 |
| | ×33 | ×5.3 | ×42 |
| LHC(8 TeV) | 234 | 5.55 | 87.2 |

(N. Kidonakis, arXiv:1210.7813)

# Why measure Single Top Production ?

- $\sigma_{\text{single top}} \propto |V_{tb}|^2$
- Give access to the W-t-b vertex
  - $\Rightarrow$ probe V-A structure
  - $\Rightarrow$ access to top quark spin
- Allows direct measurement of Cabibbo-Kobayashi-Maskawa (CKM) matrix element $|V_{tb}|$:




Direct measurements

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Ratio from Bs oscillations

Not precisely measured
Inferred using unitarity

# Why measure Single Top Production ?

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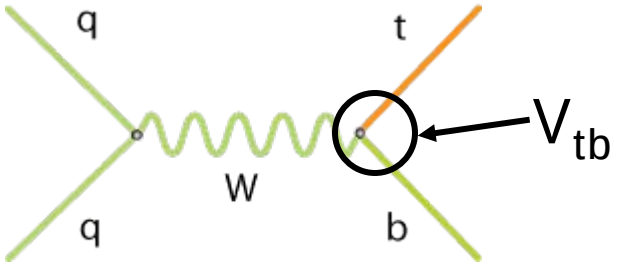



- Allows direct measurement of Cabibbo-Kobayashi-Maskawa (CKM) matrix element $|V_{tb}|$:
  - ⇒ Is this Matrix 3x3 ?
  - ⇒ Is there a 4th generation ?
  - ⇒ Does unitarity hold ?

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

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

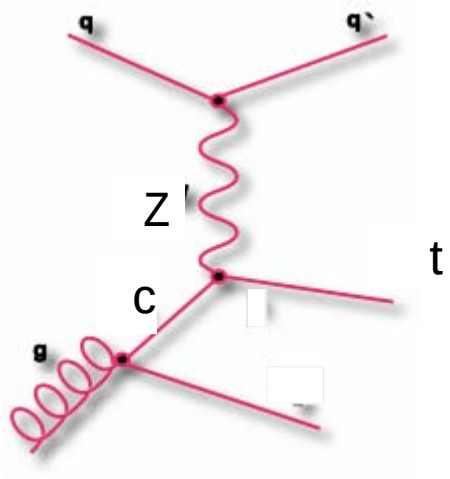
- Precision electroweak measurements rule out "simple" fourth generation extensions, but see for example:

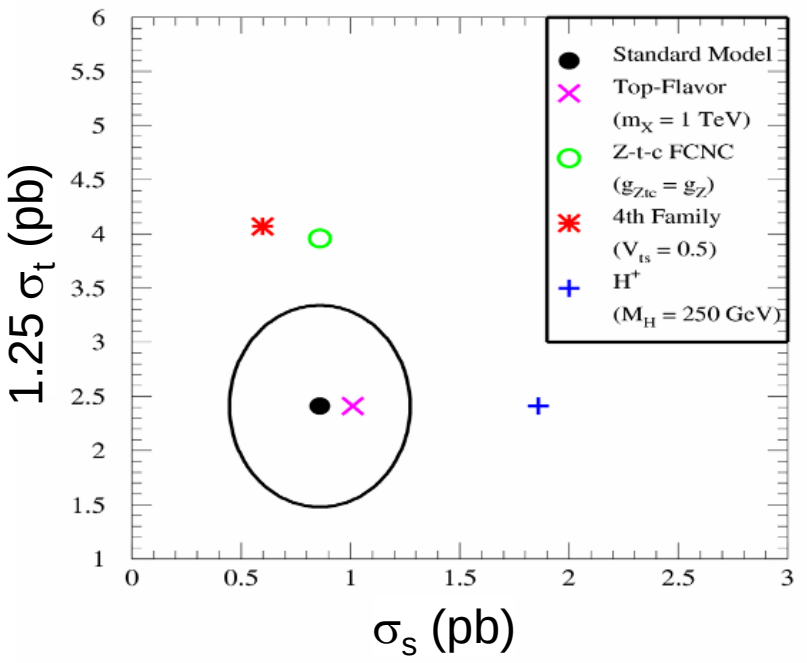
  J. Alwall et. al., "Is $|V_{tb}|$~1?" Eur. Phys. J. C49 791-801 (2007).

# Sensitivity to New Physics

- New physics may affect the rate of t and s channel differently

t-channel

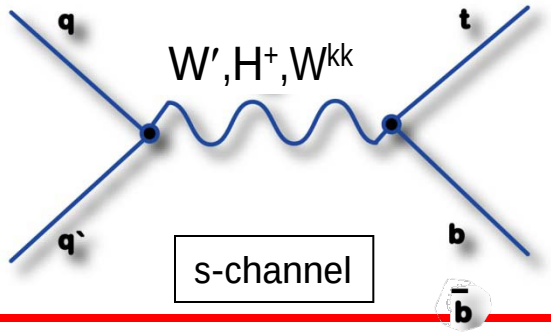



T. Tait, CP Yuan PRD63, 014018 (2001)

- Flavor changing neutral currents (t-Z-c, t-γ-c, t-g-c)

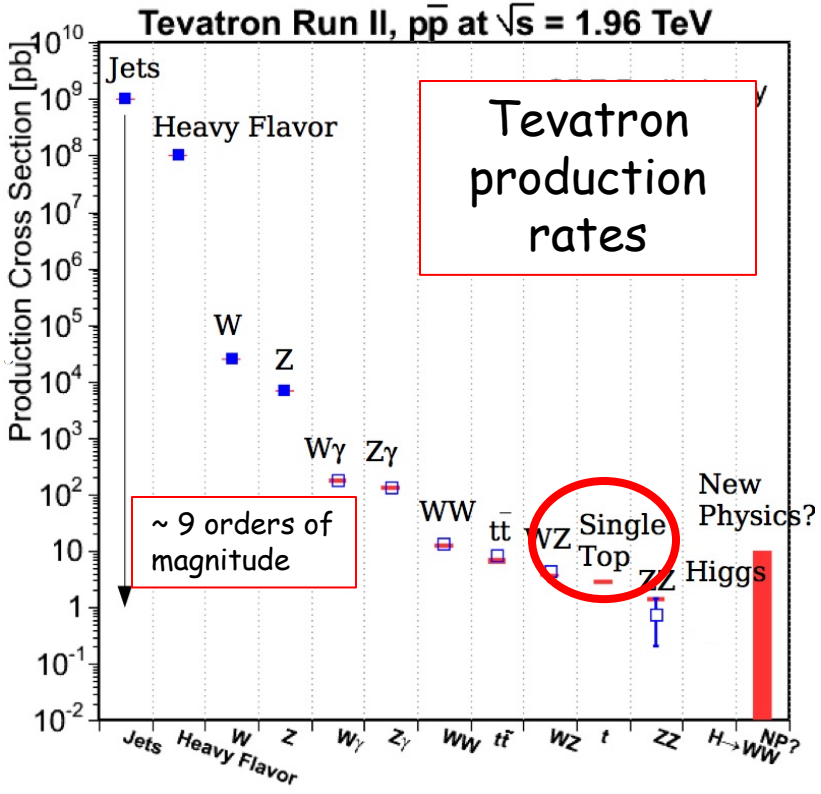
- heavy W′ boson
- charged Higgs $H^+$
- Kaluza Klein excited $W^{kk}$



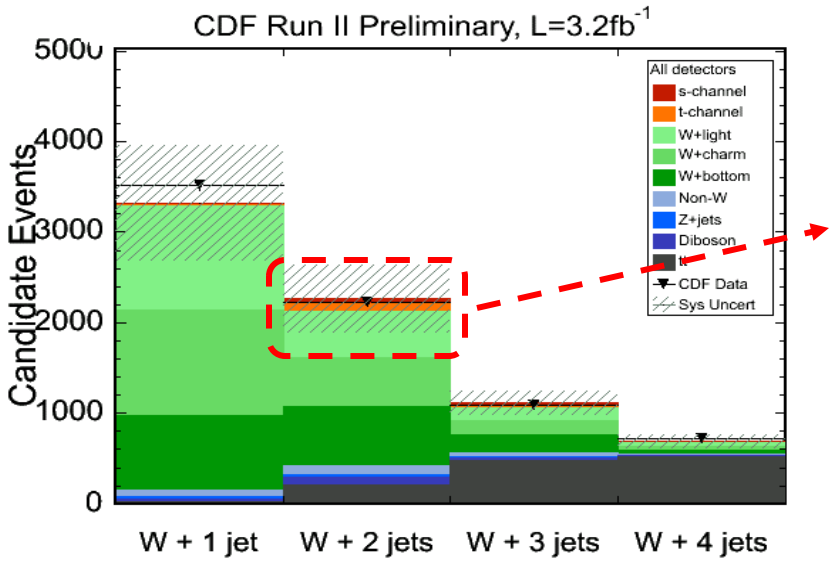

s-channel

# The Challenge

- Single Top observation came 14 years after top discovery….
  - ⇒ Single Top production is a rare process at the Tevatron: S/B ~ 1: $10^9$ before any selection
  - ⇒ not an easy measurement
- First step:
  - ⇒ Trigger on high $P_T$ leptons/MET
  - ⇒ Improves S:B by ~ $10^6$
- Second step:
  - ⇒ Topological event selection
  - ⇒ Efficient *b*-jet selection
  - ⇒ Careful background estimates → average S/B ~1/20



# The Challenge (2)




Single top top quark production with decay into Lepton + 2 Jets final state hidden behind large backgrounds with large uncertainties (i.e. W+HF uncertainty ~ 30%)
⇒ Makes counting experiment impossible!

- Third step: no single variable provides sufficient signal-background separation:

⇒take advantage of small signal-background separation in many variables

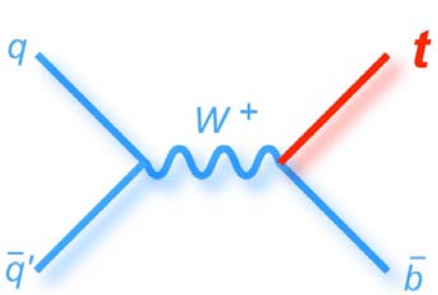
⇒Perform multivariate analysis (MV)

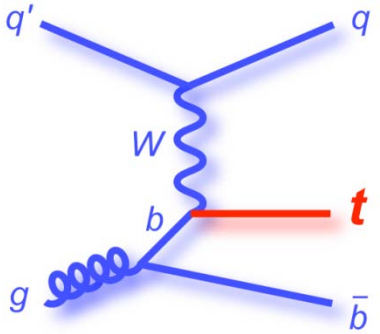
⇒ Multiple variables combined into a single more powerful discriminant to separate S from B

⇒ analyses shown here use artificial NN techniques

# Event Selection

- In the SM top quark decays most of the times to Wb
- (1) W + 2 or 3 energetic jets selection
  - ⇒ One high $p_T$ isolated lepton (e or $\mu$) from the decay of the W
  - ⇒ Large missing transverse energy, MET , from the neutrino
  - ⇒ At least one jet identified as "b" jet



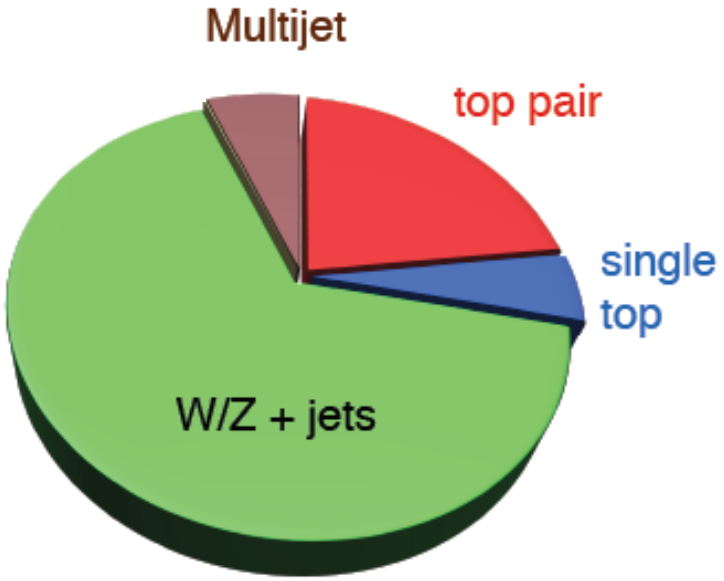




- (2) MET + jets Selection
  - ⇒ MET > 35 GeV
  - ⇒ Veto leptons
  - ⇒ 2 or 3 energetic jets
  - ⇒ At least one jet identified as "b" jet

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

# Background Modeling

- W + jets
  - ⇒ Normalization and flavor composition from data
  - ⇒ Shape from simulation
- Diboson, Z+jets from simulation
- top pair production
  - ⇒ normalization to NNLO
  - ⇒ Shape from Alpgen
- QCD multijet production
  - ⇒ Normalization from data
  - ⇒ Shape from data

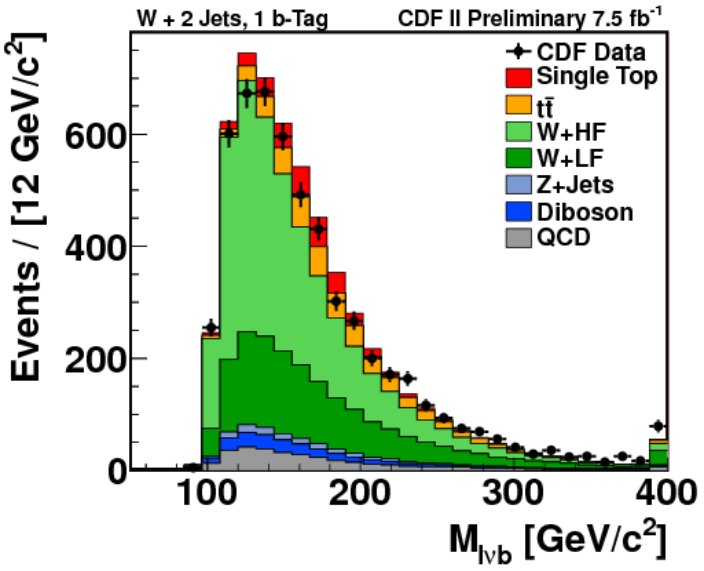


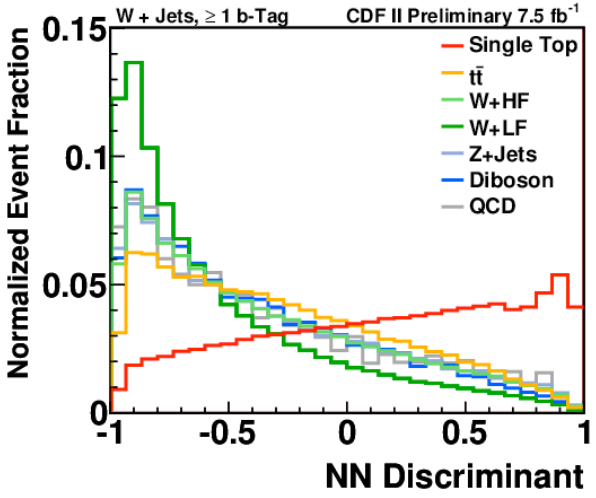

CDF 7.5 fb$^{-1}$

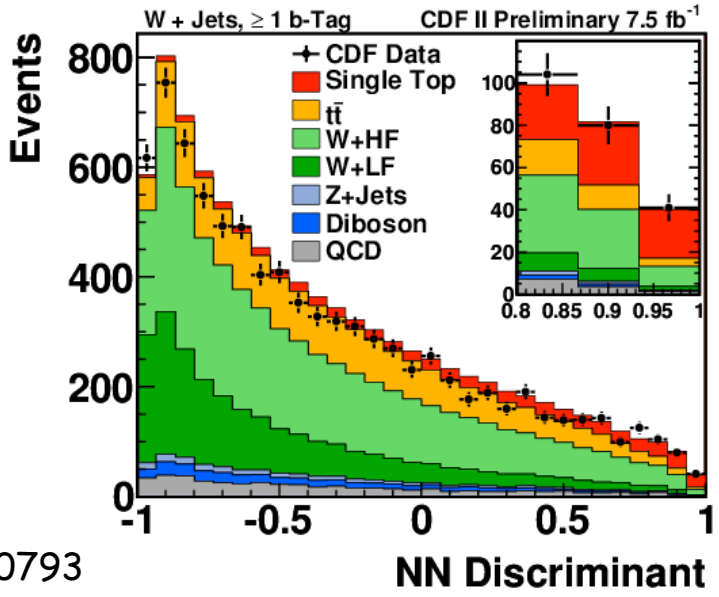
| Process | 2 jets 1 b-tag | 3 jets 1 b-tag | 2 jets 2 b-tags | 3 jets 2 b-tags |
|---|---|---|---|---|
| W/Z+jets | 4378 ± 547 | 1295 ± 164 | 213 ± 56 | 84 ± 20 |
| tt | 474 ± 49 | 1067 ± 109 | 98 ± 14 | 284 ± 42 |
| Diboson | 203 ± 22 | 62.7 ± 7 | 10 ± 1 | 4 ± 1 |
| Non-W | 316 ± 126 | 141 ± 57 | 7 ± 4 | 3 ± 3 |
| t-channel | 193 ± 25 | 84 ± 11 | 6 ± 1 | 15 ± 2 |
| s-channel | 128 ± 11 | 43 ± 4 | 32 ± 4 | 12 ± 2 |
| Wt-channel | 16 ± 4 | 26 ± 7 | 1 ± 0 | 2 ± 1 |
| **Total** | 5707 ± 877 | 2719 ± 293 | 367 ± 66 | 403 ± 53 |
| **Observed** | 5533 | 2432 | 335 | 355 |

# $\ell\nu b\bar{b}$ s+t Analysis

- Lepton+jets with 7.5 $fb^{-1}$
- # of jets/b-tags to define samples (4)
- Train NN with 11-14 variables
- Use s-channel as signal in only 2jet-2tag channel, t-channel for the rest
- Use admixture of systematics shifted samples → 3% improvement
- Validate data-background agreement in 0-tag sample



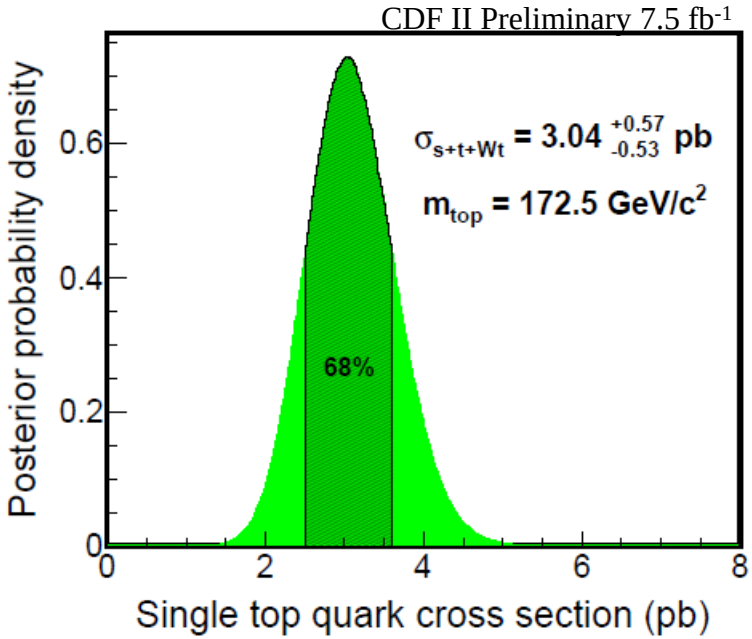




CDF Pub. Note 10793

# $\ell\nu b\bar{b}$ s+t+Wt cross section

- Measure cross section using maximum likelihood fit to the binned NN output distributions
- Assume uniform prior probability density for the c.s.
- Integrate the posterior probability density over the parameters associated with all sources of systematic uncertainties



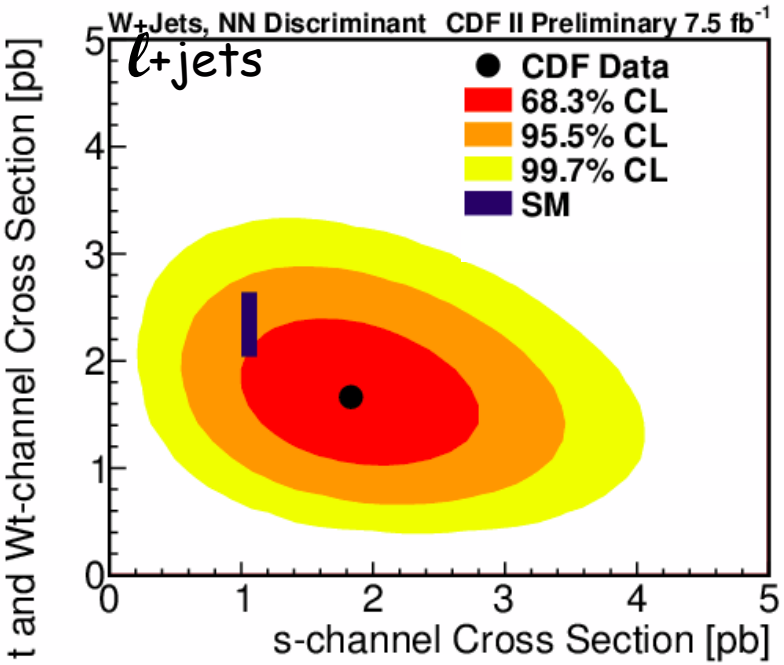

$$\sigma_{s+t+Wt} = 3.04\ ^{+0.57}_{-0.53}\ \text{pb}$$

CDF Pub. Note 10793

# t-channel vs s-channel

- We assume a uniform prior-probability density distribution in the two-dimensional plane ($\sigma_s$ , $\sigma_{(t+Wt)}$ )
- Determine the cross sections that maximize the posterior-probability density distribution
- The t-channel and Wt processes are combined as they share the same final-state topology.

CDF 7.5 fb$^{-1}$:




$\sigma_s = 1.81\ ^{+0.63}_{-0.58}$ pb

$\sigma_{(t+Wt)} = 1.66\ ^{+0.53}_{-0.47}$ pb

CDF Pub. Note 10793

- $\sigma_s^{SM} = 1.06 \pm 0.06$ pb
- $\sigma_{t+Wt}^{SM} = 2.34 \pm 0.30$ pb

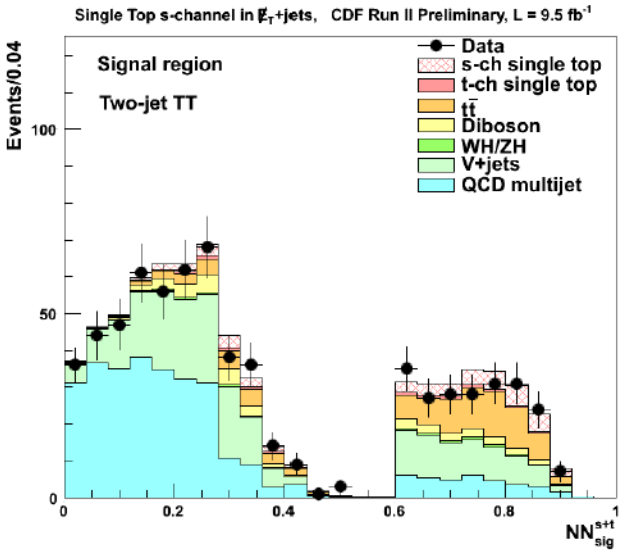
Theor:
PRD 83, 091503 (2011)
PRD 81, 054028 (2010)
PRD 82, 054018 (2010)

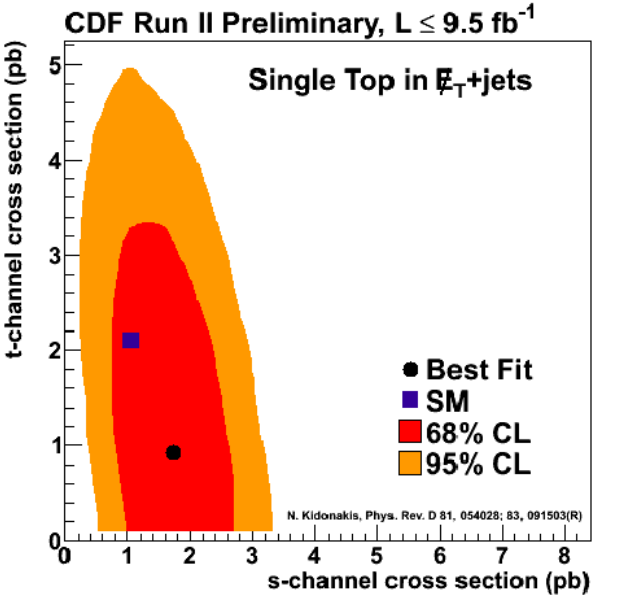
# METbb̄ s+t analysis

- Full CDF Run II dataset (9.5 fb$^{-1}$)
- Recover non-reconstructed electrons and muons and W→τν (hadronic decay)
- Completely orthogonal dataset to ℓ+jets selection
- # of jets/b-tags to define samples (6)
- Several NN used against QCD, V+jets and ttbar, for s- and t-channels
- $NN_{sig}^{s+t}$ final discriminant is used to separate both s- and t-channel signal from remaining background
- Assume SM $\sigma_s/\sigma_t$

$$\sigma_{s+t} = 3.53\ ^{+1.25}_{-1.16}\ \text{pb}$$

CDF Pub. Note 11033



# CKM matrix element $|V_{tb}|$

- $\sigma(s+t+Wt) \propto |V_{tb}|^2 \rightarrow$ calculate posterior pdf in terms of $|V_{tb}|^2$
- To transform $\sigma(s+t)$ measurement into $|V_{tb}|$, assume:
  - $\Rightarrow$SM top quark decay: $|V_{td}|^2+|V_{ts}|^2 \ll |V_{tb}|^2$
  - $\Rightarrow$V-A and CP conserving Wtb vertex
  - $\Rightarrow$No assumption on number of families or CKM unitarity
- Complementary with tt decay measurements of the ratio R

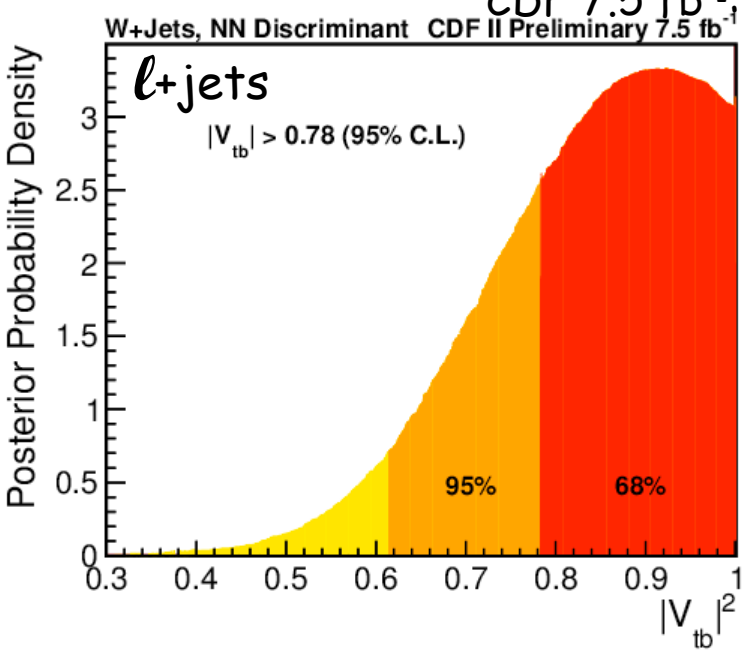
$$|V_{tb,meas}|^2 = \frac{\sigma_{meas}}{\sigma_{SM}} \cdot |V_{tb,SM}|^2$$

$|V_{tb}|$ = 0.95 ±0.09 (stat+syst) ± 0.05 (theo)

$|V_{tb}|$ > 0.78 (95 % C.L.)

11% precision

CDF Pub. Note 10793



# CDF combined s+t channel

- The results of the two analyses ($\ell$+jets and MET+jets) are combined by taking the product of their likelihoods and simultaneously varying correlated uncertainties

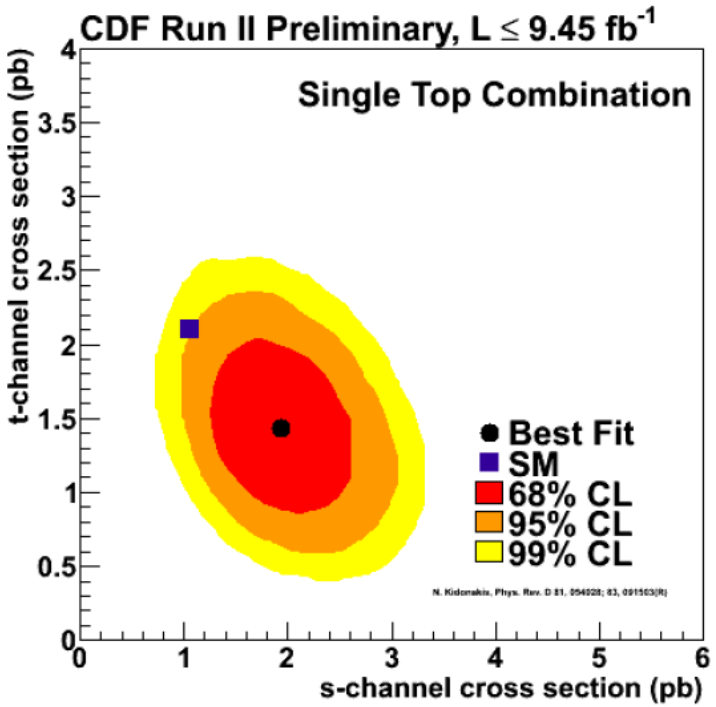
$$\sigma_{s+t} = 3.02\ ^{+0.49}_{-0.48}\ \text{pb}$$ ± 16% precision

- t-channel , considering the s-channel as background constrained to theoretical prediction:

$$\sigma_{t} = 1.65\ ^{+0.38}_{-0.36}\ \text{pb}$$ ± 23% prec.

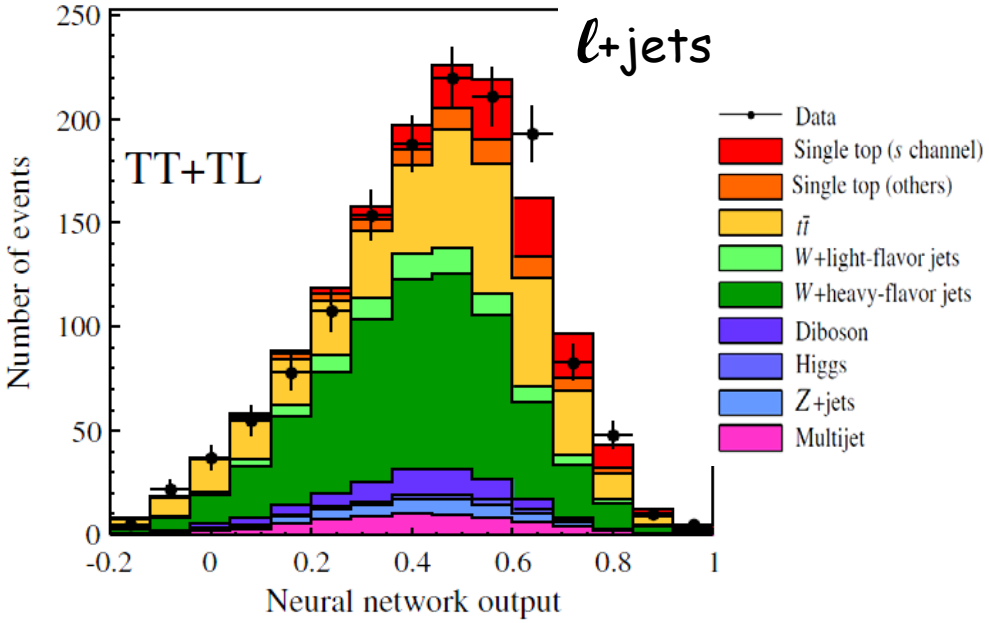
$$|V_{tb}| > 0.84 \text{ @ } 95\% \text{ C.L.}$$

CDF Pub. Note 11033



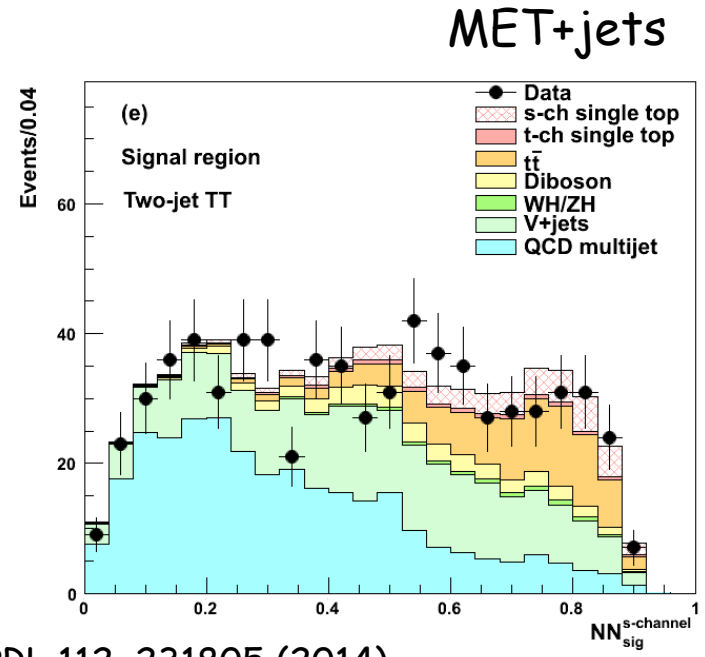
# s-channel optimized analyses

- New lepton+jets and MET+jets s-channel optimized analyses based on Higgs search techniques and selection
- Use CDF full Run II data set, extra lepton trigger adds 10% more leptons
- Innovative multivariate tagger, non-overlapping tagging categories
- Both use NN trained for s-channel in all categories




PRL 112, 231804 (2014)

$\sigma_s = 1.41^{+0.44}_{-0.42}$ (stat+syst) pb

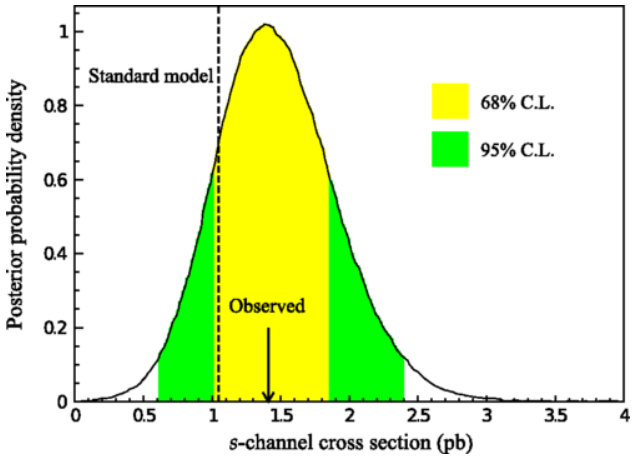


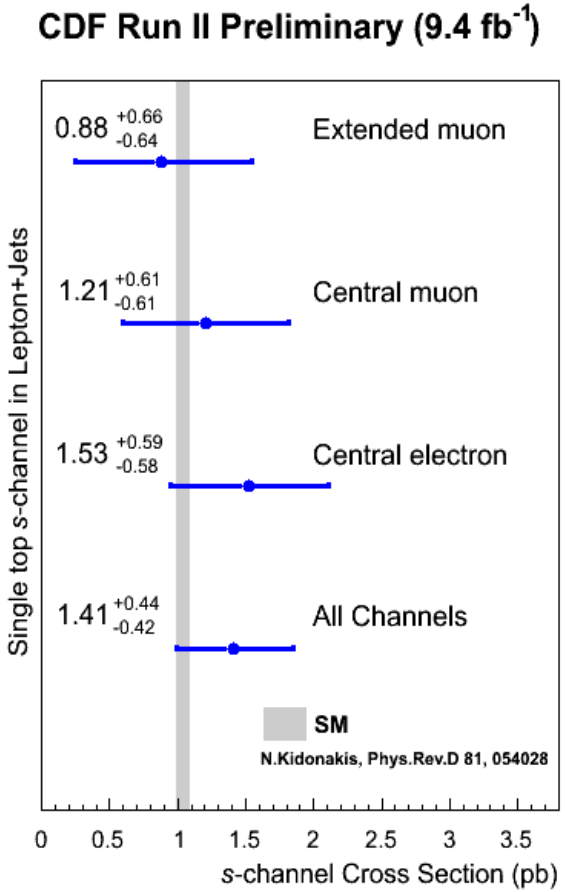

PRL 112, 231805 (2014)

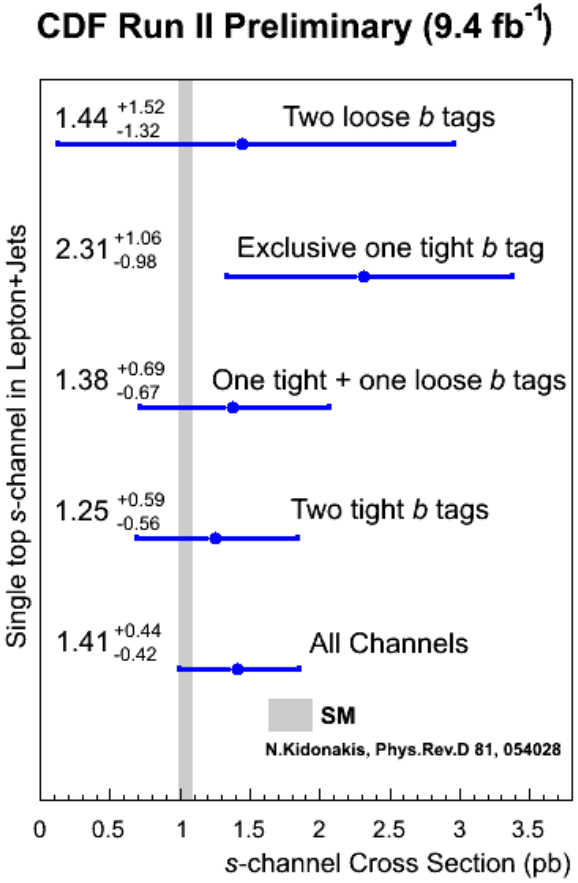
$\sigma_s = 1.12^{+0.61}_{-0.57}$ (stat+syst) pb

# s-channel results

ℓ+jets



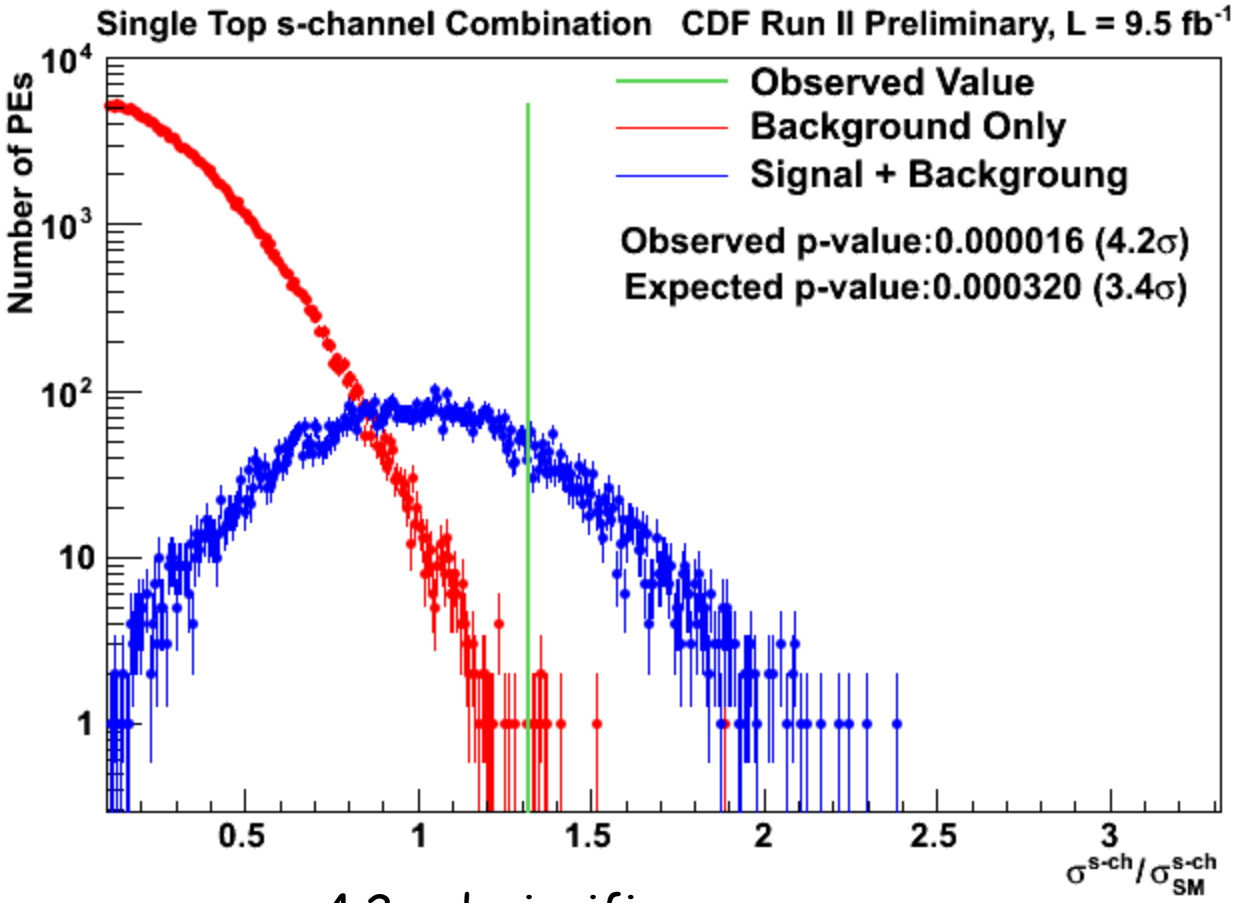

$\sigma_s = 1.41^{+0.44}_{-0.42}$ (stat+syst) pb

PRL 112, 231804 (2014)

# CDF s-channel combination

$\sigma_s = 1.36^{+0.37}_{-0.32}$ (stat+syst) pb

± 27% precision




4.2 s.d. significance

PRL 112, 231805 (2014)

# Conclusion

- Single top quark was observed by CDF and D0 in 2009
- Since then, single top measurements have been refined
- Single top quark s-channel production evidence in 2014
- See next talk by C. Schwanenberger for Tevatron combined s-channel observation
- Now CDF single top quark program is almost complete
  - ⇒ All measurements in agreement with the SM prediction
  - ⇒ Single top quark is one of Tevatron legacies!
- Tevatron combined s+t production cross section is underway
- 2.5 years after the end of RunII CDF continues providing valuable top physics results

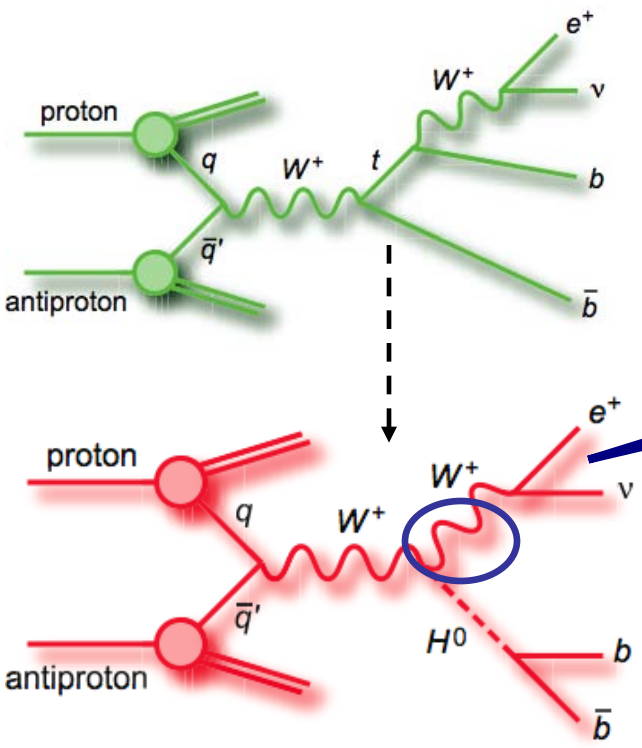
# Single top & Higgs search

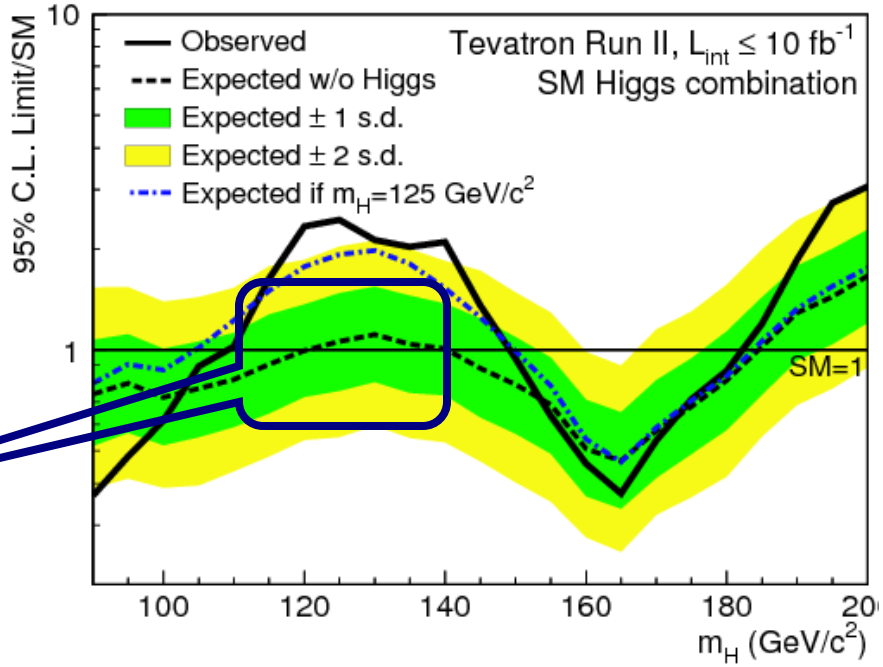
- Single top quark production was a background for searches for a low mass Higgs boson at the Tevatron

  ⇒s-channel single top shares same final state lvbb with Higgs production associated with a W-boson (WH-production)

- Single top observation was a Benchmark to WH Higgs search

  $\sigma_{WH} \sim 1/10\ \sigma_{Singletop}$

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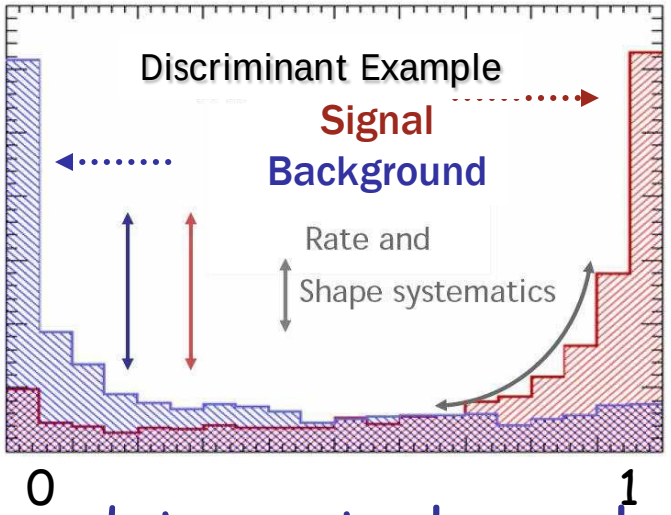
# Analysis strategy

- Goal: combine multiple variables into single, more powerful, discriminant to separate signal from background
- Several method have been used:

  Likelihood functions, Matrix Element , Neural network (NN),

  Boosted decision tree




- Check discriminant performance using data control samples
- Perform the statistical analysis
  - ⇒ Build Bayesian posterior probability density to measure cross section
  - ⇒ Shape normalization and systematics treated as nuisance parameters
  - ⇒ Correlations between uncertainties properly accounted for