Measurement of $t\bar{t}$ production in the tau + jets channel using $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV


We present a measurement of the $t\bar{t}$ production cross section multiplied by the branching ratio to tau lepton decaying semi-hadronically ($\tau_h$) plus jets, $\sigma(pp \to t\bar{t} + X) \cdot \text{BR}(t\bar{t} \to \tau_h + \text{jets})$, at a center of mass energy $\sqrt{s} = 1.96$ TeV using 1 fb$^{-1}$ of integrated luminosity collected with the D0 detector. Assuming a top quark mass of 170 GeV, we measure $\sigma_{t\bar{t}} \cdot \text{BR}_{\tau_h} = 0.60^{+0.22}_{-0.22} \text{(stat)}^{+0.15}_{-0.14} \text{(syst)} \pm 0.04 \text{ (lumi)}$ pb. In addition, we extract the $t\bar{t}$ production cross section using the $t\bar{t} \to \tau_h + \text{jets}$ topology, with the result $\sigma_{t\bar{t}} = 6.9^{+1.2}_{-1.2} \text{(stat)}^{+0.7}_{-0.7} \text{(syst)} \pm 0.4 \text{ (lumi)}$ pb. These findings are in good agreement with standard model predictions and measurements performed using other top quark decay channels.

PACS numbers: 13.85.Lg, 13.85.Ni, 13.85.Qk, 14.65.Ha

The decay $t \to Wb \to \tau\nu\tau b$ provides a unique laboratory in which to investigate the properties of the third generation fermions — the top ($t$) and bottom ($b$) quarks, the tau lepton ($\tau$), and the tau neutrino ($\nu_\tau$) — in a single process. In the standard model (SM), the $t$ quark branching ratio (BR) to a $W$ boson and a $b$ quark is $\approx 100\%$, and the final state is determined by the SM BR of the $W$ boson. Since the $t$ is the heaviest quark and the $\tau$ the heaviest lepton, any non-SM mass- or flavor-dependent couplings could change the $t$ quark decay rate into final states with $\tau$ leptons. Therefore, any deviation in the BR of $t \to \tau\nu\tau b$ from that predicted by the SM can be an indication of non-SM physics. For example, in the Type 2 two-Higgs doublet model [1], such as required by the minimal supersymmetric standard model [2], the $t$ quark can have a significant BR to a charged Higgs bo-

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*with visitors from *Augustana College, Sioux Falls, SD, USA, *The University of Liverpool, Liverpool, UK, *SLAC, Menlo Park, CA, USA, *ICREA/IFAE, Barcelona, Spain, *Centro de Investigacion en Computacion - IPN, Mexico City, Mexico, *ECFM, Universidad Autonoma de Sinaloa, Culiacan, Mexico, and *Universität Bern, Bern, Switzerland.
son ($H^\pm$) and a $b$ quark if $m_{H^\pm} < m_t - m_b$. For large values of $\tan \beta$, the ratio of the vacuum expectation values of the two Higgs doublets, the charged Higgs boson preferentially decays to $\tau \nu_\tau$, thereby increasing the BR of $t \rightarrow \tau \nu_b$ relative to the SM expectation and leading to a larger measured $\sigma(pp \rightarrow t\bar{t} + X) \cdot \text{BR}(t\bar{t} \rightarrow \tau + \text{jets})$ compared to the value expected from SM assumptions for the BRs and the production cross section $\sigma$. Other possible non-SM processes that can enhance the $t \rightarrow \tau$ lepton BR are $R$-parity violating decays of the $t$ quark in supersymmetric models and new $Z'$ bosons with non-universal couplings.

In this article, we present the first measurement of $t\bar{t}$ production in the $\tau + \text{jets}$ final state using a data sample corresponding to an integrated luminosity of $1 \text{ fb}^{-1}$ collected with the D0 detector at the Fermilab Tevatron $p\bar{p}$ Collider operating at a center of mass energy $\sqrt{s} = 1.96 \text{ TeV}$. This measurement uses semi-hadronic $\tau$ lepton decays, with BR $\approx 65\%$, as secondary electrons and muons from $\tau$ lepton decays are difficult to distinguish from primary electrons and muons resulting from $W$ decays. Previous measurements of $t\bar{t}$ production using $\tau$ leptons in the final state have been performed by the D0 $[9]$ and CDF $[10]$ collaborations in the $\tau_\pm + \ell$ channel, where $\tau_\pm$ represents semi-hadronic $\tau$ lepton decay modes and $\ell$ represents either an electron or a muon.

We apply the following preselection requirements: events must satisfy a multijet trigger requiring at least four jets; this is the same trigger used in the $t\bar{t}$ cross section measurement in the all-hadronic decay mode $[11]$. Reconstructed events are required to have missing transverse energy $E_T \geq 15 \text{ GeV}$ and $E_T$ significance $\geq 3$, where the $E_T$ significance is a measure of the likelihood that the $E_T$ arises from physical sources rather than fluctuations in the measurement of the energies of the physics objects (jets, muons, electrons and unclustered energy) $[12]$. Each event must also have at least four reconstructed jets with pseudorapidity $|\eta| < 2.5$ and transverse momentum $p_T > 15 \text{ GeV}$ using an iterative jet cone algorithm $[13]$ with a cone size $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.5$ $[14]$. The jet energies are corrected for the energy response of the calorimeter, the cone size, multiple $p\bar{p}$ interactions, event pile-up, and calorimeter noise $[15]$. At least one jet is required to have $p_T > 35 \text{ GeV}$, and at least two jets are required to have $p_T > 25 \text{ GeV}$. Each event is also required to have at least one $\tau_\ell$ candidate with $p_T > 10 \text{ GeV}, |\eta| < 2.5$, and tau neural network output, $NN_{\tau} > 0.3$ $[16]$. Finally, to ensure this analysis is statistically independent of other D0 $t\bar{t}$ cross section measurements so that it can be included in a combined cross section measurement, events satisfying the requirements of the $t\bar{t} \rightarrow e(\mu) +$ jets channel $[17]$, which include an isolated electron (muon) with $p_T > 20 \text{ GeV}$, are rejected, as are events satisfying the requirements of the $t\bar{t}$ cross section measurement in the all-hadronic channel $[11].$

A semi-hadronic $\tau$ lepton candidate is a calorimeter cluster of cone size $\Delta R = 0.5$ that includes any sub-clusters that might be present with $E > 800 \text{ MeV}$ constructed from cells in the electromagnetic (EM) section of the calorimeter and the associated tracks with $p_T > 1.5 \text{ GeV}$ in a cone $\Delta R = 0.5$ contained within the calorimeter cluster. These $\tau$ candidates are classified according to one of three types based on the number of tracks and activity in the EM calorimeter, motivated by the semi-hadronic $\tau$ lepton decays: $(1) \tau^{\pm} \rightarrow \pi^{\pm} \nu_\tau$, $(2) \tau^{\pm} \rightarrow \pi^{\pm}\pi^0 \nu_\tau$, $(3) \tau^{\pm} \rightarrow \pi^{\pm} \pi^0 \pi^0 \nu_\tau$. We define the three tau-types as follows: a single track with no EM sub-clusters (tau-type 1); a single track and $\geq 1$ EM sub-clusters (tau-type 2); and at least two tracks and $\geq 0$ EM sub-clusters (tau-type 3).

To further reduce the number of quark and gluon jets reconstructed as $\tau$ leptons, we train separate neural networks for each semi-hadronic $\tau$ lepton decay type to improve the discrimination of $\tau$ lepton candidates from the jet background. The input variables to $NN_{\tau}$ are chosen to be minimally dependent on the $\tau$ lepton energy and to exploit the low track multiplicity and the narrow width of the calorimeter cluster produced by $\tau$ leptons decaying semi-hadronically, the low mass of the $\tau$ lepton, and the differences in longitudinal and transverse shower shapes between $\tau$ leptons and jets $[11]$. Each $NN_{\tau}$ is trained on $Z \rightarrow \tau^+\tau^-$ Monte Carlo (MC) events for signal and jets from data, where a jet and a non-isolated muon are back-to-back in $\phi$, for background.

To measure the number of $t\bar{t} \rightarrow \tau_\ell + \text{jets}$ signal events in data, the physics and instrumental backgrounds must be determined. The main physics backgrounds are $W + \text{jets}$ events, where the $W$ boson decays to a $\tau$ lepton, and to a smaller extent $Z + \text{jets}$ events, where the $Z$ boson decays to a pair of $\tau$ leptons with one misidentified as a jet and the $E_T$ is due to the neutrinos from the decays of the $\tau$ leptons. The main instrumental background is multijet production where a jet is misidentified as a $\tau$ lepton and the energy is mismeasured leading to a net $E_T$.

The preselection efficiencies and SM BRs for $t\bar{t}$ to final states with leptons $[18]$ are given in Table I. These, as well as the final efficiencies, are calculated using a MC simulation of the experiment. The $t\bar{t}$ signal with leptons in the final state and $W(Z) + \text{jets}$ background are simulated using the ALPGEN 1.2 $[19]$ matrix element generator assuming a $t$ quark mass of $170 \text{ GeV}$ and using the CTEQ6L1 $[20]$ parton distribution function (PDF) set. These events are then processed through PYTHIA 6.2 $[21]$ to simulate parton showering, fragmentation, hadronization, and decays of short lived particles, except for $b$ hadrons and $\tau$ leptons. EVTGEN $[22]$ is used to model the decays of $b$ hadrons, while $\tau$ leptons are decayed using TAUOLA $[23]$. To avoid double counting final states generated by the leading-order parton-level calculation of ALPGEN and the parton-level shower evolution of PYTHIA, a matching algorithm is used $[24]$. The
generated events are then processed through the GEANT-based simulation of the DØ detector providing tracking hits, calorimeter cell energies and muon hit information. The same reconstruction algorithm is applied to data and simulated events.

The preselected data sample is used to extract the signal and to study the multijet background after additional selection criteria are applied. To extract the signal sample, we require $\text{NN}_\tau > 0.95$. The selected events are then separated on the basis of tau-type according to the uncertainties on the higher misidentification rate and thus results in larger uncertainties.

We start with the preselected sample and apply a loose $\tau$ lepton veto, $\text{NN}_\tau < 0.9$. Using MC events, we expect that the resulting sample contains $< 2\%$ $tt \rightarrow \tau h + +jets$ events and $< 3\%$ $W(Z) + +jets$ events, and therefore provides a good representation of the multijet background. To further improve the modeling, the $W(Z) + +jets$ expectation is subtracted from the multijet background data sample.

The numbers of signal and background events are extracted from the final selected sample using a neural network ($\text{NN}_{sb}$) event discriminant with the following input variables: (1) the scalar sum of the $p_T$ of all jets and the $\tau$ lepton candidate in the event; (2) the aplanarity; (3) the $E_T$ significance; (4) the invariant mass of all jets and the $\tau$ lepton candidate in the event; and (5) a $\chi^2$ representing how well the 2 and 3 jet invariant masses agree with values expected for hadronic $t$ quark decays, $\chi^2 = (M_{3\text{jett}} - m_t)/\sigma^2 + (M_{2\text{jett}} - m_W)^2/\sigma^2_W$, with $M_{2\text{jett}}$ ($M_{3\text{jett}}$) being the 2 (3) jet invariant mass, $m_t = 170$ GeV, $\sigma_t = 45$ GeV and $m_W = 80$ GeV, $\sigma_W = 10$ GeV are the mass and its resolution in the all-hadronic final state for the $t$ quark and $W$ boson, respectively. The jet combination minimizing the $\chi^2$ is used. The $\text{NN}_{sb}$ is trained using a generated $tt \rightarrow \tau + +jets$ MC sample for signal and half the multijet data sample for background.

We apply the trained $\text{NN}_{sb}$ to the signal data sample, the remaining half of the multijet sample, a $tt$ MC sample with leptons in the final state that is independent of the $\text{NN}_{sb}$ training sample, and a $W(Z) + +jets$ MC sample. The application of $\text{NN}_{sb}$ on the multijet and MC samples is used to generate templates, as shown in Fig. 1 that are used to determine the fraction of $tt$ and multijet events using a negative log-likelihood fit. The normalization of the $W(Z) + +jets$ MC sample is derived by scaling the $W(Z)$ transverse (dilepton) mass distribution to data. The normalization for $tt \rightarrow e(\mu) + +jets$ is fixed to the theoretical cross section [3] and BRs.

The number of $tt \rightarrow \tau + +jets$ events extracted from the fit to data are $25.1^{+11.2}_{-10.5}$ (stat) and $18.0^{+11.3}_{-10.5}$ (stat) for channels with tau-types 1 and 2 together, and with tau-type 3, respectively. The fitted numbers of the multijet background events are $336.4^{+11.2}_{-10.5}$ (stat) and

### Table I: A summary of the SM BRs of the various $tt$ subprocesses and the preselection efficiencies, where the uncertainties are derived from MC statistics. The leptonic $\tau$ lepton decays are included in the $e$ and $\mu$ channels, and $t^\pm$ represents an $e$, $\mu$ or $\tau$ lepton.

<table>
<thead>
<tr>
<th>Process</th>
<th>BR (%)</th>
<th>$\epsilon_{\text{preselection}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$tt \rightarrow \tau h + +jets$</td>
<td>9.75</td>
<td>42.1±0.2</td>
</tr>
<tr>
<td>$tt \rightarrow e + +jets$</td>
<td>17.7</td>
<td>17.5±0.2</td>
</tr>
<tr>
<td>$tt \rightarrow \mu + +jets$</td>
<td>17.6</td>
<td>11.5±0.1</td>
</tr>
<tr>
<td>$tt \rightarrow t^+t^-$ + +jets</td>
<td>11.1</td>
<td>4.16±0.03</td>
</tr>
</tbody>
</table>

![Fig. 1](image-url)
TABLE II: The efficiencies for the tight \( \tau \) lepton candidate \((NN_{\tau} > 0.95)\) and \( b \)-tagging selections for tau-type 1 and 2, and tau-type 3 channels. The uncertainties are based on MC statistics.

<table>
<thead>
<tr>
<th>Tau-type 1 and 2</th>
<th>Tau-type 1 and 2</th>
<th>Tau-type 3</th>
<th>Tau-type 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t\bar{t} \rightarrow \tau_{\ell} + jets )</td>
<td>23.7( \pm )0.3</td>
<td>60.1( \pm )2.7</td>
<td>19.4( \pm )0.2</td>
</tr>
<tr>
<td>( \tau \bar{t} \rightarrow e + jets )</td>
<td>33.1( \pm )0.4</td>
<td>58.7( \pm )2.8</td>
<td>8.1( \pm )0.2</td>
</tr>
<tr>
<td>( \tau \bar{t} \rightarrow \mu + jets )</td>
<td>3.8( \pm )0.1</td>
<td>60.3( \pm )2.7</td>
<td>7.7( \pm )0.2</td>
</tr>
<tr>
<td>( \tau \bar{t} \rightarrow t^+t^- + jets )</td>
<td>43.7( \pm )0.4</td>
<td>60.2( \pm )2.7</td>
<td>20.6( \pm )0.3</td>
</tr>
</tbody>
</table>

TABLE III: Expected event yields in the two analysis channels assuming the measured \( t\bar{t} \) production cross section of 6.9 pb.

<table>
<thead>
<tr>
<th>Channel</th>
<th>( t\bar{t} \rightarrow \tau_{\ell} + jets )</th>
<th>( t\bar{t} \rightarrow e + jets )</th>
<th>( t\bar{t} \rightarrow \mu + jets )</th>
<th>( t\bar{t} \rightarrow t^+t^- + jets )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total ( t\bar{t} \rightarrow leptons )</td>
<td>61.32( \pm )7.83</td>
<td>34.12( \pm )5.87</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( W + jets )</td>
<td>13.48( \pm )3.67</td>
<td>6.01( \pm )2.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( Z + jets )</td>
<td>3.35( \pm )1.83</td>
<td>1.96( \pm )1.40</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1083.2\( \pm \)11.3 \((stat)\), for the two channels, respectively. The numbers of \( t\bar{t} \) events are comparable to the expected values given in Table III.

To minimize the statistical uncertainty of the measurement of \( \sigma(pp \rightarrow t\bar{t} + X) \cdot BR(t\bar{t} \rightarrow \tau_{\ell} + jets) \), which we denote as \( \sigma_{t\bar{t}} \cdot BR_{\tau_{\ell} + j} \), we fit the entire \( NN_{sb} \) output distribution rather than counting events above a given value. The value of \( \sigma_{t\bar{t}} \cdot BR_{\tau_{\ell} + j} \) and the fraction of multijet background in the sample are obtained from a negative log-likelihood fit to the \( NN_{sb} \) distributions for tau-types 1 and 2 and tau-type 3, independently:

\[
L(\sigma_{t\bar{t}}, \tilde{N}_i, N_i^{obs}) = -\log \left( \prod_i \frac{\tilde{N}_i^{obs}}{N_i^{obs}} \right),
\]

where \( \tilde{N}_i = \sigma_{t\bar{t}} \times \sum_j \epsilon_{t\bar{t}(j)} \times BR(t\bar{t}(j)) \times \mathcal{L} + N_{bgg,i} \) is the expected number of events in the \( i^{th} \) bin of the \( NN_{sb} \) histogram for a given \( \sigma_{t\bar{t}} \), with integrated luminosity \( \mathcal{L} \), number of background events \( N_{bgg,i} \), and the efficiency (BR) for the \( j^{th} \) \( t\bar{t} \) leptonic channel \( \epsilon_{t\bar{t}(j)} \) (\( BR(t\bar{t}(j)) \)), and \( N_i^{obs} \) is the observed number of events in the \( i^{th} \) bin.

The measured value of \( \sigma_{t\bar{t}} \cdot BR_{\tau_{\ell} + j} \) is 0.60\( \pm \)0.23 \((stat)\) \( + 0.15 \pm 0.14 \)(syst) \( \pm 0.04 \)(lumi) pb, where we combine the tau-type 1 and 2 measurement with the tau-type 3 measurement. Using the theoretical cross section \( \sigma_{t\bar{t}} \) = 8.06\( \pm \)0.52 pb for \( m_{t\bar{t}} \) = 170 GeV from Ref. \[3\], we measure \( BR_{\tau_{\ell} + j} \) = 0.074\( \pm \)0.029 which is consistent with the SM value given in Table II.

Table IV summarizes the systematic uncertainties on \( \sigma_{t\bar{t}} \cdot BR_{\tau_{\ell} + j} \). These are calculated by varying the source by plus and minus one standard deviation, and propagating the uncertainty to the final \( \sigma_{t\bar{t}} \cdot BR_{\tau_{\ell} + j} \). The jet energy corrections account for the effect of the jet energy scale and resolution. Jet identification takes account of the difference in the jet finding efficiency in data and MC. The \( b \)-tagging entry accounts for the systematic uncertainties on its efficiency. The \( \tau \) lepton identification uncertainty is derived by fluctuating the value of each input variable within its statistical uncertainty and observing its effect on the \( NN_{\tau} \) output. The trigger category accounts for the uncertainty in the multijet trigger turn-on and also takes into account the possibility that a multijet event with a \( \tau \) lepton can have a different trigger turn-on. Multijet modeling accounts for the uncertainty of the multijet sample to model the \( t\bar{t} \rightarrow \tau_{\ell} + jets \) background and its limited statistics. The category \( W + jets \) modeling accounts for the uncertainty in the scale factor both for light flavor jets and heavy flavor jets, and the uncertainty in the PDF. The \( t\bar{t} \) cross section systematic uncertainty represents the effect of the normalization of the non-tau lepton \( b \) background, which is normalized to the theoretical value of the cross section. In addition to the sources listed in Table IV there is a \( +0.1 \% \) uncertainty in the luminosity measurement \[28\].

In addition, we present the combined measurement of the production cross section for \( t\bar{t} \) using all measured \( t\bar{t} \) channels with leptons in the final state listed in Table III that satisfy the selection criteria described above. We repeat the negative log-likelihood fit for the number of \( t\bar{t} \) signal and multijet background events fixing the \( t\bar{t} \) BRs to their SM values, but this time fit for all \( t\bar{t} \) channels arriving at 60.5\( \pm \)11.8 (stat) events and 24.0\( \pm \)11.4 (stat) events for channels with tau-types 1 and 2 and with tau-type 3 characteristics, respectively. The fitted multijet backgrounds in this case are 336.7\( \pm \)11.8 (stat) events and 1083.2\( \pm \)11.4 (stat) events, for the two channels, respectively. The production cross section is calculated using the negative log-likelihood defined in Eq. [1] for tau-types 1 and 2 and tau-type 3 separately. The two cross sections are then combined to give

\[
\sigma_{t\bar{t}} = 6.9_{-1.2}^{+1.2} (stat)_{-0.7}^{+0.8} (syst) \pm 0.4 (lumi) \text{ pb},
\]

To estimate the dependence on \( m_{t\bar{t}} \), we repeat the mea-
measurement using $m_t = 175$ GeV and find

$$\sigma_{\ell\ell} = 6.3^{+1.2}_{-1.1} \text{ (stat)} \pm 0.7 \text{ (syst)} \pm 0.4 \text{ (lumi)} \text{ pb}.$$  

In summary, we have performed a measurement of $\sigma_{\ell\ell} \cdot \text{BR}(\tau_h \to j + \text{jets}) = 0.60^{+0.26}_{-0.28}$ pb and, using the theoretical $t\bar{t}$ production cross section, extracted $\text{BR}(\tau_h \to j + \text{jets}) = 0.07^{+0.029}_{-0.027}$, which agrees with the SM expectation. In addition, we have performed a measurement of the $p\bar{p} \to t\bar{t} + X$ production cross section, $\sigma_{\ell\ell} = 6.9^{+1.5}_{-1.4}$ pb, using the $t\bar{t} \to \tau_h + \text{jets}$ topology. The measurement is in agreement with the SM and previous experimental measurements using other $t\bar{t}$ channels at the Tevatron.

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<table>
<thead>
<tr>
<th>Source</th>
<th>$\tau_h$+jets (types 1 and 2)</th>
<th>$\tau_h$+jets (type 3)</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet energy corrections</td>
<td>$-0.078$</td>
<td>$+0.081$</td>
<td>$-0.047$</td>
</tr>
<tr>
<td>Jet identification</td>
<td>$-0.019$</td>
<td>$+0.019$</td>
<td>$-0.012$</td>
</tr>
<tr>
<td>$b$ tagging</td>
<td>$-0.074$</td>
<td>$+0.084$</td>
<td>$-0.035$</td>
</tr>
<tr>
<td>Tau identification</td>
<td>$-0.035$</td>
<td>$+0.035$</td>
<td>$-0.020$</td>
</tr>
<tr>
<td>Trigger</td>
<td>$-0.002$</td>
<td>$+0.053$</td>
<td>$-0.000$</td>
</tr>
<tr>
<td>Multijet modeling</td>
<td>$-0.090$</td>
<td>$+0.090$</td>
<td>$-0.169$</td>
</tr>
<tr>
<td>$W$+jets modeling</td>
<td>$-0.028$</td>
<td>$+0.028$</td>
<td>$-0.012$</td>
</tr>
<tr>
<td>$t\bar{t}$ cross section</td>
<td>$-0.064$</td>
<td>$+0.068$</td>
<td>$-0.029$</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>$-0.16$</td>
<td>$+0.15$</td>
<td>$-0.18$</td>
</tr>
</tbody>
</table>

[14] The D0 coordinate system has the positive $z$-axis along the proton beamline, and $z = 0$ at the center of the detector. The polar and azimuthal angles are denoted as $\theta$ and $\phi$, respectively. The pseudorapidity is defined as $\eta = -\ln(\tan(\theta/2))$.
[27] The aplanarity is $3/2\lambda_3$, with $\lambda_3$ being the smallest eigenvalue of the momentum tensor $M^{ij} = \sum_i \rho_i \rho_i^* / \sum_i |\rho_i|^2$, where $i$ runs over the number of jets and the $\tau$ lepton candidate, and $\alpha, \beta = 1, 2, 3$ specifies the three spatial components of the momentum.