Central Exclusive Production with the STAR detector at RHIC

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STAR **A G H** **U.S. DEPARTMENT OF ENERGY**

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
  $M = f_0(500), \rho, f_0(980), f_2(1270), f_0(1500), ...$ Interference effects might be significant.
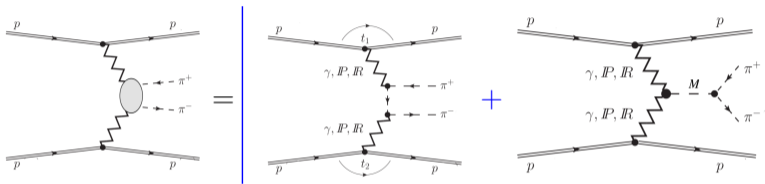
- Significant rescattering effects:
  - cross section reduced by additional interaction between the protons (and/or hadron–proton) - embedded in so-called Survival Factor (SF). The SF depends on the collision energy. Suppression can be even by a factor of 5 at RHIC energies and a factor of 10 at LHC 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.

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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 πp 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. Goulianos, arXiv:1205.1446) tuned to CDF data on inclusive Central Diffraction (CD).

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Experimental setup

Data samples: $\mathcal{L} = 14.2$ pb^{-1}, $\mu = 0.2 - 0.9$ taken in proton-proton collisions at $\sqrt{s} = 200$ GeV in 2015 year. 10 times larger luminosity with slightly higher μ at $\sqrt{s} = 510$ GeV
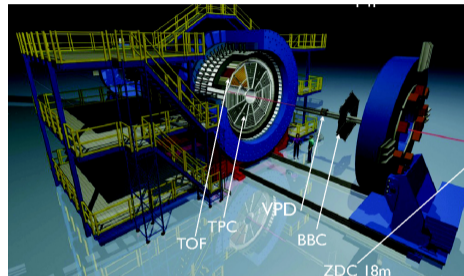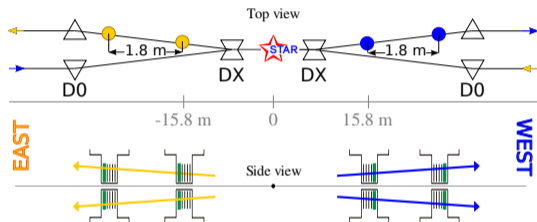
- **Intact forward protons** are scattered through a small angle of typically 2 - 5 $m$rad. Protons are measured in the Roman Pot (RP) detectors at 16 m from the IP, the RP were placed at 35 mm from the beam in standard RHIC run of $\beta^* = 10$ m optics.
- **Central charged particles** with $p_T > 0.2$ 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 $3.3 < |\eta| < 5.2$.
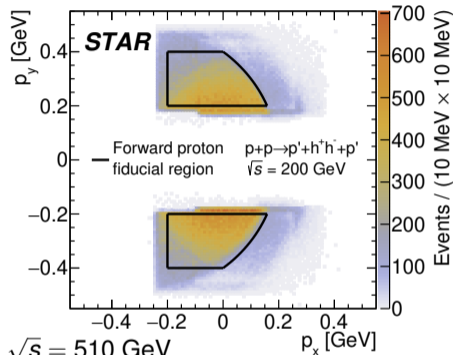
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Event selection and definition of the fiducial region

$\sqrt{s} = 200$ 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
  $(p_x + 0.3\,\text{GeV})^2 + p_y^2 < 0.25\,\text{GeV}^2$
  $0.2\,\text{GeV} < |p_y| < 0.4\,\text{GeV}, \quad p_x > -0.2\,\text{GeV}$.
- Transverse momentum balance:
  $p_T^{\text{miss}}(p' + h^+ h^- + p') < 75$ 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^-: $p_T > 0.3$ GeV
  $min(p_T^+, p_T^-) < 0.7$ GeV,
$p\bar{p}$: $p_T > 0.4$ GeV
  $min(p_T^+, p_T^-) < 1.1$ GeV.

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Forward proton fiducial region

$p + p \rightarrow p' + h^+ h^- + p'$
$\sqrt{s} = 200$ GeV

$\sqrt{s} = 510$ GeV

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

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

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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 $(h^+ h^- + p')$.
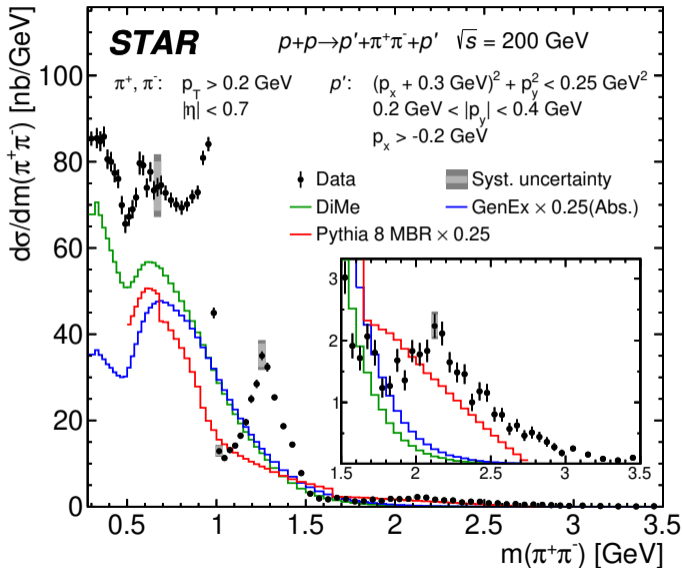
All sources lead to much flatter p_T^{miss} distribution. Bkg. estimated based on the extrapolation into the signal region of the second-degree polynomial function fitted to the signal-free region. Done differentially in all observables.
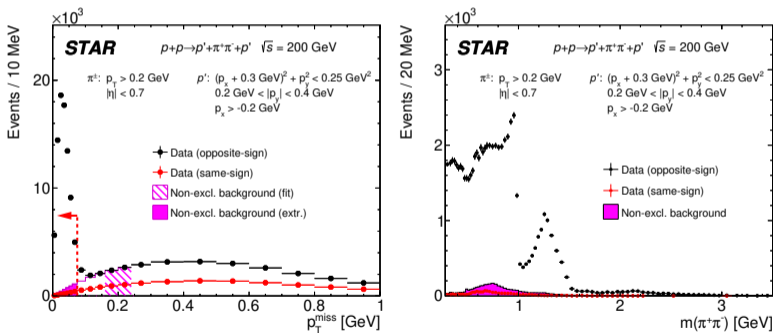
On average, non-excl. bkg. amounts to $< 6\%$ for $\pi^+ \pi^-$ and $K^+ K^-$ and $< 12\%$ for $p\bar{p}$.
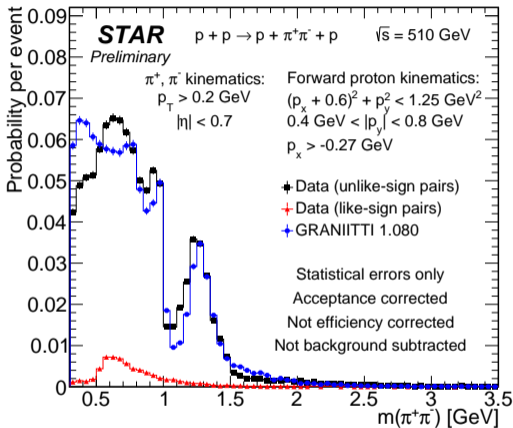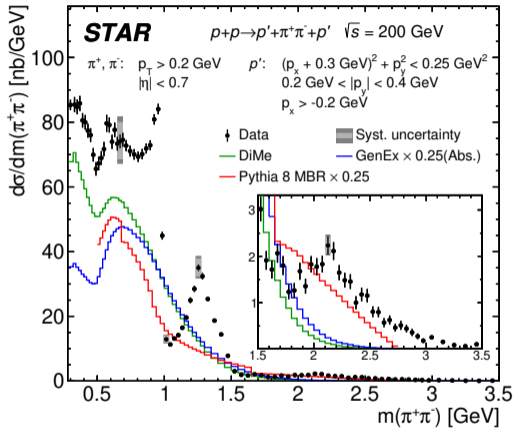Preliminary $\sqrt{s} = 510$ GeV results not corrected for background.

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)

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- 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.

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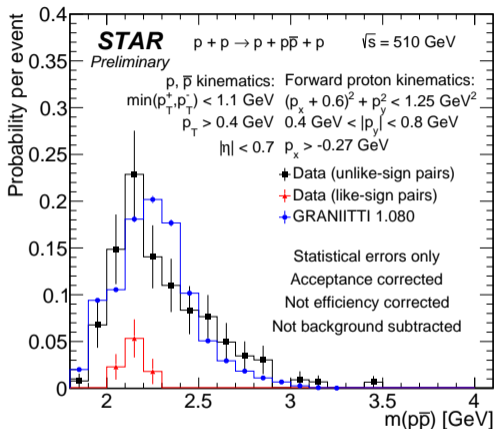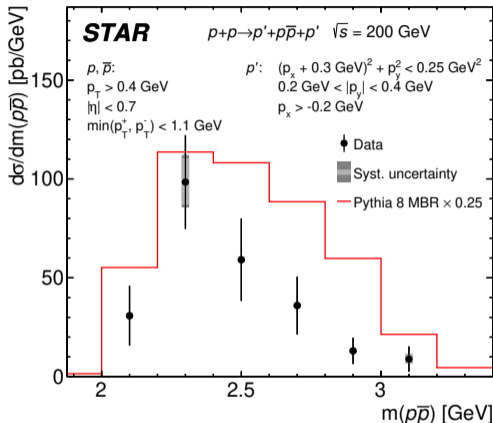# Invariant mass of exclusively produced K^+K^-
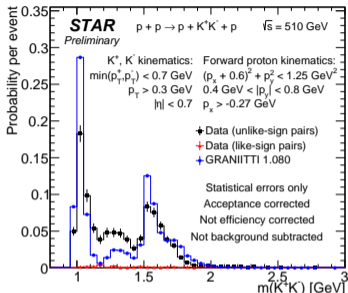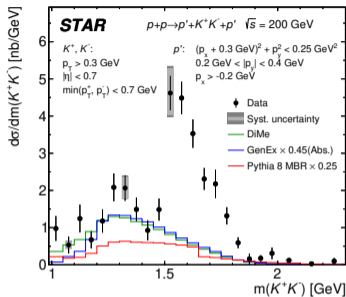
- $\sqrt{s} = 200$ GeV
  - $d\sigma/dm(K^+K^-)$ shows significant enhancement in the $f_2'(1525)$ mass region and smaller resonant signals in the mass regions of $f_2(1270)$ and $f_0(1710)$.
  - The ratio of the cross sections for $\pi^+\pi^-$ to K^+K^- production in the $f_2(1270)$ mass region is roughly 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 Graniitti :
    - Peak 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 fairly well predicts shape at $\sqrt{s} = 510$ GeV.

Left panel: STAR, $p+p \rightarrow p'+p\bar{p}+p'$, $\sqrt{s} = 200$ GeV

$p, \bar{p}$: $p_T > 0.4$ GeV, $|\eta| < 0.7$, $\min(p_T^+, p_T^-) < 1.1$ GeV

p': $(p_x + 0.3 \text{ GeV})^2 + p_y^2 < 0.25 \text{ GeV}^2$, $0.2 \text{ GeV} < |p_y| < 0.4 \text{ GeV}$, $p_x > -0.2$ GeV

- Data
- Syst. uncertainty
- Pythia 8 MBR $\times$ 0.25

$d\sigma/dm(p\bar{p})$ [pb/GeV] vs $m(p\bar{p})$ [GeV]

Right panel: STAR Preliminary, $p + p \rightarrow p + p\bar{p} + p$, $\sqrt{s} = 510$ GeV

$p, \bar{p}$ kinematics: $\min(p_T^+, p_T^-) < 1.1$ GeV, $p_T > 0.4$ GeV, $|\eta| < 0.7$

Forward proton kinematics: $(p_x + 0.6)^2 + p_y^2 < 1.25 \text{ GeV}^2$, $0.4 \text{ GeV} < |p_y| < 0.8 \text{ GeV}$, $p_x > -0.27$ GeV

- Data (unlike-sign pairs)
- Data (like-sign pairs)
- GRANIITTI 1.080

Statistical errors only
Acceptance corrected
Not efficiency corrected
Not background subtracted

Probability per event vs $m(p\bar{p})$ [GeV]

- The invariant mass spectrum of $p\bar{p}$ pairs does not show any obvious resonance peaks
- MBR PYTHIA8 model overestimate the $d\sigma/dm(p\bar{p})$ by a factor of 8 at $\sqrt{s} = 200$ GeV
- GRANIITTI 1.08 fairly well predicts shape at $\sqrt{s} = 510$ GeV.
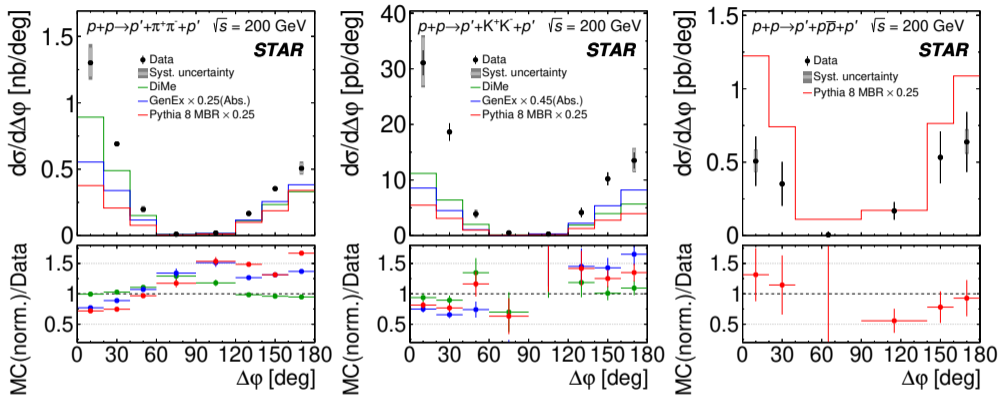
- Suppression of $d\sigma/dm(\Delta\phi)$ close to $90°$ is due to fiducial cuts (acceptance).
- Significant asymmetry observed in cross section depending on the $\Delta\phi$ for $\pi^+\pi^-$ and K^+K^-.
- Distribution sensitive to the absorption effects. DiMe model predictions agree in shape with data for $\pi^+\pi^-$ and K^+K^-.
- GenEx does not describe the data.
- MBR model describes the data fairly well in shape for $p\bar{p}$.
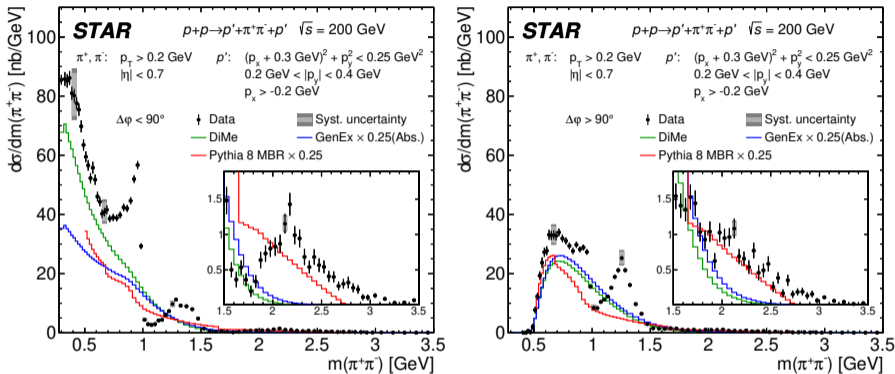
- Suppression of the cross section at $m(\pi^+\pi^-) < 0.6$ GeV for the $\Delta\phi > 90°$ range is due to the fiducial cuts.
- In the $\Delta\varphi < 90°$ range, the peak around the $f_2(1270)$ resonance in data is significantly suppressed, while the peak at $f_0(980)$ and resonances in the regions $1.3 - 1.5$ GeV and $2.2 - 2.3$ GeV, are enhanced compared to the $\Delta\varphi > 90°$ range.
- In the $\Delta\varphi < 90°$, 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
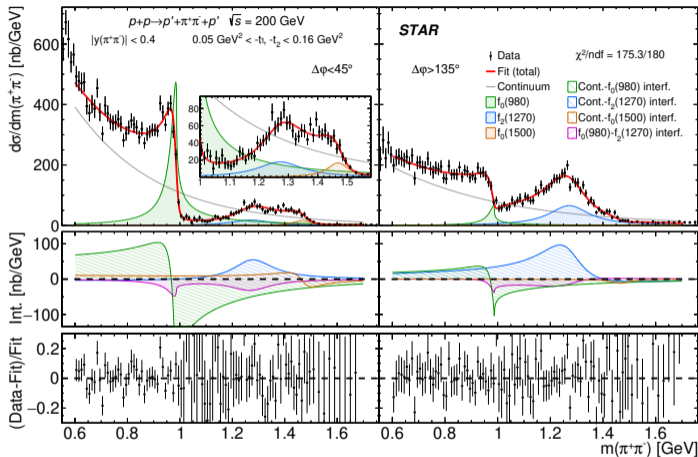
- Fiducial $d\sigma/dm(\pi^+\pi^-)$ have been extrapolated to
  $|y(\pi^+\pi^-)| < 0.4$,
  $0.05 < -t1, -t2 < 0.16$ GeV^2,
  $\Delta\phi < 45°$ and $\Delta\phi > 135°$.
- Minimal model of continuum with coherently added three resonances (all parameters free except the mass and width of $f_2(1270)$) fitted simultaneously in two $\Delta\phi$ regions (amplitudes independent) in the mass range $0.6 < m < 1.7$ 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.

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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: $f_0(980), f_2(1270), f0(1500), f_2'(1525)$. 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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