# Study of central exclusive production in proton-proton collisions at $\sqrt{s} = 510$ GeV with STAR detector at RHIC

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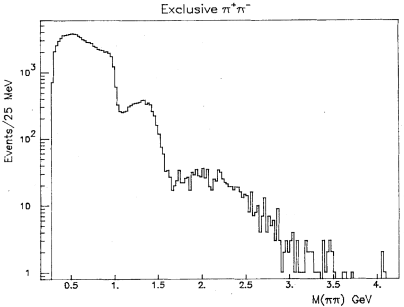
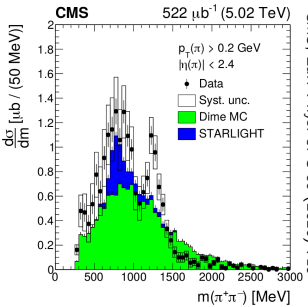
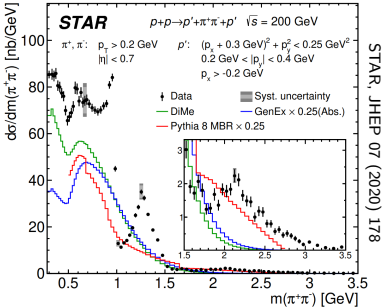
- Central Exclusive Production (CEP) through Double Pomeron Exchange (DPE) provides a gluon-rich environment for particle production
- CEP is considered to be a potential source of glueballs
- Glueballs are bound states consisting of only gluons and are predicted by the QCD theory
- Despite its theoretical predictions, the existence of a glueball has not been confirmed yet
- The first CEP through DPE was measured at Intersecting Storage Rings and since then it has been studied at numerous experiments (AFS, WA76, NA22, CDF, UA8, STAR, CMS, ATLAS...)




AFS, Nuclear Physics B (1986) 264




CMS, Eur. Phys. J. C 80 (2020) 718

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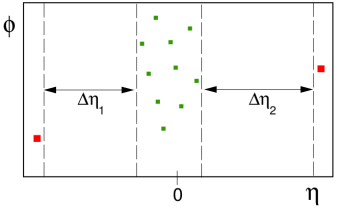
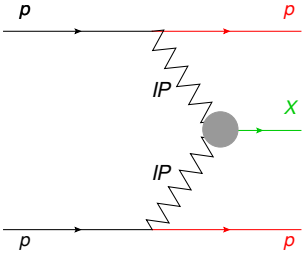
- Colliding protons stay intact and are measured in the Roman Pots (RP)
- Produced **central** system $X$ is well separated by rapidity gaps $\Delta\eta_{1,2}$ from the outgoing protons $p$
- **Central** system $X$ is fully measured in the Time Projection Chamber (TPC) and in the Time-of-Flight (TOF) systems
- Each proton "emits" a Pomeron
- The Pomerons fuse and produce neutral system $X$
- Double Pomeron Exchange (DPE) is expected to be dominant at the RHIC energies
- I focus on $p + p \to p\ h^+h^-\ p$, $h^+h^-$ stands for $\pi^+\pi^-$, $K^+K^-$ and $p\bar{p}$
- To verify **exclusivity** of the process we used

$$p_T^{miss} := \left(\vec{p}_1 + \vec{p}_2 + \vec{h}_+ + \vec{h}_-\right)_T = 0$$

$\Rightarrow$ events with small $p_T^{miss}$ are **Exclusive**

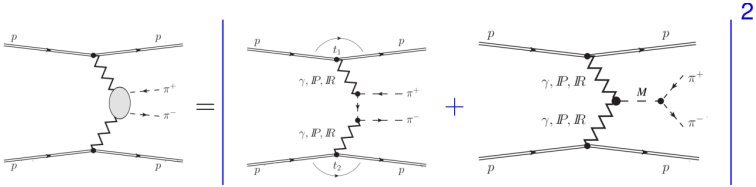
$$p + p \to p \overset{\Delta\eta_1}{\oplus} X \overset{\Delta\eta_2}{\oplus} p$$



# Theoretical predictions - GRANIITTI

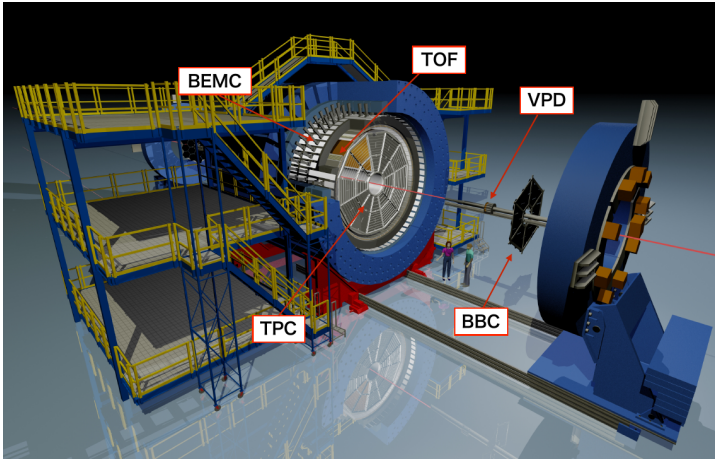
- CEP of $h^+h^-$ is the simplest four(three) body QCD process: $p + p \to p + M(h^+h^-) + p$
- Experimentally simple, theoretically complex
- Significant interference effects between resonance and continuum production
- Significant rescattering effects via additional interaction between the protons




- GRANIITTI, a Monte Carlo event generator for high energy diffraction
  - M. Mieskolainen, arXiv:1910.06300
- GRANIITTI calculates inv. mass spectra assuming continuum and resonances contributions
  $M = f_0(500),\ \rho(770),\ f_0(980),\ \phi(1020),\ f_2(1270),\ f_0(1500),\ f_2(1525),\ f_0(1710)$
- GRANIITTI v. 1.080 with added CEP resonance couplings also tuned to STAR 200 GeV results

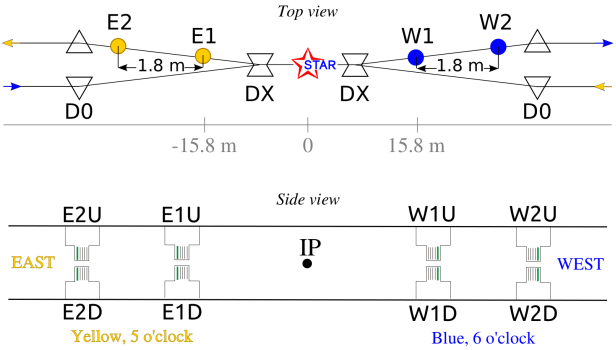
# Experimental setup - Solenoidal Tracker at RHIC

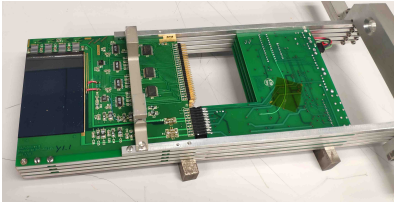
- Tracking of charged particles in the TPC covering $|\eta| < 1$ and full azimuthal angle
- Precise particle identification through the measurement of dE/dx and TOF
- Forward rapidity Beam-Beam Counters ($2.1 < |\eta| < 5.0$) used to ensure rapidity gaps
- Silicon Strip Detectors (SSD) in RP allow full reconstruction of the forward proton momentum and verification of interaction's exclusivity



# Experimental setup - Roman Pots (RP)

- Roman Pot Phase II* setup has been used since 2015
- Detectors are mounted in 4 stations, 2 stations on each side of STAR
- Each station holds one RP above and one RP below the beamline
- Each RP vessels contains a SSD package with active area of roughly $79 \times 49$ mm$^2$
- Each package consists of a scintillation trigger counter and 4 SSDs with spatial resolution of $\approx$ 30 $\mu$m



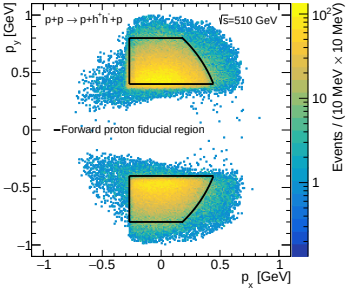



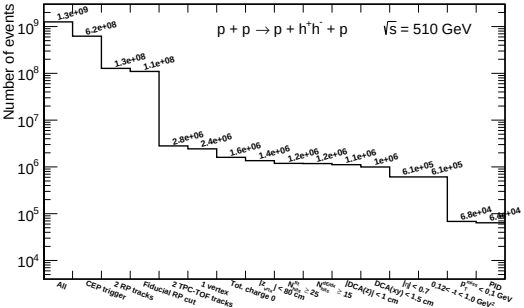
## Data sample:

- Data from proton-proton collisions at $\sqrt{s} = 510$ GeV
- 622M events with CEP triggers were analyzed

## Events selection:

- Exactly two tracks in Roman Pots inside the $p_x, p_y$ fiducial region with all eight silicon planes used in reconstruction
- Exactly two primary TPC tracks matched with two TOF hits and originating from the same vertex
- Total charge of those tracks equals 0 (looking for $h^+h^-$)
- $|z$-position of vertex$| < 80$ cm
- Good TPC track quality cuts and $|\eta| < 0.7$
- Exclusivity cut: $p_T^{miss} < 100$ MeV
- Particles were identified using the dE/dx and TOF
- After all the above selection criteria: 62077 $\pi^+\pi^-$, 1697 $K^+K^-$ and 125 $p\bar{p}$



# Particle identification

- Particles were identified using combined information from the TPC ($\chi^2_{dE/dx}$) and TOF ($m^2_{\mathrm{TOF}}$)

$$\chi^2_{dE/dx}(XX) = \left(n\sigma_X^{trk1}\right)^2 + \left(n\sigma_X^{trk2}\right)^2 \tag{1}$$

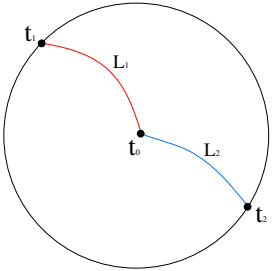
- $m^2_{\mathrm{TOF}}$ is derived from the assumption that both particles are of the same type ($m_1^2 = m_2^2 = m^2_{\mathrm{TOF}}$)

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

$$t_2 - t_0 = L_2\sqrt{1 + \frac{m_2^2}{p_2^2}} \tag{3}$$

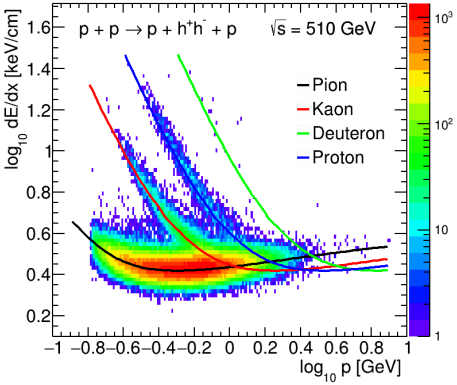
$$t_1 - t_2 = L_1\sqrt{1 + \frac{m_1^2}{p_1^2}} - L_2\sqrt{1 + \frac{m_2^2}{p_2^2}} \tag{4}$$

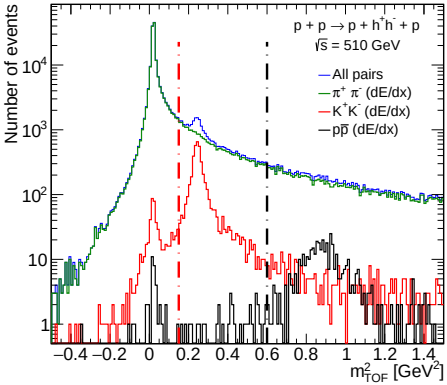
$$A \cdot (m^2_{\mathrm{TOF}})^2 + B \cdot m^2_{\mathrm{TOF}} + C = 0, \tag{5}$$



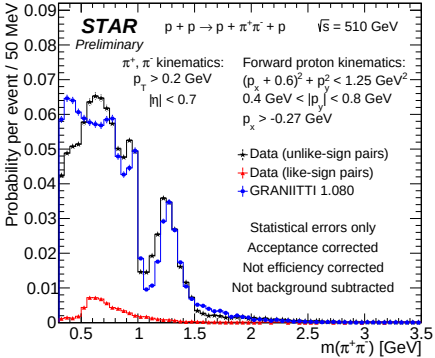
# Particle identification

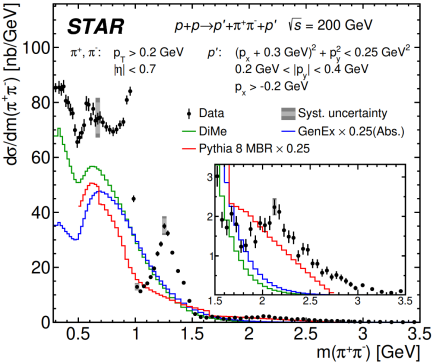
- $\pi^+\pi^-$ pairs production is dominant, as expected in DIPE process at RHIC energies
- Kaons and protons can be seen in dE/dx plot
- Peaks of pions, kaons and protons about their real mass squared can be seen
- Pions misidentified as kaons, using only the dE/dx information, can be seen as well



# Invariant mass of $\pi^+\pi^-$ compared to $\sqrt{s} = 200$ GeV results

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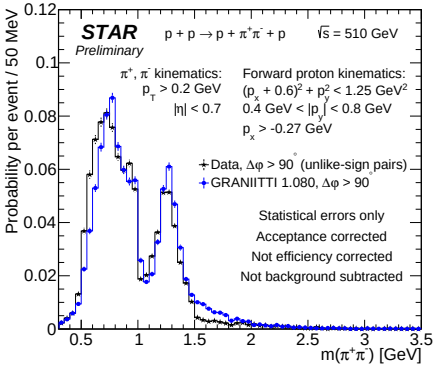
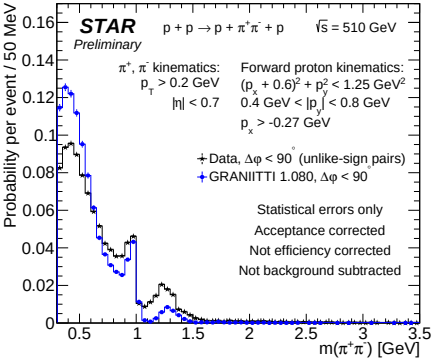
- The expected features in the invariant mass distribution are seen:
  - a drop at about 1 GeV, negative interference of $f_0(980)$ with continuum
  - a peak at about 1270 MeV, consistent with $f_2(1270)$
- The structure below 0.6 GeV is caused by the fiducial cuts (acceptance)
- Features similar to those at $\sqrt{s} = 200$ GeV are observed

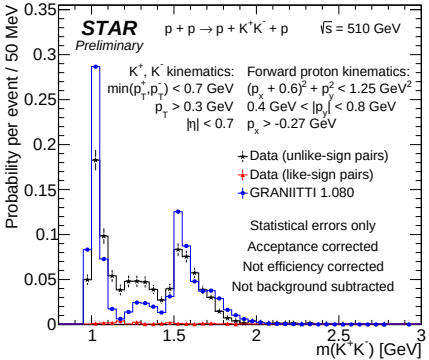
# Invariant mass of $\pi^+\pi^-$ differentiated into two $\Delta\varphi$ regions

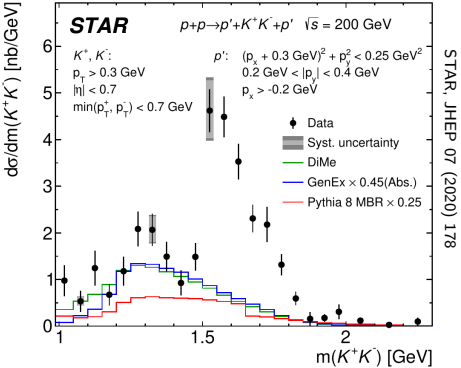
- Spectra were divided into two $\Delta\varphi$ regions, the difference of azimuthal angles of the forward protons $\Rightarrow$ different Pomeron dynamics
- A suppression of $f_2(1270)$ in $\Delta\varphi < 90^\circ$ can be seen
- An enhancement at low invariant mass in $\Delta\varphi < 90^\circ$ is observed



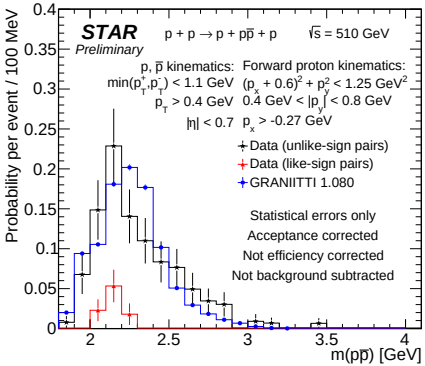
# Invariant mass of $K^+K^-$ compared to $\sqrt{s} = 200$ GeV results

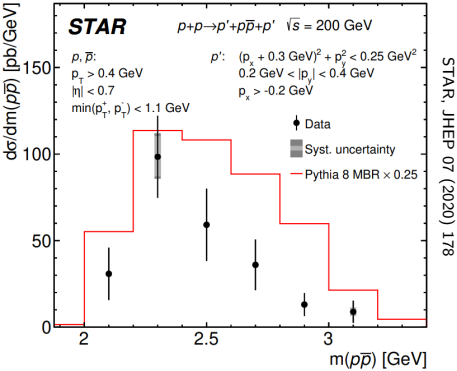



- A peak at 1 GeV (possible $\phi(1020)$) is close to the $K^+K^-$ mass threshold, more studies have to be made: determination of non-exclusive background ($p + \phi + X + p$)
- GRANIITTI shows the enhancement around 1 GeV at 510 GeV while it does not at 200 GeV
- Peaks at 1.3 and 1.5 GeV are consistent with $f_2(1270)$ and $f_2(1525)$, respectively
- Differentiation into two $\Delta\varphi$ regions needs to be done and studied

# Invariant mass of $p\bar{p}$ compared $\sqrt{s} = 200$ GeV results




- The invariant mass spectrum of $p\bar{p}$ pairs does not show any resonances
- Consistent with the measurement at $\sqrt{s} = 200$ GeV
- Data has large statistical errors and more studies need to be done to make any conclusions

**Summary:**

- The first results on the CEP of $\pi^+\pi^-$, $K^+K^-$ and $p\bar{p}$ pairs in $pp$ collisions at $\sqrt{s} = 510$ GeV measured by the STAR experiment at RHIC have been presented
- Measurement of the diffractively scattered protons allowed full control of the interaction's kinematics and verification of its exclusivity
- The invariant mass spectra of $\pi^+\pi^-$, $K^+K^-$ and $p\bar{p}$ pairs confirmed features seen in previous measurements
- Interesting features are seen, like the peak at about 1 GeV in $K^+K^-$
- The new MC event generator, GRANIITTI, was compared to the data giving promising results

**Outlook:**

- There are ongoing studies of $\pi^+\pi^-$, $K^+K^-$, $p\bar{p}$ and also $\pi^+\pi^-\pi^+\pi^-$ channels
- An analysis involving the partial wave analysis in the $\pi^+\pi^-$ channel is planned

**Thank you!**