

Central exclusive production of  $\pi\pi$ ,  $KK$  and  $p\bar{p}$  pairs with forward proton measured in Roman Pot detectors in proton proton collisions at  $\sqrt{s} = 200$  GeV with the STAR detector.

J. High Energ. Phys. 2020, 178 (2020), arXiv:2004.11078 [hep-ex]

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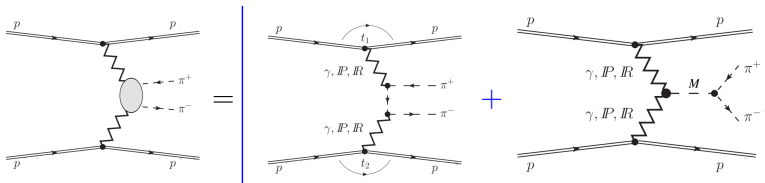


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# Motivation

- 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):

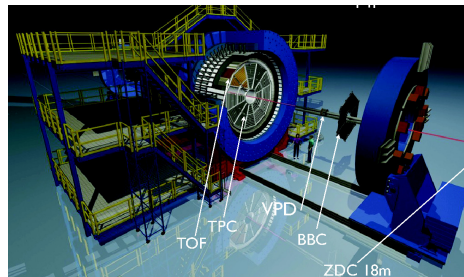
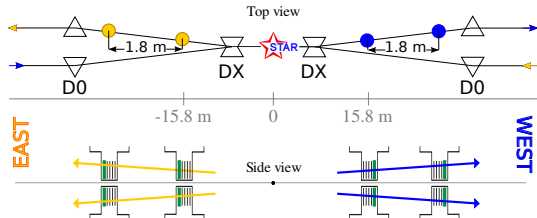
- *P. Lebiedowicz, O. Nachtmann and A. Szczurek*
  - Central exclusive diffractive production of  $\pi^+\pi^-$  continuum, scalar and tensor resonances in  $pp$  and  $\bar{p}p$  scattering within tensor pomeron approach, Phys.Rev. D93 (2016) 054015.
  - Towards a complete study of central exclusive production of  $K^+K^-$  pairs in proton-proton collisions within the tensor Pomeron approach, Phys. Rev. D 98 (2018) 014001.
  - Central exclusive diffractive production of  $p\bar{p}$  pairs in proton-proton collisions at high energies, Phys. Rev. D 97 (2018).

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.](#)

# 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.

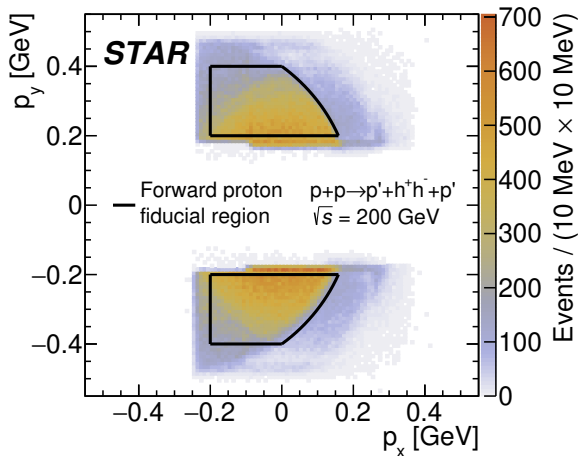


- **Intact forward protons** are scattered through a small angle of typically 2 - 5 *mrad*. Protons are measured in the **Roman Pot (RP)** detectors at 16 m from the IP, the RP were placed at 35 mm from the beam in standard RHIC run of  $\beta^* = 10 \text{ m}$  optics.
- **Central charged particles** 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

- 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:

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

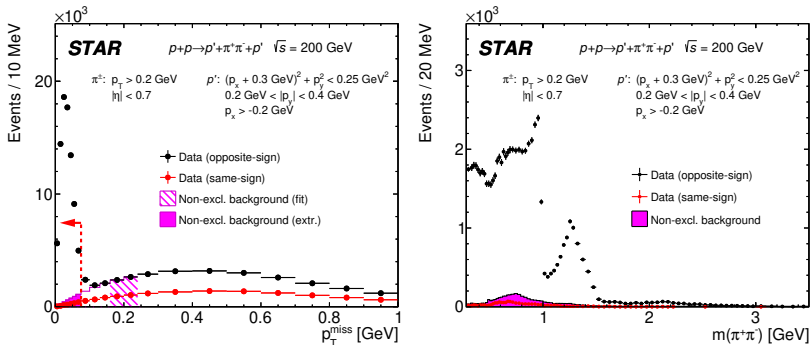


# Non-exclusive background (data-driven method)

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

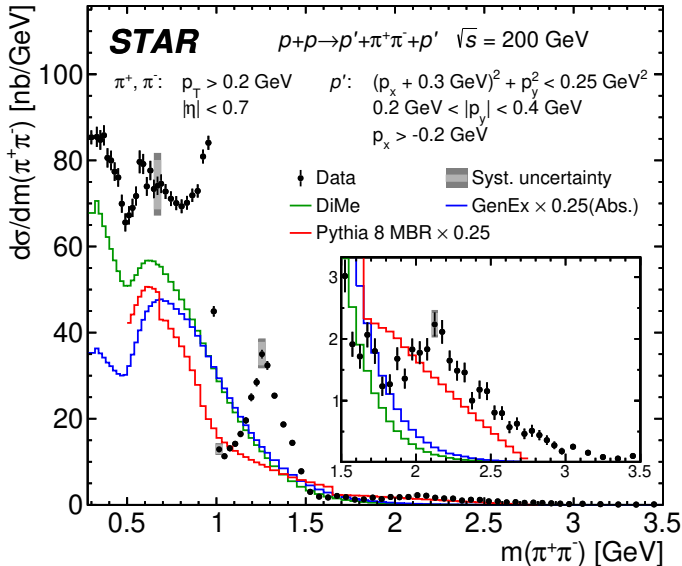
- Inclusive CD with more than two charged hadrons, mainly  $p + p \rightarrow p' + h^+ h^- + n(h^+ h^-) + p'$ .
- Inclusive CD with two charged hadrons + neutrals, mainly  $p + p \rightarrow p' + h^+ h^- + nh^0 + p'$ .
- Accidental overlap: elastic ( $p', p'$ ) + non-elastic ( $h^+ h^-$ ), beam-halo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

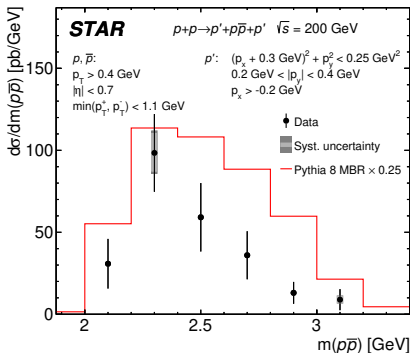
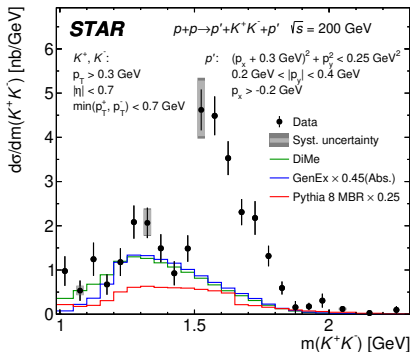
# Invariant mass of exclusively produced $\pi^+\pi^-$



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) resonances.

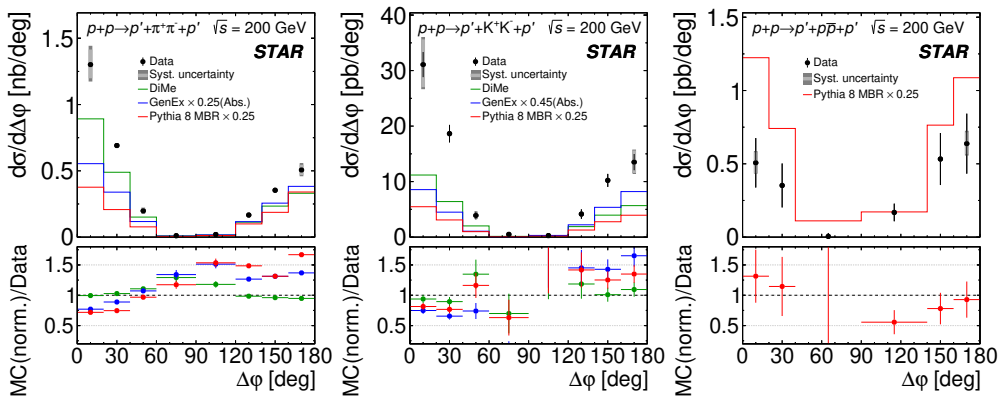
# Invariant mass of exclusively produced $K^+K^-$ and $p\bar{p}$



- $d\sigma/dm(K^+K^-)$  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.
- MBR model overestimates the  $d\sigma/dm(p\bar{p})$  by a factor of 8.

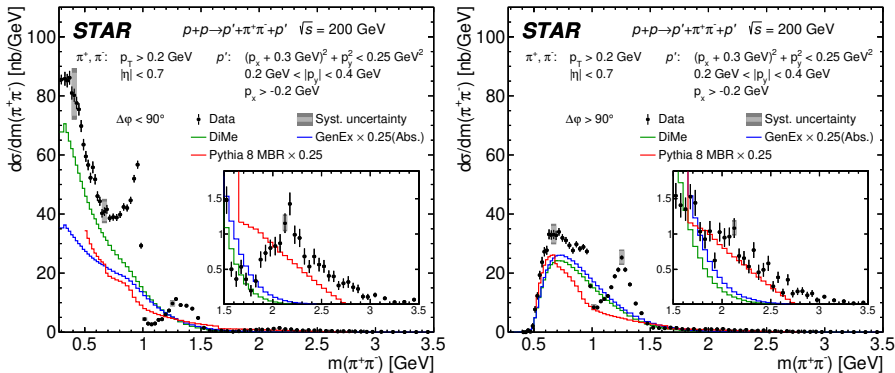


# Angular separation of forward protons in the transverse plane ( $\Delta\phi$ )



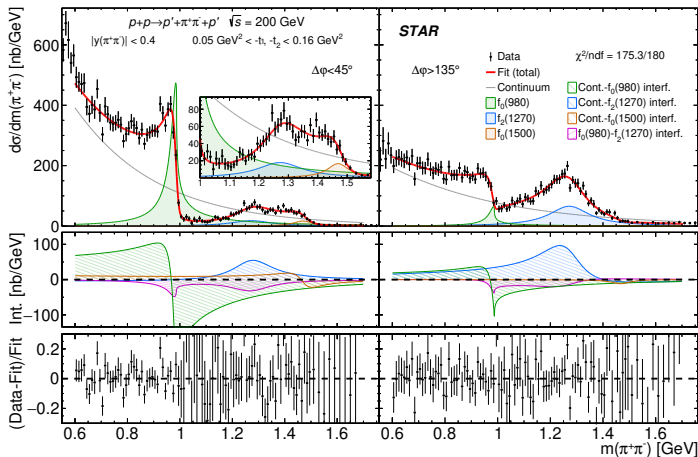
- Suppression of  $d\sigma/dm(\Delta\phi)$  close to  $90^\circ$  is due to fiducial cuts (acceptance).
- Significant asymmetry observed in cross section depending on the  $\Delta\phi$  for  $\pi^+\pi^-$  and  $K^+K^-$ .
- Distribution sensitive to the absorption effects. DiMe model predictions agree 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 well the normalisation and the shape of the mass spectrum at  $m(\pi^+\pi^-) < 0.5$  GeV.

# 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 by the STAR experiment at RHIC have been presented.
- These are currently the highest center-of-mass energies at which the Double Pomeron Exchange has been measured with the detection of the forward-scattered protons.
- 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 presented in poster session by T. Truhlar.