Measurement of the $t\bar{t}$ production cross section at DØ using all-hadronic events

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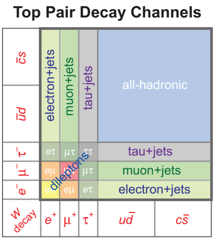
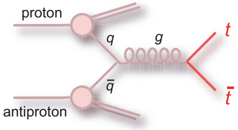
For the DØ Collaboration

Motivation

- Top quark as the heaviest elementary particle provides a unique window to precision tests of Quantum Chromodynamics.
- **The multijet channel** has the largest branching ration and reduced sensitivity to Electroweak $W/Z+$jets and instrumental backgrounds.



- Since there is no missing neutrino from the hard scatter process, one can fully reconstruct the $t\bar{t}$ system and also individual top quarks.



- The challenge in channels involving hadrons is the huge multijet background coming from QCD processes.

The Multijet Channel

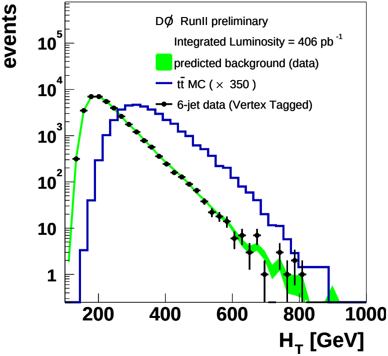
- We present two analyses: Neural Network (to be published) and Topological (preliminary).
- The data sample was collected using dedicated multijets triggers corresponding to the integrated luminosity of about 410 pb^{-1}.
- Require one or more jets marked as originating from a b quark by the Secondary Vertex Tagger.
- We include hadronic decay modes of τ leptons from W's.
- Preselected data can be taken as background sample.
- Still, such BG is Signal contaminated, and we correct for the effect.
- We suppress the background from mutijets events coming from multiple interactions.

Neural Net Analysis: Sample and Preselection

- At least six jets (Run II Cone $\mathcal{R} = 0.5$).
- Each jet of $p_T > 15$ GeV and rapidity $|y| < 2.5$.
- At least one jet marked as originating from a b quark.
- Further background removed by an artificial Neural Network approach and a cut on it discriminant.
- Probability to tag a background event derived from per-jet probabilities measured in the preselected sample with $n_{\text{tags}} \leq 1$, b-tagging efficiency measured in μ-tagged data dijet events.
- We use recently updated DØ luminosity constant and assume top mass of 175 GeV for the cross section extraction.

Topological Variables

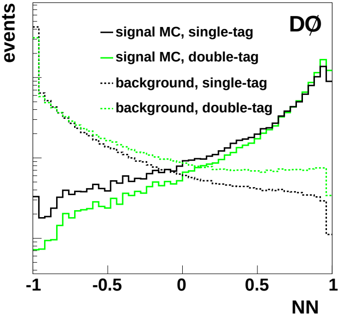
- Six topological variables chosen as input for the artificial Neural Network:



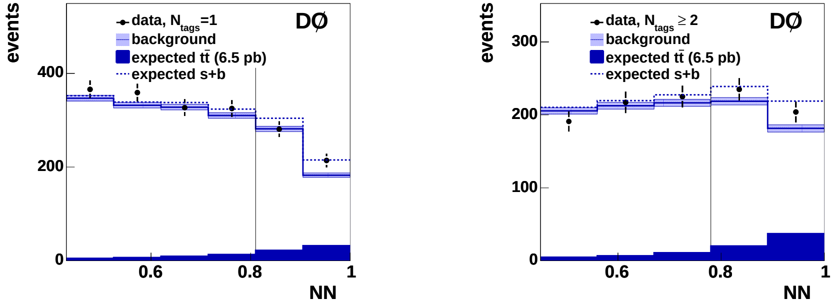
- $H_T \equiv \sum_{4\text{jets}} E_T$, Aplanarity $\mathcal{A}$
- Geometrical mean of E_T's of the 5$^{\text{th}}$ and 6$^{\text{th}}$ jet.
- Jets' $\langle \eta^2 \rangle$.
- The second smallest dijet mass
- $\mathcal{M} \equiv \frac{(M_{W1} - M_W)^2}{\sigma_W^2} + \frac{(M_{W2} - M_W)^2}{\sigma_W^2} + \frac{(M_{t_2} - M_{t_1})^2}{\sigma_t^2}$

Neural Net Approach

- The Neural net (NN) was trained on a subsample of randomly selected untagged data.
- NN output used to select events enriched in signal by NN cut NN$>$ 0.81 (0.78) for Single (Double) tagged analysis.
- Dashed: Background, Solid: Signal MC. **Single tag**, **Double tag**.



Neural Network Analysis: Result



Single Tag   Double Tag

$$\sigma_{t\bar{t}} \equiv \frac{N_{\text{obs}} - N_{\text{BG}}}{\epsilon_{t\bar{t}} \cdot \mathcal{L} \cdot (1 - \epsilon_{\text{BG}})}$$

- $\epsilon_{t\bar{t}}$: signal efficiency, $(1 - \epsilon_{\text{BG}})$: correction to the BG contaminated by signal.

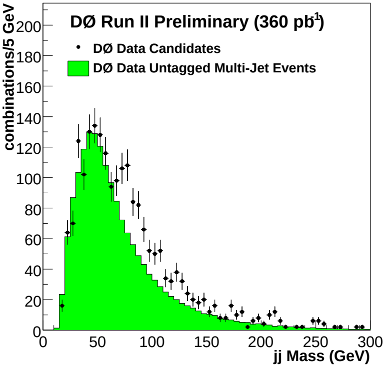
$$\sigma_{t\bar{t}} = 4.5^{+2.0}_{-1.9}\,(\text{stat.})\,^{+1.1}_{-1.1}\,(\text{syst.}) \pm 0.3\,(\text{lumi})\,\text{pb}$$

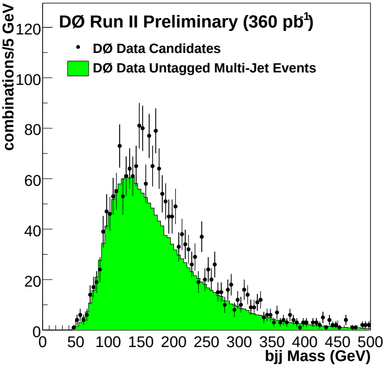
Topological Analysis: Events Selection

- Require at least two jets with $p_T > 45\,\mathrm{GeV}$, other two jets with $p_T > 20\,\mathrm{GeV}$, the remaining jets with $p_T > 15\,\mathrm{GeV}$.
- All jets are required to be within 2.4 in |rapidity|.
- Recently updated DØ luminosity constant has not been propagated to this preliminary analysis.
- At least two jets with $p_T > 45\,\mathrm{GeV}$ required to be identifies as b-jets by the Secondary Vertex Tagger.
- The above criteria define the **Loose** event sample.
- In addition, topological variables Aplanarity ($\mathcal{A}$), Centrality ($\mathcal{C}$) and Sphericity ($\mathcal{S}$); and the angular correlation between the two b-tagged jets $\Delta\mathcal{R}_{b\bar{b}}$ have been used to define Medium and Tight samples:

Medium: $\mathcal{A} > 0.05$, $\mathcal{C} > 0.6$, $\mathcal{S} > 0.2$, $\Delta\mathcal{R}_{b\bar{b}} > 1$.
Tight: $\mathcal{A} > 0.05$, $\mathcal{C} > 0.7$, $\mathcal{S} > 0.5$, $\Delta\mathcal{R}_{b\bar{b}} > 2$.

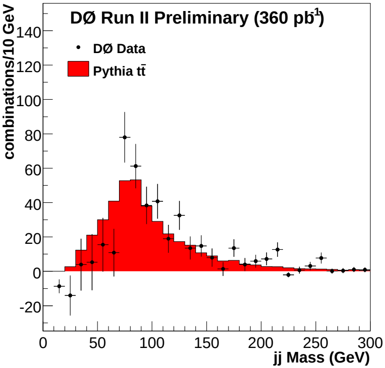
Mass Distributions - Loose



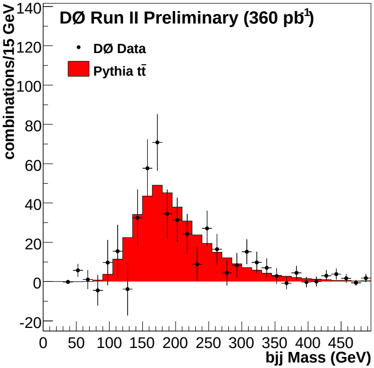


- The light jets invariant mass distribution m_{jj}.
- Invariant mass of a b-jet and two light jets m_{bjj}.
- **Preselected Data** with overlaid expected **Background**.
- All b-jets assignment respecting permutations included.

Background Subtracted m_{bjj} Distributions - Loose



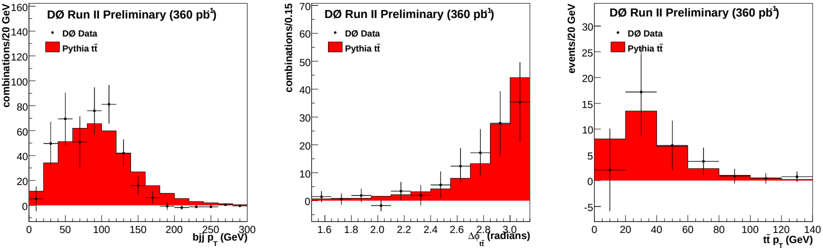
m_{jj}



m_{bjj}

- First comparison of candidate events to the Signal MC ($t\bar{t}$ Pythia).

BG-Subtracted Distributions Compared to Signal MC



- The analysis provides a unique window to more complex $t\bar{t}$ system properties.
- First look at differential distributions after the background subtraction, compared to Signal MC.
- Combinatorial background not subtracted.

Cross Section Extraction

- The cross section was extracted as

$$\sigma = \frac{1}{\mathcal{L}} \frac{N^{\text{candidates}} - N^{\text{background}}}{\epsilon_{SB}\, \epsilon_{t\bar{t}}\, \epsilon_{\text{SVT}}}$$

where

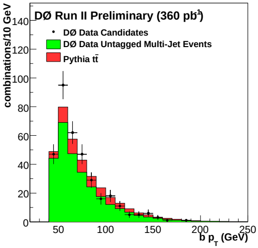
- ϵ_{SB} is the signal fraction surviving the background subtraction.
- $\epsilon_{t\bar{t}}$ is the signal selection efficiency, determined on Pythia Tune A $t\bar{t}$ Monte Carlo with $m_t = 175\,\text{GeV}$.
- $\epsilon_{\text{SVT}} = 0.62 \pm 0.11$ is the b-tagging efficiency scale factor between Data and MC.
- In addition, the Jet Energy Scale in MC was scaled by $1.05^{+0.07}_{-0.05}$ to match the W mass peak position in Data.

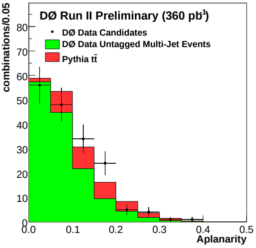
Signal Events, Efficiencies and Cross Sections

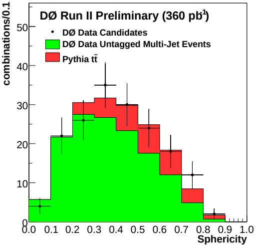
Sample	$N^{\text{candidates}}$	$N^{\text{background}}$	$\epsilon_{SB}[\%]$	$\epsilon_{t\bar{t}}[\%]$	σ [pb]
Loose	173 ± 13	140.4 ± 0.8	80	1.51 ± 0.03	12.1 ± 4.9
Medium	96 ± 9	60.7 ± 0.5	82	1.17 ± 0.02	11.9 ± 4.3
Tight	14 ± 4	5.6 ± 0.1	79	0.37 ± 0.01	12.9 ± 5.8

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

Sanity plots (**Signal MC**, **BG**, **Data**):



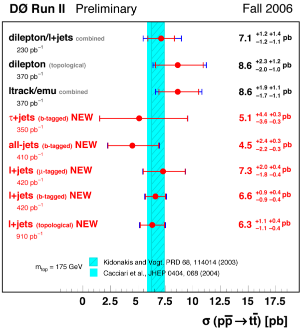




Conclusions

- **The $t\bar{t}$ production cross section in the multijet channel has been measured by the DØ Collaboration using two different approaches as:**

- **Neural Net**: $\sigma_{t\bar{t}} = 4.5^{+2.0}_{-1.9}\,(\text{stat.})\,^{+1.1}_{-1.1}\,(\text{syst.}) \pm 0.3\,(\text{lumi})\,\text{pb}$
- **Topological**: $\sigma_{t\bar{t}} = 12.1 \pm 4.9\,(\text{stat.}) \pm 4.6\,(\text{syst.})\,\text{pb}$



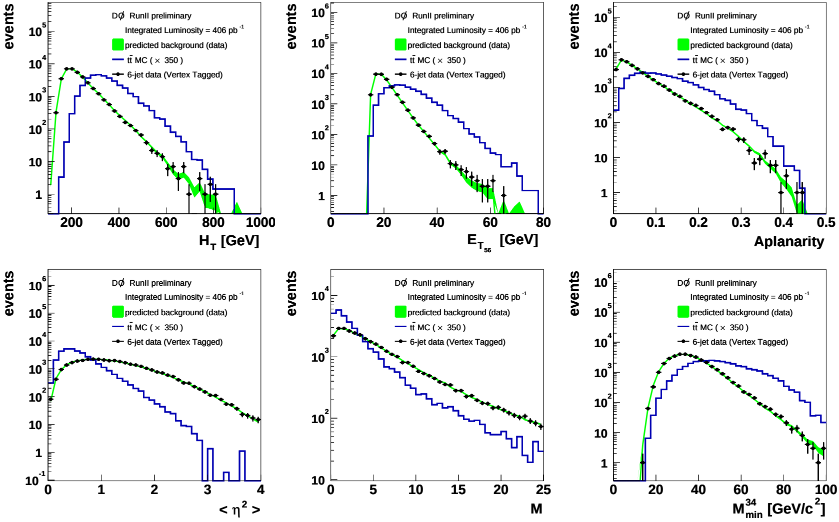
- **This is in consistency with the Standard Model.**

- **More advanced analysis is ongoing on the $1\,\text{fb}^{-1}$ sample at the DØ!**

NN: Topological Variables I

- Six optimised topological variables have been chosen as input for the artificial Neural Network:
- $H_T \equiv \sum_{\text{4jets}} E_T$.
- Aplanarity $\mathcal{A}$ derived from normalised momentum tensor.
- $E_{T_{5,6}}$, the geometrical mean of E_T's of the 5$^{\text{th}}$ and 6$^{\text{th}}$ jet.
- $\langle \eta^2 \rangle$, the weighted RMS of 6 leading jets.
- $M^{3,4}_{\text{min}}$, the second smallest dijet mass in the event.
- χ^2-like variable
  $\mathcal{M} \equiv \frac{(M_{W1}-M_W)^2}{\sigma_W^2} + \frac{(M_{W2}-M_W)^2}{\sigma_W^2} + \frac{(M_{t_2}-M_{t_1})^2}{\sigma_t^2}$
  computed for every possible (b-tag consistent) permutation, the lowest $\mathcal{M}$ used only.

NN: Topological Variables II



Background Modelling

- The probability to tag a background jet (Tag Rate Function, TRF) has been measured on preselected data as these are dominated by BG.
- Probability to tag an event is derived from per-jet probabilities parametrised in p_T, y, ϕ, and Primary Vertex z position (along the beam axis), measured in preselected data with $n_{\text{tags}} \leq 1$, b-tagging efficency obtained from μ-tagged data dijet events.
- As the flavour content changes, TRF's are derived in four $H_T \equiv \sum_{\text{jets}} E_T$ bins.
- Multijet BG originating from $g \rightarrow b\bar{b}$ splitting removed by a $\Delta\mathcal{R} > 1.5$ between two tagged jets in $\eta \times \phi$ space.

NN: Neural Net Approach

- The Neural net (NN) was trained on a small sample of randomly selected untagged data ($\approx 2\%$), in addition a random number $\in (0,1)$ was required to be below the event tagging probability.
- Similarly, Signal MC events were randomly selected (but no tagging veto applied).
- `JETNET` program used for training.
- NN output was used to select events enriched in signal by NN cut NN> 0.81 (0.78) for Single (Double) tagged analysis, which was optimised to minimise the fractional error

$$\sigma_{\text{frac}} \equiv \frac{\sqrt{S_{\text{exp}} + B_{\text{exp}}}}{S_{\text{exp}}}$$

derived using expected number of events obtained from MC and TRF's.

NN: Result

- The master cross section formula:

$$\sigma_{t\bar{t}} \equiv \frac{N_{\text{obs}} - N_{\text{TRF}}}{\epsilon_{t\bar{t}} \cdot \mathcal{L} \cdot \left(1 - \frac{\epsilon_{\text{TRF}}}{\epsilon_{\text{btag}}}\right)}$$

- $\epsilon_{t\bar{t}}$ is the signal efficiency (including hadronic τ decays).
- $\left(1 - \frac{\epsilon_{\text{TRF}}}{\epsilon_{\text{btag}}}\right)$ is the correction to the bias introduced by using the entire sample ("contaminated by signal") to predict the number of BG events.
- ϵ_{btag} is the efficiency to tag the $t\bar{t}$ event.

NN: Result

- The cross section was extracted by minimising the Poisson negative log likelihood function

$$-2\ln Q = -2(N_{\text{obs}}\ln(N_{\text{exp}}) - N_{\text{exp}})$$

where

$$N_{\text{exp}} = \epsilon_{t\bar{t}}\sigma_{t\bar{t}}\mathcal{L}\left(1 - \frac{\epsilon_{\text{TRF}}}{\epsilon_{\text{btag}}}\right) + N_{\text{TRF}}$$

- The combined cross section in single and double tagged events has been measured as

$$\sigma_{t\bar{t}} = 4.5^{+2.0}_{-1.9}(\text{stat})^{+1.1}_{-1.1} \pm 0.3(\text{lumi})\,\text{pb}$$

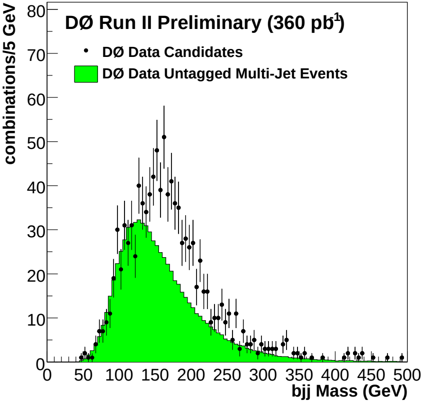
assuming top mass of $175\,\mathrm{GeV}$.

Topo: Background Normalisation

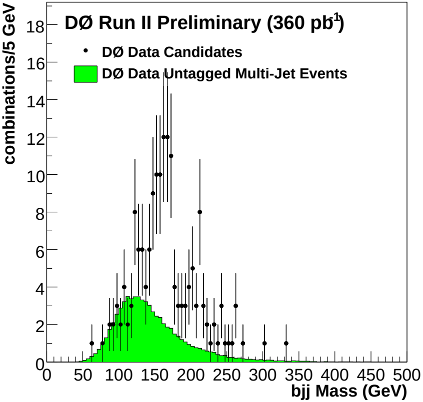
- Background has been normalised using m_{jj} distribution to match the integral below $m_{jj} < 65\,\mathrm{GeV}$ in all candidate events distribution.
- Signal events also contribute to this integral.
- Therefore, normalisation factor was further reduced in 1% steps until sum of negative bins in the m_{bjj} distribution was smaller than a significance as follows:

$$\frac{1}{2}\sum_{i=1}^{n_{\text{bins}}}\left[|N_{bjj}^{\text{signal}}(i)| - N_{bjj}^{\text{signal}}(i)\right] \leq \frac{1}{2}\frac{N_{bjj}^{\text{signal}}}{\sqrt{N_{bjj}^{\text{candidates}}}}$$

Topo: m_{bjj} Distributions

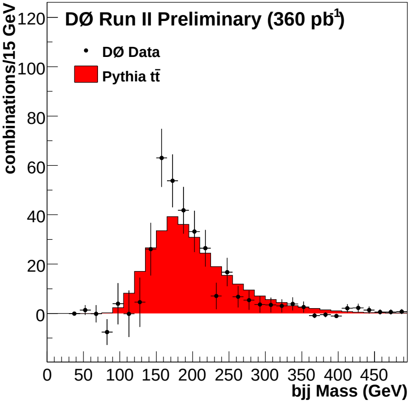


Medium

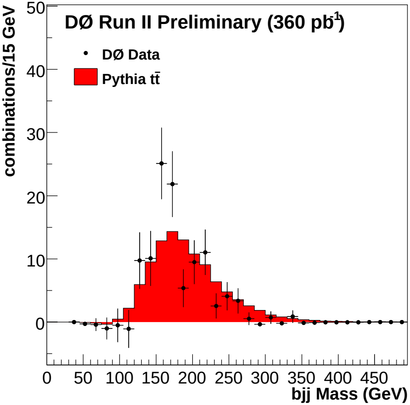


Tight

Topo: Background Subtracted m_{bjj} Distributions



Medium



Tight

Topo: Distributions Compared to Signal MC and Multijet BG