International Journal of Modern Physics A

STUDY OF THE CENTRAL EXCLUSIVE PRODUCTION OF $\pi^+\pi^-$, K^+K^-, AND $p\bar{p}$ PAIRS IN PROTON-PROTON COLLISIONS AT $\sqrt{s} = 510$ GEV WITH THE STAR DETECTOR AT RHIC.

TOMÁŠ TRUHLÁŘ*

Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague,
Address
Brehova 78/7, Prague 115 19, Czech Republic
Tomas.Truhlar@fjfi.cvut.cz

Received Day Month Year
Revised Day Month Year

We report on the measurement of the central exclusive production process $pp \rightarrow pXp$ in proton-proton collisions at $\sqrt{s} = 510$ GeV with the STAR detector at RHIC. At this energy, the process is dominated by a double Pomeron exchange mechanism. The tracks of the centrally produced system X were reconstructed in the central detector of STAR, the time projection chamber and the time of flight systems. Particles were identified using the ionization energy loss and the time of flight method. The diffractively scattered protons, moving intact inside the RHIC beam pipe after the collision, were measured in the Roman Pots system allowing full control of the interaction's kinematics and verification of its exclusivity. Preliminary results on the invariant mass distributions of centrally produced $\pi^+\pi^-$, K^+K^-, and $p\bar{p}$ pairs measured within the STAR acceptance are presented.

Keywords: Double Pomeron exchange; STAR; Roman Pots.

PACS numbers:

1. Introduction

Central Exclusive Production[1] (CEP) through double Pomeron exchange is considered to be a gluon rich process. Thus, it is suitable to look for hadronic production of glueballs,[2] bound states consisting only of gluons, predicted by non-Abelian nature of quantum chromodynamics. The CEP of two hadrons is a process, where protons stay intact and a central state is produced with quantum numbers of vacuum and is well separated from outgoing protons by rapidity gaps. A generic diagram of CEP with resonance and continuum production is shown in Fig. 1. The CEP mechanism, where two Pomerons are exchanged, is considered to be dominant at the Relativistic Heavy Ion Collider[3] (RHIC) energy.[4] Although, this process is the simplest four body quantum chromodynamics process, it is theoretically very complex due to

*For the STAR Collaboration.

significant interference effects between resonance and continuum production. Furthermore, there may be significant rescattering effects via additional interactions between the protons.

GRANIITTI[5] is a Monte Carlo event generator for high energy diffraction capable to describe both resonance and continuum production in CEP. Presented results are compared to the newest tune of GRANIITTI, version 1.080, with added CEP resonance couplings also tuned to STAR results from proton-proton collisions at $\sqrt{s} = 200$ GeV,[4] the highest center-of-mass energies at which the double Pomeron exchange has been measured with the detection of the forward-scattered protons. The following resonances were included in the resonance production: $f_0(500)$, $\rho(770)$, $f_0(980)$, $\phi(1020)$, $f_2(1270)$, $f_0(1500)$, $f_2(1525)$, and $f_0(1710)$. Significant interference effects between resonance and continuum production are taken into account.

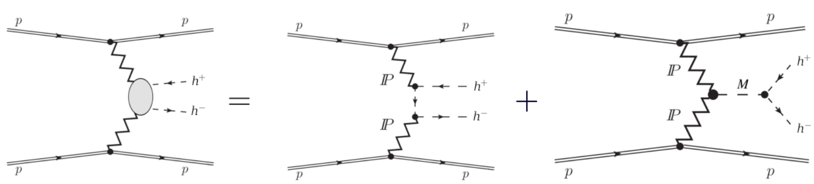

Fig. 1. A generic diagram of central exclusive production of two hadron as combination of continuum and resonance production.

2. Experimental setup

The Solenoidal Tracker at RHIC[6] (STAR) is a multi-purpose detector consisting of many sub-detectors, allowing measurement and identification of charged particles. In the Time Projection Chamber[7] (TPC), charged particles are tracked and their energy loss as a function of their momenta is measured in pseudorapidity $|\eta| < 1$ and full azimuthal angle. In combination with measuring the time-of-flight information in the Time Of Flight[8] (TOF) system, STAR enables precise particle identification. Forward rapidity Beam-Beam Counters[9] (BBC), covering $2.1 < |\eta| < 5.0$, are used to ensure rapidity gaps. A schematic view of the STAR detector with highlighted main sub-detectors can be seen in Fig. 2. In addition, the STAR experiment has forward silicon strip detectors installed in Roman Pots[10] at 15.8 and 17.6 meters on both sides of the interaction point. In each Roman Pot, a package of four silicon strip detectors and a scintillation trigger counter is installed giving spatial resolution of 30 μm and active area of 79×49 mm^2. Figure 3 shows the layout of all eight Roman Pot detectors allowing to measure forward-scattered protons' momenta and therefore verification of interaction's exclusivity.

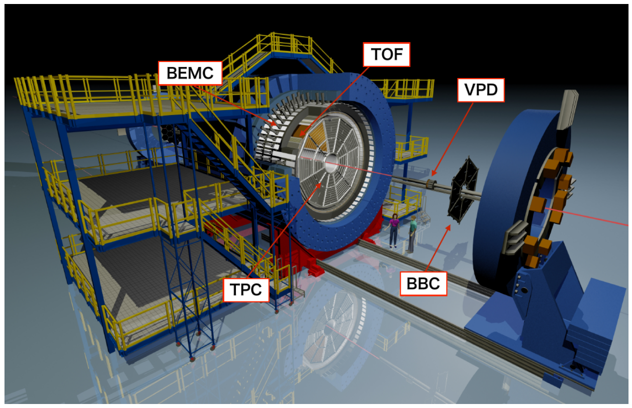

Fig. 2. A schematic view of the STAR detector, main sub-detectors are highlighted.

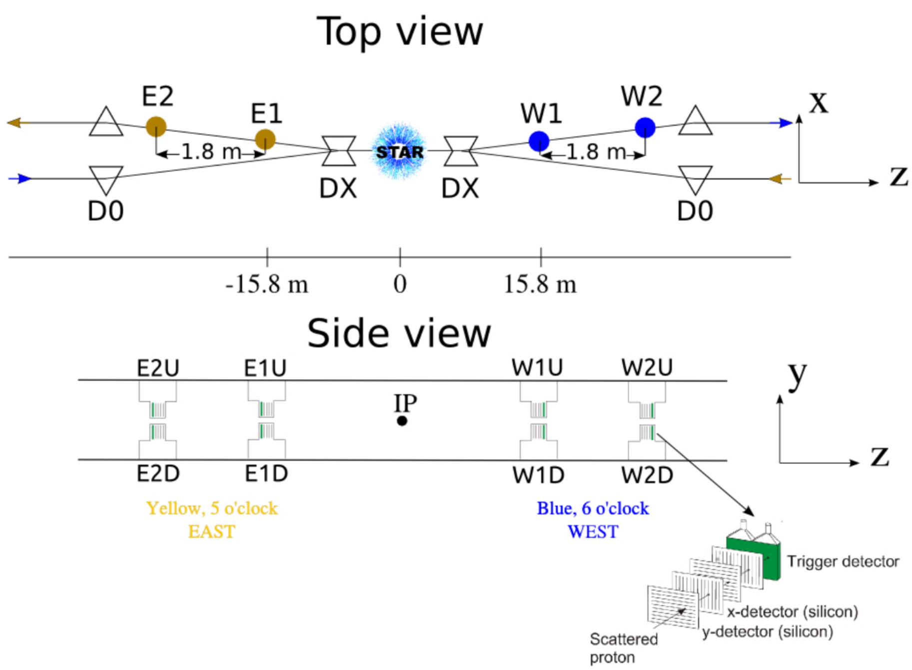

Fig. 3. The Roman Pot system. Top view shows Roman Pot stations E1, E2, W1, W2 and dipole magnets DX, D0 installed on both sides of the central detector. Side view illustrates individual Roman Pots consisting from four Silicon Strip Detector package and a scintillation counter.

3. Data sample and event selection

In 2017, the STAR experiment measured proton-proton collisions at $\sqrt{s} = 510$ GeV. More than 620 million events from these collisions were collected and analysed. The events were triggered on a signal in the Roman Pot detectors on both side of the

STAR detector. Moreover, the trigger required low TOF multiplicity and a veto on BBC signal to ensure the double rapidity gap topology characteristic for CEP events. A sample of CEP candidate events was obtained by applying the selection criteria listed below.

First, only events with one forward-scattered proton on each side are selected. In addition, all eight silicon strip detectors have to be used in the proton reconstruction to ensure good quality of the proton track. Furthermore, the proton transverse momentum is required to be inside a fiducial region to ensure pure geometrical acceptance. The fiducial region is illustrated by black lines in Fig. 4 (left) and listed in legends of Figs. 6, 7, and 8.

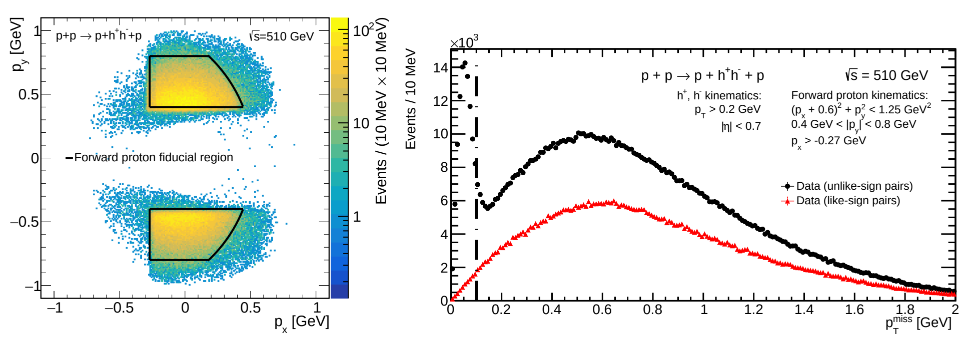

Fig. 4. Left: The distribution of reconstructed proton momenta. The black contours indicate the fiducial region used in the analysis. Right: The distribution of the missing transverse momentum p_{T}^{miss} for CEP event candidates with the used cut ($p_{\mathrm{T}}^{miss} < 100$ MeV) illustrated by the black dot-dashed line.

Second, only events with exactly two primary TPC tracks matched with two TOF hits and originating from the same vertex are selected. Next, track quality cuts are applied on the number of hits used in the track reconstruction and on the number of hits used for measuring the energy loss. To ensure high geometrical acceptance for the central tracks in the entire fiducial phase space, further criteria are used: a cut on the $z-$position of the vertex ($|z$-position of vertex$| < 80$ cm) and a cut on pseudorapidity of central tracks ($|\eta| < 0.7$).

Third, a cut on missing transverse momenta p_{T}^{miss} ($p_{\mathrm{T}}^{miss} < 100$ MeV) is applied to ensure exclusivity of the event. The p_{T}^{miss} is the transverse momentum of the sum of of all measured particles and it should be equal to zero for the CEP due to conservation of momentum. Figure 4 (right) depicts the distribution of p_{T}^{miss} for CEP event candidates with the used cut.

Finally, particle identification is done based on combined information from the TPC, the energy loss, and TOF (m^2_{TOF}). The m^2_{TOF}, as determined from TOF, is the squared invariant mass of a particle type ($\pi, K,$ and p). Details on the computation of m^2_{TOF} can be found in Appendix A. In addition, more restrictive cuts on track momenta are imposed to provide high purity of the pair sample. These cuts are listed in legends of Figs. 6, 7, and 8. Figure 5 shows the energy loss of charged particles as a function of their momenta (left) and the distribution of m^2_{TOF} for exclusive events (right), where peaks of pions, kaons, and protons about their real mass squared values can be seen.

In the end, 62077 $\pi^+\pi^-$, 1697 K^+K^-, and 125 $p\bar{p}$ CEP event candidates were obtained after applying all the selection criteria mentioned above.

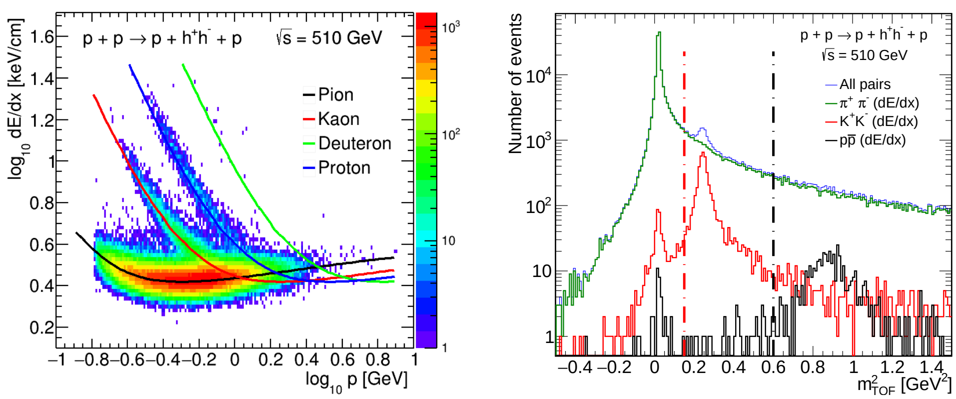

Fig. 5. Left: The energy loss of charged particles as a function of their momenta for exclusive events. Theoretical predictions for pions, kaons, protons, and deuterons are depicted by coloured curves. Right: The distribution of m^2_{TOF} for exclusive pairs and for $\pi^+\pi^-, K^+K^-$, and $p\bar{p}$ pairs determined solely from the energy loss. Dot-dash lines indicate used m^2_{TOF} cuts.

4. Results

In Figs. 6 and 7, invariant mass distributions of selected centrally produced $\pi^+\pi^-$, K^+K^-, and $p\bar{p}$ pairs measured within the STAR acceptance in proton-proton collisions at $\sqrt{s} = 510$ GeV are shown. All presented invariant mass distributions were corrected for the detector acceptance using the pure single particle STAR detector simulation. Also, they were normalized such that the area under the distribution is equal to one. The error bars represent statistical uncertainties only and natural units were used.

The invariant mass distribution of $\pi^+\pi^-$ pairs shows expected features: a drop at about 1 GeV, possibly due to the negative interference of $f_0(980)$ with the continuum contribution, and a peak consistent with the $f_2(1270)$. In the invariant mass of K^+K^-, a peak at about 1.5 GeV, possible $f_2(1525)$, and a strong enhancement at about 1.5 GeV, possible $f_0(980)$ or $\phi(1020)$, are seen. The invariant mass of $p\bar{p}$ does not show any resonances. In general, GRANIITTI can describe shapes of distributions. Even the strong enhancement at a mass about 1 GeV for K^+K^- pairs is predicted by GRANIITTI, while the enhancement is not seen and it is not predicted in fiducial region of STAR measurement at $\sqrt{s} = 200$ GeV.[4]

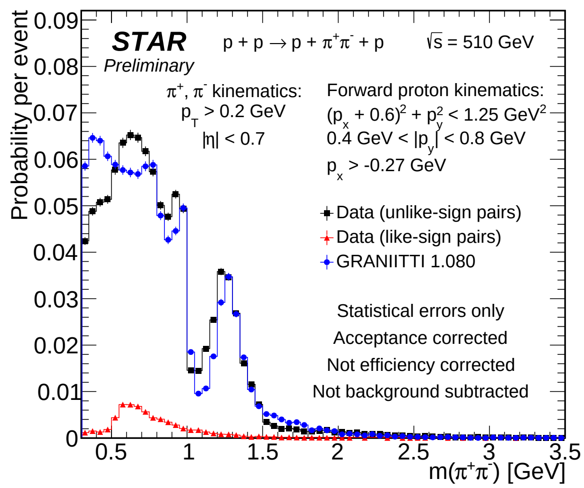

Fig. 6. The acceptance corrected invariant mass spectrum of exclusively produced $\pi^+\pi^-$ pairs. Results are compared with the newest tune of GRANIITTI,[5] version 1.080. Error bars represent the statistical uncertainties.

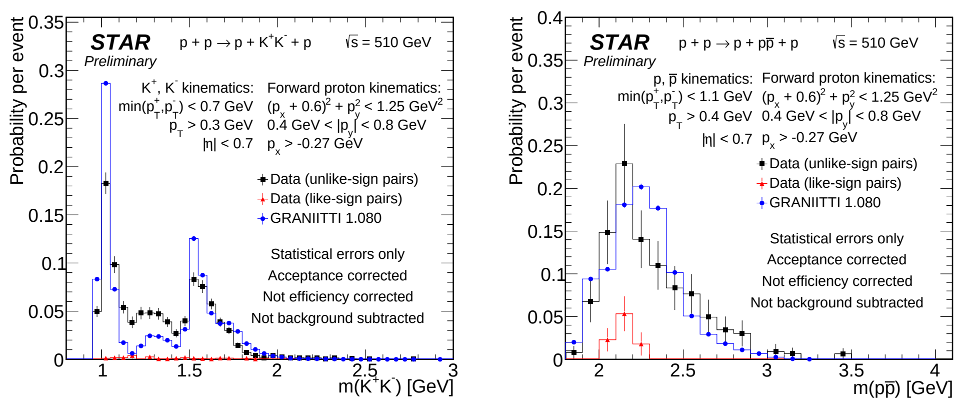

Fig. 7. Acceptance corrected invariant mass spectra of exclusively produced K^+K^- pairs (left) and $p\bar{p}$ pairs (right). Results are compared with a new tune of GRANIITTI,[5] version 1.080. Error bars represent the statistical uncertainties.

The invariant mass distribution of selected $\pi^+\pi^-$ pairs is differentiated in two regions of $\Delta\varphi$, $\Delta\varphi < 90°$ and $\Delta\varphi > 90°$, where $\Delta\varphi$ is the difference between the azimuthal angles of the forward protons. The selection of events with $\Delta\varphi > 90°$ could act as a glueball filter[11] since the production of quark-antiquark states is suppressed compared to glueballs in the limit $|\vec{p}_{1,T} - \vec{p}_{2,T}| \to 0$ corresponding to the limit $\Delta\varphi \to 180°$.

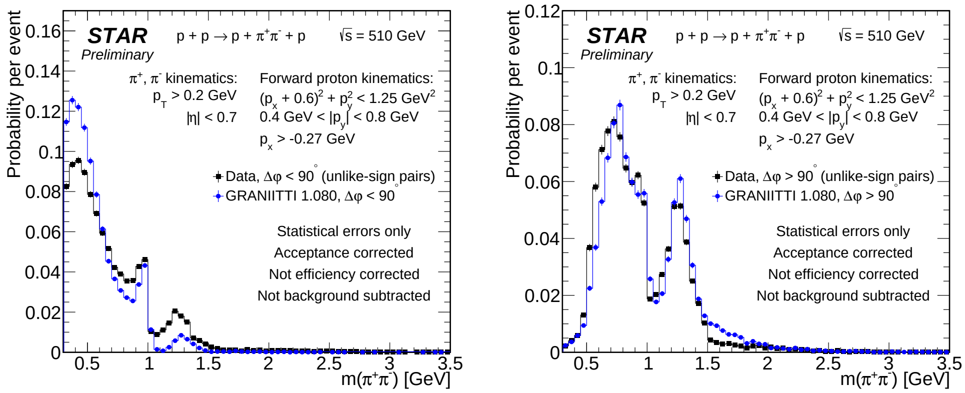

Fig. 8. The acceptance corrected invariant mass spectrum of exclusively produced $\pi^+\pi^-$ pairs differentiated in two regions of the difference of azimuthal angles of the forward protons: $\Delta\varphi < 90°$ (left) and $\Delta\varphi > 90°$ (right). Results are compared with a new tune of GRANIITTI,[5] version 1.080. Error bars represent the statistical uncertainties.

5. Summary

The preliminary STAR results on CEP of charged particle pairs produced in proton-proton collisions at $\sqrt{s} = 510$ GeV with measured forward-scattered protons have been presented.

The results confirm features seen in previous experiments even though new features are seen, like the peak at the invariant mass of about 1 GeV for K^+K^- pairs. The results were compared with the newest tune of the Monte Carlo event generator, GRANIITTI, that can describe the shape of the data quite well suggesting significant role of resonance production.

Acknowledgments

This work was supported from the project LTT18002 of the Ministry of Education, Youth, and Sport of the Czech Republic and from European Regional Development Fund-Project "Center of Advanced Applied Science" No. CZ.02.1.01/0.0/0.0/16-019/0000778.

Appendix A. The m^2_{TOF} method

The m^2_{TOF} method is based on the assumption that two hadron of the same type (same mass) are produced from the same vertex. Then, their masses squared can be derived. Assuming that two hadrons are produced in the same vertex at time t_0 and they are detected in the TOF detector at time t_1 and t_2. Then, we can write following equations:

$$t_1 - t_0 = L_1\sqrt{1 + \frac{m_1^2}{p_1^2}}, \tag{A.1}$$

$$t_2 - t_0 = L_2\sqrt{1+\frac{m_2^2}{p_2^2}}, \tag{A.2}$$

where p_1 and p_2 are momenta and L_1 and L_2 are lengths of the first and the second central track. The time t_0 can be removed by subtracting A.2 from **??**:

$$\Delta t = t_1 - t_2 = L_1\sqrt{1+\frac{m_1^2}{p_1^2}} - L_2\sqrt{1+\frac{m_2^2}{p_2^2}}. \tag{A.3}$$

Since we assume the two particles have the same mass, we can write $m_1^2 = m_2^2 = m_{\mathrm{TOF}}^2$ and transform A.3 into a quadratic equation in the following form:

$$A\cdot(m_{\mathrm{TOF}}^2)^2 + B\cdot m_{\mathrm{TOF}}^2 + C = 0, \tag{A.4}$$

where parameters $A,\ B,$ and C are defined as follows:

$$A = -2\frac{L_1^2L_2^2}{p_1^2p_2^2} + \frac{L_1^4}{p_1^4} + \frac{L_2^4}{p_2^4}, \tag{A.5}$$

$$B = -2L_1^2L_2^2\left(\frac{1}{p_1^2}+\frac{1}{p_2^2}\right) + 2\frac{L_1^4}{p_1^4} + 2\frac{L_2^4}{p_2^4} - 2(\Delta t)^2\left(\frac{L_1^2}{p_1^2}+\frac{L_2^2}{p_2^2}\right), \tag{A.6}$$

$$C = (\Delta t)^4 - 2(\Delta t)^2(L_1^2+L_2^2) + L_1^4 + L_2^4 - 2L_1^2L_2^2. \tag{A.7}$$

Finally, m_{TOF}^2 can be determined using the formula:

$$m_{\mathrm{TOF}}^2 = \frac{-B+\sqrt{B^2-4AC}}{2A}. \tag{A.8}$$

References

1. M. G. Albrow, T.D. Coughlin and J.R. Forshaw, *Prog. Part. Nucl. Phys.* **65**, 149 (2010).
2. K. Ishikawa, G. Schierholz and M. Teper, *Z. Phys. C* **19**, 327 (1983).
3. H. Hahn *et al.*, *Nucl. Instrum. Meth.* **499**, 245 (2003).
4. STAR Collaboration, (J. Adam *et al.*), *JHEP* **07**, 178 (2020).
5. M. Mieskolainen, *arXiv*:1910.06300
6. STAR Collaboration, (K. H. Ackermann *et al.*), *Nucl. Instrum. Meth.* **499**, 624 (2003).
7. M. Anderson *et al.*, *Nucl. Instrum. Meth.* **499**, 659 (2003).
8. STAR Collaboration, (J. Wu *et al.*), *J. Phys. G* **34**, 729 (2007).
9. STAR Collaboration, (C. A. Whitten *et al.*), *AIP Conf. Proc.* **980**, 1 (2008).
10. S. Bultmann *et al.*, *Nucl. Instrum. Meth.* **535**, 415 (2004).
11. F. E. Close and A. Kirk, *Nucl. Instrum. Meth.* **397**, 3 (1997).