RECENT RESULTS FROM STAR FOR PARTON DISTRIBUTION FUNCTIONS AT LOW AND HIGH x IN PROTON–PROTON COLLISIONS*

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According to perturbative quantum chromodynamic calculations, in pp collisions at $\sqrt{s} = 200$ and 510 GeV studied at RHIC, jet production in mid-pseudorapidity, $|\eta| < 1$, is dominated by quark–gluon and gluon–gluon scattering processes. Therefore, jets at RHIC are direct probes of the gluon parton distribution functions (PDFs) for momentum fractions $0.01 < x < 0.5$. Moreover, W boson cross-section ratio, $\sigma(W^+)/\sigma(W^-)$, in pp collisions at $\sqrt{s} = 510$ GeV, is an effective tool to explore anti-quark PDFs, $\bar{d}/\bar{u}$. Last but not least, di-π^0 correlation in forward pseudorapidity, $2.6 < \eta < 4.0$, is an important indication of the non-linear gluon dynamics at low x where the gluon density is high in protons and nuclei. In this contribution, we present recent STAR results of mid-pseudorapidity inclusive jet cross sections at $\sqrt{s} = 200$ and 510 GeV in pp collisions, W boson cross-section ratio at $\sqrt{s} = 510$ GeV in pp collisions, and forward di-π^0 correlations in pp, pAl, and pAu collisions at $\sqrt{s_{NN}} = 200$ GeV.

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1. Introduction

As the wavelength of a probe decreases below a Fermi (10^{-15} m) in high-energy scattering experiments, the image of the proton evolves from a naive picture of three quarks, uud, to a complex system of quarks, anti-quarks, and gluons known as the parton model. Parton distribution functions (PDFs), interpreted as probabilities of finding a parton carrying a fractional momentum of the proton, x, at the probe scale, Q^2, are crucial to describe the proton structure. By colliding proton–proton beams at $\sqrt{s} = 200$ and

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510 GeV, the STAR experiment [1] has provided a unique venue to unravel the proton's PDFs since the 2000s. In this contribution, three important measurements at STAR, inclusive jet cross sections, $W^{\pm}$ boson cross-section ratio, and di-π^0 correlation in the forward region, are discussed.

2. Inclusive jet cross sections

Jets are defined as clusters of collimated final-state particles. For each production channel, the cross sections can be factorized into the PDFs and partonic scattering cross sections. The partonic scattering cross sections are calculated perturbatively at a large $Q^2 \gg \Lambda^2_{\mathrm{QCD}}$. Due to their non-perturbative nature, the PDFs are parametrized as a function of x at an initial Q_0^2 scale and then evolved to the proper Q^2. Given their universality, the parameters are determined by fits to global experimental data.

Recent global analyses at next-to-next-to-leading order (NNLO) with TeV-scale $p\bar{p}$ and pp data from the Tevatron and LHC, respectively, yielded gluon PDFs at $Q = 100$ GeV with small uncertainties for x from 10^{-4} to 0.1, but with large uncertainties, especially for $x > 0.2$ [2]. At RHIC energies, $\sqrt{s} = 200$ and 510 GeV, the jet production is dominated by quark–gluon and gluon–gluon scatterings [3]. Therefore, jet cross sections are ideal to constrain the gluon PDFs at $x > 0.1$.

At STAR, jets are identified from tracks reconstructed by the Time Projection Chamber and energy deposits in the towers (0.05×0.05 in η–ϕ) of the electro-magnetic calorimeters (EMC) [3]. We chose to use the anti-k_{T} algorithm with jet parameters $R = 0.6$ and 0.5 at $\sqrt{s} = 200$ and 510 GeV, respectively. The smaller R at the higher $\sqrt{s}$ is to reduce the contributions from pile-up events and soft backgrounds.

The inclusive jet cross sections at $\sqrt{s} = 200$ and 510 GeV were analyzed from data collected in 2012. Compared to the previous analysis of the 2006 data, a number of technical advancements were made to improve the systematic uncertainties. One is an off-axis cone method to correct for the underlying event (UE) contribution to the jet p_{T} [3]. Another is an improved event generator tune based on the PYTHIA 6 Perugia 2012 tune [3]. The simulation is essential in order to unfold the jet cross sections from the measured detector-level jet p_{T} and η bins to the true particle-level jet p_{T} and η bins. In addition, it is necessary to estimate hadronization corrections needed to compare with theoretical calculations at the parton level.

The preliminary results of the inclusive jet cross sections, $\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta}$, as a function of particle jet p_{T} after UE corrections are presented in Fig. 1 [4]. The 200 GeV results cover $|\eta| < 0.8$, and the 510 GeV results are split into $|\eta| < 0.5$ and $0.5 < |\eta| < 0.9$. The luminosities are determined from Van der Meer scans [5] with uncertainties of 10% and 5.2% at 200 and 510 GeV, respectively. The dominant systematic uncertainties come from the jet energy scale for both results. The results sit about 20% below the perturbative calculations with the CT14 next-to-leading order (NLO) PDF after hadronization corrections. Although the results match the shape of the PYTHIA 6 predictions quite well, an overall scale difference of 20% is observed.

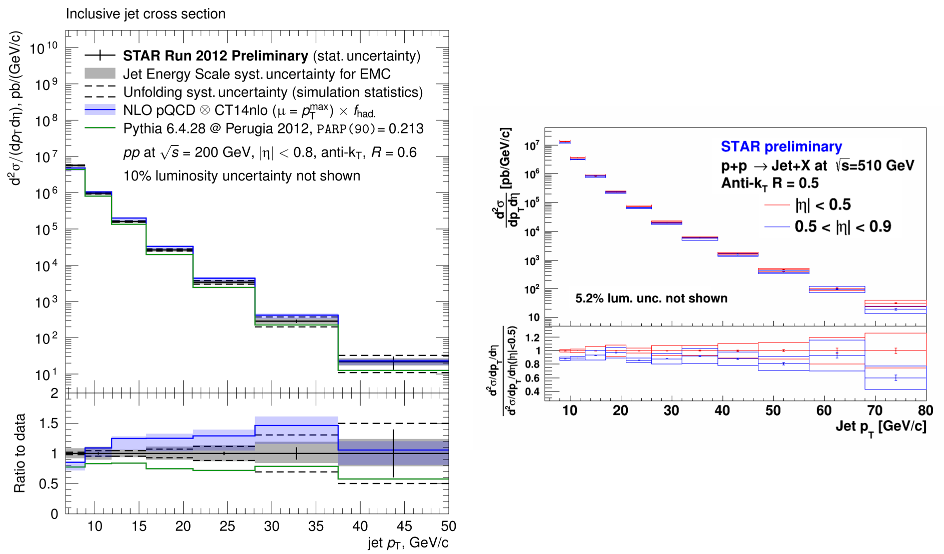

Fig. 1. STAR preliminary inclusive jet cross section $\frac{d^2\sigma}{dp_T d\eta}$ *versus* particle jet p_T after UE corrections from pp collisions at $\sqrt{s} = 200$ (left) and 510 (right) GeV [4].

3. $W^{\pm}$ cross-section ratio

The New Muon Collaboration discovered that there were more d-flavor sea quarks, $\bar{d}$, than u-flavor sea quarks, $\bar{u}$, in the proton [6]. This spurred interest in studying the sea quark distributions from pp collisions through the Drell–Yan (DY) process. The recent SeaQuest experiment, in which proton beams impinged on fixed hydrogen and deuterium targets, demonstrated that $\bar{d}/\bar{u} > 1$ as a function of x [7]. However, the results showed a different trend at high x than the previous NuSea results. Several theoretical predictions have been proposed to explain both trends at high x from these two results.

In pp collisions at $\sqrt{s} = 510$ GeV, $W^{\pm}$ can be produced by the s-channel from quark and anti-quark interactions [8]. $W^{\pm}$ cross-section ratio, $R_W = \sigma(W^+)/\sigma(W^-)$, is proportional to $\bar{d}/\bar{u}$ at leading order. Unlike the DY process, R_W is sensitive to the sea quark PDFs at $Q^2 = M_W^2$, where M_W^2 is the invariant mass of the W boson. The sampled x range is $0.06 < x < 0.4$ when $-1.0 < \eta_W < 1.5$.

At STAR, $W^{\pm}$s are reconstructed from the high-energy decay $e^{\pm}$ [8]. The $e^{\pm}$ candidates are captured by clusters of EMC towers, each of which spans 0.1×0.1 in η–ϕ. A large-p_{T} imbalance is required in the event to account for the missing final-state neutrino. Corrections are made for backgrounds from electroweak residuals and the QCD dijet contributions.

The preliminary results of R_W as a function of the reconstructed η of $e^{\pm}$, are shown in Fig. 2 [9]. The plot includes data collected in 2011, 2012, 2013, and 2017 with a total integrated luminosity of 700 pb^{-1}. The results agree well with the recent predictions from the NLO PDF sets, such as CT18 [10], MSHT20 [11], and NNPDF4.0 [2]. Note that the NNPDF4.0 PDF has incorporated the recent SeaQuest data.

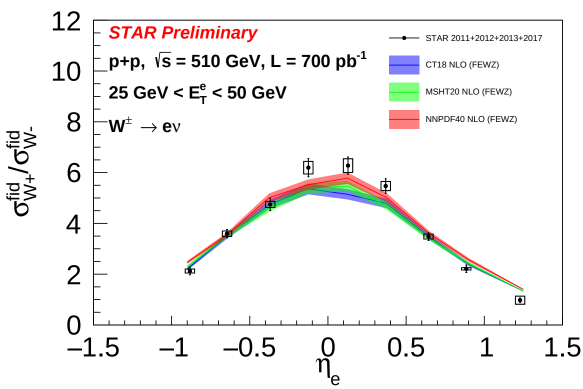

Fig. 2. STAR preliminary $W^{\pm}$ cross-section ratio, R_W, *versus* reconstructed η_e from pp collisions at $\sqrt{s} = 510$ GeV [9].

4. Di-π^0 correlations in the forward region

High-energy physics experiments have shown that gluons dominate at low x inside the proton, and the number of gluons grows as x decreases [2, 10, 11]. An interesting theoretical expectation is that the gluon density must begin to saturate at a certain x where the rate of gluon splittings balances out gluon recombinations. The probe scale where the saturation happens, Q^2_{S}, varies inversely as a function of x. In heavy nuclei, Q^2_{S} is proportional to $A^{1/3}$, where A is the atomic number of a nucleus.

The color glass condensate (CGC) framework predicts a suppression and an azimuthal broadening of the back-to-back di-hadrons in pA collisions compared to pp when gluon saturation appears [12]. The di-π^0 azimuthal correlation in $2.6 < \eta < 4.0$ allows one to study gluons with x as low as 10^{-4} in pp, pAl, and pAu collisions at $\sqrt{s_{NN}} = 200$ GeV.

At STAR, π^0s can be reconstructed from decay photons detected in the Forward Meson Spectrometer (FMS). A correlation function in terms of di-π^0 opening angle, $\Delta\phi$, can be defined by $C(\Delta\phi) = \frac{N_{\rm pair}(\Delta\phi)}{N_{\rm trig}\times\Delta\phi_{\rm bin}}$, where $N_{\rm pair}(\Delta\phi)$ is the number of di-π^0 pairs in a $\Delta\phi$ bin, $\Delta\phi_{\rm bin}$ is the $\Delta\phi$ bin width, and $N_{\rm trig}$ is the number of trigger π^0s. The trigger π^0 is the higher $p_{\rm T}$ of the pair, and the associate π^0 is the lower $p_{\rm T}$ one. $C(\Delta\phi)$ extracted from the 2015 STAR *pp*, *p*Al, and *p*Au collisions is shown in Fig. 3 [12].

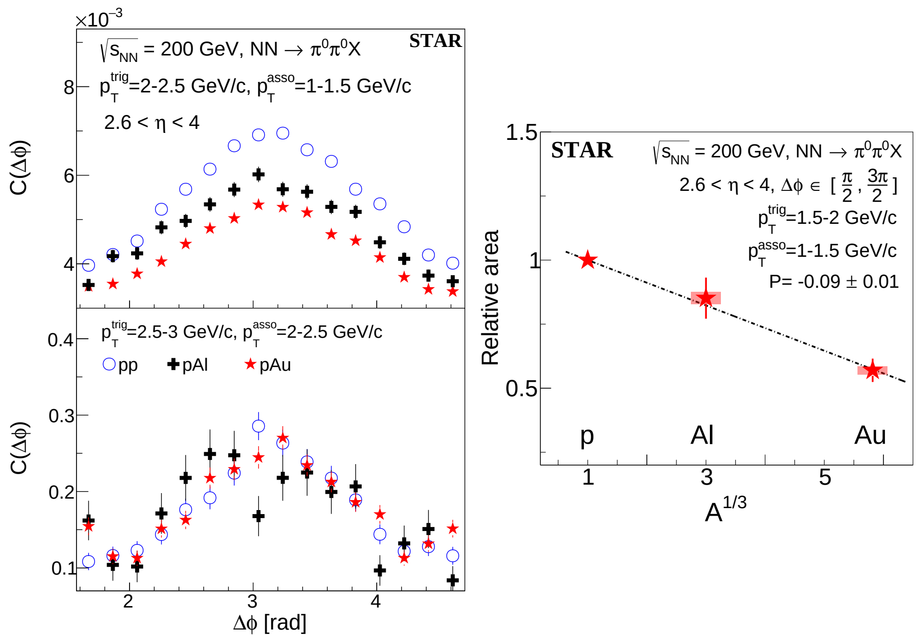

Fig. 3. STAR di-π^0 correlation function $C(\Delta\phi)$ in selected $p_{\rm T}$ ranges of trigger and associate π^0s from *pp*, *p*Au, and *p*Al collisions at $\sqrt{s_{NN}} = 200$ GeV on the left panel, and the corresponding relative areas on the right panel [12].

As plotted in Fig. 3, the relative area under $C(\Delta\phi)$ from $\Delta\phi = \pi/2$ to $3\pi/2$ compared to the *pp* collisions, follows linearly as a function of $A^{1/3}$. The kinematic choices with the trigger π^0, $p_{\rm T}^{\rm trig} = 1.5$–$2$ GeV$/c$, and the associate π^0, $p_{\rm T}^{\rm asso} = 1$–1.5 GeV$/c$ are where gluon density is large and expected to saturate. Surprisingly, no angular broadening is observed.

5. Forward upgrade

The STAR forward upgrade [13] adds new capabilities in place of the FMS over a similar η range, $2.6 < \eta < 4.0$. A new hadronic calorimeter is located behind an upgraded EMC. Together they constitute the forward calorimeter system. In addition, a forward tracking system consists of a silicon tracker and a small thin-gap gas chamber. The forward upgrade has the capability of separating the charge signs of charged hadrons. The detectors were commissioned in 2022 and have been successfully taking data since then. The forward upgrade enables STAR to study asymmetric partonic collisions, where $x_1 \gg x_2$, therefore, one can explore both high-x and low-x regimes. In particular, it allows one to study valence quark distributions as high as $x > 0.5$ where no current experiment has reached.

6. Conclusion

STAR has a vigorous physics program centered around exploring the internal structure of the proton. Inclusive jet production is sensitive to the large-x gluon PDFs in the proton that are loosely constrained by data from TeV-scale colliders. $W^{\pm}$ cross-section ratio is complementary to the DY process to constrain $\bar{d}/\bar{u}$. The di-π^0 correlation at $2.6 < \eta < 4.0$ in pp and pA collisions enables the study of the non-linear dynamics of gluons at low x. With upcoming exciting physics results from the forward upgrade, STAR will lay the essential groundwork for the future Electron Ion Collider.

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