Top quark production cross section at E_{cm}= 2 TeV

For the CDF and DØ Collaborations

Elizaveta Shabalina
University of Illinois at Chicago
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Top quark production today

- 11 years since the top quark discovery in Run I of the Tevatron
- Production cross section measured with $\mathcal{L}$>100 pb^{-1} $\sqrt{s}$ = 1.8 TeV with precision ~25% – statistics limited
- At present
  - **$\sqrt{s}$ = 1.96 TeV** - 30% higher production rate
  - much higher luminosity
- NLO QCD (12% uncertainty):

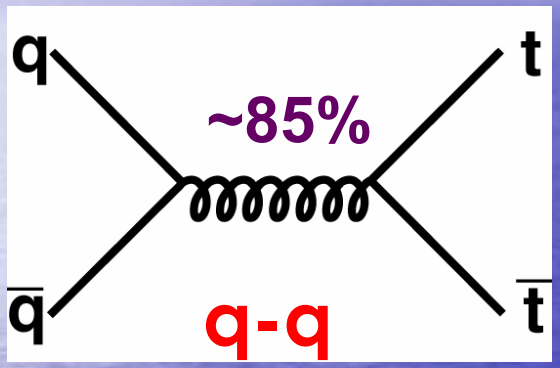
  σ = 6.8±0.8 pb (Kidonakis, Vogt)

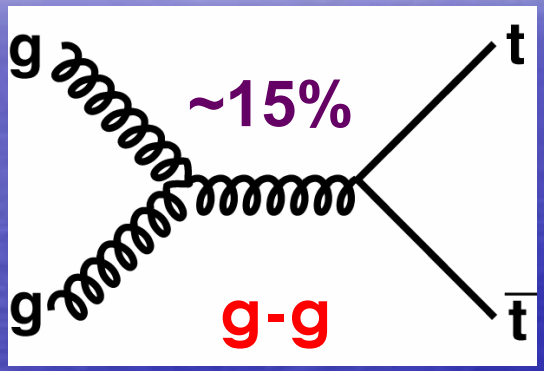
  $\sigma = 6.7^{+0.7}_{-0.9}$ pb (Cacciari et al)
- Goal – precision measurements

- Test of perturbative QCD
- Higher production rate ➡ e. g. ttbar resonances
- Measurements in different decay channels are complimentary
  - Exotic top decays (to charged Higgs or light stop) ➡ different cross sections in different channels
  - Dilepton to l+jets cross sections ratio probes non-W boson top decays
- Measure with different methods
  - b-jet tagging method normally assumes $Br(t \to Wb) = 1$
    - an implicit use of the SM prediction: $|V_{tb}|$~1
  - Topological method is free of this assumption

Top production mechanism

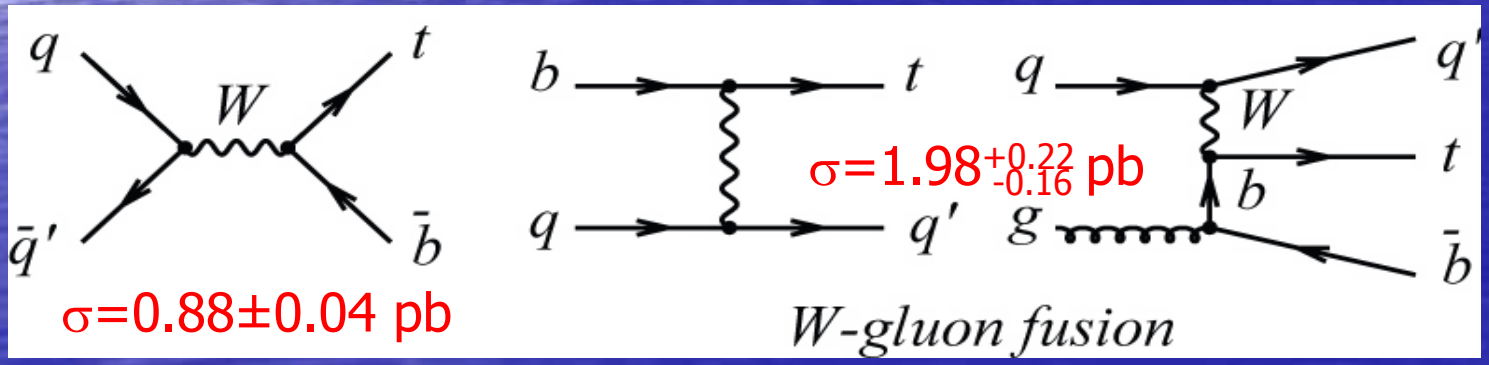
- Standard model pair production via the strong interaction





Discovered in Run I

- Standard model electroweak production (single top)



To be observed in Run II

Top pair production is one of the main backgrounds to single top

… and decay

- Very short lifetime → decays as a free quark
- $Br(t \to Wb) \cong 100\%$

Top Pair Decay Channels

W decay	e^+	μ^+	τ^+	$u\bar{d}$	$c\bar{s}$
e^-	ee	$e\mu$	$e\tau$	electron+jets	
μ^-	$e\mu$	$\mu\mu$	$\mu\tau$	muon+jets	
τ^-	$e\tau$	$\mu\tau$	$\tau\tau$	tau+jets	
$\bar{u}d$	electron+jets	muon+jets	tau+jets	all-hadronic	
$\bar{c}s$					

dileptons

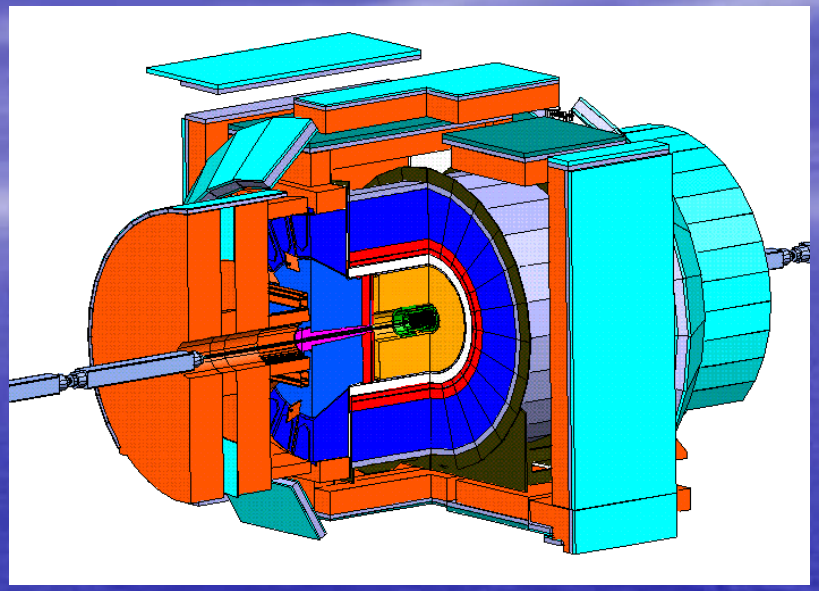
- W decay modes determine top quark final state
- Dilepton (ee, μμ, eμ)
  - Both W's decay leptonically
  - BR = 6%
- Lepton (e or μ) + jets
  - One W decays leptonically, another one hadronically
  - BR = 34%
- All-hadronic
  - Both W's decay hadronically
  - BR = 46%
- τ_{had} +X
  - BR = 14%
- Leptonic τ decays are included in e and μ final states

Experimental challenge – the best performance of all detector systems is crucial

The detectors

- New tracking and vertex detectors
- Upgraded muon systems
- Upgraded calorimeters/preshowers
- Upgraded DAQ/trigger

CDF



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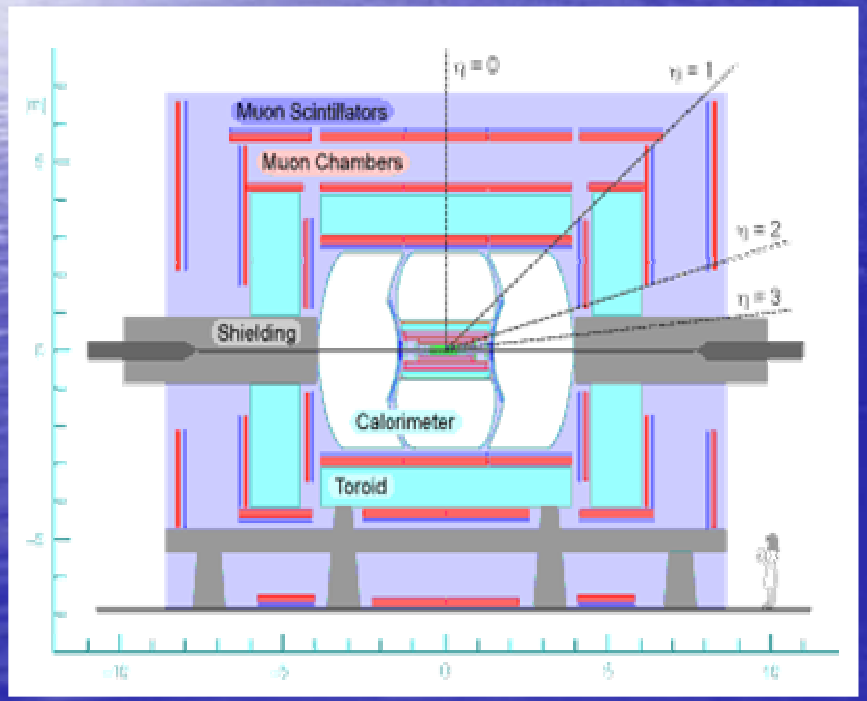
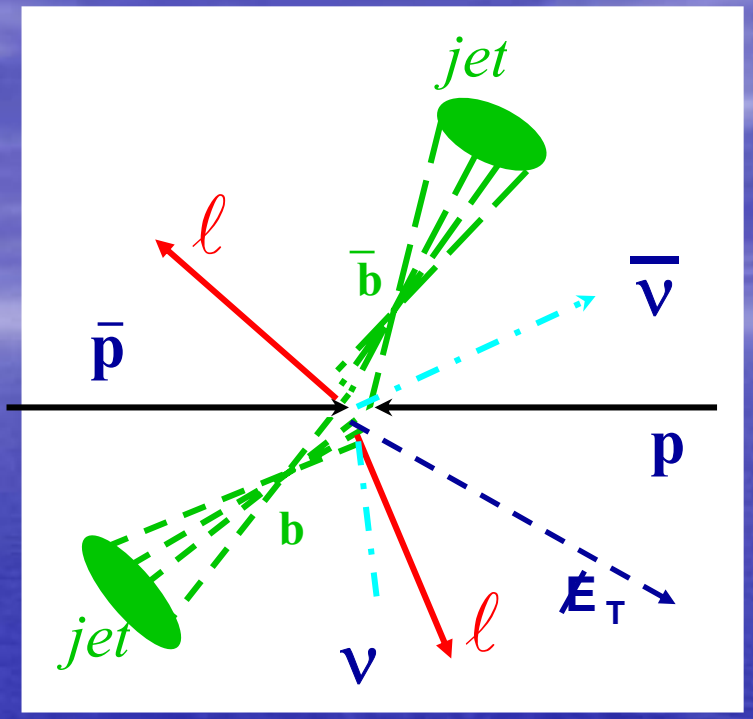


- Electrons - energy clusters in EM section of the calorimeter and track in the central tracking system
- Muons - track segments in muon chambers and track in the central tracking system
- Jets - clusters of energy in EM and hadronic parts of calorimeter
- Jet flavor tagging requires tracks

Dilepton channels

- Selection
  - Two charged high p_T opposite sign leptons
  - Large missing transverse energy
  - At least two high p_T jets
- Physics backgrounds
  - Leptons from W/Z decay and missing E_T from neutrinos: WW/WZ, $Z/\gamma^* \to \tau\tau \to ll$
  - Estimated from MC

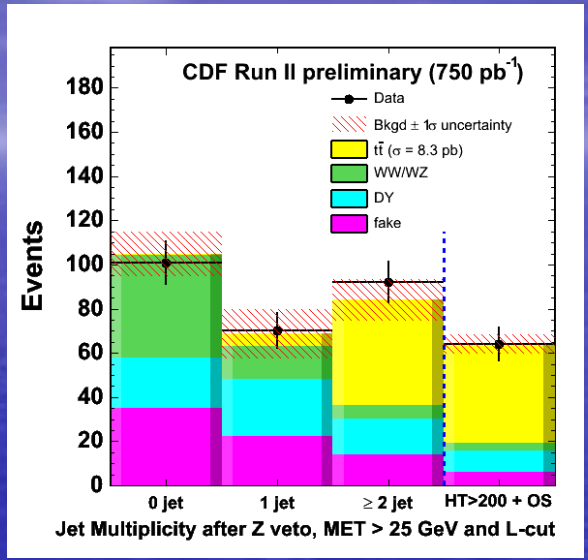


Instrumental backgrounds

- jet or lepton in jet fakes isolated lepton (multijet, W+jets)
- missing E_T originates from resolution effects, misreco jet or lepton or noise in calorimeter (Drell-Yan processes $Z/\gamma^* \to ee(\mu\mu)$ (except eμ channel)
- Estimated from data

ee, eμ, μμ final states

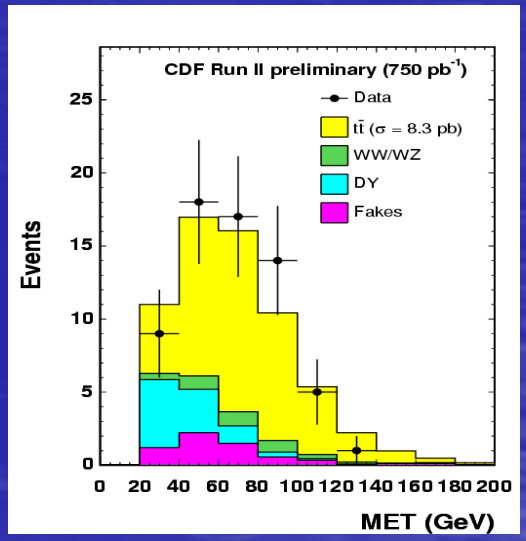
	Events per 750 pb^{-1} after ≥2 jet cut			
Source	ee	$\mu\mu$	$e\mu$	$\ell\ell$
WW	0.79±0.15	0.45±0.09	1.45±0.25	2.70±0.42
WZ	0.41±0.07	0.31±0.06	0.20±0.04	0.93±0.15
DY→ $\tau\tau$	0.38±0.10	0.39±0.10	0.83±0.21	1.60±0.38
DY→ $ee + \mu\mu$	3.52±1.57	4.31±1.86	0.00±0.00	7.83±3.15
Fakes	1.00±0.50	2.06±0.63	3.23±1.30	6.29±1.53
Total background	6.10±1.87	7.52±2.12	5.72±1.38	19.34±4.26
$t\bar{t}$ ($\sigma = 6.7$ pb)	8.25±0.38	8.57±0.39	19.27±0.88	36.09±1.24
Total SM expectation	14.35±2.08	16.09±2.30	24.99±1.75	55.43±5.11
Candidates in 750 pb^{-1}	12	24	28	64



L = 750 pb^{-1}, m_{top} = 175 GeV

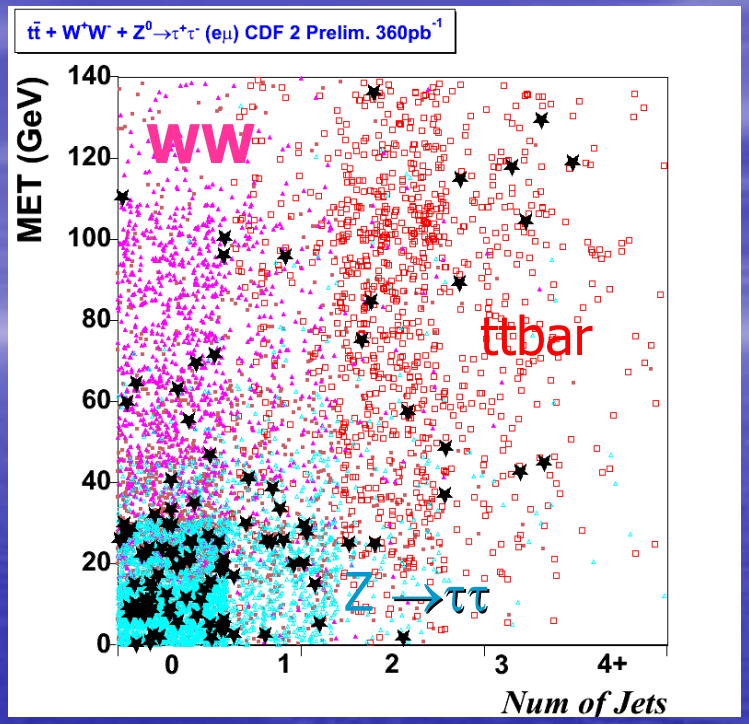
$$\sigma_{t\bar{t}} = 8.3 \pm 1.5(stat) \pm 1.0(syst) \pm 0.5(lumi)\, pb$$

- Total relative uncertainty ~ 22%!
- Statistical uncertainty is comparable with systematic
- Main sources:
  - Lepton identification
  - Jet energy calibration
  - ttbar modeling



Inclusive dilepton

- Perform global 2D fit to the high p_T dilepton sample in N_{jet} vs missing E_T plane
  - ttbar – large missing E_T, high N_{jet}
  - WW – large missing E_T, low N_{jet}
  - $Z/\gamma^* \rightarrow \tau\tau \rightarrow ll$ – lower missing E_T, low N_{jet}
- Only ttbar and WW are fitted in ee and μμ channels because of hard cut to suppress DY contribution
- Backgrounds (WZ, ZZ, DY, W+fake lepton, Wγ) are fixed to expected values in the fit



Theory:

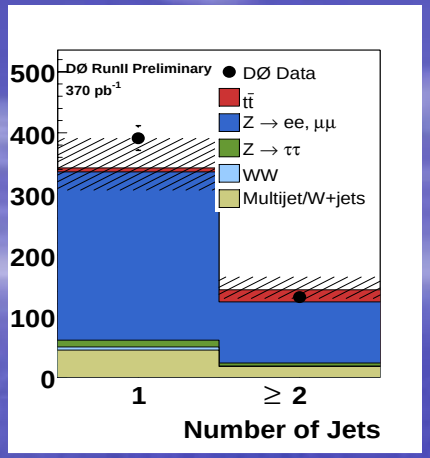
WW	12.5±0.8 pb
$Z \rightarrow \tau\tau$	253.1±0.5 pb

$L = 360\ pb^{-1}$, $m_{top} = 178$ GeV

Cross Section	emu	ee+emu+mm
ttbar Cross Section	$9.2_{-2.6}^{+3.0}$ (fit)$_{-0.2}^{+0.6}$ (shape) pb	$6.6_{-1.9}^{+2.2}$(fit)$_{-0.2}^{+0.5}$(shape) pb
WW Cross Section	$11.4_{-4.3}^{+5.2}$(fit)$_{-0.1}^{+0.5}$(shape) pb	$15.4^{+5.1}_{-4.4}$(fit)$_{-0.2}^{+0.8}$(shape) pb
Z tautau Cross Section	$282.1_{-44.3}^{+48.5}$(fit) ± 5.6(shape) pb	-

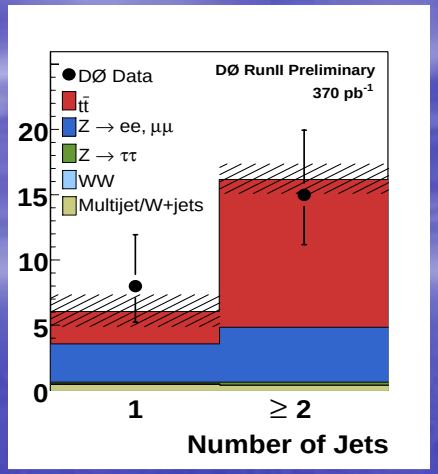
Lepton+track

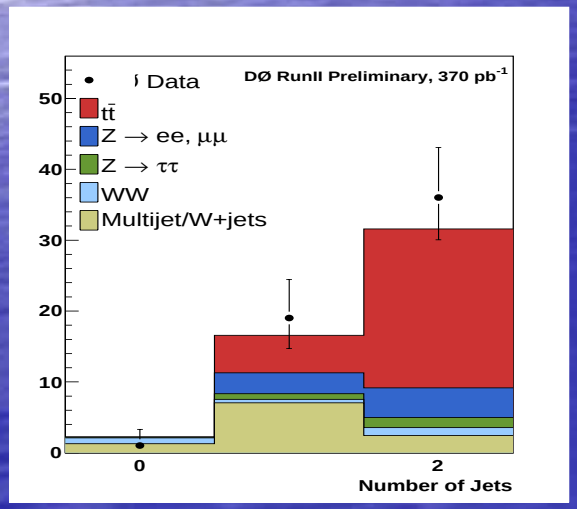
- Gain efficiency by requiring one well identified lepton and one track
- Loosen missing ET cuts
- Use *b*-tagging to reduce background
- Include events with one jet in cross section calculation



l+track

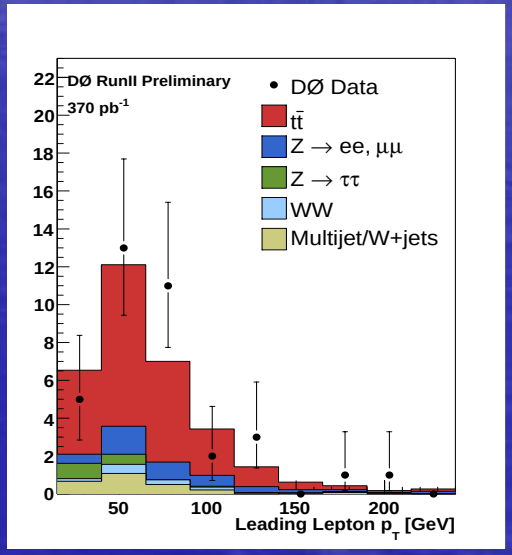
b-tag





Combined eμ and l+track

L = 370 pb^{-1}, m_{top} = 175 GeV

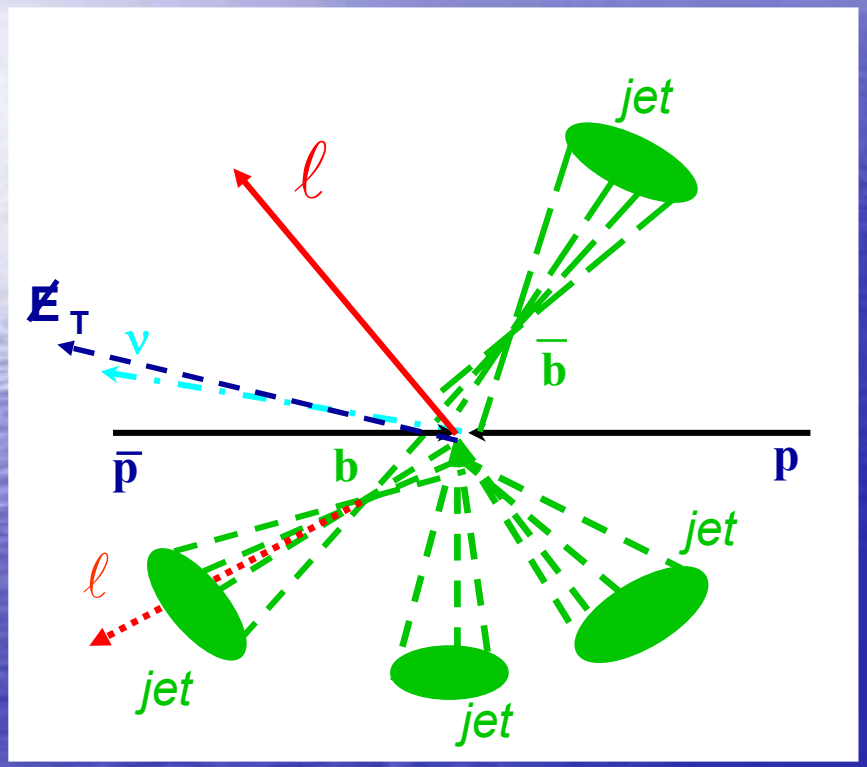


$$\sigma_{t\bar{t}} = 8.6^{+1.9}_{-1.7}(stat) \pm 1.1(syst) \pm 0.6(lumi)\, pb$$

Uncertainty ~25% with half luminosity of dilepton channel

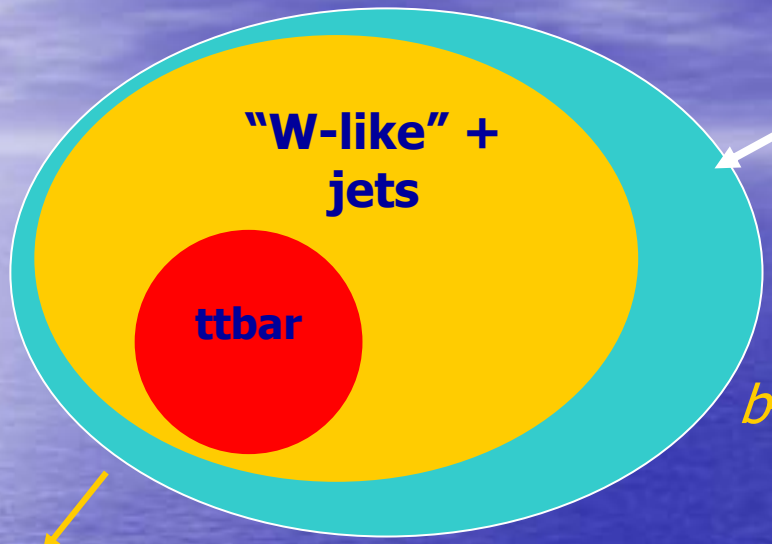
Lepton+jets channel

- Signature



- Selection
  - One high p_T isolated lepton
  - At least three high p_T jets
  - Large missing transverse energy
- Features:
  - Relatively high branching fraction
  - Manageable background
  - Perfect for studies of top properties

Sample composition



Multijet background due to fake isolated leptons determined from data

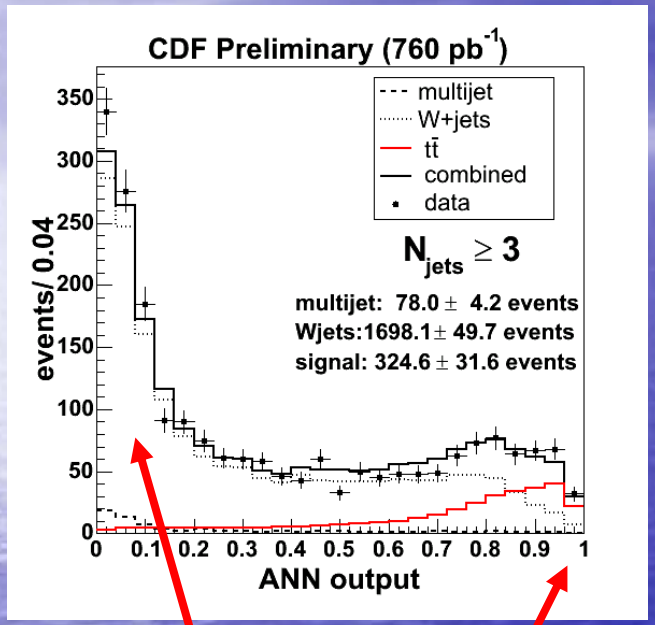
b-tagging

Signature of a *b* decay is:

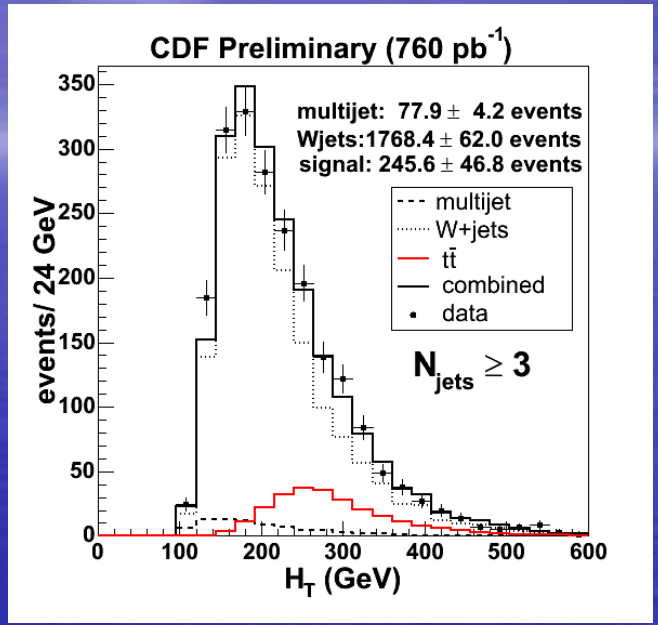
- lepton in jet (semileptonic decay)
- a displaced vertex
  - Forms long lifetime of B-hadrons ($c\tau \sim 450\mu m$, $L_{xy} \sim 3mm$)
  - S/B = 2:1 (3:1) $njet \geq 3$ ($njet \geq 4$)
  - ~60% signal efficiency

- S/B = 1:5 (1:1.5) $n_{jet} \geq 3$ ($n_{jet} \geq 4$)
- Due to large mass ttbar events are:
  - energetic
  - central
  - spherical
- Combine kinematic event information into a topological discriminant or Neural Network and perform fit to the data

Using event kinematics (ANN)



- 7 variables combined in ANN
- binned likelihood fit to ANN output
- extract ttbar, W and multijet
- multijet background is fixed in the fit to expected value



background

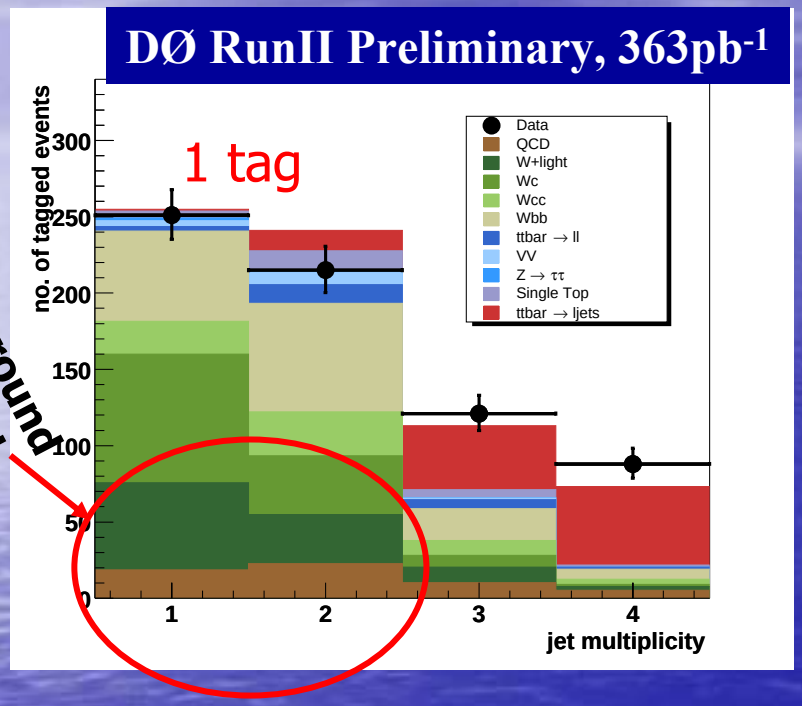
ttbar

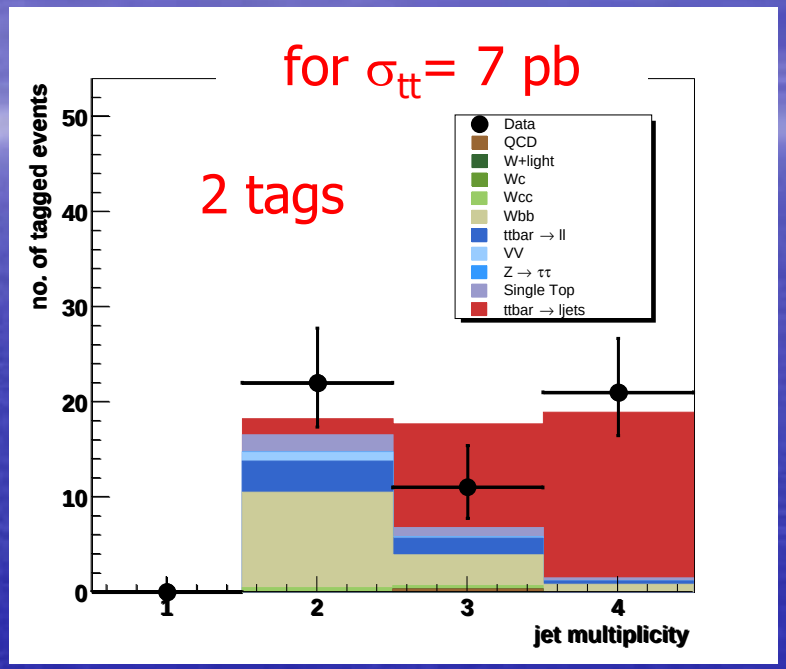
Statistical uncertainty is lower than systematic!

CDF Preliminary (760 pb^{-1})

Sample	Events	Fitted $t\bar{t}$	$\sigma(t\bar{t})$
$W+ \geq 3$ jets	2102	324.6 ± 31.6	$6.0 \pm 0.6 \pm 0.9$ pb
$W+ \geq 4$-Jet	461	166.0 ± 22.1	$5.8 \pm 0.8 \pm 1.3$ pb

Using *b*-jet tagging





- Perform fit in 8 channels: (e, μ, =3jet, ≥4jet, =1 *b*-tag, ≥2 *b*-tags)
- Gaussian term for each source of errors
- Each source affects the central value of the cross section

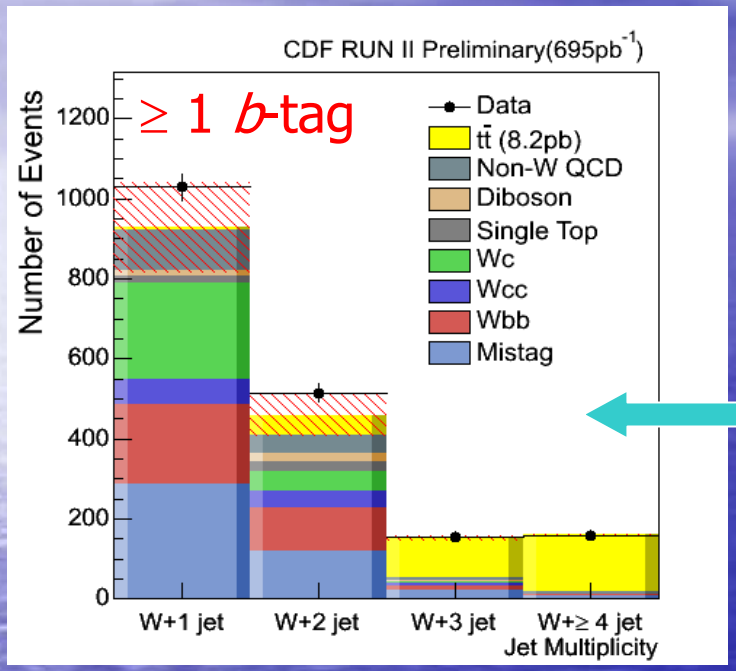
$$\sigma_{t\bar{t}} = 8.1^{+1.3}_{-1.2}(stat + syst) \pm 0.5(lumi)\,pb$$

Systematic and statistical uncertainties are similar ~ 11%, total 17%

Main sources:

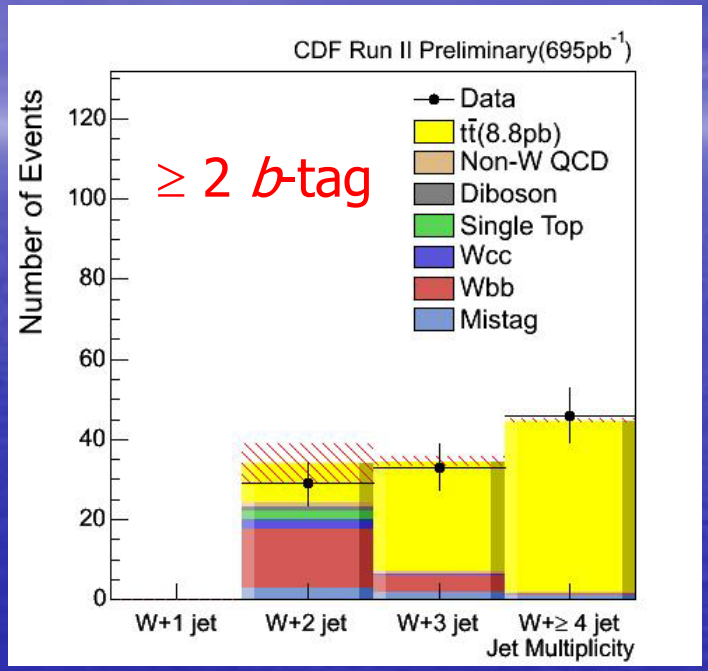
- JES and jet ID
- *b*-tagging efficiency in data
- W flavor composition
- Luminosity

Using b-jet tagging



Njet ≥ 3

Additional cut in ≥ 1 *b*-tag sample to reduce background: H_T>200 GeV

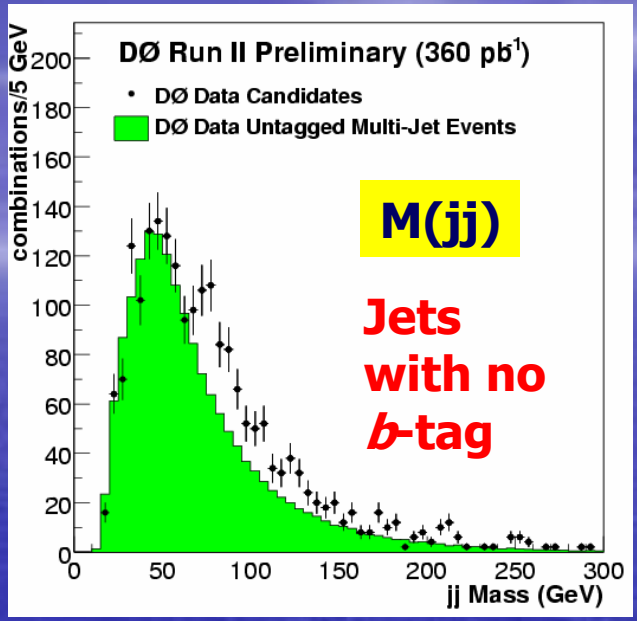


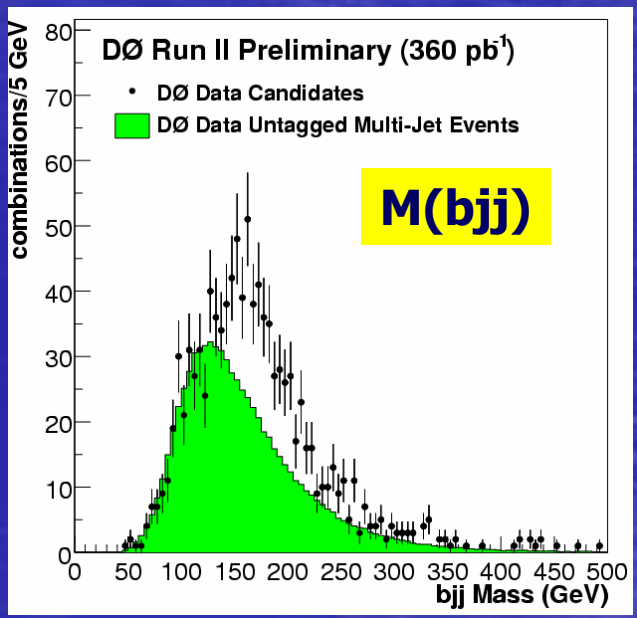
Results W + >=3 jets in ~ 700 pb^{-1}	Total ~ 14%
Cross Section with ≥1 *b*-tag with H_T >200 GeV	**8.2 ± 0.6 (stat.) ± 1.0 (sys.)**
Cross Section with ≥2 *b*-tag	**$8.8\ ^{+1.2}_{-1.1}$ (stat.) $^{+2.0}_{-1.3}$ (sys.)**

The most precise single measurement in the world!

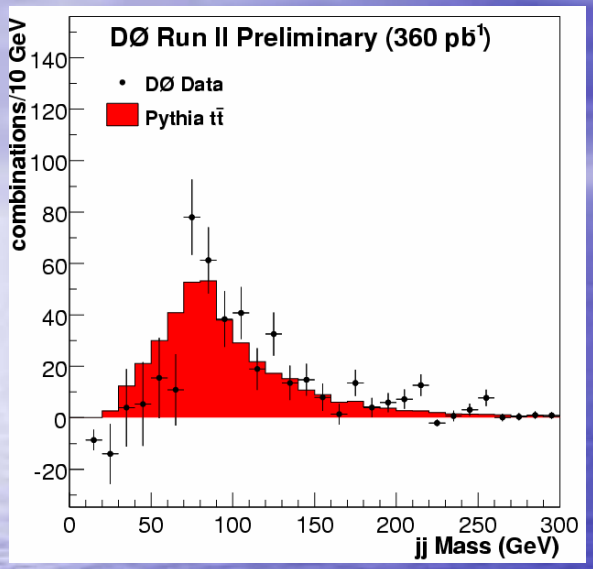
All jets channel

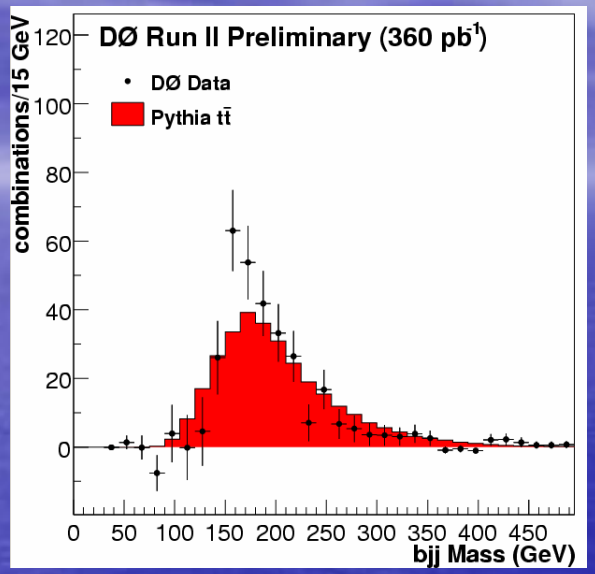
- Signature: 6 jets, 2 *b*-quark jets
  - Six jet multijet production rate is many orders of magnitude larger than ttbar
  - Impossible to extract signal without tagging *b*-jets
  - All decay products should be visible in the detector, no energetic neutrinos produced
- Directly reconstruct top quark decay
- Selection: 6 high p_T jets, at least two with p_T>45 GeV, exactly two are *b*-tagged with SVT
- Background – from data with random assignment of a jet to be a *b*-jet





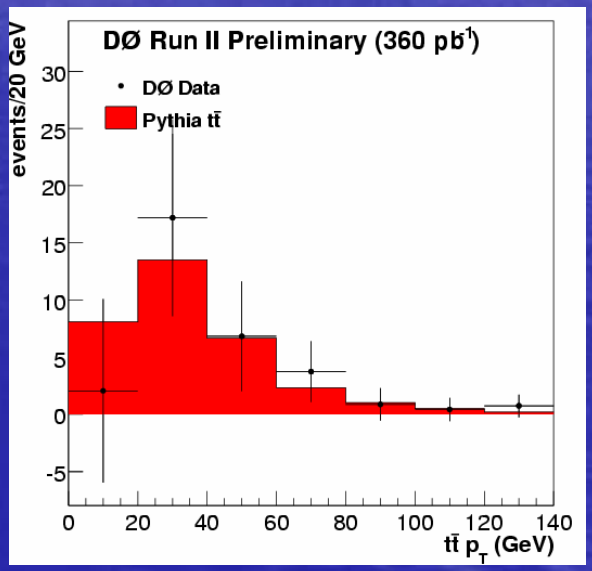
All jets channel

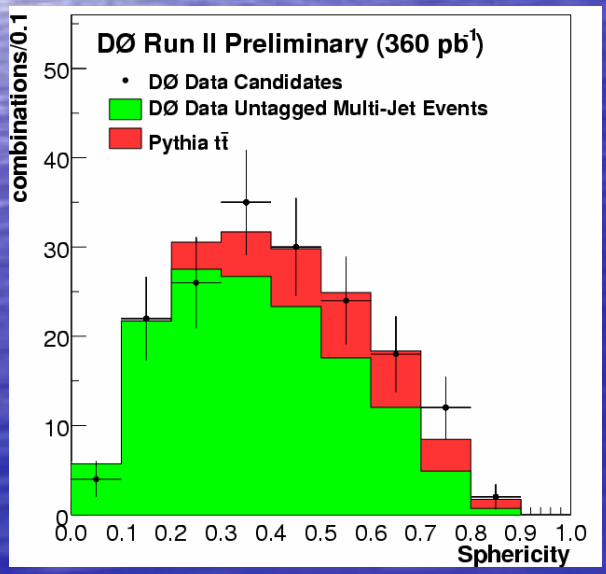




Reconstructed events can be used to extract

- Production rate
- Properties of ttbar system





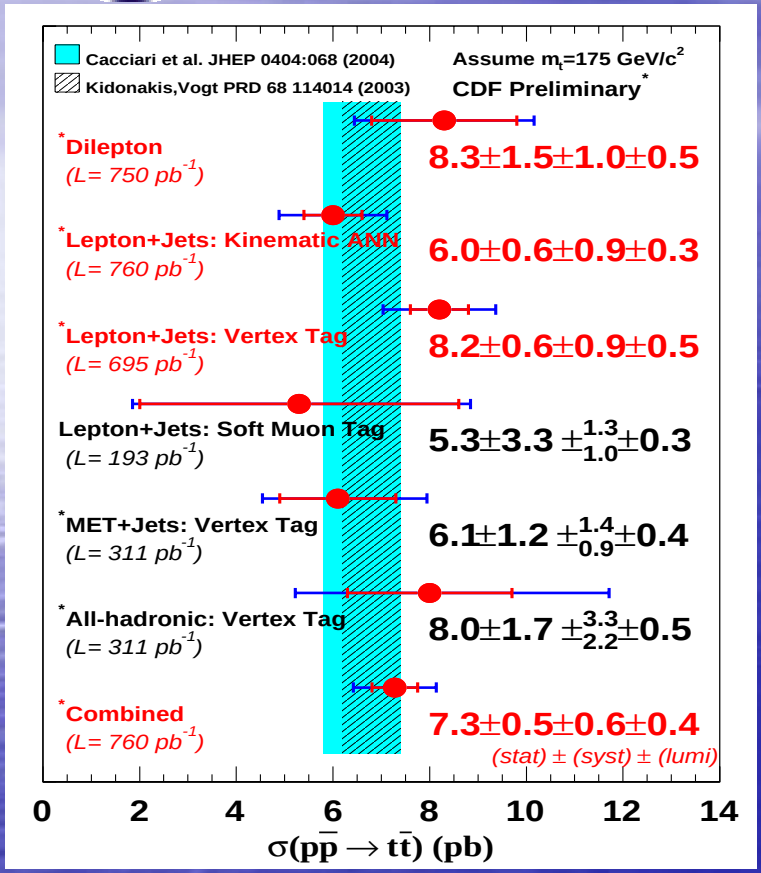
Main source of systematics:

- JES
- *b*-tagging efficiency
- background model

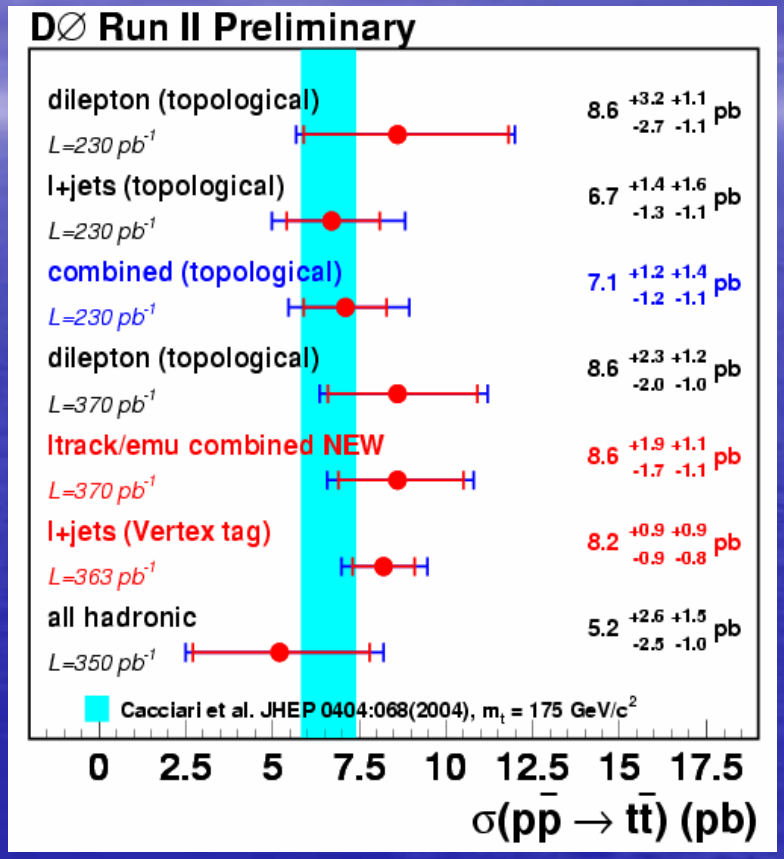
L = 360 pb^{-1}, m_{top} = 175 GeV

$$\sigma_{t\bar{t}} = 12.1 \pm 4.9(stat) \pm 4.6(syst)\, pb$$

Cross section summaries



For top quark mass of 175 GeV



Combined cross section from 6 channels, up to 760 pb^{-1}

12% relative uncertainty!

CDF: 7.3±0.5(stat)±0.6(syst)±0.4(lumi) pb

15% better than the best single measurement

Conclusion

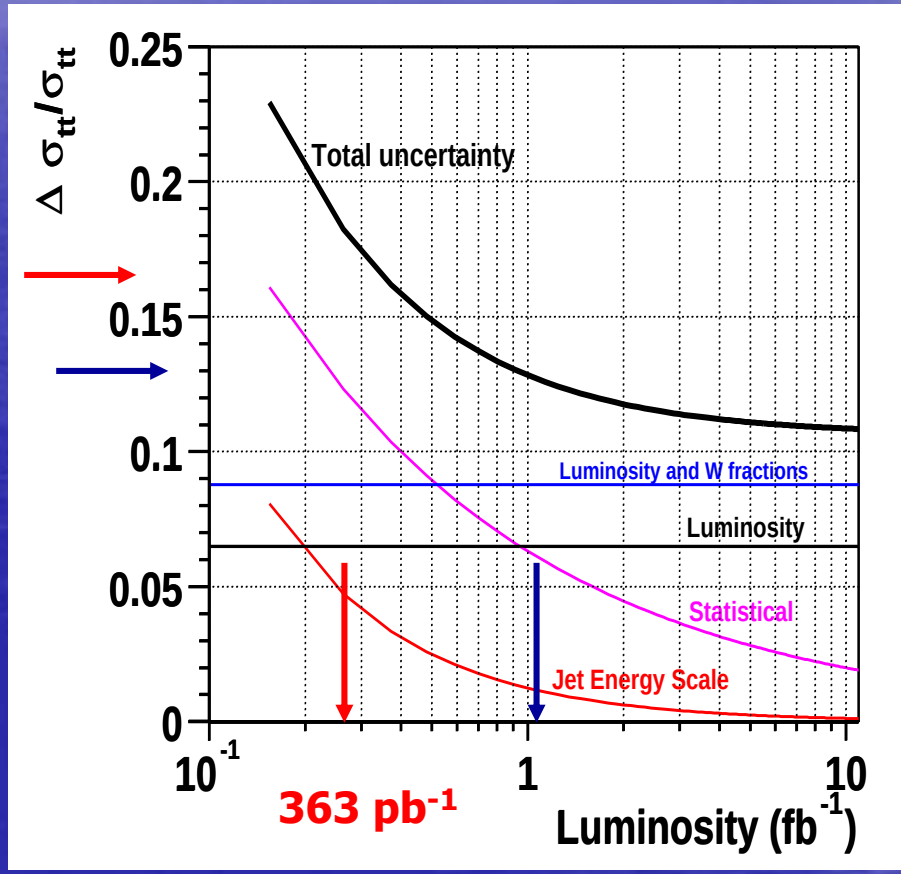
- New era in the top pair production cross section measurements:
  - the accuracy of the theoretical prediction has been achieved
  - statistical uncertainties are not dominant any more
  - reduction of systematic uncertainties becomes crucial
- A new tool for sensitive probing of the Standard Model

Backup slides

Glance into the future

- Assumptions:
  - Zero errors from limited MC statistics
  - Luminosity dependent and constant terms:
    - JES
    - *b*-tagging efficiency
    - Lepton identification
- Limiting factors:
  - Luminosity (6.5%)
  - Heavy flavor fractions (6%)
- Solutions:
  - Luminosity from W's (2-3%)
  - Measure ratio of ttbar to W cross section
  - Use large data sets to constrain model assumptions (W fractions, gluon radiation, …)
  - Combine channels

Total projected error / exp on l+jets/btag channel



ANN analysis

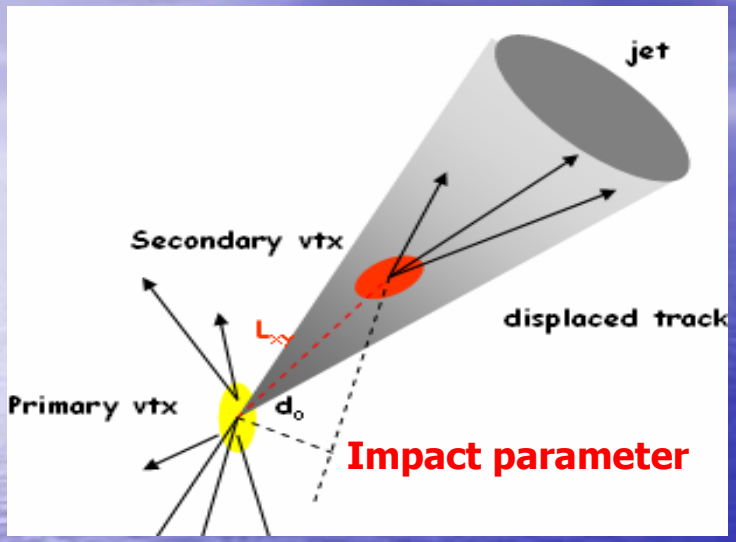
- Feed-forward perceptron with one intermediate layer and one output node
- Training
  - 5000 Pythia ttbar
  - 5000 Alpgen W+jets
  - Other sources not considered in training
- Default JETNET back-propagation training
- 7 hidden nodes

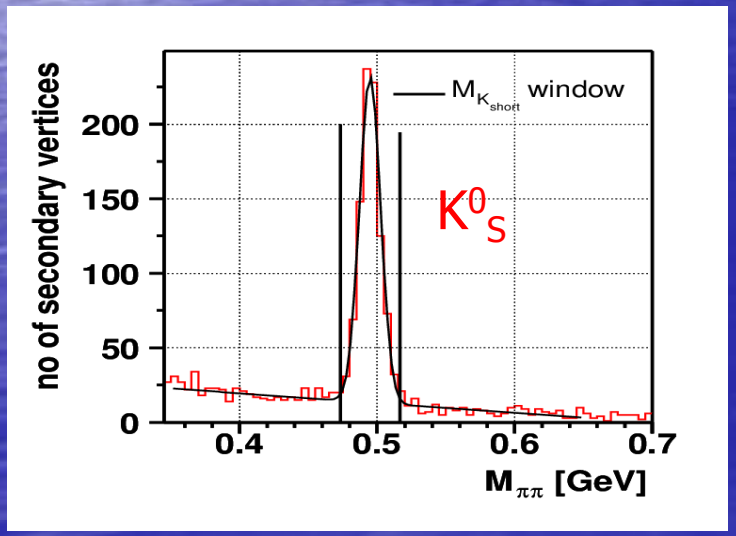
- 20 variables studied, 7 have been chosen
  - Total transverse energy
  - Aplanarity
  - Minimum dijet mass
  - Maximum jet rapidity
  - Minimum dijet separation
  - Sum of transverse energy for all jets beyond the third
  - Ratio between jet longitudinal momenta and the jet transverse energy
- W-like shape include:
  - W+3p, Wbb+1p
  - Z->ll
  - W->$\tau\nu$+2p, WW+1p
  - WZ
  - Single top

All jets analysis

- Two jets with p_T>45 GeV and *b*-tag
- Other – no tag
  - 2 p_T>20 GeV
  - 2 p_T>15 GeV
- JES uncertainty
  - Relative data-MC scale from W mass peak
- Background
  - Two jets are chosen at random and defined to be b-jets (p_T>45 Gev)
  - Two weights:
    - p_T dependent from NTRF
    - ΔR(jj) dependent
- Normalization
  - Scale background M(jj) distribution to M(bjj) so that the area with M(jj)<65 GeV is equal
  - Adjust downwards to minimize large negative deviations in the background-subtracted sample
  - Reduce by 1% increments until the sum of the negative bins in the bjj background-subtracted sample is less than half of significance

b-tagging algorithm - SVT

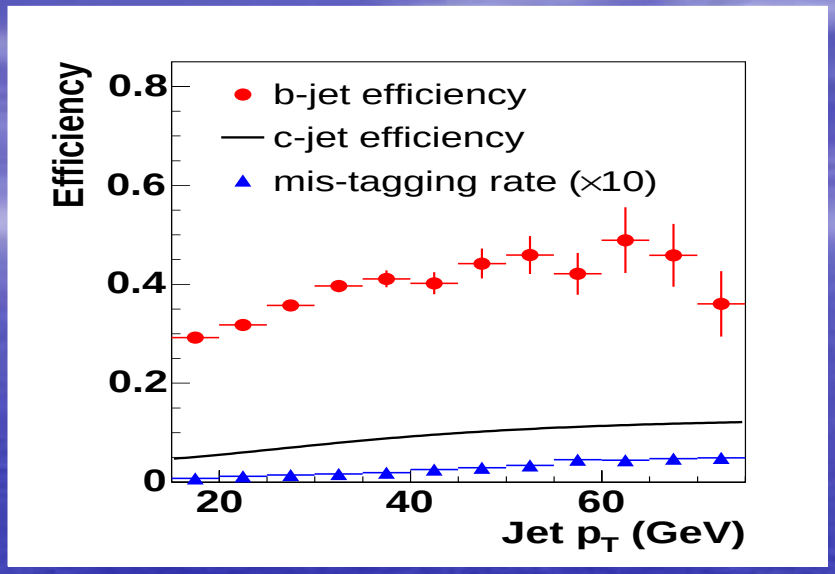




- Reconstructs secondary vertex
  - ≥2 tracks with $p_T \geq 1$GeV, ≥1 SMT hit, impact parameter significance >3.5
- Remove tracks associated with K^0_S, Λ^0 and photon conversions ($\gamma \rightarrow e^+e^-$)
- **Positive tag:**
  - Secondary vertex within a jet with a decay length significance $L_{xy}/\sigma_{Lxy}>7$
- **Negative tag:**
  - Secondary vertex within a jet with a decay length significance $L_{xy}/\sigma_{Lxy}<-7$ (due to resolution effects)

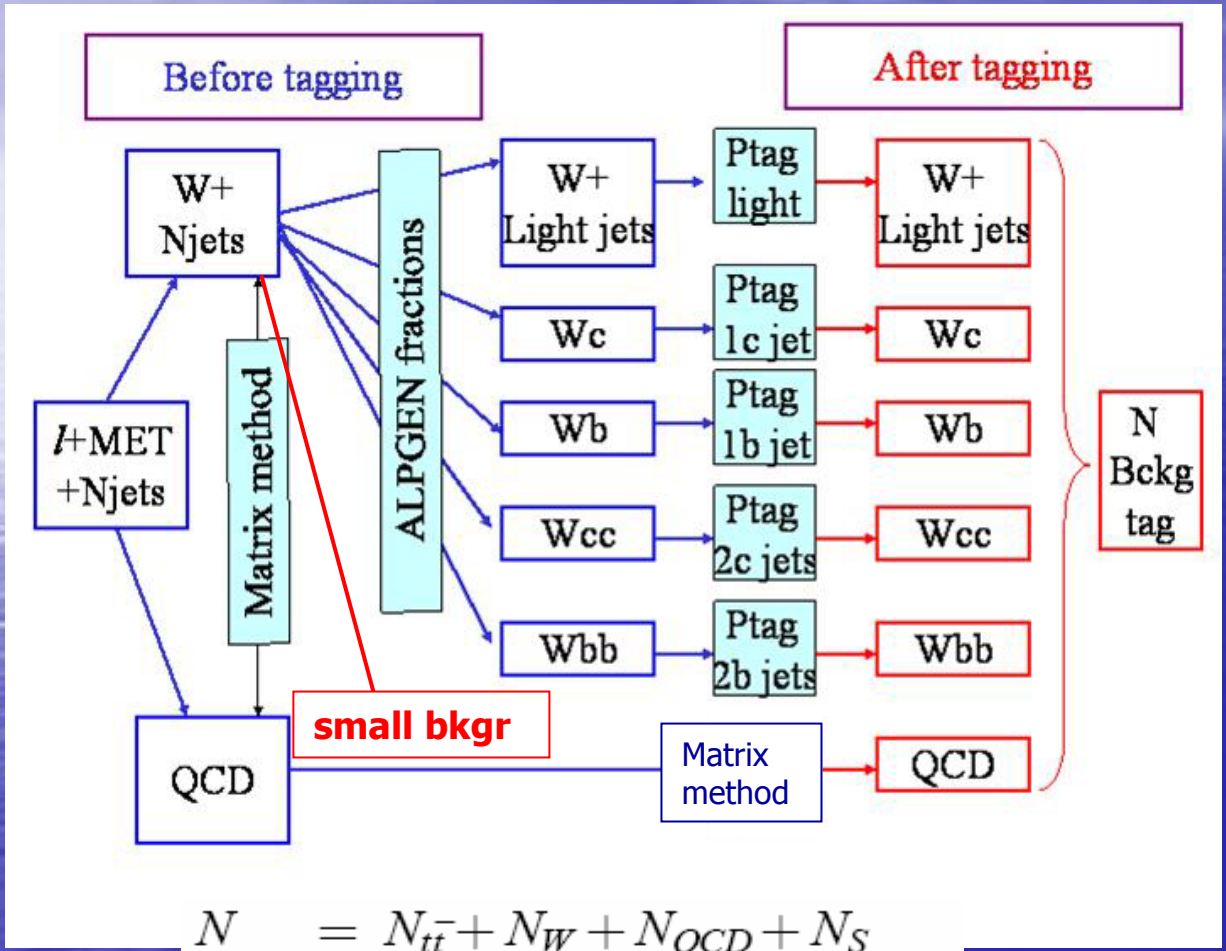
Tagging rates

- *b*-tagging efficiency
  - **Measured in dijet data events for jets with muon inside**
  - Compare two samples with different heavy flavor content
  - Tag jets with two tagging algorithms SVT and SLT (SLT = soft muon with p_T^{rel}> 0.7 GeV inside a jet)
  - Solve system of 8 eqs in bins of jet p_T and y to extract semileptonic *b*-tagging efficiency
  - Use MC to correct measured efficiency to inclusive one



- Light tagging rate
  - Measure negative tagging rate in dijet events (low missing E_T)
  - Correct for long-lived particles in light jets
  - Heavy flavor contribution in dijet events
- *c*-tagging rate
  - From MC corrected with the SF derived for *b*-tagging

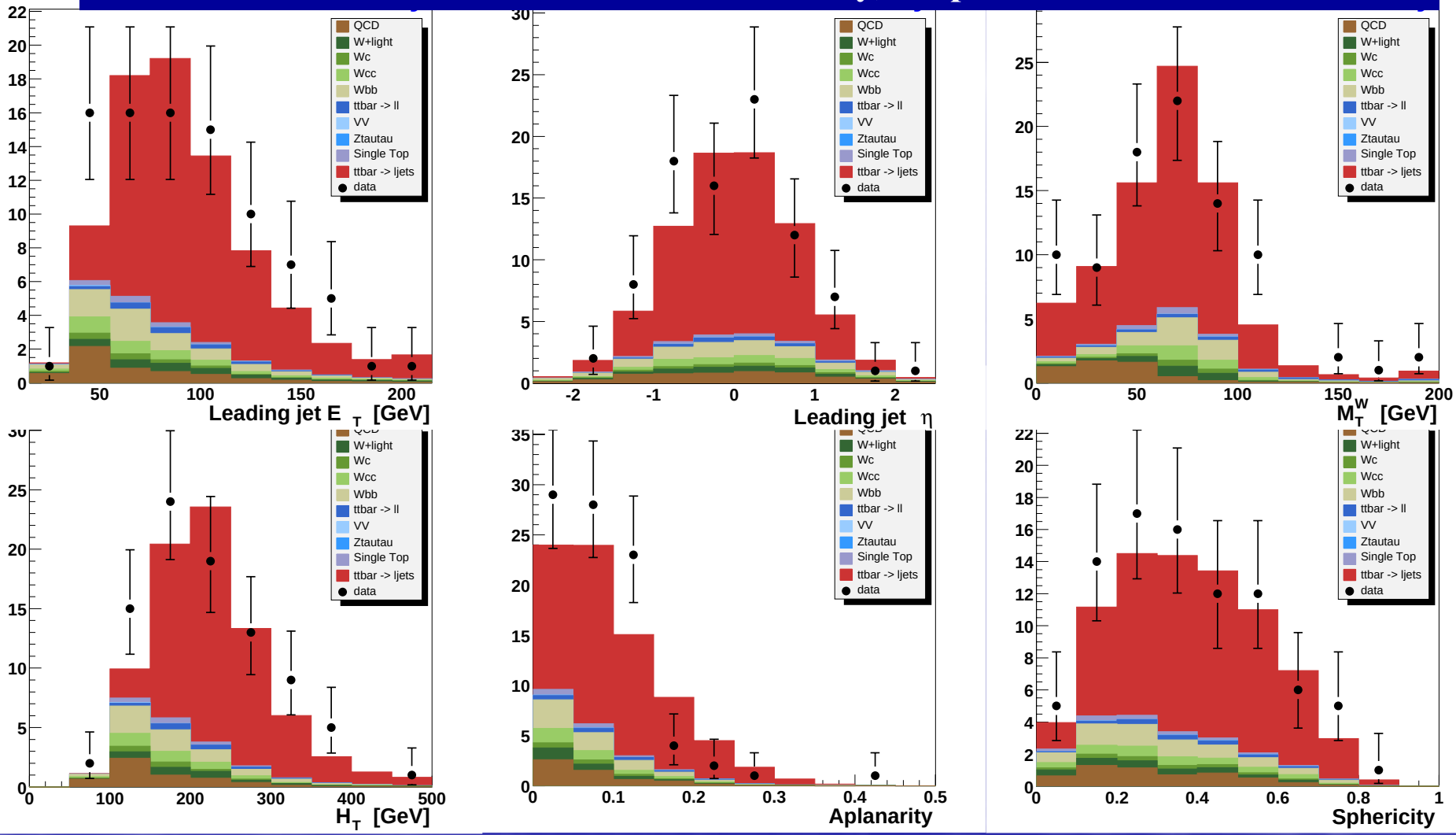
Backgrounds



$$N = N_{t\bar{t}} + N_W + N_{QCD} + N_S$$

$$N^{tag} = N_{t\bar{t}}^{tag} + N_W^{tag} + N_{QCD}^{tag} + N_S^{tag}$$

- Calculate QCD (non-W) contribution from Matrix Method
- Subtract small backgrounds (single top, diboson, $Z \rightarrow \tau\tau$) using known cross sections
- Predict number of background events after tagging
- Interpret excess in observed tagged events with ≥ 3 jets over predicted background as ttbar signal

Kinematics of l+lets tagged sample

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