Single Top Quark Physics at the Tevatron and Beyond

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For the LHC part, valuable help received from:

Sergey Sablospitsky, IHEP Protvino, CMS
Dugan O'Neil, Simon Fraser Univ., ATLAS

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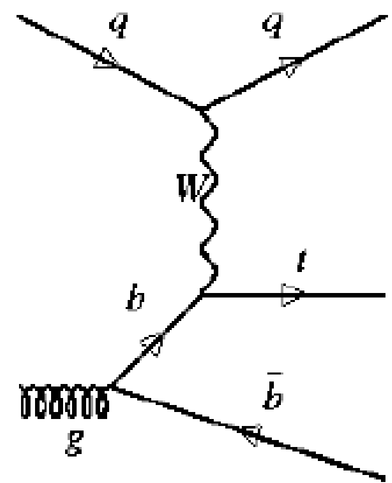
Single Top Production

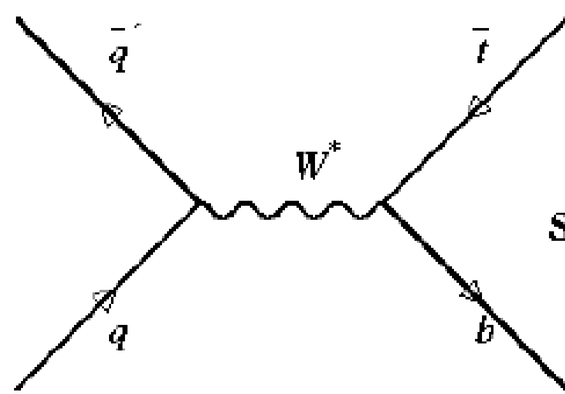
- Why look for single top:
  - Cross section ~ $|V_{tb}|^2$: the only way to directly measure CKM matrix el. V_{tb}
  - Single top is background to other signals: e.g. Higgs searches.
  - Test non-SM phenomena:
    - Heavy W' boson
    - Anomalous Wtb couplings
    - FCNC couplings tug or tcg
- At the Tevatron relevant channels are:
  - t-channel W-gluon fusion:
    - 1.98 pb at $\sqrt{s}$=1.96 TeV
    - Hard b-jet, W decay products, soft b (usually lost), light quark jet
  - s-channel W*:
    - 0.88 pb at $\sqrt{s}$=1.96 TeV
    - Two hard b-jets, W decay products
  - B.W. Harris et al.: Phys. Rev. D 66, 054024 (theoretical calculations)

W-gluon fusion process



Signal is W+b+q

s-channel W* process



Signal is W+b+$\bar{b}$

From Run I to Run II

- Results at $\sqrt{s}$ = 1.8 TeV from CDF and D∅ :
  - Single top has not been observed; 95% CL limits were set:
  - t-channel: D∅ limit: **22** pb, CDF limit: **13** pb (theoretical x-section: **1.40** pb)
  - s-channel: D∅ limit: **17** pb, CDF limit: **18** pb (theoretical x-section: **0.76** pb)
  - combined s- and t- channels search: CDF limits: 14 pb (H_T , M_{lnb})
  - most recent Run 1 CDF study finds a 2.2σ excess and limit of 24 pb (7-inp NN)
  - D∅:Phys. Lett. B 517, 282 (2001); CDF: PRD65, 091102 (2002), C. Ciobanu's Ph.D. thesis
- For Run II:
  - Higher rate: 32% increase in the combined s and t channel x-section:
    - still small: 2.9 pb versus 6.7 pb for top pair production
  - More luminosity – right now CDF has 180 pb^{-1} – that is 70% more data!
  - Better detector acceptance
  - Preliminary CDF analysis done for 107 pb^{-1} of data:
    - Search for s- and t-channels combined production
    - Seaparate search for t-channel

Combined Search

- Look in the W+2 tight jets channel:
  - "tight" jet: $E_T > 15$ GeV, $|\eta| < 2.8$
  - at least one SVX B-tag
  - exactly one lepton with $E_T > 20$ GeV, $|\eta| < 2.0$
  - missing energy: $\not{E}_T > 20$ GeV
  - veto Z's, dilepton events
  - apply a top mass window cut: $140 < M_{lnb} < 210$ GeV/c^2

- Monte Carlo samples:
  - single top signal:
    - Pythia (1M events)
    - Madevent+Pythia (~200k)
  - HERWIG tt background
  - ALPGEN+HERWIG Wbb used to model the shapes of the non-top backgrounds: Wbb, Wcc, Wc, mistags, non-W events

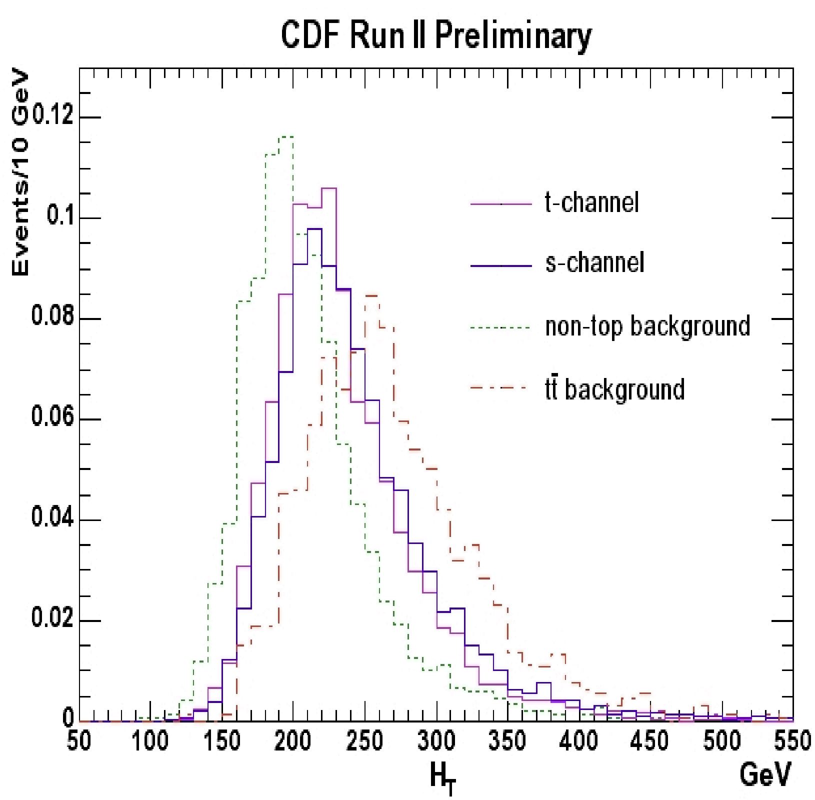
Expected Yield

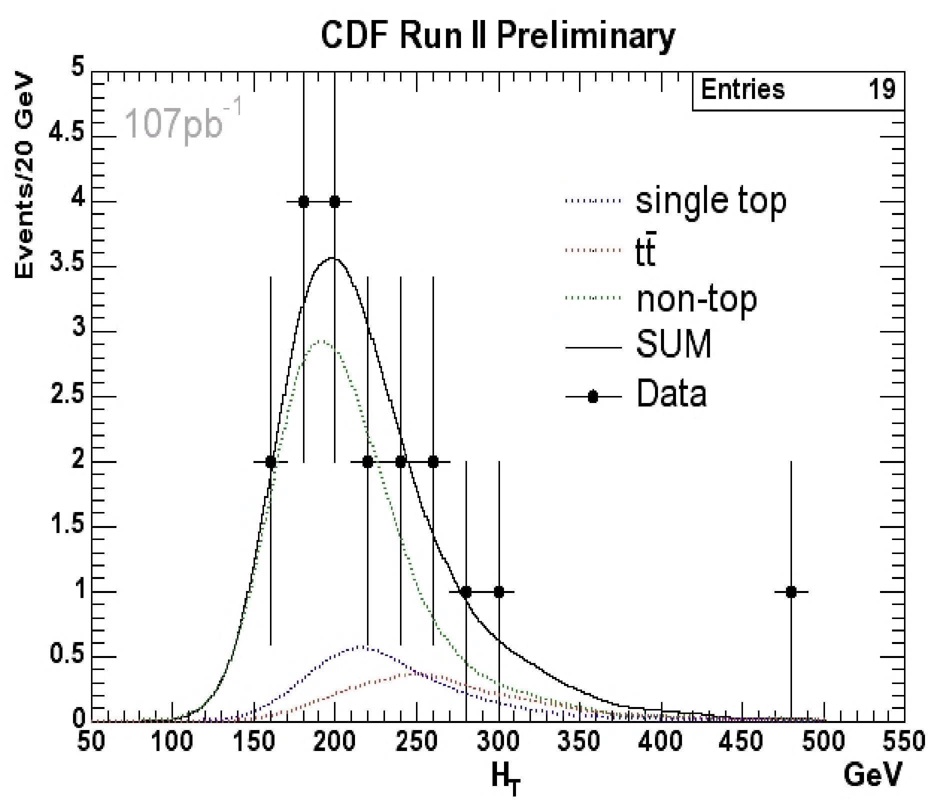
- For $L=107.1\ pb^{-1}$:
  - expect 2.4 signal events
  - expect 16.1 backgrd events
  - observe 19 (expect 18.5)
- The variable with the most discrimination power is H_T, the total transverse energy in the event:
  - Will fit the H_T shape in data as the sum of weighted MC shapes.
  - Use maximum likelihood method with Gaussian background constraints

Process	N in 107.1 pb^{-1}
W-gluon	1.61 ± 0.51
W*	0.80 ± 0.18
tt	2.33 ± 0.70
Wbb	3.5 ± 1.5
Wcc	1.4 ± 0.8
Wc	3.1 ± 1.0
Mistags	2.9 ± 0.9
Non-W	2.2 ± 0.7
Diboson	0.7 ± 0.2
Z+bb	0.07 ± 0.03
Total non-top	13.8± 2.8

Fitting H_T distributions

- H_T distributions for signal and backgrounds:
  - signal shapes similar for s- and t- channels
  - fit yields 2.9±4.5 signal events (exp. 2.4 events).



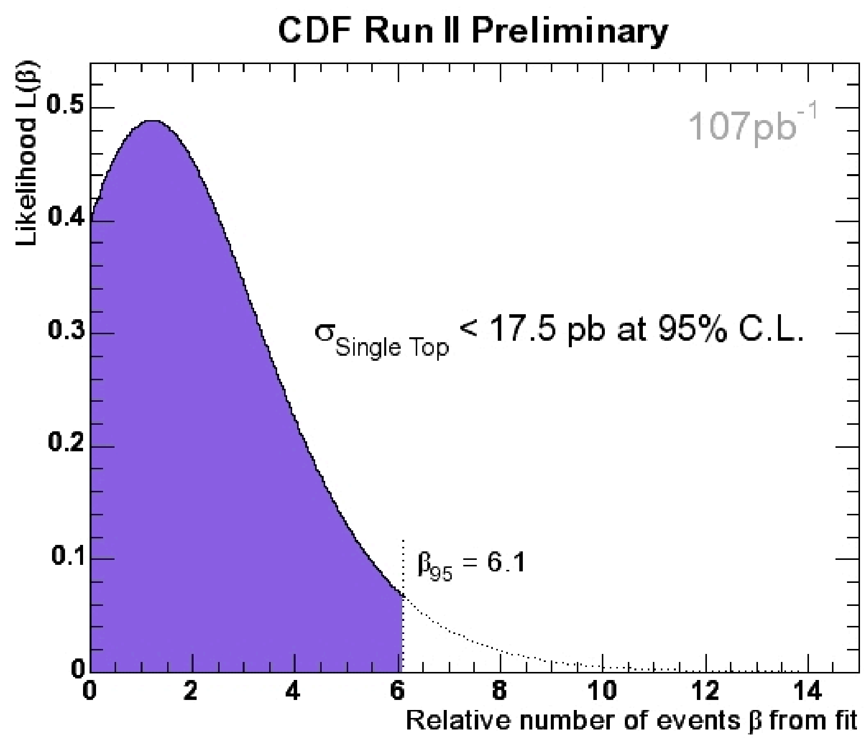


95% C.L. limit

- Limit at 95% C.L. is 17.5 pb
- This accounts for the systematics:
  - Jet E_T scale: 20.9%
  - ISR/FSR: 4.0%
  - Top Mass: 6.2%
  - PDF, signal generator, background model 1-2%
- Compare to Run I:
  - Same luminosity 107 vs 106 (pb^{-1})
  - 14 pb limit for 2.16 pb x-section
  - Now: 17.5 pb limit for 2.86 pb x-s.

    marginally better limit!

  - Several ways to improve this will be discussed later.



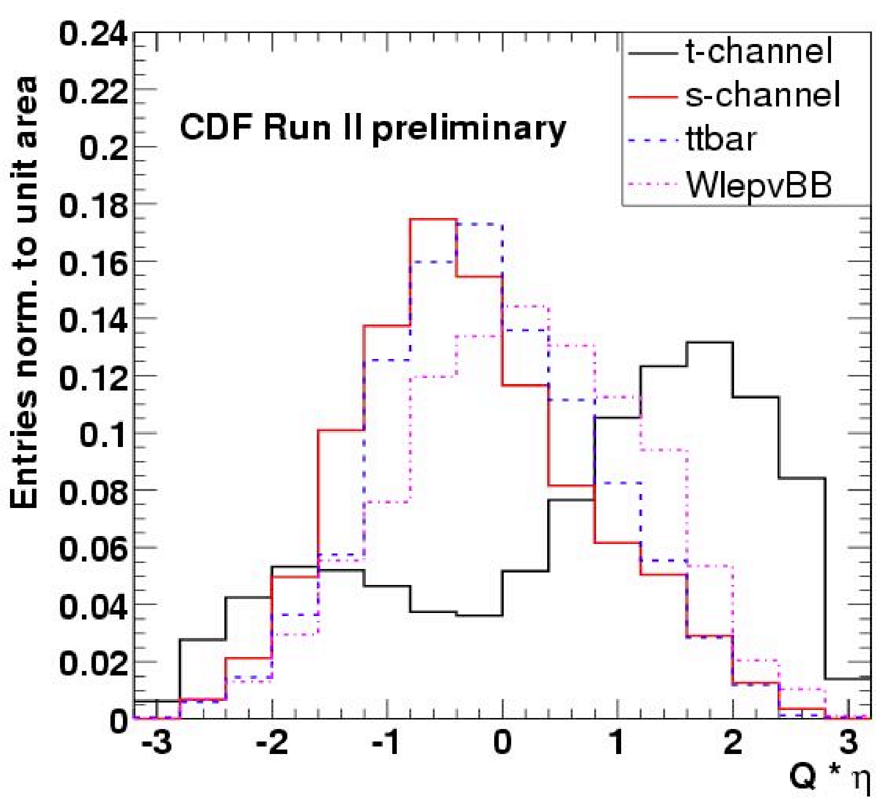
Separate Search

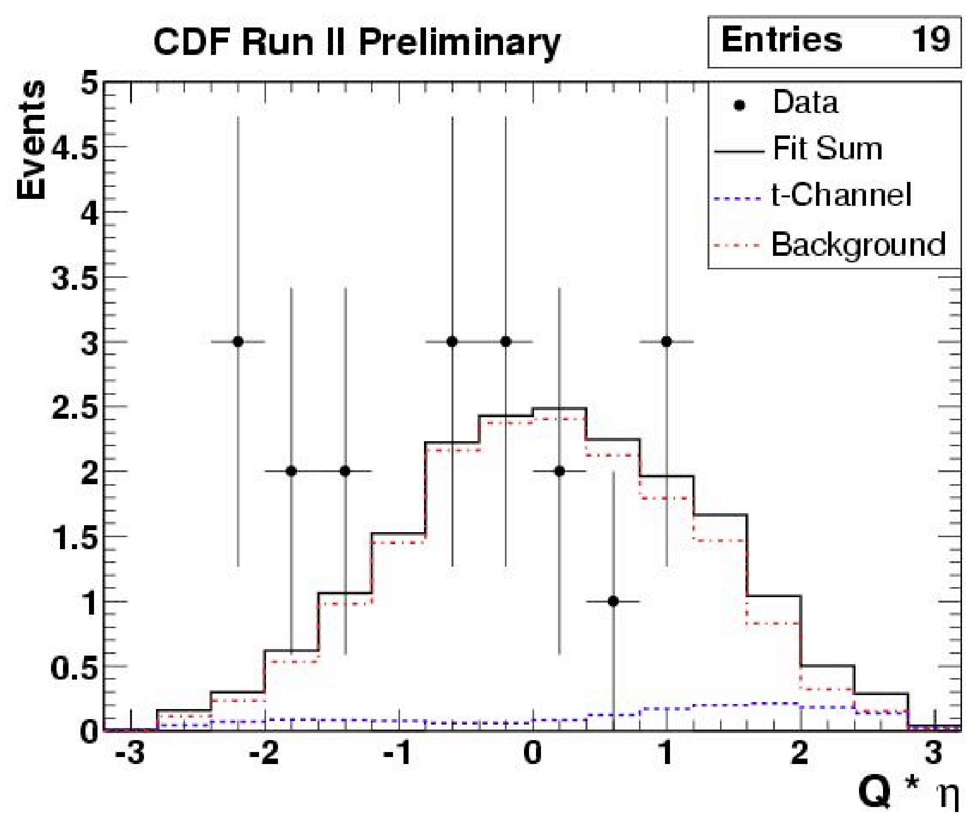
- Looking for the two signal channels individually is desired:
  - Different sensitivities to new physics:
    - s-channel: heavy charged vector bosons W', CP-violation effects within MSSM, Kaluza-Klein excited W-boson within MSSM
    - t-channel: FCNC couplings, anomalous V+A contributions to the W-t-b vertex, etc.
  - To go back to extracting V_{tb} we will have to know the individual rates

- We use the same selection as in the combined search.
  - However, using H_T is no longer appropriate
  - A variable with good W* - W-gluon separation potential is Q x η, where Q is the lepton charge and η the pseudorapidity of the non-b jet.
  - Now treat W* as a background, therefore perform a 4-component fit

Fitting Q□□

- t-channel exhibits an asymmetry toward Qx□ positive values (twice as many events than in the negative Qx□ range)
- fit to data yields: 1.9± 3.7 t-channel signal events (exp. 1.6 events).

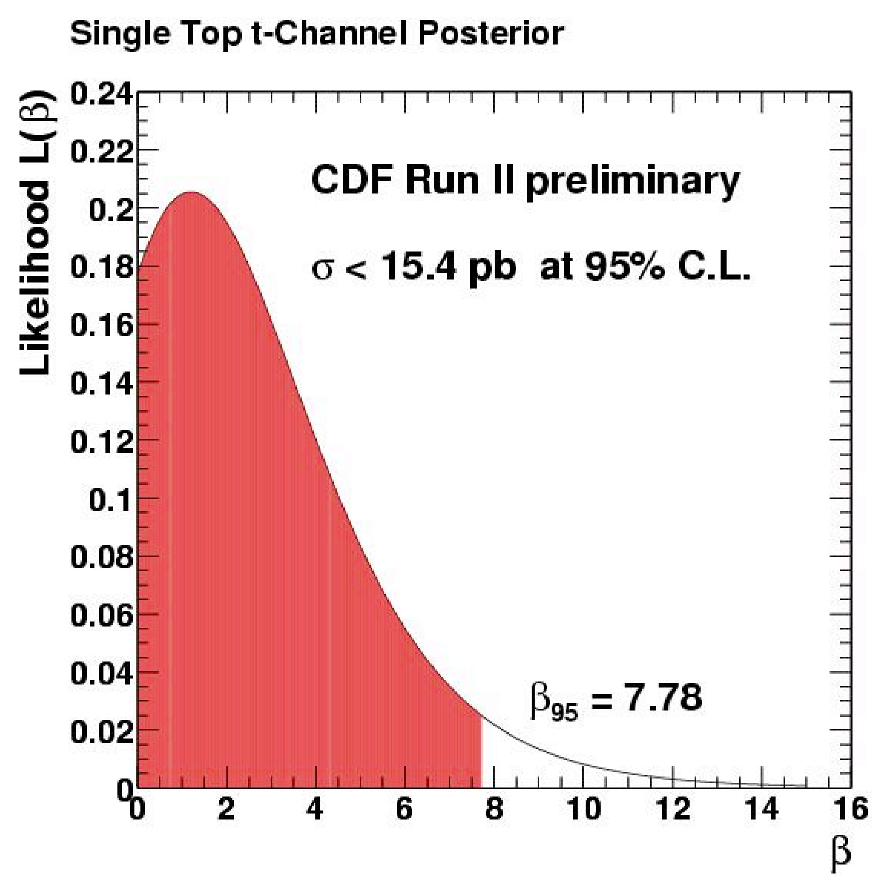




95% C.L. limit

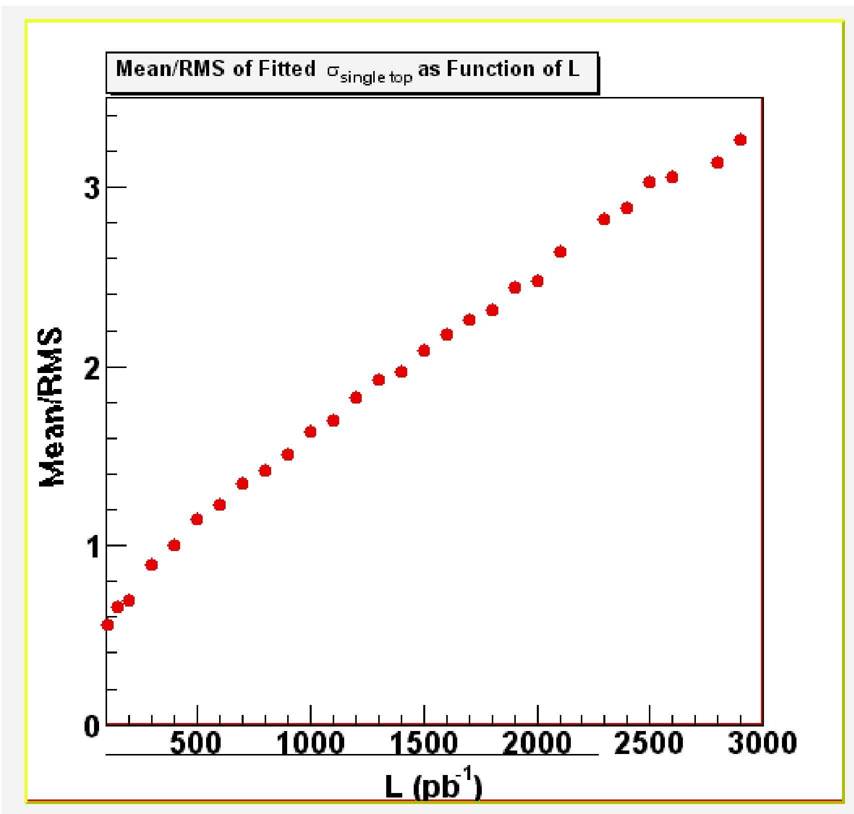
- Limit at 95% C.L. is 15.4 pb
- This accounts for the systematics:
  - Jet E_T scale: 21.5%
  - Signal generator: 21.1%
  - Background model: 43.0%
  - ISR/FSR: 6.9%
  - Top Mass: 6.7%
  - PDF 4.3%
- Compare to Run I:
  - 13 pb limit for 1.40 pb x-section
  - Now: 15.4 pb limit for 1.98 pb x-s.

again a better limit!



Future Prospects

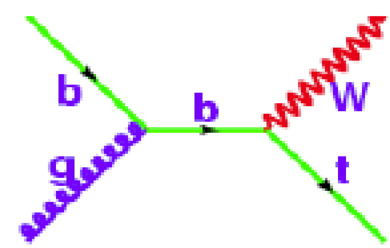
- Neural Network with 5 input variables: H_T, $E_T(j1)$, $E_T(j2)$, E_T, $P_T(j1-j2)$,
  Looking in the W+2j channel, no M_{lnb} cut
  Assuming the background uncertainties will scale as $L^{-1/2}$



- Right now: 3 sigma with 2.5 fb^{-1}
- Improvements to come. We try:
  - Soft lepton tagger, Jet Prob. tagger
  - Use of forward electrons
  - Better discriminant variables:
    - Matrix elements (or ratios of these)
  - Use the top mass hypothesis to constrain the event
    - Will lead to better M_{lnb} resolution
  - Better understanding of the systematic uncertainties is crucial.

Single Top at the LHC

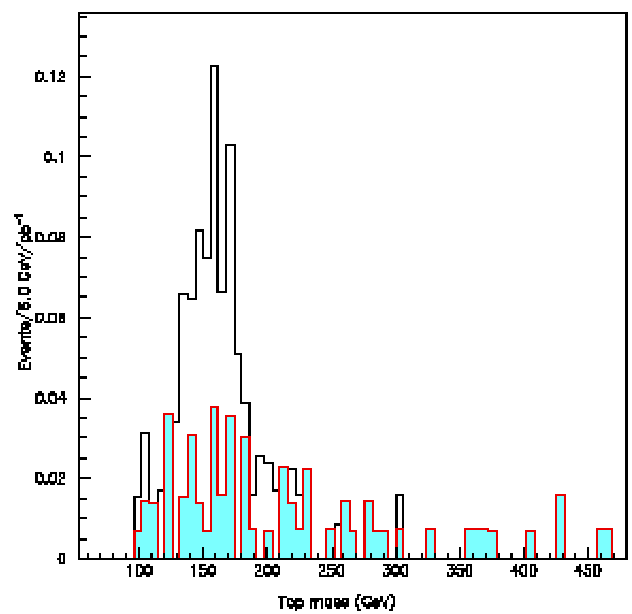
- LHC will be a top quark factory:
  - 8 million top pairs per experiment per year (10 fb^{-1} / year)
  - Some cross section values for $\sqrt{s}$ = 14 TeV:
    - top pair production: ~ 800 pb (mostly via gluon-gluon fusion)
    - t-channel single top: 153 (top) and 90 (antitop) = 243 pb
      - **e.g.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



- Will discuss each of the three modes in what follows

t-channel single top (CMS)

- CMS study (hep-ph/0003033):
  - Full calorimeter simulation + b-tag efficiency parametrization
  - Pythia 5.72 signal, tt, WZ; Vecbos+Herwig W+jets. Selection:
    - One isolated lepton with P_T>20 GeV/c, |□|<2.5
    - Missing E_T>20 GeV, 50 < $M_{l□}$ <100 GeV/c^2
    - Two jets with E_T > 20 GeV, |□| < 4.0
      - **One jet: E_T > 20 GeV, |□| < 2.5, the other E_T > 50 GeV, 2.5<|□| < 4.0**
      - **Leading jet E_T<100 GeV (to reduce tt)**
      - **Exactly one b-tagged jet – the central one**
    - Reject WZ candidates with: 80 < M_{jj} <100 GeV/c^2
  - Signal peak visible in reconstructed M_{top} distribution
  - With 10 fb^{-1}, (S+B)/S = 1.4%



- The quest continues – newer det. simulation
  - use fancier generators: TopRex, Single Top
  - Work-in-progress, unofficial results □□ / □ ~ 10%

V.Abramov, CMS Week 9/17/03

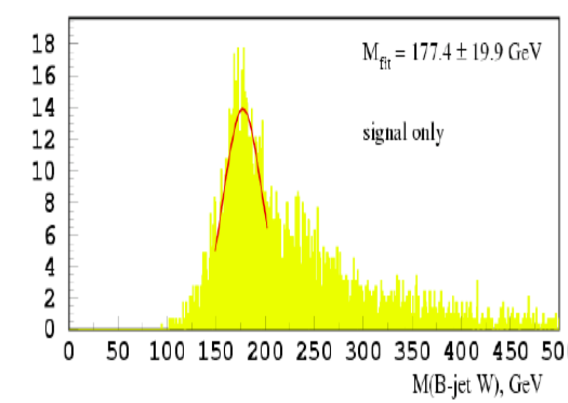
t-channel single top (ATLAS)

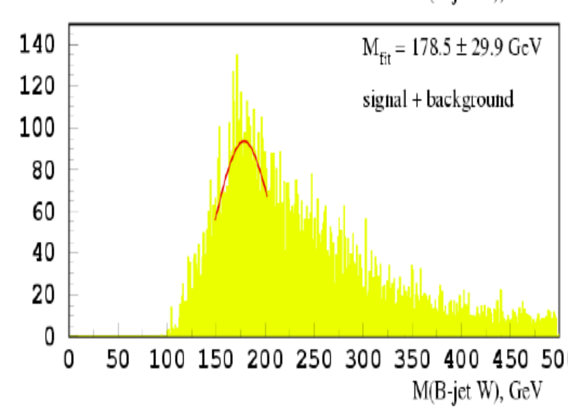
- ATLAS study of W-gluon single top (Dugan O'Neil's Ph.D. thesis):
  - ATLFAST parametrized detector simulation
  - Onetop+Pythia 5.72 signal, tt; M.E.+HERWIG Wbb, Wjj
  - Selections are rather similar to CMS study, plus:
    - $150<M_{top}<200$ GeV/c^2
  - Result: (S+B)/S = 0.9% with 10 fb^{-1}.

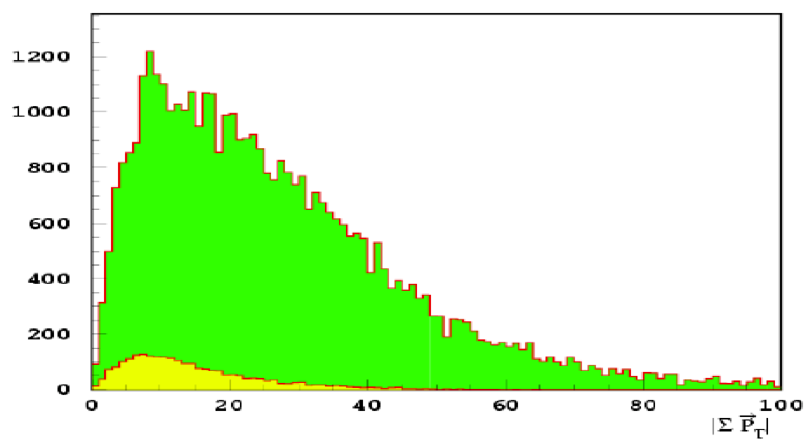
- What about V_{tb}? Extracting $|V_{tb}|^2$ from x-section picks up uncertainties:
  - x-section uncertainty:
    - Statistical: 5% is a perhaps reasonable/optimistic guess for L=10 fb^{-1}
    - Systematic <20%. Here things can easily be off by a lot, especially in the 1st year…
  - Luminosity uncertainty: traditionally 4-5%
  - Theoretical uncertainty:
    - From factorization and renormalization scale dependence (3% from NLO calculation)

s-channel single top (CMS)

- CMS study (S. Sablospitsky, CMS week 9/17/03)
  - disclaimer: work-in-progress, not yet 'official' results
  - use TopRex to generate single top, tt, Wbb. Pythia W+jets. Use CMSJET 4.801
  - selection:
    - one lepton with E_T>10 GeV, |□|<2.5
    - 2 B-tags with E_T>20 GeV, no other jets with E_T>20GeV
    - Vector sum all final state P_T: |□$\mathbf{P_T}$|<15 GeV
    - Reconst. top mass: 150 GeV<M_{top}<200 GeV/c^2
  - Results: (S+B)/S = 12% , S/B = 8% for L = 30 fb^{-1}
  - which implies □$|V_{tb}|$=8.3%



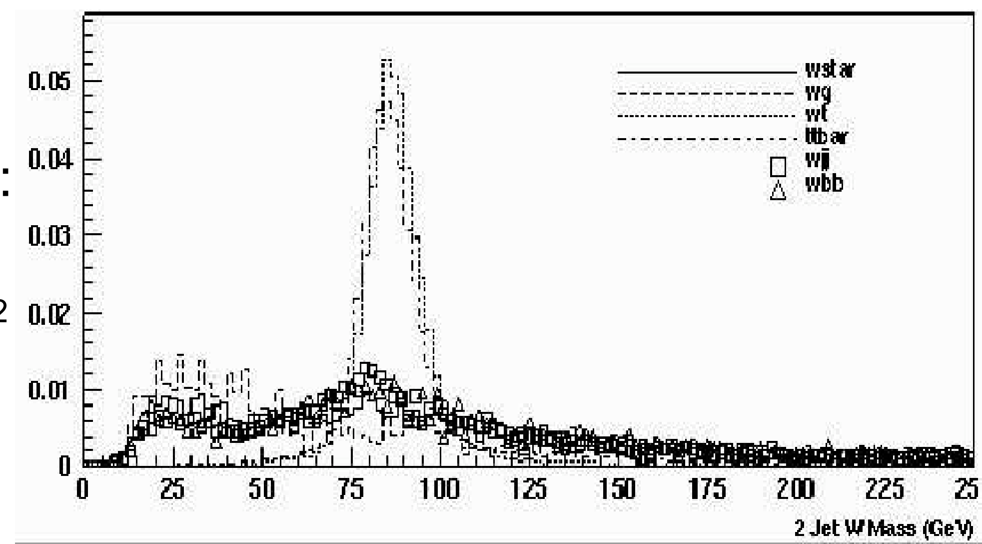




s-channel single top (ATLAS)

- ATLAS study (hep-ph/0003033)
  - Onetop+Pythia 5.72 signal, tt; M.E.+HERWIG Wbb, Wjj
  - Selection:
    - One isolated lepton with P_T>20 GeV/c, |□|<2.5
    - 2 b-jets with E_T>75 GeV
    - Scalar sum all final state P_T: |□P_T|<175 GeV
    - Reconst. top mass: 150 GeV<M_{top}<200 GeV/c^2
  - Results: (S+B)/S = 5.5% for L = 30 fb^{-1}, □|V_{tb}|~1%

- Wt single top production at ATLAS:
  - 65< M_{jj} < 95 GeV/c^2
  - Event invariant mass < 300 GeV/c^2
  - □ (S+B)/S=4.4% for L = 30 fb^{-1}



Top Polarization in Single Top Events

- EW-produced top quarks are highly polarized:
  - In the top rest frame, its spin points along the direction of the down (d) quark.
  - Restrict to t-channel single top:80% (69%) of the top (antitop) events have the 'd' quark in the final state. The angular distrib. of the charged lepton:

$$f(\cos\theta_l) = \frac{1}{2}\left(1 + P\cos\theta_l\right)$$

  - used signal samples with P=+1 and P=-1. Consider only W+jet background.
  - Chisquare fit, letting the two P contributions float.
  - The error on polarization measurement is 1.6% for 10 fb^{-1} (Dugan'sPh.D.thesis)
- W boson helicity measurement:
  - Again restrict to t-channel signal.
  - Measure $\cos(\theta_l)$ distribution. θ_l between the direction of the lepton in W rest frame and the direction of the W in the top rest frame.
  - Three component fit: f_L , f_R , f_{Long} , with $f_L+f_{FR}+f_{Long}=1$
  - Uncertainties of the order 2-3% for 30 fb^{-1} of data.

Conclusions

- CDF and DØ accumulated more events than in entire Run I (factor of 2).
- Preliminary CDF study from 107 pb^{-1} sets promising single top limits
- However, many improvements needed if we are to observe single top in the next 2-3 years.
- Precise measurements of $|V_{tb}|$, as well as top polarization are not within (immediate) sight

- LHC will see very exciting results in the first (few) years of running:
  - 10 –30 fb^{-1} needed for observation in most searches.
  - Higher collider energy = considerable higher cross sections
- ATLAS and CMS single top studies are very mature
  - The Monte Carlo efforts are particularly strong: Top Rex, SingleTop.
- CDF/DØ can help with insight into systematics. Search strategies are already similar between Tevatron and CERN, but big improvements are just an idea away!