

# Central Exclusive Production with the STAR detector at RHIC

J. High Energ. Phys. 2020, 178 (2020), arXiv:2004.11078 [hep-ex] :  $\sqrt{s} = 200$  GeV  
Preliminary results :  $\sqrt{s} = 510$  GeV

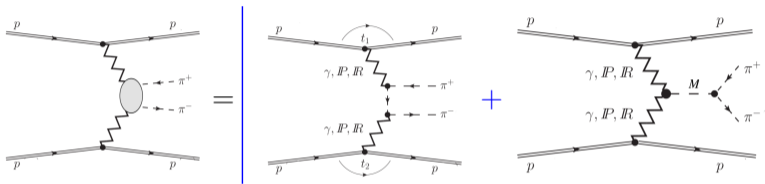
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# Motivation

- Exclusive  $h^+h^-$  production - the simplest four(three) body QCD process:  $p + p \rightarrow p + M(h^+h^-) + p$ .
- Experimentally simple: final state containing two forward protons and two charged hadrons.
- Prediction complex: photon, pomeron or reggeon exchanges producing direct  $h^+h^-$  pair or resonance  $M = f_0(500), \rho, f_0(980), f_2(1270), f_0(1500), \dots$  **Interference effects might be significant.**



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- **Significant rescattering effects:**

- cross section reduced by additional interaction between the protons (and/or hadron-proton) - embedded in so-called Survival Factor (SF). The SF depends on the collision energy. Suppression can be even by a factor of 5 at RHIC energies and a factor of 10 at LHC energies,
- additionally cross section redistributed by Final State Interactions between directly produced hadrons.

- **With protons measured in Roman Pots:**

- photoproduction processes suppressed ( $-t \ll 0$ ),
- direct proof of exclusivity.

- At high energy the reaction is **dominated by Double Pomeron Exchange (DPE)**.

- DPE processes favorable place to look for hadronic production of **glueballs**.

# Theoretical predictions

Two models based on Regge theory for direct pion/kaon pair production with parameters of the Pomeron and sub-leading Reggeon exchanges were adjusted to describe the total and elastic  $\pi p$  or  $Kp$  scatterings and implemented in the form of MC generator:

- *L.A. Harland-Lang et al.*
  - The phenomenology of CEP at hadron collider Eur.Phys.J. C72 (2012) 2110, implemented in **DiMe** generator with dynamical treatment of absorption effects.
- *P. Lebiedowicz and A. Szczurek*
  - Exclusive  $pp \rightarrow pp\pi\pi$  from the threshold to LHC, Phys. Rev. D81(2010)036003 implemented in **GenEx** generator without absorptive corrections.

and resonant contributions (not implemented in GenEx generator):

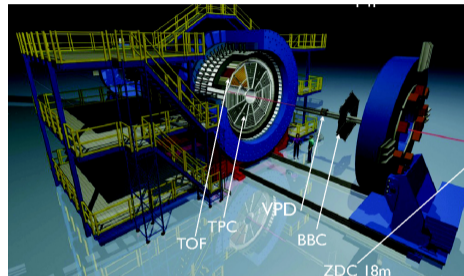
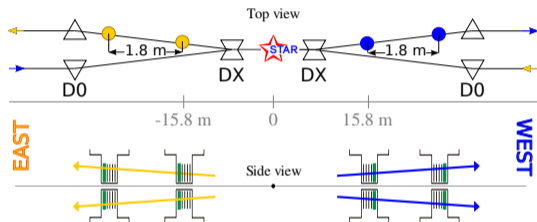
- *P. Lebiedowicz, O. Nachtmann and A. Szczurek*
  - $\pi^+\pi^-$ : Phys.Rev. D93 (2016) 054015.
  - $K^+K^-$ : Phys. Rev. D 98 (2018) 014001.
  - $p\bar{p}$ : Phys. Rev. D 97 (2018).

- Above continuum models were implemented also in **GRANIITTI** (M. Mieskolainen, arXiv:1910.06300) generator including production of several resonances  $f_0(500)$ ,  $f_0(980)$ ,  $f_2(1270)$ ,  $f_0(1500)$ ,  $f_2(1525)$ ,  $f_0(1710)$  and interferences between all possible decay channels. Some resonance couplings were tuned to STAR results at  $\sqrt{s} = 200$  GeV.

- Continuum is also generated in **Pythia8**, with MBR model (R. Ciesielski, K. Goulios, arXiv:1205.1446) tuned to CDF data on inclusive Central Diffraction (CD).

# Experimental setup

Data samples:  $\mathcal{L} = 14.2 \text{ pb}^{-1}$ ,  $\mu = 0.2 - 0.9$  taken in proton-proton collisions at  $\sqrt{s} = 200 \text{ GeV}$  in 2015 year. 10 times larger luminosity with slightly higher  $\mu$  at  $\sqrt{s} = 510 \text{ GeV}$



- **Intact forward protons** are scattered through a small angle of typically 2 - 5 *mrad*. Protons are measured in the **Roman Pot (RP)** detectors at 16 m from the IP, the RP were placed at 35 mm from the beam in standard RHIC run of  $\beta^* = 10 \text{ m}$  optics.
- **Central charged particles** with  $p_T > 0.2 \text{ GeV}$  and  $|\eta| < 1.0$  are measured in **Time Projection Chamber (TPC)** allowing determination of the primary vertex position and Particle Identification (PID) through  $dE/dx$  measurement.
- **Central charged particles** are measured in **Time of Flight (ToF)** detector allowing: triggering, in-time TPC tracks selection and PID.
- **Trigger:** Coincidence of the signal in RP with TOF activity and veto on inner part of **Beam-Beam Counter (BBC)**. Inner part of BBC covers pseudorapidity range of  $3.3 < |\eta| < 5.2$ .

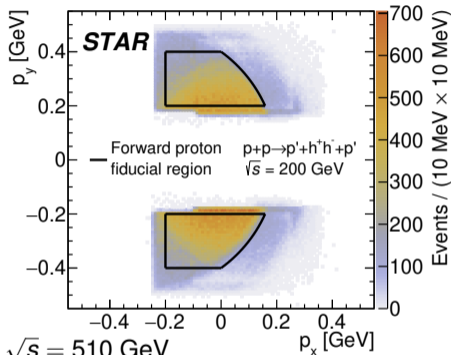
# Event selection and definition of the fiducial region

$\sqrt{s} = 200$  GeV

- Two opposite-charge particles in TPC of  $p_T > 0.2$  GeV,  $|\eta| < 0.7$ , both matched with TOF hits.
- Two forward-scattered proton tracks in RP, one on each side of the interaction region, each of transverse momentum satisfying  $(p_x + 0.3 \text{ GeV})^2 + p_y^2 < 0.25 \text{ GeV}^2$   
 $0.2 \text{ GeV} < |p_y| < 0.4 \text{ GeV}$ ,  $p_x > -0.2 \text{ GeV}$ .
- Transverse momentum balance:  
 $p_T^{\text{miss}}(p' + h^+h^- + p') < 75 \text{ MeV}$ .
- Veto on particles in the region  $2.1 < |\eta| < 5.0$  covered by BBC.
- PID cuts to separate central state  $\pi^+\pi^-$ ,  $K^+K^-$  and  $p\bar{p}$  using  $dE/dx$  and ToF.
- Additional cuts after identification:

$K^+K^-$ :  $p_T > 0.3 \text{ GeV}$   
 $\min(p_T^+, p_T^-) < 0.7 \text{ GeV}$ ,  
 $p\bar{p}$ :  $p_T > 0.4 \text{ GeV}$   
 $\min(p_T^+, p_T^-) < 1.1 \text{ GeV}$ .

$\sqrt{s} = 510$  GeV sample probes larger values of  $-t$  and larger  $p_T$  of the central state.



$\sqrt{s} = 510$  GeV

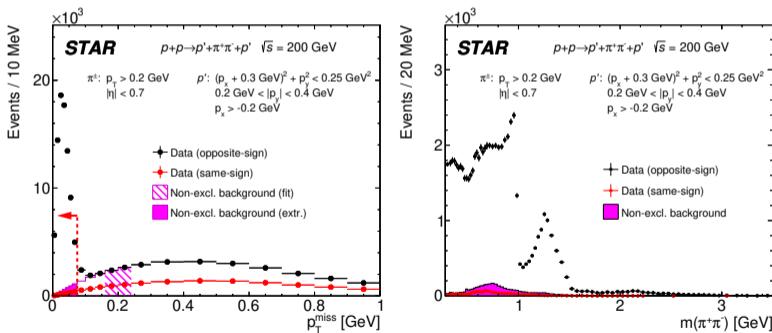
- 2.5 larger proton energy moves RP geometrical acceptance towards larger proton momenta.
- $(p_x + 0.6 \text{ GeV})^2 + p_y^2 < 1.25 \text{ GeV}^2$   
 $0.4 \text{ GeV} < |p_y| < 0.8 \text{ GeV}$ ,  $p_x > -0.27 \text{ GeV}$ .

# Non-exclusive background (data-driven method): $\sqrt{s} = 200$ GeV

Origin of the non-exclusive background to exclusive  $p + p \rightarrow p' + h^+ h^- + p'$ :

- Inclusive CD with more than two charged hadrons, mainly  $p + p \rightarrow p' + h^+ h^- + n(h^+ h^-) + p'$ .
- Inclusive CD with two charged hadrons + neutrals, mainly  $p + p \rightarrow p' + h^+ h^- + n h^0 + p'$ .
- Accidental overlap: elastic ( $p', p'$ ) + non-elastic ( $h^+ h^-$ ), beam-halo ( $p'$ ) + SD ( $h^+ h^- + p'$ ).

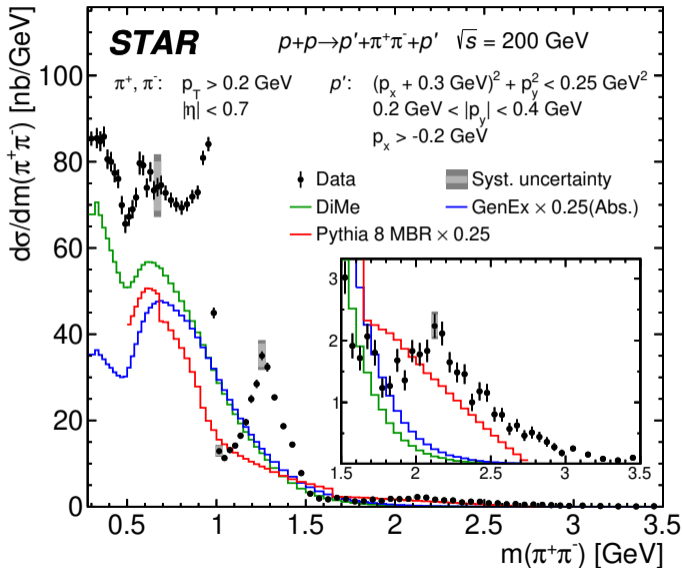
All sources lead to much flatter  $p_T^{\text{miss}}$  distribution. Bkg. estimated based on the extrapolation into the signal region of the second-degree polynomial function fitted to the signal-free region. Done differentially in all observables.



On average, non-excl. bkg. amounts to  $< 6\%$  for  $\pi^+\pi^-$  and  $K^+K^-$  and  $< 12\%$  for  $p\bar{p}$ .

Preliminary  $\sqrt{s} = 510$  GeV results not corrected for background.

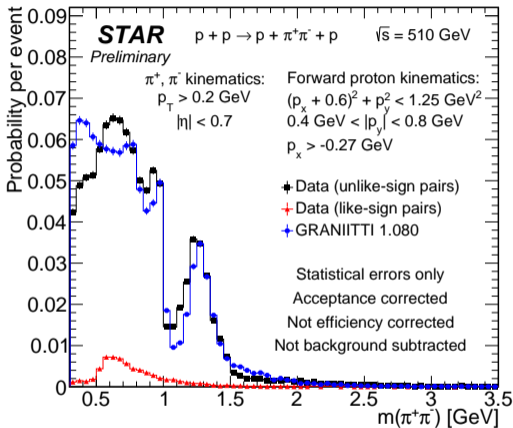
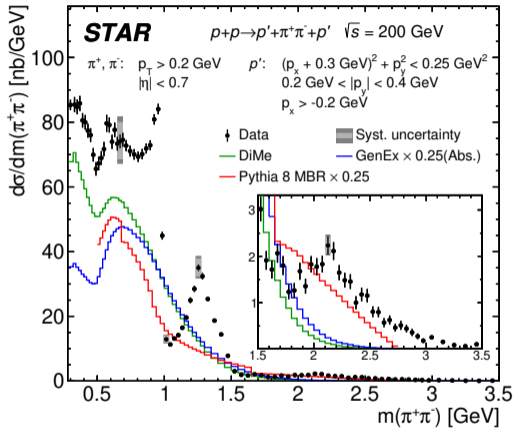
# Invariant mass of exclusively produced $\pi^+\pi^-$ : $\sqrt{s} = 200$ GeV



Syst. unc. are shown only for a few selected bins because they are strongly correlated between bins (affect mainly normalization).  
**Four times better precision of the cross section (normalization) compared to previous DPE measurement with forward proton tagging.**

- The structure ('hole') in cross section below 0.6 GeV is caused by the fiducial cuts (acceptance).
- Peak at 1 GeV followed by sharp drop of the cross section consistent with  $f_0(980)$ , peak between 1-1.5 GeV consistent with  $f_2(1270)$  - both expected in DPE.
- Another resonance is observed at 2.2 GeV.
- DiMe describes the continuum best (shape and normalization)

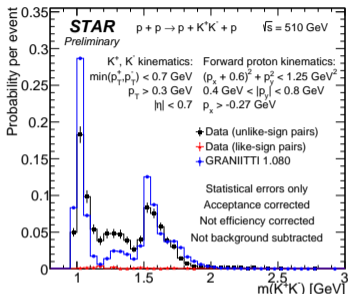
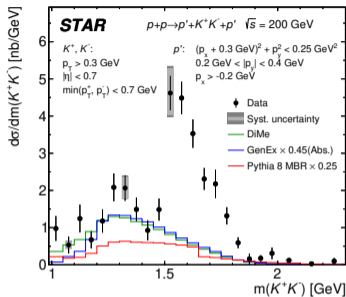
# Invariant mass of exclusively produced $\pi^+\pi^-$



- Ratio  $f_2(1270)/f_0(980)$  significantly smaller at  $\sqrt{s} = 510$  GeV compared to  $\sqrt{s} = 200$  GeV
- Peak around 0.6 GeV at  $\sqrt{s} = 510$  GeV possible due to the unsubtracted background.
- GRANIITTI 1.08 tuned to  $\sqrt{s} = 200$  GeV data fairly well predicts shape at  $\sqrt{s} = 510$  GeV.



# Invariant mass of exclusively produced $K^+K^-$



- $\sqrt{s} = 200$  GeV

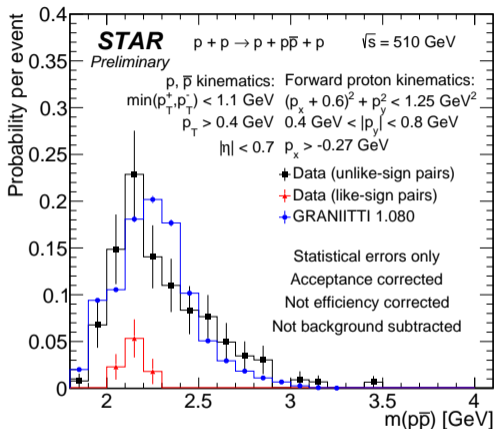
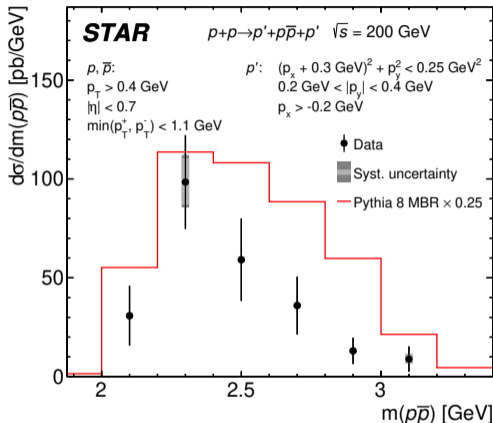
- $d\sigma/dm(K^+K^-)$  shows significant enhancement in the  $f_2'(1525)$  mass region and smaller resonant signals in the mass regions of  $f_2(1270)$  and  $f_0(1710)$ .
- The ratio of the cross sections for  $\pi^+\pi^-$  to  $K^+K^-$  production in the  $f_2(1270)$  mass region is roughly 18, consistent with the PDG ratio of the  $f_2(1270)$  branching fractions for its decays into  $\pi^+\pi^-$  and  $K^+K^-$ .
- DiMe and GenEx roughly describe the non-resonant contribution to the data.

- $\sqrt{s} = 510$  GeV

- Peak above  $K^+K^-$  mass threshold not visible at  $\sqrt{s} = 200$  GeV
- 510 GeV setup opened acceptance for relatively high  $0.8 < p_T < 1.6$  GeV central states and therefore observation of states close to the  $K^+K^-$  mass threshold.
- According to Ganiotti :
  - Peak near the  $K^+K^-$  mass threshold predominantly due to interference of the  $f_0(980)$  with continuum.
  - Much smaller effect is expected due to interference of the  $\phi(1020)$  with continuum

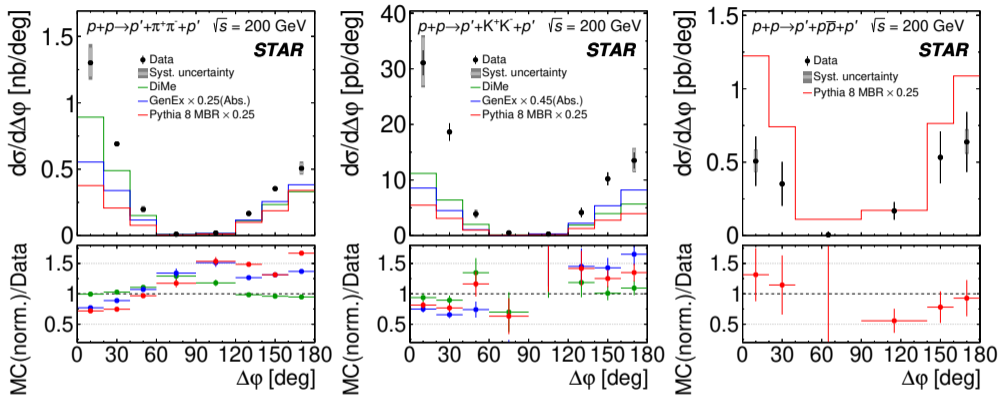
- GRANIITTI 1.08 predicts the shape at  $\sqrt{s} = 510$  GeV fairly well.

# Invariant mass of exclusively produced $p\bar{p}$



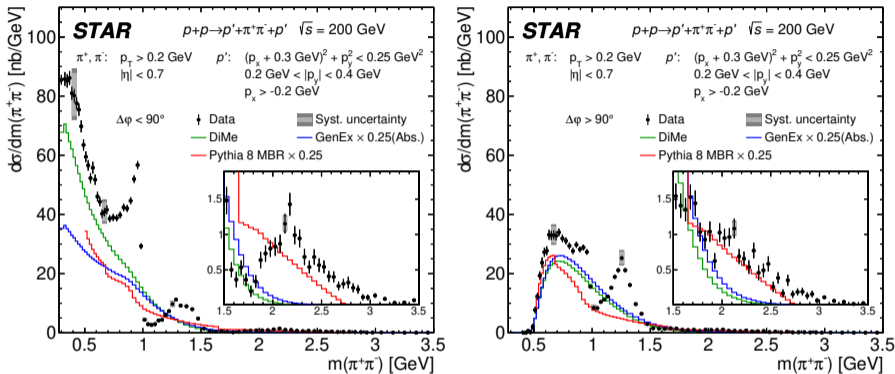
- The invariant mass spectrum of  $p\bar{p}$  pairs does not show any obvious resonance peaks
- **MBR PYTHIA8** model overestimates the  $d\sigma/dm(p\bar{p})$  by a factor of 8 at  $\sqrt{s} = 200$  GeV
- **GRANIITTI 1.08** predicts the shape at  $\sqrt{s} = 510$  GeV fairly well.

# Angular separation of forward protons in the transverse plane ( $\Delta\phi$ )



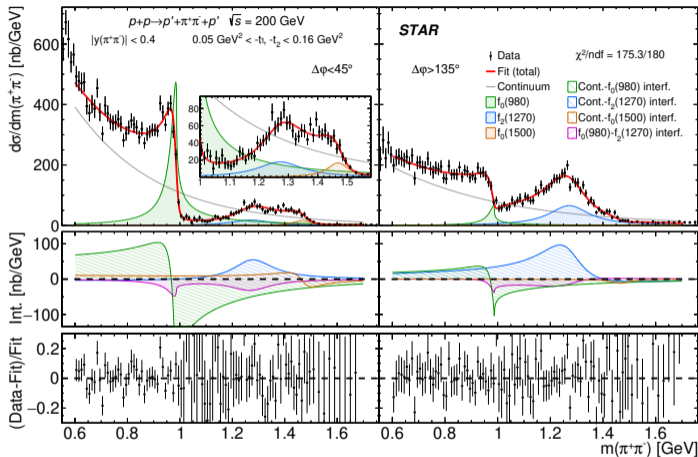
- Suppression of  $d\sigma/dm(\Delta\phi)$  close to  $90^\circ$  is due to fiducial cuts (acceptance).
- Significant asymmetry observed in cross section depending on the  $\Delta\phi$  for  $\pi^+\pi^-$  and  $K^+K^-$ .
- Distribution sensitive to the absorption effects. DiMe model predictions agree in shape with data for  $\pi^+\pi^-$  and  $K^+K^-$ .
- GenEx does not describe the data.
- MBR model describes the data fairly well in shape for  $p\bar{p}$ .

# Invariant mass of exclusively produced $\pi^+\pi^-$ in bins of $\Delta\phi$



- Suppression of the cross section at  $m(\pi^+\pi^-) < 0.6$  GeV for the  $\Delta\phi > 90^\circ$  range is due to the fiducial cuts.
- In the  $\Delta\phi < 90^\circ$  range, the peak around the  $f_2(1270)$  resonance in data is significantly suppressed, while the peak at  $f_0(980)$  and resonances in the regions 1.3 – 1.5 GeV and 2.2 – 2.3 GeV, are enhanced compared to the  $\Delta\phi > 90^\circ$  range.
- In the  $\Delta\phi < 90^\circ$ , the DiMe describes better normalisation and shape of the mass spectrum at  $m(\pi^+\pi^-) < 0.5$  GeV.
- Preliminary results at  $\sqrt{s} = 510$  GeV show consistency with  $\sqrt{s} = 200$  GeV results

# Extrapolated invariant mass cross section for $\pi^+\pi^-$



- Fiducial  $d\sigma/dm(\pi^+\pi^-)$  have been extrapolated to  $|y(\pi^+\pi^-)| < 0.4$ ,  $0.05 < -t_1, -t_2 < 0.16 \text{ GeV}^2$ ,  $\Delta\phi < 45^\circ$  and  $\Delta\phi > 135^\circ$ .
- Minimal model of continuum with coherently added three resonances (all parameters free except the mass and width of  $f_2(1270)$ ) fitted simultaneously in two  $\Delta\phi$  regions (amplitudes independent) in the mass range  $0.6 < m < 1.7 \text{ GeV}$ .

- Data very well described by the model, parameters of resonances consistent with  $f_0(980)$  and  $f_0(1500)$ .
- Potential presence of an additional moderately narrow state around 1.37 GeV.
- Significant asymmetry of resonances production depending on  $\Delta\phi$  was observed.

# Summary

- Measurements of the Central Exclusive Production of charged hadron pairs in proton-proton collisions at  $\sqrt{s} = 200$  GeV and  $\sqrt{s} = 510$  GeV by the STAR experiment at RHIC have been presented.
- High-purity samples of exclusively produced  $\pi^+\pi^-$ ,  $K^+K^-$  and  $p\bar{p}$  pairs were selected and the differential fiducial cross sections were calculated.
- Cross sections were compared with existing models of continuum production implemented in the MC generators.
- The uncertainty of the absolute normalization of the STAR measurement is a factor of four better compared to measurements at the ISR, giving much stronger constraints for phenomenological models.
- Structures observed in the measured mass spectra are consistent with resonances:  $f_0(980)$ ,  $f_2(1270)$ ,  $f_0(1500)$ ,  $f'_2(1525)$ . A resonance is also observed for  $\pi^+\pi^-$  around  $m(\pi^+\pi^-) 2.2$  GeV.
- Measurement of forward protons provides insight to relations between the central state observables and forward-scattered protons' kinematics.
- Preliminary STAR results at  $\sqrt{s} = 500$  GeV show interesting features, like the peak at about 1 GeV in  $K^+K^-$ .
- GRANIITTI 1.08, was compared to the data at  $\sqrt{s} = 510$  GeV giving promising results.

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