

# 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

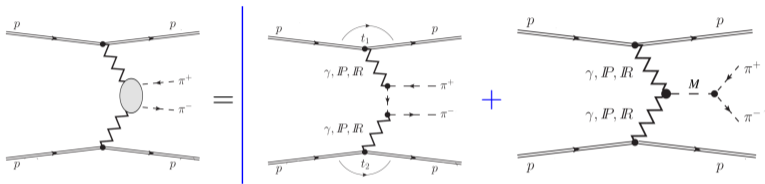
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# Motivation

- 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

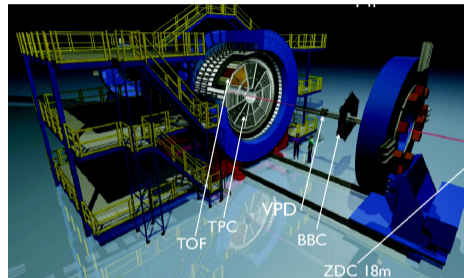
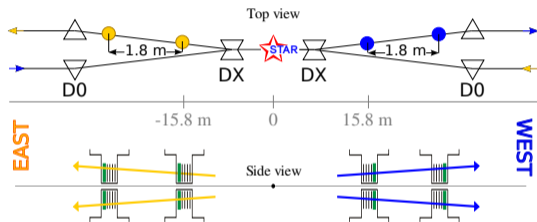
- Continuum is also generated in **Pythia8**, with MBR model (R. Ciesielski, K. Goulios, arXiv:1205.1446) tuned to CDF data on inclusive Central Diffraction (CD).

Predictions from **DiMe**, **GenEx** and **Pythia8** are compared with the STAR results at  $\sqrt{s} = 200$  GeV

Predictions from **GRANIITTI** are compared with the STAR results at  $\sqrt{s} = 510$  GeV

# 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  $3.3 < |\eta| < 5.2$ .

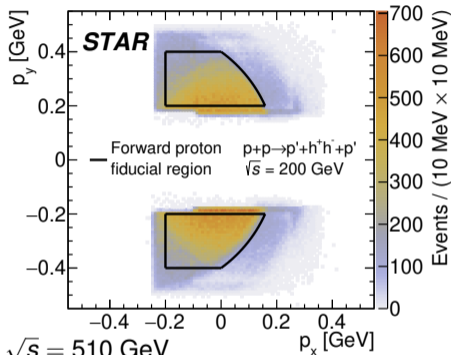
# Event selection and definition of the fiducial region

$\sqrt{s} = 200$  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.



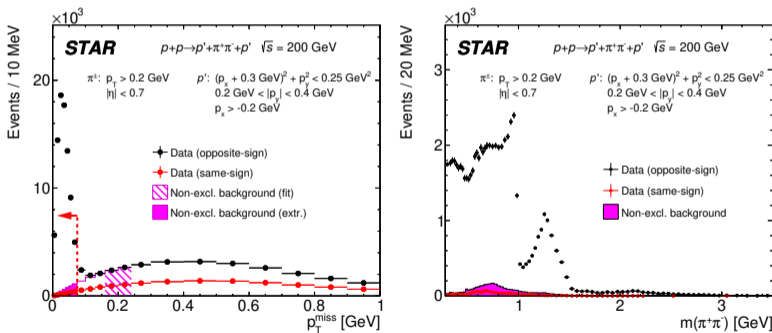
- 2.5 larger proton energy moves RP geometrical acceptance towards larger proton momenta.
- $(p_x + 0.6 \text{ GeV})^2 + p_y^2 < 1.25 \text{ GeV}^2$   
 $0.4 \text{ GeV} < |p_y| < 0.8 \text{ GeV}$ ,  $p_x > -0.27 \text{ GeV}$ .

# 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 ( $h^+ h^- + p'$ ).

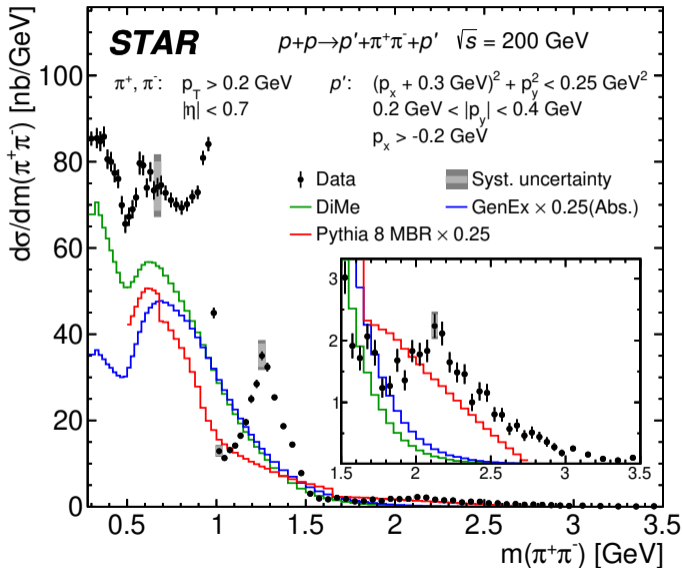
All sources lead to much flatter  $p_T^{\text{miss}}$  distribution. Bkg. estimated based on the extrapolation into the signal region of the second-degree polynomial function fitted to the signal-free region. Done differentially in all observables.



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.

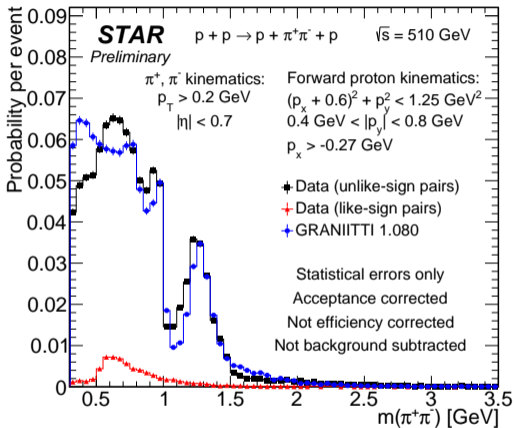
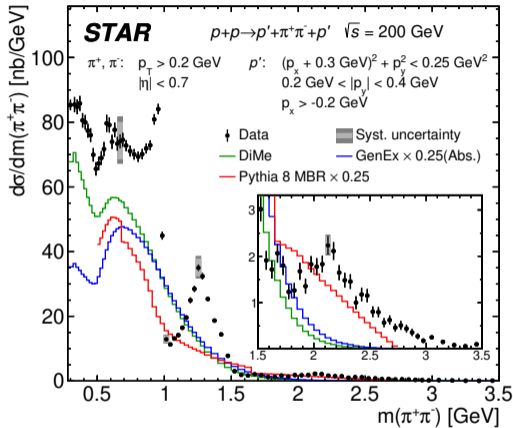
# Invariant mass of exclusively produced $\pi^+\pi^-$ : $\sqrt{s} = 200$ GeV



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)

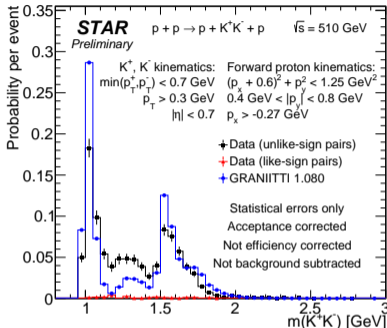
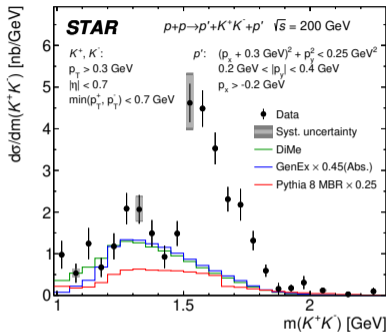
# Invariant mass of exclusively produced $\pi^+\pi^-$



- 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 tuned to  $\sqrt{s} = 200$  GeV data fairly good predicts shape at  $\sqrt{s} = 510$  GeV.

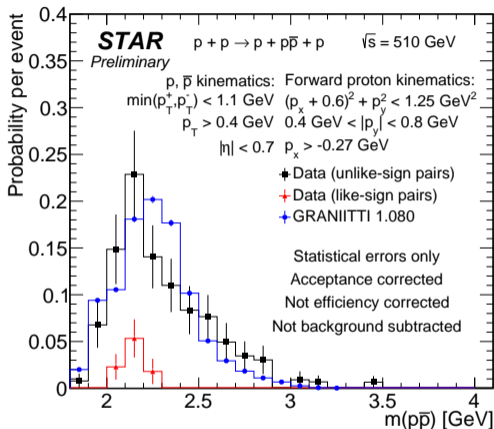
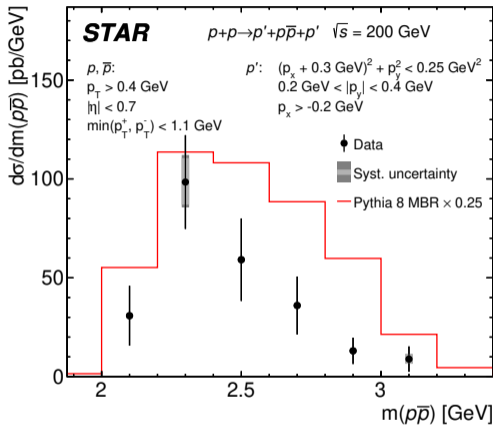


# Invariant mass of exclusively produced $K^+K^-$



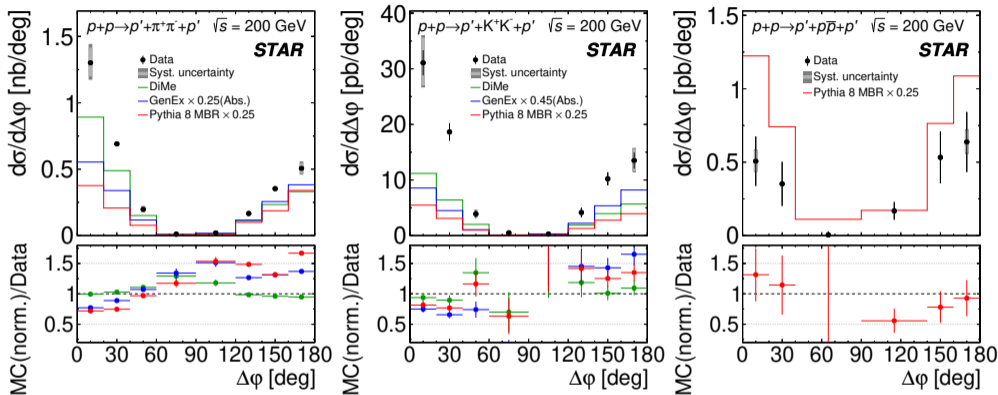
- $\sqrt{s} = 200$  GeV
  - $d\sigma/dm(K^+K^-)$  shows significant enhancement in the  $f_2'(1525)$  mass region and smaller resonant signals in the mass regions of  $f_2(1270)$  and  $f_0(1710)$ .
  - The ratio of the cross sections for  $\pi^+\pi^-$  to  $K^+K^-$  production in the  $f_2(1270)$  mass 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
  - Production of  $f_0(980)$  close to the  $K^+K^-$  mass threshold supported by high acceptance for large  $p_T$   $f_0(980)$  production at  $\sqrt{s} = 510$  GeV but  $\phi(1020)$  not excluded. More studies have to be done.
  - GRANIITTI fairly good predicts shape at  $\sqrt{s} = 510$  GeV.

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



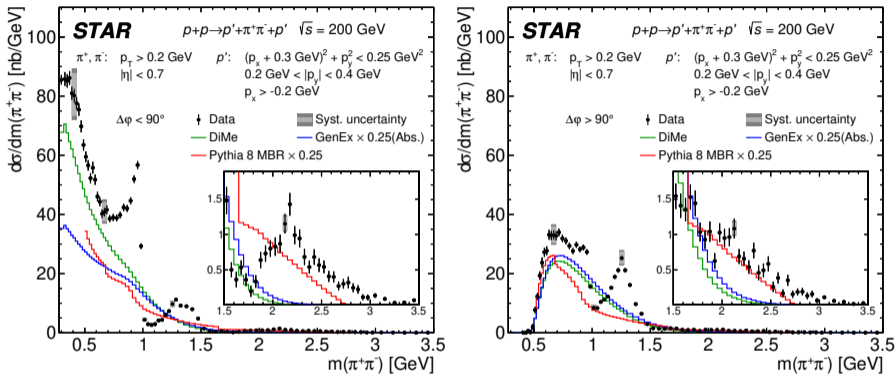
- The invariant mass spectrum of  $p\bar{p}$  pairs does not show any obvious resonance peaks
- **MBR PYTHIA8** model overestimates the  $d\sigma/dm(p\bar{p})$  by a factor of 8 at  $\sqrt{s} = 200$  GeV
- **GRANIITTI** fairly good predicts shape at  $\sqrt{s} = 510$  GeV.

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



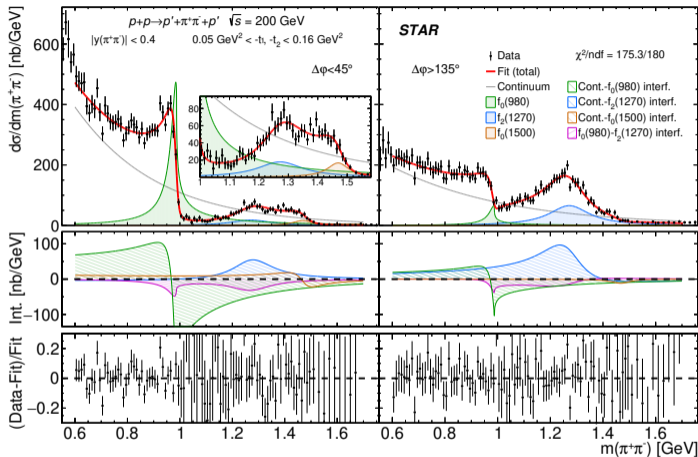
- Suppression of  $d\sigma/dm(\Delta\phi)$  close to  $90^\circ$  is due to fiducial cuts (acceptance).
- Significant asymmetry observed in cross section depending on the  $\Delta\phi$  for  $\pi^+\pi^-$  and  $K^+K^-$ .
- Distribution sensitive to the absorption effects. DiMe model predictions agree 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, was compared to the data at  $\sqrt{s} = 500$  GeV giving promising results.

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