Measurement of the central exclusive production of charged particle pairs in proton-proton collisions with the STAR detector at RHIC

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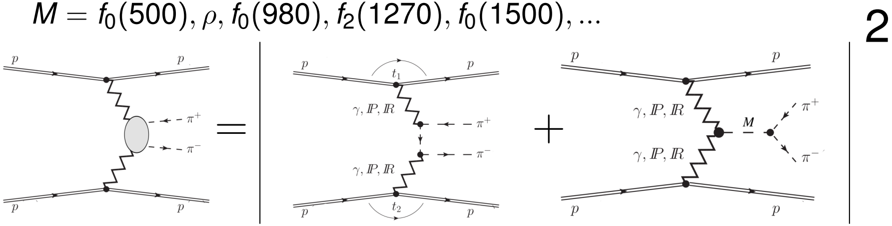
Motivation

- Exclusive h^+h^- - the simplest four(three) body QCD process
- 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
  $M = f_0(500), \rho, f_0(980), f_2(1270), f_0(1500), \ldots$

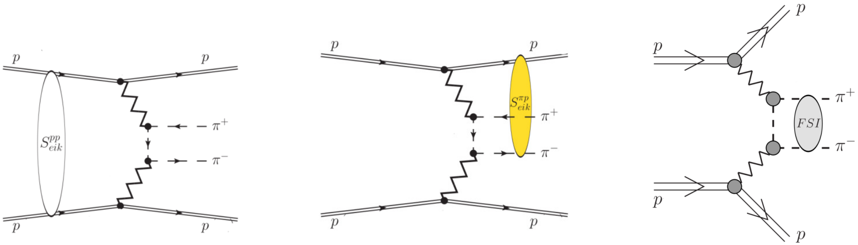


- With protons measured in Roman Pots ($-t \ll 0$): photoproduction processes suppressed
- Reaction dominated by Double Pomeron Exchange (DPE)
- DPE processes favorable place to look for hadronic production of glueballs

Motivation

Simplest DPE process but Born-level cross-sections:

- reduced by additional interaction between the protons (and/or pion–proton) - embedded in so-called Survival Factor (S)
- redistributed by Final State Interactions (FSI) between directly produced pions



The suppression factor depends on the collision energy. They usually reduce the cross sections, even by a factor of 5 at RHIC energy and a factor of 10 at LHC energies

Theoretical predictions

Two models of direct pion/kaon pair production and absorptive corrections:

- *L.A. Harland-Lang et al.*
  - The phenomenology of CEP at hadron collider Eur.Phys.J. C72 (2012) 2110, implemented in DiMe generator
- *P.Lebiedowicz and A.Szczurek*
  - Exclusive $pp \to pp\pi\pi$ from the threshold to LHC , Phys. Rev. D81(2010)036003 implemented in GenEx generator (no absorptive corrections)

and resonant contributions (not implemented in GenEx):

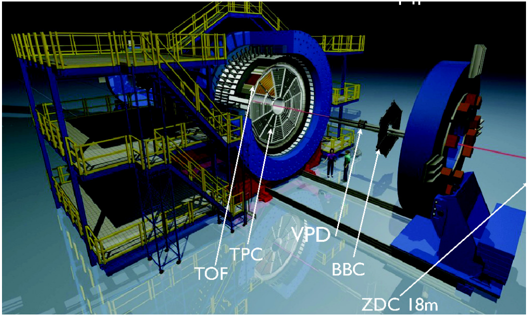
- *P.Lebiedowicz, O. Nachtmann and A.Szczurek*
  - Central exclusive diffractive production of $\pi^+\pi^-$ continuum, scalar and tensor resonances in pp and $\bar{p}p$ scattering within tensor pomeron approach, Phys.Rev. D93 (2016) 054015
  - Towards a complete study of central exclusive production 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)

Theoretical models implemented in form of MC generators

- DiMe and GenEx generators
  - Approach based on Regge theory. In these models,
  - The parameters of the Pomeron and sub-leading Reggeon exchanges were adjusted to describe the total and elastic πp or Kp scatterings.
  - The amplitude for the $p + p \to p' + \pi\pi(KK) + p'$ process is expressed in terms of the product of two amplitudes describing the interaction of each of the two protons with one of the two mesons.
  - For DiMe predictions:
    chose exponential form of intermediate meson form factor and absorption model which best fit our data
  - For GenEx predictions:
    the same form of meson form factor as used for DiMe
    to account for absorption not implemented in GenEx:
    - for $\pi\pi$ scaled by 0.25 to fit DiMe predictions for masses above 0.8 GeV
    - for KK scaled by 0.45 to fit DiMe predictions for masses above 1.2 GeV
- MBR implemented in PYTHIA8 was tuned to describe the inclusive cross section for central diffraction at CDF experiment. In this model exclusive h^+h^- occurs from fragmentationand hadronisation of the central state based on the Lund string model.

Experimental setup

Data samples: $\mathcal{L} = 14.2\ \text{pb}^{-1}$, $\mu = 0.2 - 0.9$ taken in proton-proton collisions at $\sqrt{s} = 200$ GeV



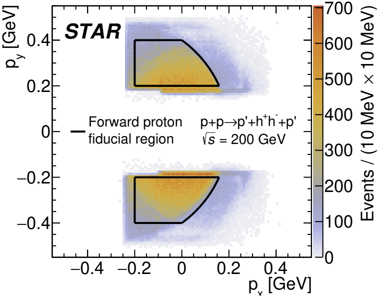
- high resolution tracking with TPC: $-1 < \eta < 1$
- particle identification: TPC dE/dx
- central state tagging/triggering: ToF
- forward proton tagging : Roman Pots RP
- BBC veto, $2.1 < \eta < 5.2$

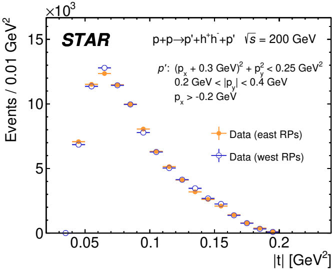
Event selection and fiducial region

- exactly two opposite-sign TPC tracks
  $|\eta| < 0.7$
  $p_{\mathrm{T}} > 0.2$ GeV
- both tracks matched to TOF hits
- exactly one proton on both STAR side
  $(p_x + 0.3\,\mathrm{GeV})^2 + p_y^2 < 0.25\,\mathrm{GeV}^2$
  $0.2\,\mathrm{GeV} < |p_y| < 0.4\,\mathrm{GeV}$
  $p_x > -0.2\,\mathrm{GeV}$
- exclusivity cut:
  $p_{\mathrm{T}}^{\mathrm{miss}}(p' + h^+h^- + p') < 75$ MeV
- no other activity in the detector
- PID cuts to separate central state
  $\pi^+\pi^-$, K^+K^- and $p\bar{p}$
- additional cuts on central particles:

K^+K^-: $p_{\mathrm{T}} > 0.3$ GeV
$min(p_T^+ p_T^-) < 0.7$ GeV

$p\bar{p}$: $p_{\mathrm{T}} > 0.4$ GeV
$min(p_T^+ p_T^-) < 1.1$ GeV



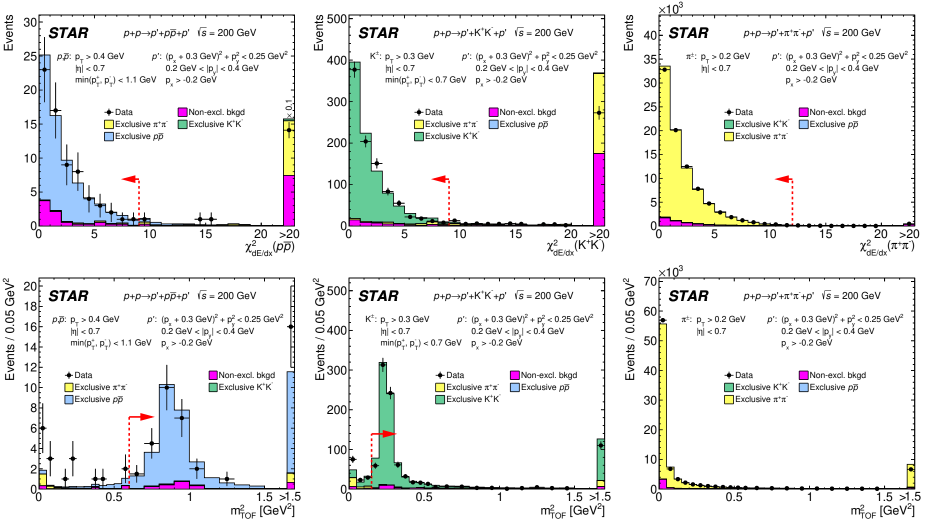


PID selections and exclusive background

$\chi^2_{dE/dx}(hh) = (n\sigma_{h,1})^2 + (n\sigma_{h,2})^2$

$m^2_{\mathrm{TOF}} : \Delta t = L_1\sqrt{1 + m^2_{\mathrm{TOF}}/p_1^2} - L_2\sqrt{1 + m^2_{\mathrm{TOF}}/p_2^2}$

$p\bar{p}$ K^+K^- $\pi^+\pi^-$



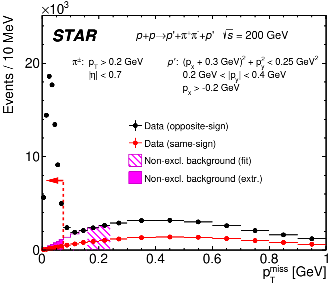
Cuts chosen to keep excl. bkg. $< 1\%$ for $\pi^+\pi^-$ and $p\bar{p}$ and $< 3\%$ for K^+K^-

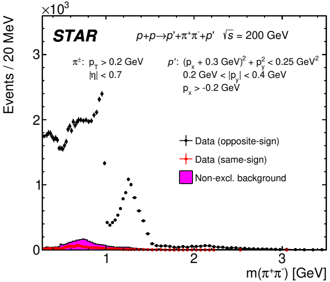
Non-exclusive background (data-driven method)

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

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

All sources lead to much flatter p_T^{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.

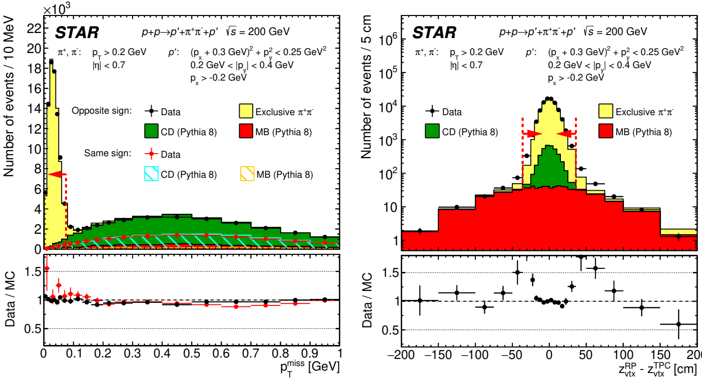




On average, non-excl. bkg. amounts to $< 6\%$ for $\pi^+\pi^-$ and K^+K^- and $< 12\%$ for $p\bar{p}$

Non-exclusive background (MC method)

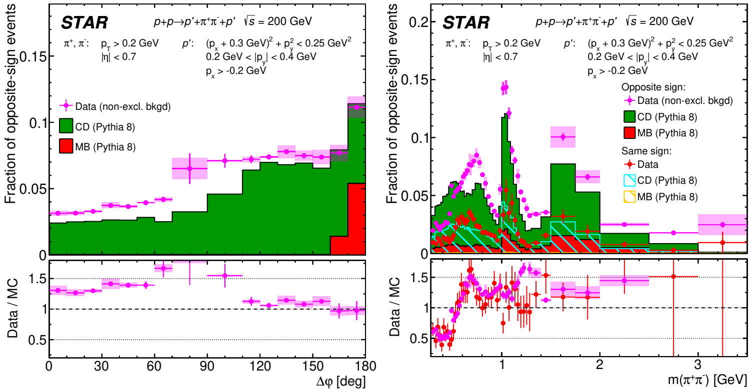
- PYTHIA8 CD for $p + p \to p' + (\pi^+\pi^-) + X + p'$ normalized to the tail of p_T^{miss} distribution.
- PYTHIA8 MinBias MC embedded into real data (accidentals) normalized to the tail of $z_{vtx}^{RP} - z_{vtx}^{TPC}$



MC well describes data. Non-exclusive bkg. subtraction under good control.

Non-exclusive background (systematic uncertainty)

Differences between data-driven and MC methods taken as syst. uncertainty.



Upto 50% uncertainty related to background subtraction which results in 3% uncertainty on cross section for $\pi^+\pi^-$.

Other corrections and systematic uncertainties

Main corrections

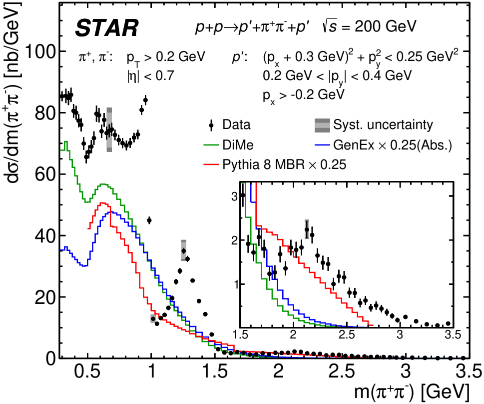
- The overall veto efficiency (event pileup) varies between 40-80%
- RP efficiency 60-98 % depending on p_x, p_y
- TPC and TOF efficiencies were calculated as 3D functions of (η, p_T, Z_{vtx}) separately for $\pi^+, \pi^-, K^+, K^-, p$ and $\bar{p}$ and are 70-80% for pions, 40-70% for kaons and 75-85% for protons.

$\delta_{\mathbf{syst}}/\sigma_{\mathbf{fid}}$ [%]

	TOF	**TPC**	**RP**	**Other**	**Lumi.**	**Total**
$\pi^+\pi^-$	3.0 −2.8	3.8 −3.6	5.8 −5.1	2.9 −2.7	6.4 −5.7	10.3 −9.3
K^+K^-	10.1 −8.8	6.7 −6.3	6.0 −5.3	5.1 −5.0	6.4 −5.7	15.8 −14.2
$p\bar{p}$	5.6 −5.1	4.1 −3.9	6.3 −5.6	10.0 −9.8	6.4 −5.7	15.1 −14.2

Systematic uncertainties weakly depends on all observables and are highly correlated between neighboring bins therefore in following plots they are shown only on few data points.

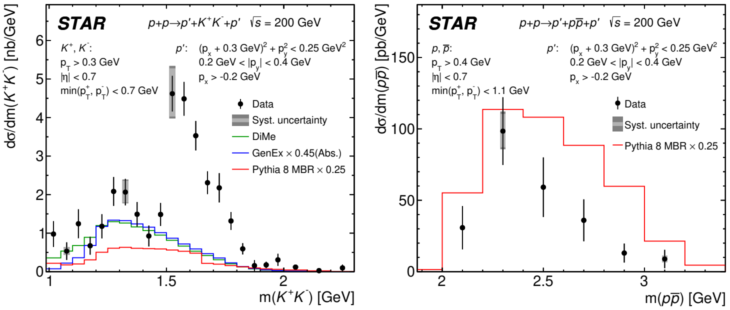
Fiducial cross section and comparison with models



- the deep hole at $m(\pi^+\pi^-) < 0.6$ GeV is mainly due to the fiducial cuts
- resonance structures consistent with $f_0(980)$ and $f_2(1270)$ mesons expected in DPE process.
- another resonance is observed at ~ 2.2 GeV

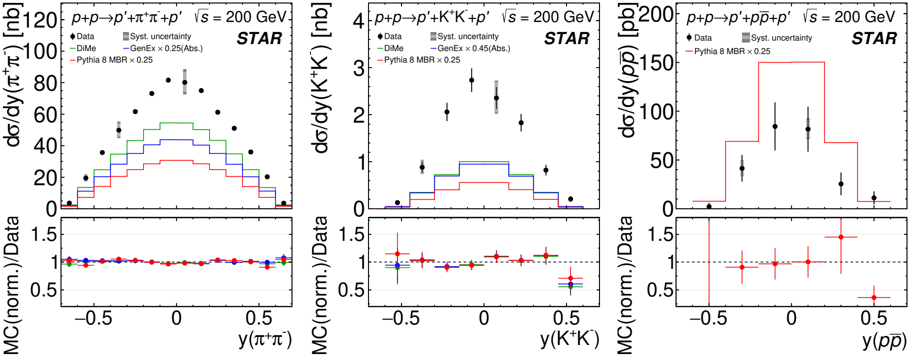
- DiMe roughly describes both the normalisation and the shape of the continuum under the resonances, up to masses of about 1.9 GeV.
- GenEx fails to describe the shape of the continuum production.
- MBR prediction generally follows the shape of DiMe and GenEx predictions at masses below 1 GeV, but falls less rapidly with mass above 1 GeV.

Fiducial cross section and comparison with models



- $d\sigma/dm(K^+K^-)$, shows significant enhancement in the $f_2'(1525)$ mass region and a possible smaller resonant signal in the mass region of $f_2(1270)$.
- 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 in the resonance region. The data are also consistent with the ratio of the non-resonant exclusive production of $\pi^+\pi^-$ to K^+K^- pairs expected by GenEx and DiMe.
- MBR model overestimates the $d\sigma/dm(p\bar{p})$ by a factor of 8.

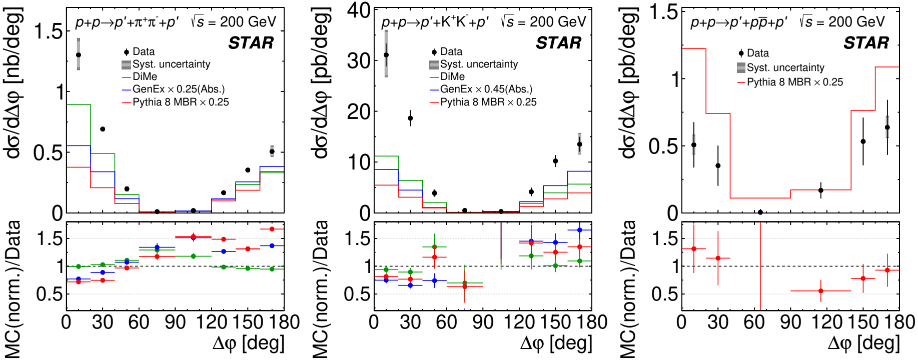
Fiducial cross section and comparison with models



In the following plots bottom panels show the ratios between the MC predictions (scaled to the data for better shape comparison) and the data

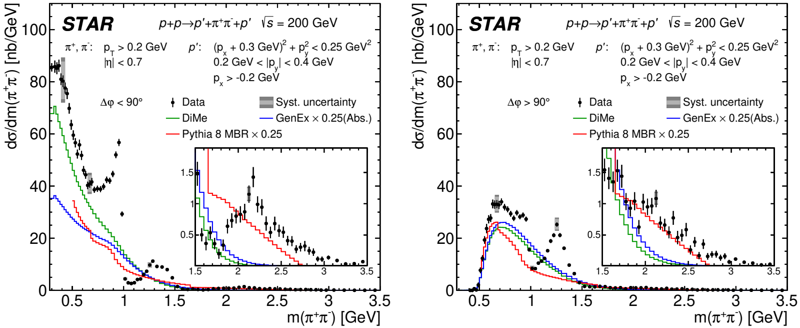
- the shapes of $d\sigma/dm(y)$ are generally well described by all the model predictions.

Fiducial cross section and comparison with models



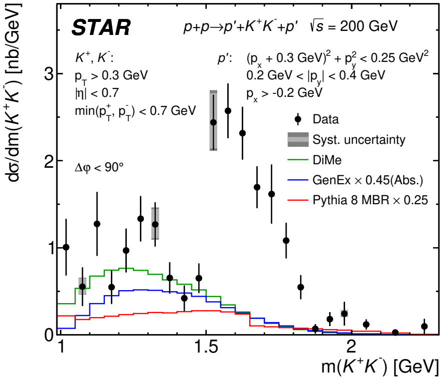
- strong suppression of $d\sigma/dm(\Delta\phi)$ close to 90° is due to the fiducial cuts applied to the forward scattered protons
- shape of DiMe model prediction agrees with data for $\pi^+\pi^-$ and K^+K^-.
- GenEx does not describe the data.
- MBR model describes the data fairly well in shape for K^+K^- and $p\bar{p}$.

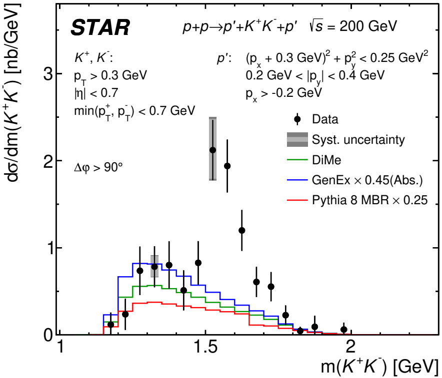
Fiducial cross section and comparison with models



- sharp drop in the measured cross sections at $m(\pi^+\pi^-) < 0.6$ GeV for the $\Delta\varphi > 90^\circ$ range are due to the fiducial cuts applied to the forward-scattered protons.
- in the $\Delta\varphi < 90^\circ$ range, the peak around the $f_2(1270)$ resonance in data is significantly suppressed while the peak at $f_0(980)$, as well as possible resonances in the mass ranges $1.3 - 1.5$ GeV and $2.2 - 2.3$ GeV, is enhanced compared to the $\Delta\varphi > 90^\circ$ range.
- in the $\Delta\varphi < 90^\circ$, the DiMe model describes well both the normalisation and the shape of the mass spectrum at $m(\pi^+\pi^-) < 0.5$ GeV.

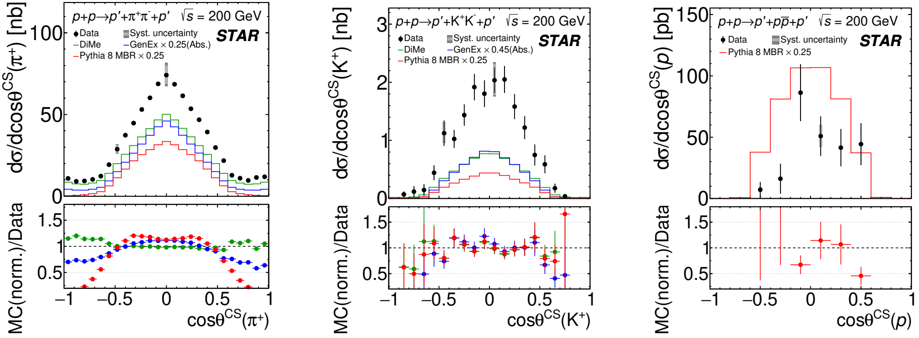
Fiducial cross section and comparison with models





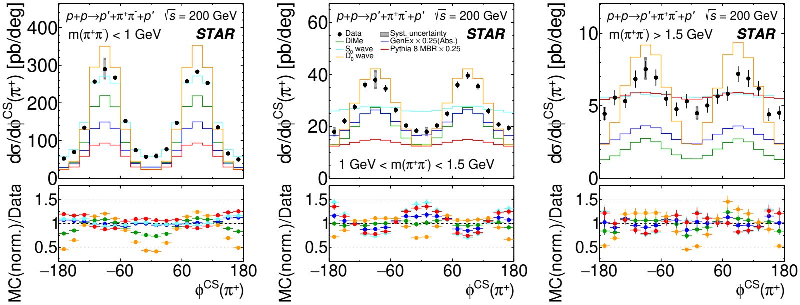
- sharp drop at $m(K^+K^-) < 1.3$ GeV for the $\Delta\varphi > 90^\circ$ range are due to the fiducial cuts applied to the forward-scattered protons.
- the data do not show any significant $\Delta\varphi$ asymmetry
- except for a possible widening of the peak at $f_2'(1520)$ in the region $\Delta\varphi < 90^\circ$. This may indicate an enhancement of additional resonances around 1.7 GeV in this configuration.

Fiducial cross section and comparison with models



- we have also studied the angular distributions of the charged particles produced in the final state using the Collins-Soper reference frame
- in general for $\cos\theta^{\rm CS}$, the model predictions are narrower than the data for all particle species pairs. The only exception is the DiMe prediction for production, which fits the data much better than other models

Fiducial cross section and comparison with models



- high statistics of the two-pion sample allow to study the CEP of $\pi^+\pi^-$ pairs in greater detail in three ranges of the invariant mass of the pair: $m(\pi^+\pi^-) < 1$ GeV (mainly non-resonant production), $1\,\text{GeV} < m(\pi^+\pi^-) < 1.5\,\text{GeV}$ ($f_2(1270)$ mass range) and $m(\pi^+\pi^-) > 1.5$ GeV (higher invariant masses).
- the shape of the ϕ^{CS} distribution for S_0 wave represents also the ϕ^{CS} shape of the STAR acceptance.
- ϕ^{CS} in the lowest mass region agree very well with the S_0 wave suggesting that this mass region is dominated by spin-0 contribution.
- At higher masses, pure S_0 or D_0 waves are not able to describe the data

Extrapolated cross section

- fiducial cross section cannot be directly used to extract yields of possible resonances without extrapolation to the full kinematic region of the central pion pair,
- extrapolation given by $p_{\mathrm{T}} \to 0$ and $|\eta| \to \infty$ (full solid angle in the central system rest frame)
- extrapolation to an unmeasured region is always model dependent
- we corrected cross sections to the full phase space using a flat angular approximation
- supported by the generally good description of the pion angular distribution by the S_0 wave distribution
- the measurement is further restricted to (Lorentz invariant) region:
    - $|y(\pi^+\pi^-)| < 0.4$.
    - $0.05\,\mathrm{GeV}^2 \leq -t_1, -t_2 \leq 0.16\,\mathrm{GeV}^2$,
    - $\Delta\varphi < 45^\circ$ and $\Delta\varphi > 135^\circ$

Extrapolated cross section

- a minimal model of the $\pi^+\pi^-$ invariant mass spectrum was fitted to the extrapolated differential cross section
- we assume contributions from direct pair production and only three resonances in the mass range of $0.6 - 1.7$ GeV: $f_0(980)$, $f_2(1270)$ and $f_0(1500)$.
-

$$
\begin{aligned}
A(m) = {} & A_{\mathrm{cont}} \times f_{\mathrm{cont}}(m) + \\
& \sqrt{\sigma_{f_0(980)}} \times \exp\left(i\phi_{f_0(980)}\right) \times \mathcal{R}_{\mathrm{F}}\left(m; M_{f_0(980)}, \Gamma_{0,f_0(980)}\right) + \\
& \sqrt{\sigma_{f_2(1270)}} \times \exp\left(i\phi_{f_2(1270)}\right) \times \mathcal{R}_{\mathrm{BW}}\left(m; M_{f_2(1270)}, \Gamma_{0,f_2(1270)}\right) + \\
& \sqrt{\sigma_{f_0(1500)}} \times \exp\left(i\phi_{f_0(1500)}\right) \times \mathcal{R}_{\mathrm{BW}}\left(m; M_{f_0(1500)}, \Gamma_{0,f_0(1500)}\right) .
\end{aligned}
$$

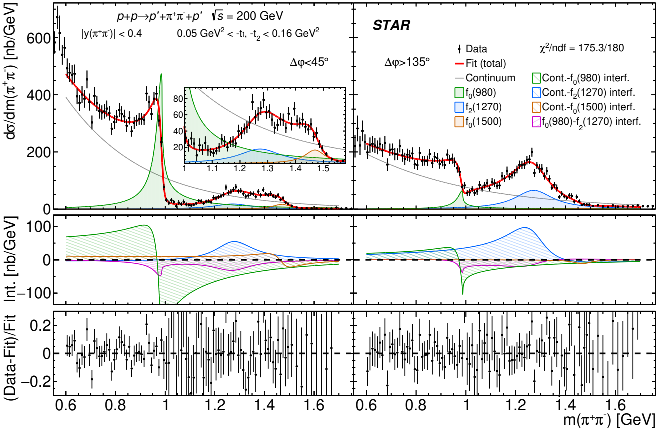
- thus all states are added coherently and can interfere with each other.
- continuum amplitude was s assumed to have the form

$$
f_{\mathrm{cont}}(m) = \sqrt{\frac{q}{m}} \times \exp\left[-\frac{B}{2} \cdot q\right],
$$

with the break-up momentum $q(m) = \frac{1}{2}\sqrt{m^2 - 4m_\pi^2}$.

Fit of the extrapolated cross section to minimal model

- χ^2 is minimised simultaneously in two $\Delta\varphi$ ranges.
- a total of 20 free parameters, gives excellent χ^2/ndf = 175/180
- a small deviation from the extrapolated data around 1.37 GeV. This might result from the presence of the $f_0(1370)$.



Fit results

- the cross section for $f_0(1500)$ production differs from zero by 5 and 2 standard deviations in the $\Delta\varphi < 45^\circ$ and $\Delta\varphi > 135^\circ$ regions, respectively.
- removing the $f_0(1500)$ from the fit makes the χ^2/ndf change to 352/186, a 7.0 standard-deviation effect
- In the case of $f_0(980)$:
  $M_{f_0(980)} = 956 \pm 7(\text{stat.}) \pm 1(\text{syst.})\,^{+4}_{-6}(\text{mod.})$ MeV
  $\Gamma_{0,f_0(980)} = 163 \pm 26(\text{stat.}) \pm 3(\text{syst.})\,^{+17}_{-20}(\text{mod.})$ MeV.
  These values differ from the PDG estimates of mass (990 ± 20 MeV) and width (from 10 MeV to 100 MeV).
- in the case of $f_0(1500)$:
  $M_{f_0(1500)} = 1469\ \pm 9(\text{stat.})\ \pm 1(\text{syst.})\ \pm 2(\text{mod.})$ MeV
  $\Gamma_{0,f_0(1500)} = 89 \pm 14(\text{stat.})\ \pm 2(\text{syst.})\,^{+4}_{-3}(\text{mod.})$ MeV.
  These values also deviate from the PDG averages 1505 ± 6 MeV for the mass and 109 ± 7 MeV for the width.
- f_0-like component added to the model in the mass range $1.2 - 1.5$ GeV gives:
  $M_{f_0} = 1372 \pm 13(\text{stat.})$ MeV
  $\Gamma_{0,f_0} = 44 \pm 24(\text{stat.})$ MeV.
  In that case, the χ^2/ndf is equal to 158/174 (p-value: 0.8), compared to the nominal value 175/180 (p-value: 0.6).

Summary

- We have studied the CEP of charged particle pairs ($\pi^+\pi^-$, K^+K^- and $p\bar{p}$) in events with forward protons tagged in the RP detectors at $\sqrt{s} = 200$ GeV.
- The centre-of-mass energy of *pp* collisions in the present measurement is three times larger than the previous highest-energy measurement of the DPE process with forward-proton tagging performed at CERN at the ISR in the AFS experiment.
- The uncertainty of the absolute normalisation of the STAR measurement is a factor of four better compared to measurements at the ISR, giving much stronger constraints for phenomenological models.
- The fits to the extrapolated cross sections as a function of the $\pi^+\pi^-$ invariant mass of the minimal model, including the $f_0(980)$, $f_2(1270)$ and $f_0(1500)$ resonances and the non-resonant contribution, provide for the first time measurements of the relative phases between all the production amplitudes.
- In the glueball sector, there is no evidence except for:
  - a small enhancement around 1.7 GeV for production of $f_0(1710)$ decaying to a pair of kaons
  - only weak evidence for $f_0(1370)$ production decaying to a pair of pions
  - evidence for resonances at 2.2 GeV decaying to a pair of pions