Recent results on Central Exclusive Production with the STAR detector

Rafał Sikora

for the STAR Collaboration

AGH University of Science and Technology, Kraków, Poland

XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects

12-16 April 2021, Stony Brook University [virtual event]

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Central Exclusive Production (CEP)

$$B_1 + B_2 \rightarrow B_1' \overset{\Delta\eta_1}{\oplus} X \overset{\Delta\eta_2}{\oplus} B_2'$$

- Colliding particles B_1 and B_2 remain intact (or become excited)
- Central state X is fully measured
- State X is well separated from the scattered beam particles by the 'pseudorapidity gaps' ($\Delta\eta_1$, $\Delta\eta_2$)
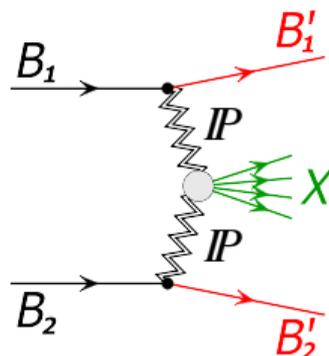
$$\xi \equiv \frac{p_0 - p}{p_0} \qquad y_X \approx \frac{1}{2}\ln\frac{\xi_1}{\xi_2} \qquad M_X \approx \sqrt{\xi_1\xi_2 s}$$

Possible mechanisms of Central Exclusive Production:

- Double Photon Exchange
  $\gamma + \gamma \rightarrow \gamma\gamma,\ l^+l^-,\ W^+W^-$

- Photon-$\mathbb{P}$omeron/$\mathbb{R}$egeon fusion (photoproduction)
  $\gamma + \mathbb{P}/\mathbb{R} \rightarrow$ (pseudo)vector mesons, continuum

- $\mathbb{P}+\mathbb{P}$ (Double $\mathbb{P}$om. Exchange, D$\mathbb{P}$E), also $\mathbb{R}+\mathbb{R}/\mathbb{P}$
 $\mathbb{P} + \mathbb{P} \rightarrow$ continuum, scalar/tensor mesons, glueballs
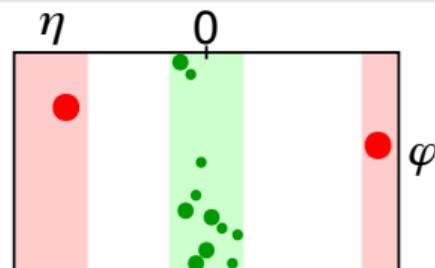
DIPE is the dominant mechanism for CEP at RHIC energies

In this talk the measurement of charged hadron pairs, $X = h^+h^-$ ($h = \pi, K, p$), in diffractive p+p interactions at $\sqrt{s} = 200$ GeV <u>with detection of forward-scattered protons</u> is presented.

Topologically simple, theoretically complex and rich in phenomena.

- The simplest $2 \to 3(4)$ QCD process: $p + p \to p' + X(h^+ h^-) + p'$.
- Pomeron in QCD at lowest order = a pair of gluons $\to$ DPE suitable for glueball production.
  Promising candidates: $f_0(1370)$, $f_0(1500)$, $f_0(1710)$, tensor glueball expected around ~ 2 GeV.
- Dominantly low masses produced ($\lesssim 2$ GeV) $\to$ lack of hard scale, pQCD not applicable.
- Cross section suppressed and modulated by the absorption (rescattering) in the final state.
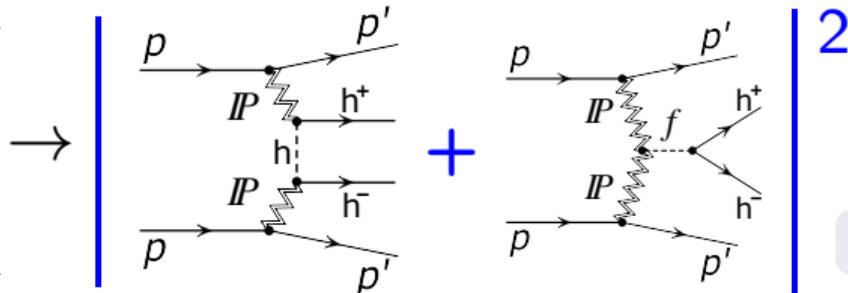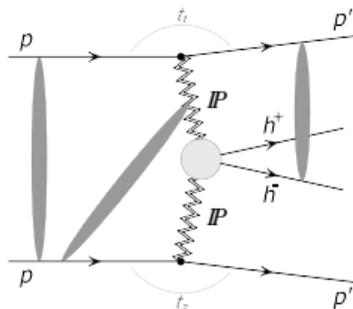
CEP can proceed via:

- direct production (continuum)
- resonant production

Significant interference effects

Phenomenological models of the process (continuum):

- L.A. Harland-Lang et al., Eur. Phys. J. C72 (2012) 2110, implemented in DiMe.
- P. Lebiedowicz, A. Szczurek, Phys. Rev. D81 (2010) 036003, implemented in GenEx.

Absorption effects are modeled only in DiMe. 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). Recently also models of resonant production are developed, but not available in generators. **Models poorly constrained due to large data uncertainties (until now)**.

**Predictions from DiMe, GenEx and Pythia8.233 are compared with the STAR results.**

STAR data: p+p at $\sqrt{s} = 200$ GeV, $\int \mathcal{L} dt = 14.2 \text{ pb}^{-1}$, nominal $\beta^* = 0.85$ m and $\mu = 0.2 - 0.9$.

- Two opposite-charge particles in Time Projection Chamber (TPC) of $p_T > 0.2$ GeV, $|\eta| < 0.7$, both matched with Time-of-Flight (TOF) hits,

- Two forward-scattered proton tracks in Roman Pot detectors, 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
  $p_T^{\text{miss}} = (\vec{p}_1 + \vec{p}_2 + \vec{h}^+ + \vec{h}^-)_T < 75$ MeV,

- Veto on particles in the region $2.1 < |\eta| < 5.0$ covered by Beam-Beam Counters (BBCs),

- Particle identification (PID) to separate central states: $\pi^+\pi^-$, K^+K^-, $p\bar{p}$, using dE/dx and TOF. Additional cuts after identification:

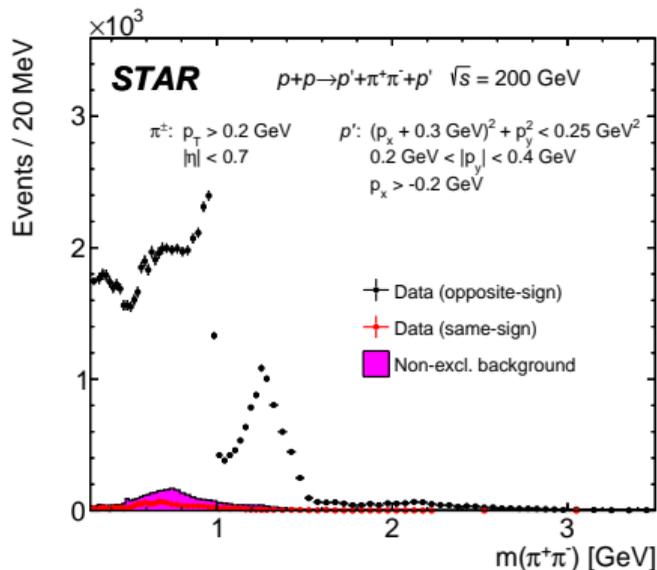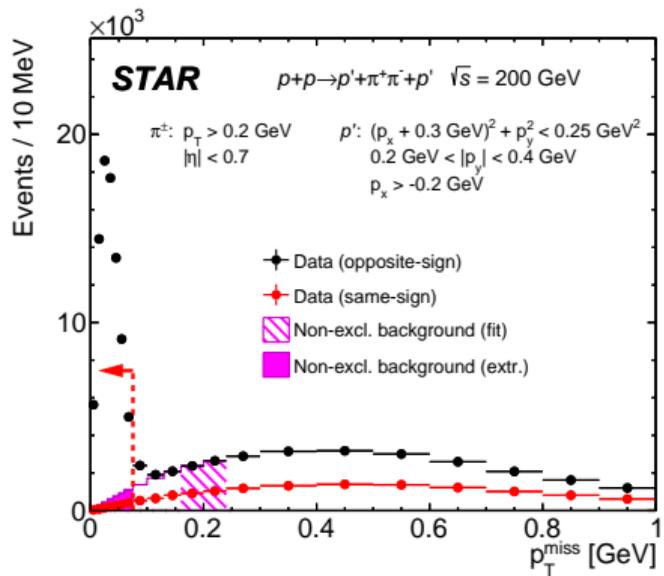 K^+K^-: $p_T > 0.3$ GeV, $\min(p_T^+, p_T^-) < 0.7$ GeV

  $p\bar{p}$: $p_T > 0.4$ GeV, $\min(p_T^+, p_T^-) < 1.1$ GeV
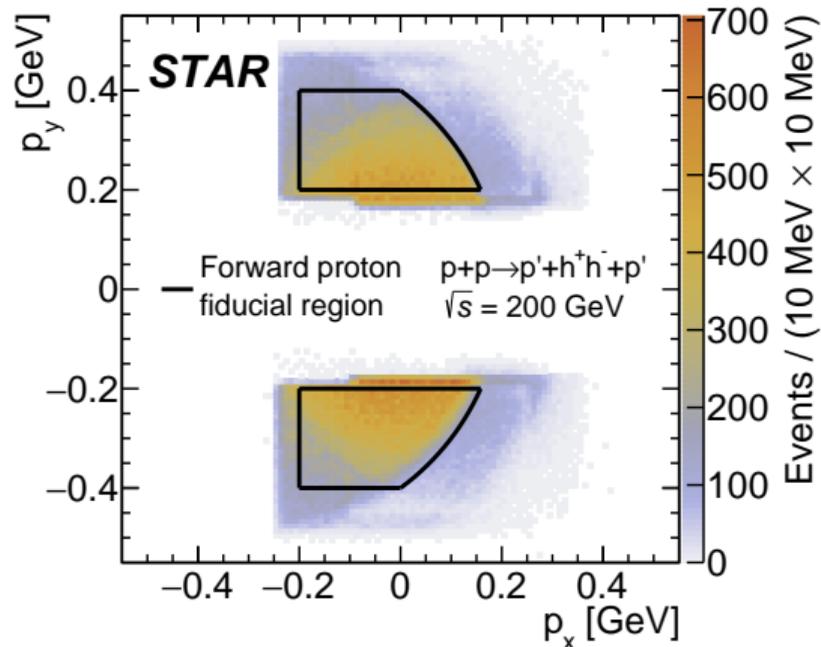
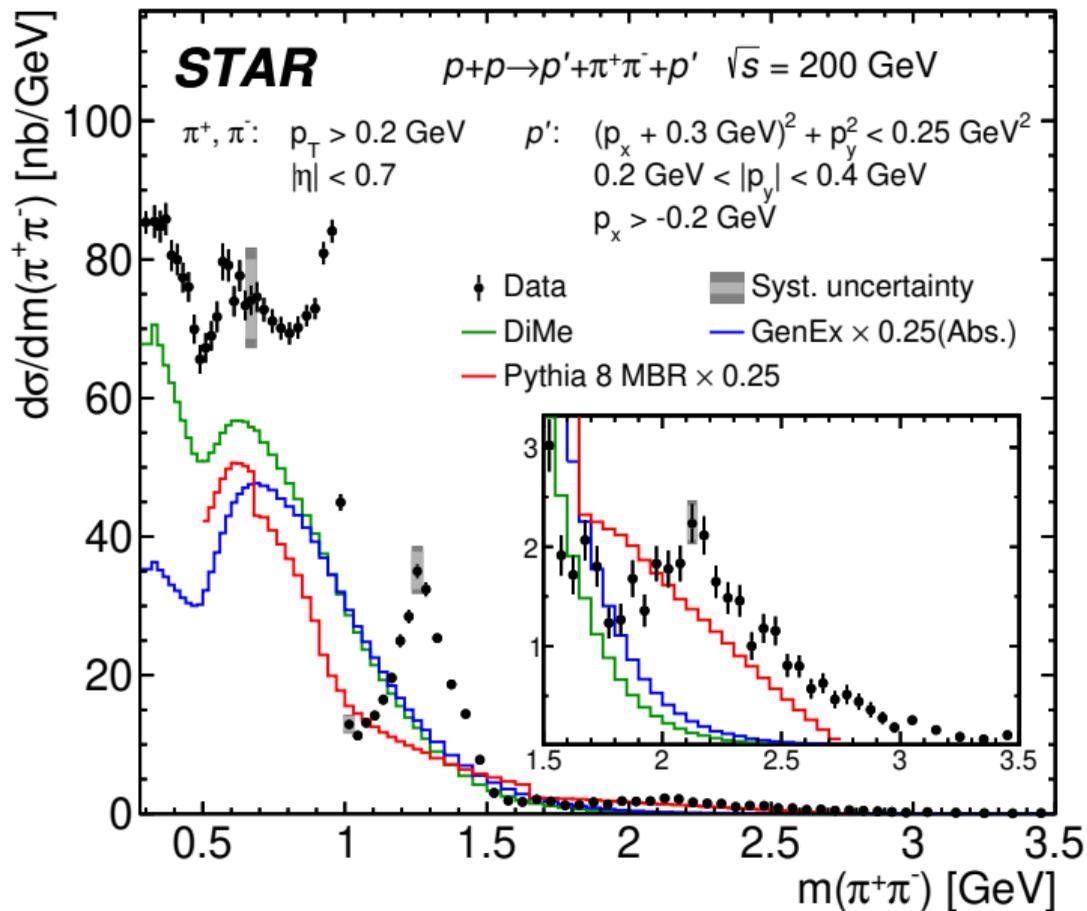**Detection of forward-scattered protons selects $-t \geq 0.04 \text{ GeV}^2$ which suppresses $\gamma\mathbb{P}$.**

Origin of the non-exclusive background:

- Inclusive CD with > 2 charged hadrons, e.g. $p + p \rightarrow p' + h^+h^- + n \cdot (h^+h^-) + p'$,
- Inclusive CD with 2 charged hadrons and neutrals, e.g. $p + p \rightarrow p' + h^+h^- + n \cdot h^0 + p'$,
- Accidental overlaps, mainly elastic (p', p') + non-elastic $(h^+h^- + Y)$.

Background is estimated from p_T^{miss} through the extrapolation into the signal region of the 2nd-order polynomial fitted to the signal-free region. It is done differentially in all observables.

**Small non-exclusive background: $< 6\%$ ($\pi^+\pi^-$, K^+K^-) and $< 12\%$ ($p\bar{p}$)**

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

π^+, π^-: p_T > 0.2 GeV p': $(p_x + 0.3\ \text{GeV})^2 + p_y^2$ < 0.25 GeV^2
$|\eta|$ < 0.7   0.2 GeV < $|p_y|$ < 0.4 GeV
                          p_x > -0.2 GeV

Data — Syst. uncertainty
DiMe — GenEx × 0.25(Abs.)
Pythia 8 MBR × 0.25

dσ/dm($\pi^+\pi^-$) [nb/GeV]

m($\pi^+\pi^-$) [GeV]

Syst. unc. are shown only for a few selected bins because they are strongly correlated between bins (affect mainly normalization).

- 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 DIPE,

- Resonance around ~ 2.2 GeV,

- The structure ('hole') in cross section below 0.6 GeV is caused by the fiducial cuts (acceptance),

- Among the drawn predictions DiMe the best describes the continuum (shape and normalization) under the resonances.

Four times better precision of the cross section (normalization) compared to previous DIPE measurement with forward proton tagging.
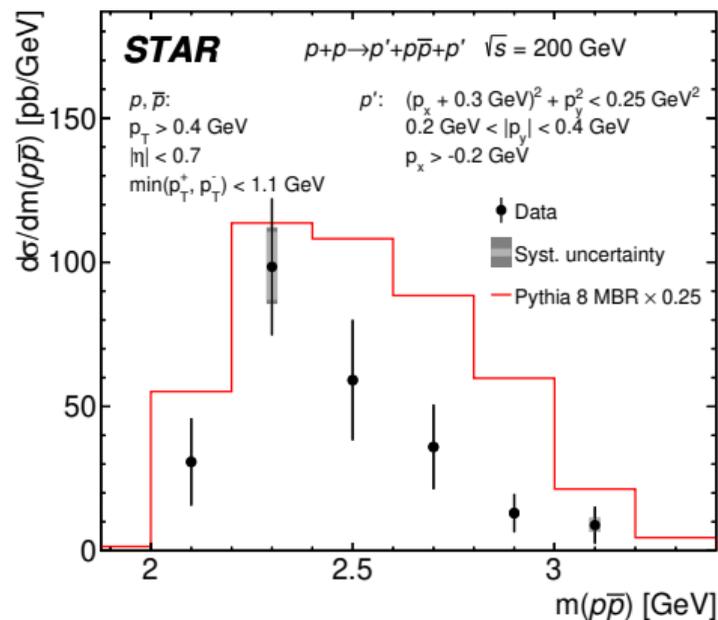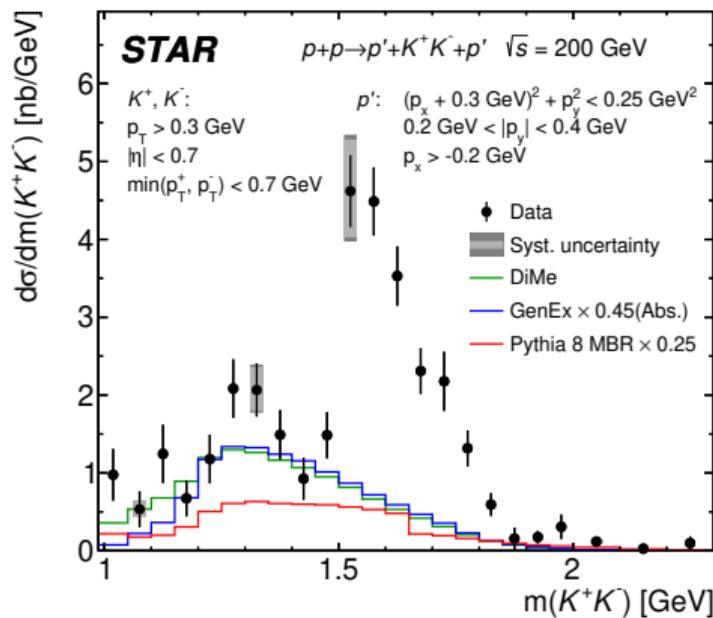
- $d\sigma/dm(K^+K^-)$ shows significant enhancement in the $f_2'(1525)$ and $f_0(1710)$ mass region and smaller resonant signal in the mass region of $f_2(1270)$.
- The ratio of the cross sections for $\pi^+\pi^-$ to K^+K^- production in the $f_2(1270)$ mass region is roughly 18, consistent with the PDG ratio of the $f_2(1270)$ branching fractions for its decays into $\pi^+\pi^-$ to K^+K^-.
- DiMe and GenEx roughly describe the non-resonant contribution under resonances.
- MBR model overestimates $d\sigma/dm(p\bar{p})$ by a factor of 8.
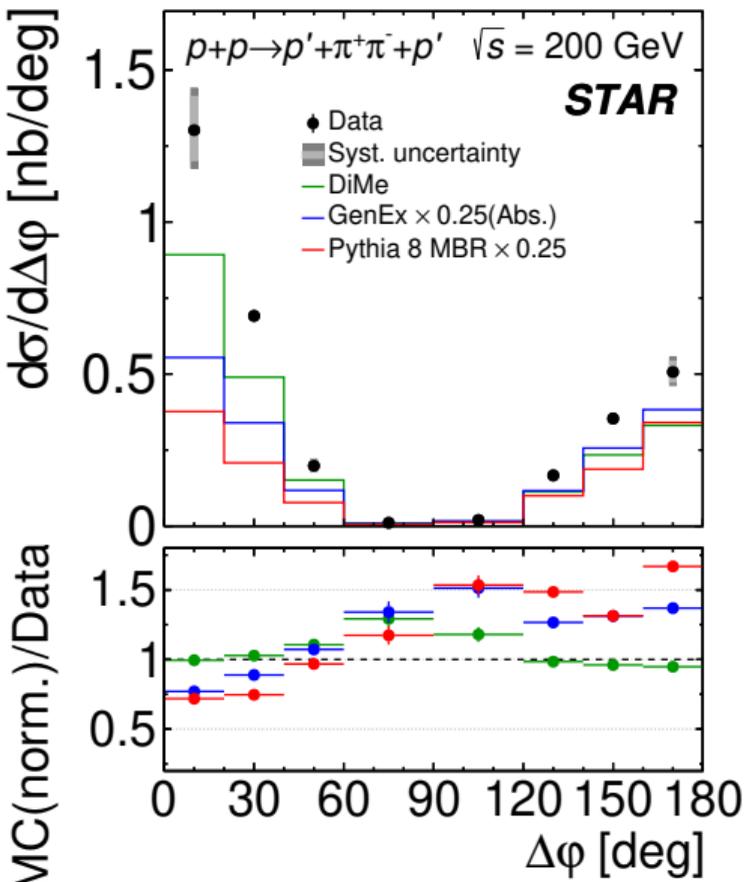
Angular separation of diffractively scattered protons in the transverse plane:

$$\boldsymbol{\Delta}\varphi = \measuredangle\{(\mathbf{p'_{x,1}}, \mathbf{p'_{y,1}}), (\mathbf{p'_{x,2}}, \mathbf{p'_{y,2}})\}$$

Close relation with the "glueball filter":

$$|\Delta\vec{p}_T| = \left(\vec{\mathbb{P}}_1 - \vec{\mathbb{P}}_2\right)_T$$

F.Close, A.Kirk, Phys.Lett.B397 (1997) 333-338

- Significant asymmetry observed in CEP cross section depending on the angle between outgoing protons.

- Suppression of $d\sigma/d\Delta\varphi$ at $90°$ is due to fiducial cuts (acceptance).

- Distribution sensitive to the absorption effects.

- DiMe describes the data well, other generators fail to describe the data.
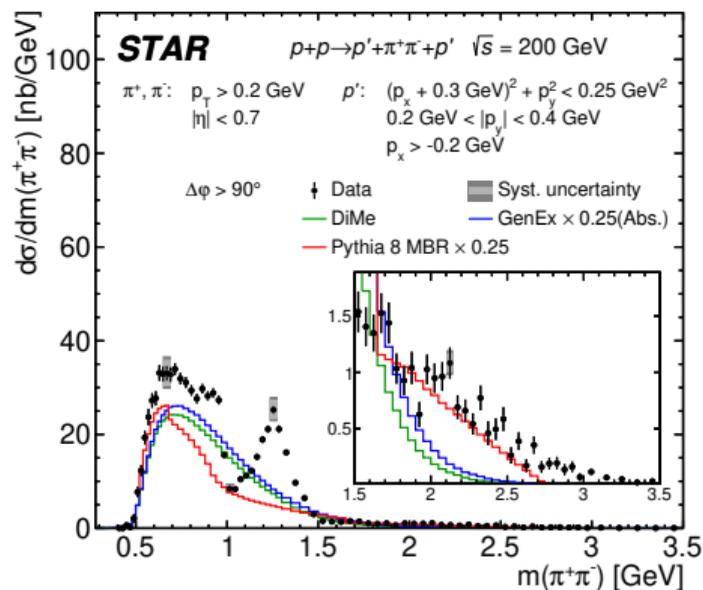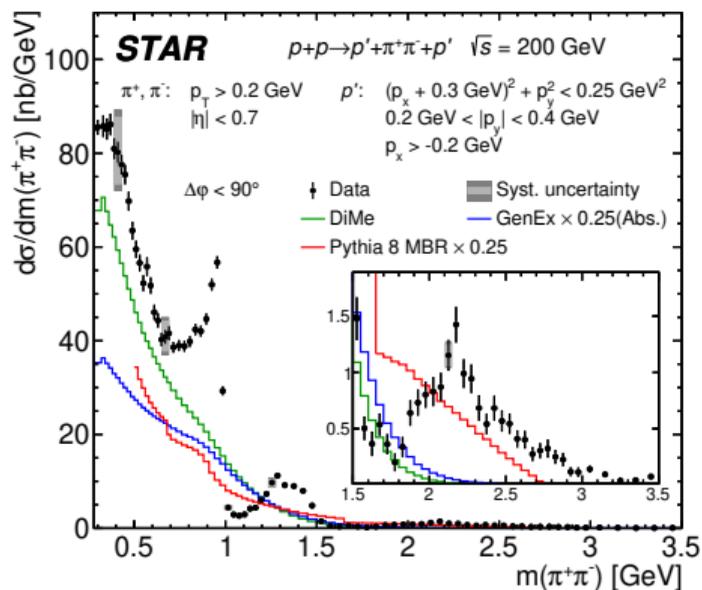
- Suppression of the measured cross sections at $m(\pi^+\pi^-) < 0.6$ GeV for the $\Delta\varphi > 90°$ range is due to the fiducial cuts applied to the forward-scattered protons.

- In the $\Delta\varphi < 90°$ range, the peak around the $f_2(1270)$ resonance in data is significantly suppressed, while the peak at $f_0(980)$, as well as possible resonances in the mass ranges $1.3 - 1.5$ GeV and $2.2 - 2.3$ GeV, are enhanced compared to the $\Delta\varphi > 90°$ range.

- In the $\Delta\varphi < 90°$ range, the DiMe model describes well both the normalization and the shape of the mass spectrum at $m(\pi^+\pi^-) < 0.5$ GeV.
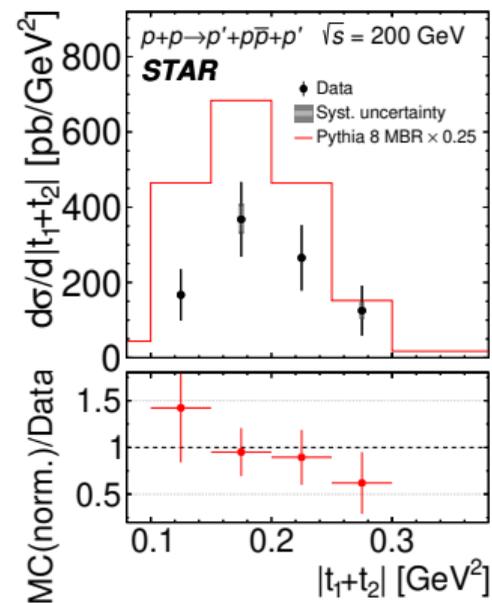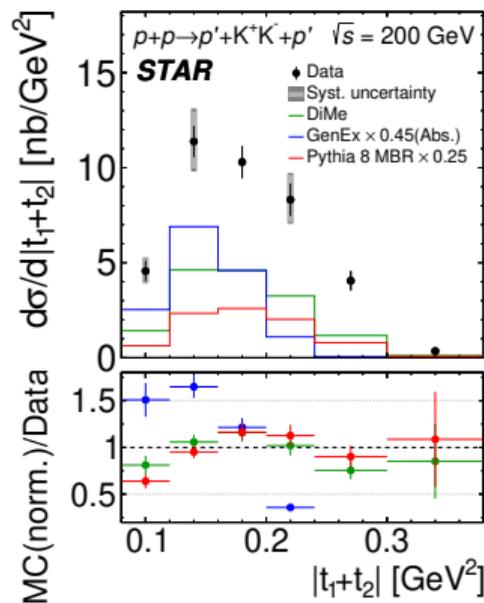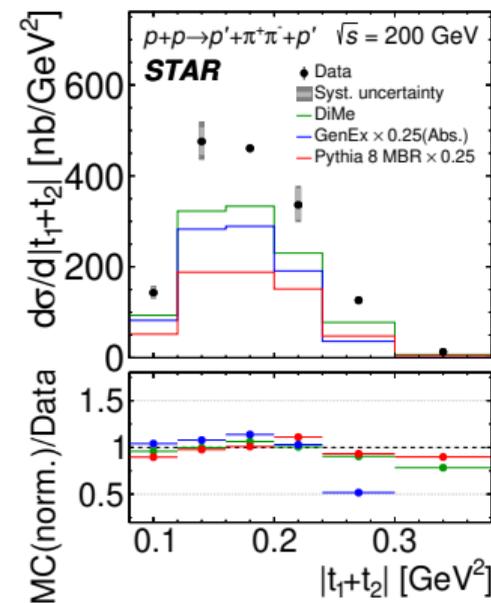
- Shape of $d\sigma/d|t_1 + t_2|$ predicted by DiMe is the closest to the data. Absorption effects (modelled in DiMe) depend on Mandelstam t.
- GenEx fails to describe the shape of the cross sections in $|t_1 + t_2|$.
- Shape predicted by Pythia8 MBR similar to DiMe. Slope in $p\bar{p}$ channel steeper in Pythia than observed in data.
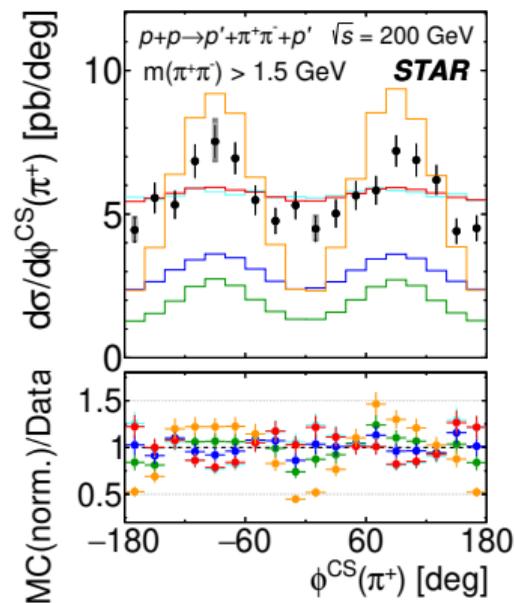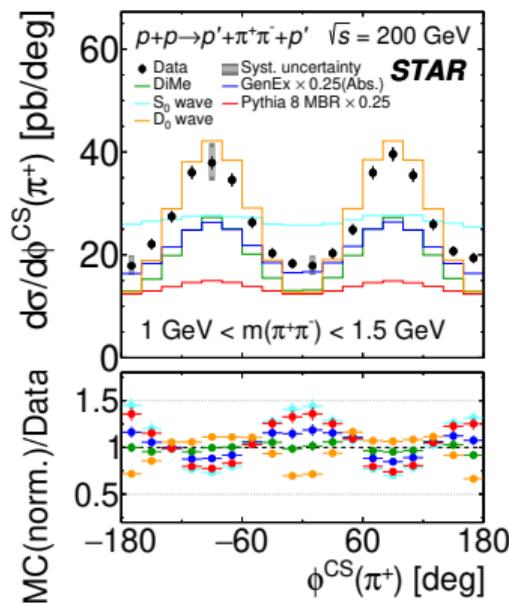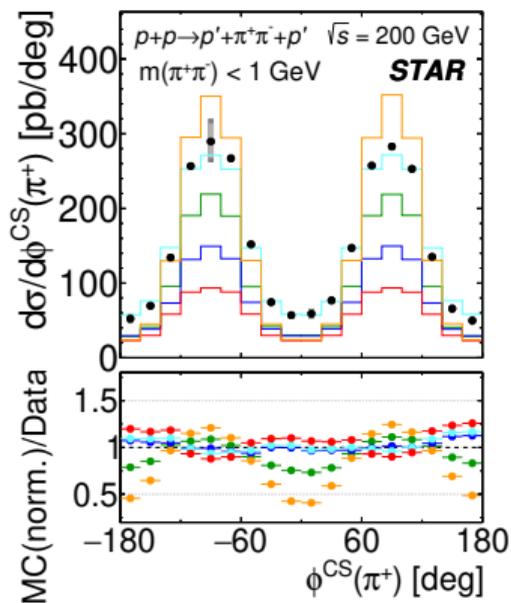
- High statistics of the $\pi^+\pi^-$ sample allow to study the CEP of $\pi^+\pi^-$ pairs in greater detail in three ranges of the invariant mass of the pair: $m(\pi^+\pi^-) < 1$ GeV (mainly non-resonant production), $1 < m(\pi^+\pi^-) < 1.5$ GeV ($f_2(1270)$ mass range) and $m(\pi^+\pi^-) > 1.5$ GeV (higher invariant masses).

- ϕ_{CS} in the lowest mass region agrees 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.
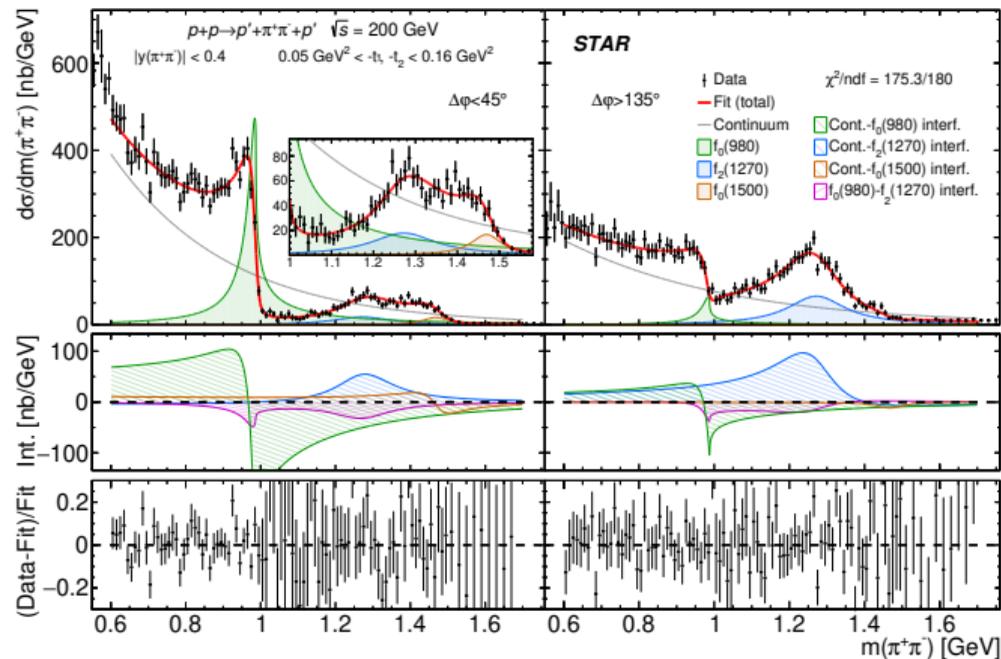
- Fiducial $d\sigma/dm(\pi^+\pi^-)$ have been extrapolated to $|y(\pi^+\pi^-)| < 0.4$, $0.05 < -t_1, -t_2 < 0.16$ GeV^2, $\Delta\varphi < 45°$ and $\Delta\varphi > 135°$.

- 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 $\Delta\varphi$ 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 $f_0(1500)$ - the last potentially containing a gluonic component.

- Potential presence of an additional moderately-narrow state around 1.37 GeV.

- Significant asymmetry of resonances production depending on $\Delta\varphi$ was observed.

Slope B (in GeV^{-2}) of $d^2\sigma/dt_1 dt_2 \propto \exp[B(t_1 + t_2)]$:

	$\Delta\varphi < 45°$	$\Delta\varphi > 135°$
$0.6 < m < 1$ GeV	$8.9 \pm 0.3\ ^{+0.9}_{-0.6}$	$14.1 \pm 0.5\ ^{+0.5}_{-0.9}$
$1 < m < 1.5$ GeV	$10.1 \pm 0.7 \pm 0.7$	$4.5 \pm 0.4 \pm 0.7$
$m > 1.5$ GeV	$8.3 \pm 1.2 \pm 0.7$	$5.0 \pm 1.0 \pm 0.7$

Large variation of the slope of $d^2\sigma/dt_1 dt_2$ is found relative to $m(\pi^+\pi^-)$ and $\Delta\varphi$, sensitive to $\mathbb{PP}$-meson couplings.
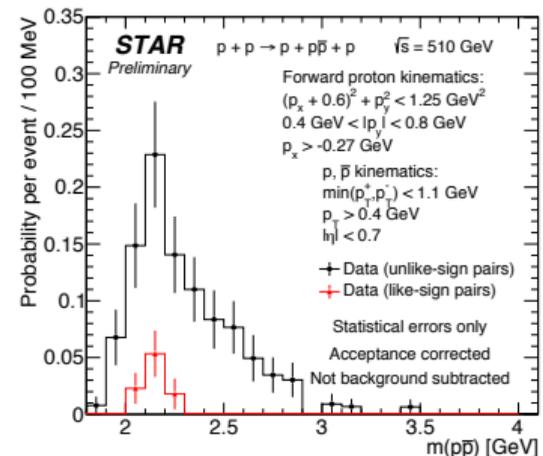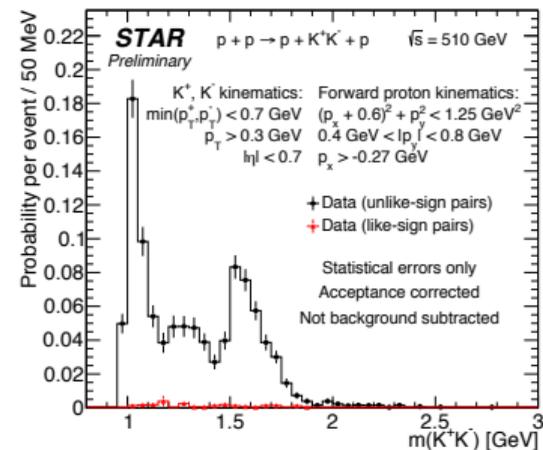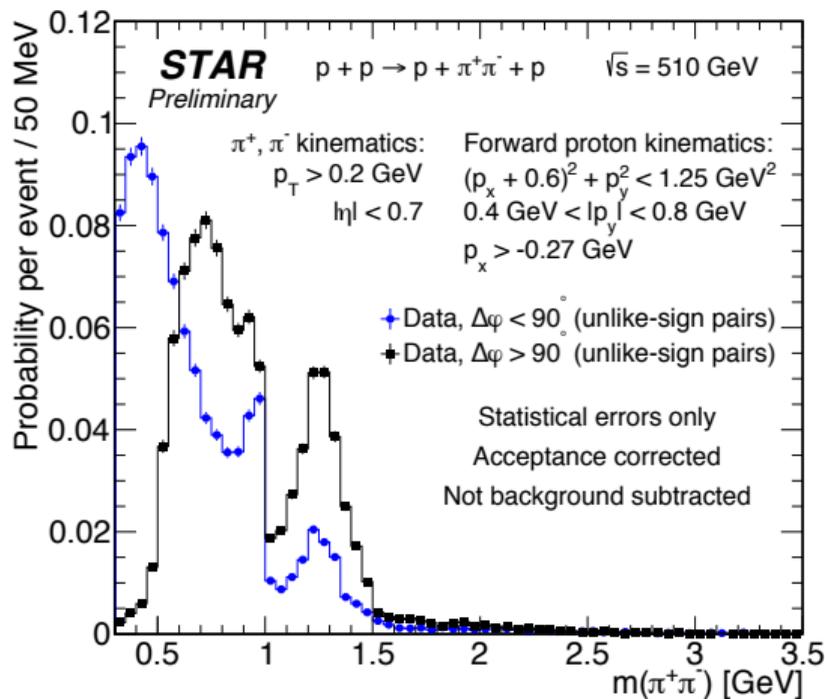
- Preliminary STAR results on CEP of $\pi^+\pi^-$, K^+K^- and $p\bar{p}$ at $\sqrt{s} = 510$ GeV are presented.
- The data demonstrate features similar to those observed at $\sqrt{s} = 200$ GeV.

- 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.

- 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. High precision of this measurement, several times better compared to existing data, should help to constrain free parameters of the 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 $m(\pi^+\pi^-) \sim 2.2$ GeV.

- Detection of the intact beam particles allowed to reconstruct e.g. $\Delta\varphi$ and Mandelstam t, providing insight to relations between the central state observables and forward-scattered protons' kinematics. Large dependence of the slope of $d^2\sigma/dt_1 dt_2$ was found relative to $m(\pi^+\pi^-)$ and $\Delta\varphi$.
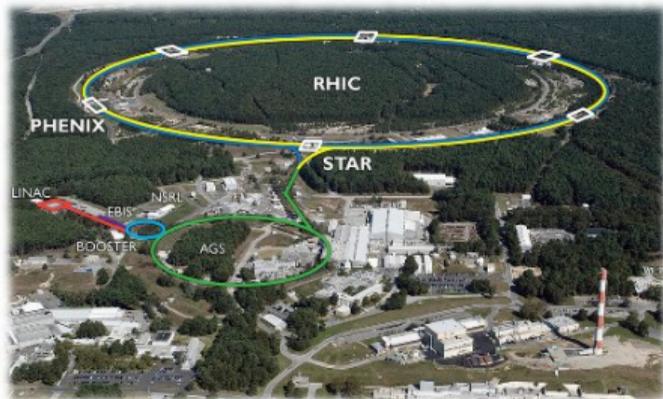
Relativistic Heavy Ion Collider:
- Circumference of 3.8 km
- Unique ability to collide **polarized protons** (transversely and longitudinally)
- Collides also *Cu, Au, U, Al*, ^2H (deuteron), ^3He (helion) in some combinations
- CMS energy in p+p up to $\sqrt{s} = 510$ GeV

STAR has great capabilities for CEP study:
- High-resolution tracking of charged particles by Time Projection Chamber (TPC) covering $|\eta| < 1, \quad 0 < \phi < 2\pi$
- Precise particle identification through dE/dx and Time-of-Flight (ToF)
- Forward rapidity $2.1 < |\eta| < 5.0$ covered by Beam-Beam Counters (BBCs) to ensure rapidity gap
- **Equipped with Silicon Strip Detectors in Roman Pots for measurement of forward protons** (next slide)
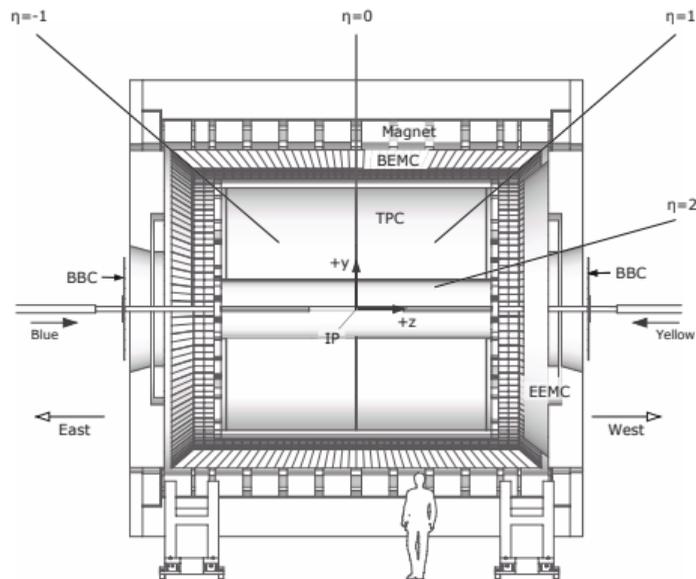
- 8 Silicon Strip Detector (SSD) packages (active area ≈ 79 mm × 49 mm) in Roman Pots

- 4 SSDs/package (2 x-type + 2 y-type), spatial resolution ≈ 30 μm

- 4 detector stations (2 stations/side of central detector) 15.8 m and 17.6 m from IP, downstream the DX dipoles

- station = 2 vertically-oriented Roman Pots (above and below the beamline)

Top view

Side view
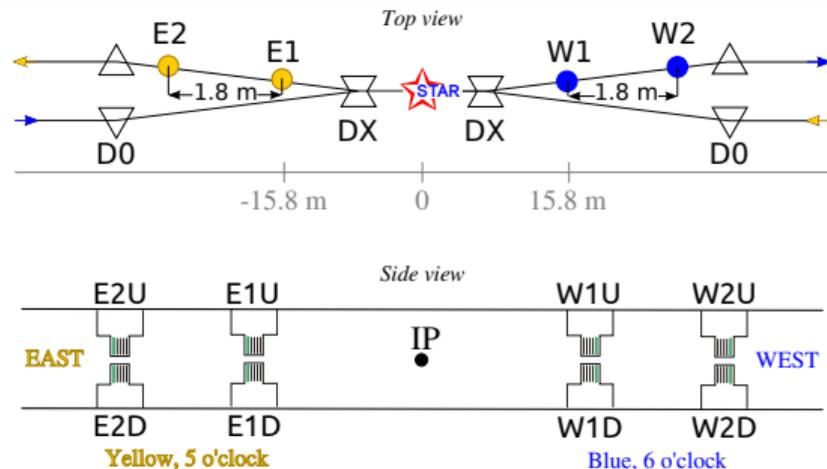
Roman Pot vessel:

Silicon Strip Detector packages:
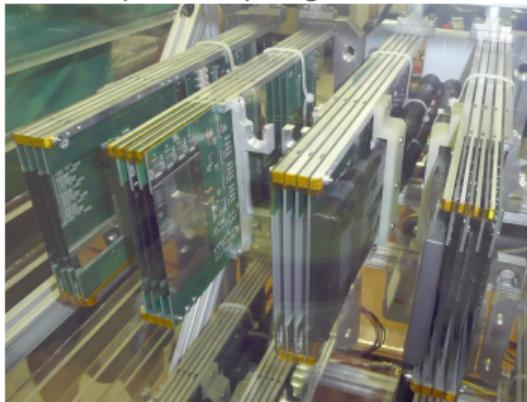
- **Dedicated runs/optics are not required → continuous data-taking is enabled**

- Routine operation during regular high--lumi runs (10^{32}cm^{-2}s^{-1}) at beam--detector distance of $8\sigma_{beam} \sim 25$ mm

- Acceptance (at $\sqrt{s} = 200$ GeV):

  $$0.03 \lesssim -t \lesssim 0.3 \text{ GeV}^2, \qquad \frac{1}{4}\pi \lesssim |\phi| \lesssim \frac{3}{4}\pi$$

- Full reconstrucion of proton momentum

Trigger definition:

1. ≥ 2 hits in Time-Of-Flight detector
2. Signal in Roman Pots at both STAR sides
3. Veto on MIP signal in small BBC tiles covering $3.3 < |\eta| < 5.0$

CEP analysis of two oppositely charged hadrons:

- 1 primary vertex, $|z_{\text{vtx}}| < 80$ cm
- 2 opposite-sign primary tracks in TPC matched with hits in TOF (both in the fiducial region)
- 2 tracks in Roman Pots - 1 per each side of the interaction point (both in the fiducial region)
- $\left| z_{\text{vtx}}^{\text{RP}} - z_{\text{vtx}}^{\text{TPC}} \right| = \left| \Delta z_{\text{vtx}} \right| < 3.5 \cdot \sigma(\Delta z_{\text{vtx}})$ $(\sigma(\Delta z_{\text{vtx}}) \approx 10$ cm$)$
- Veto on signal in large BBC tiles covering $2.1 < |\eta| < 3.3$
- Veto on > 1 extra clusters in TOF
- PID determined with dE/dx and squared mass of the particles m_{TOF}^2
- Transverse momentum of all particles balanced within resolution

$$p_{\text{T}}^{\text{miss}} = \left(\vec{p}_1 + \vec{p}_2 + \vec{h}^+ + \vec{h}^- \right)_{\text{T}} < 75 \text{ MeV}, \quad h = \pi, K, p$$
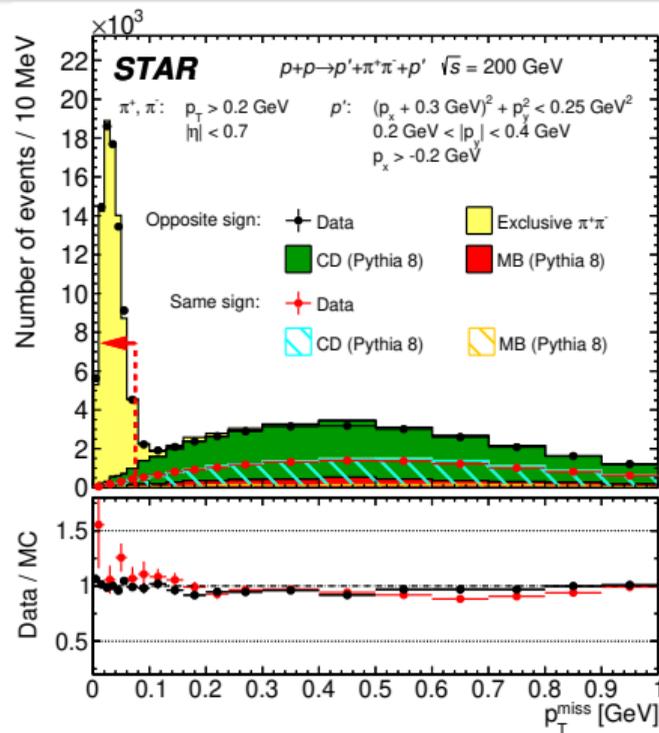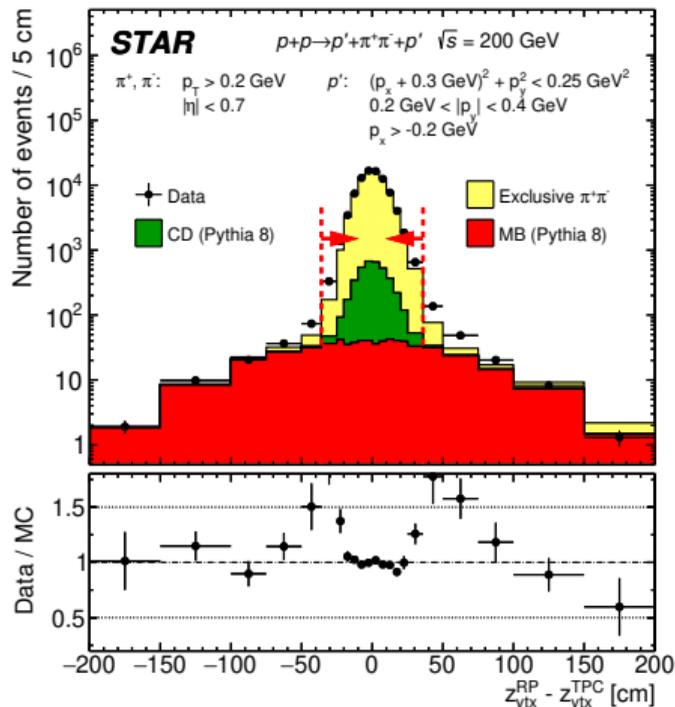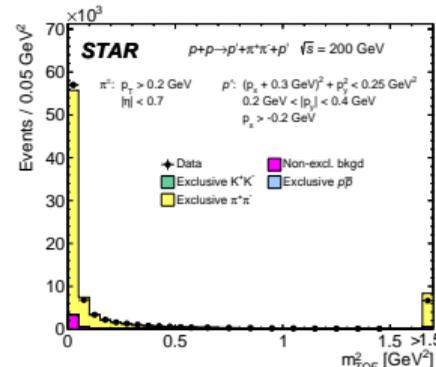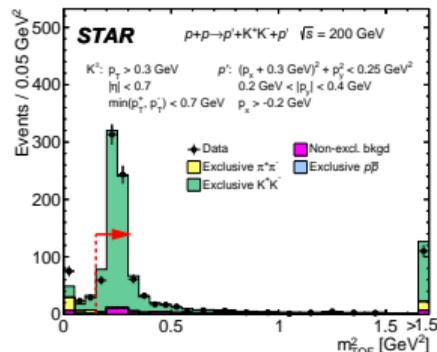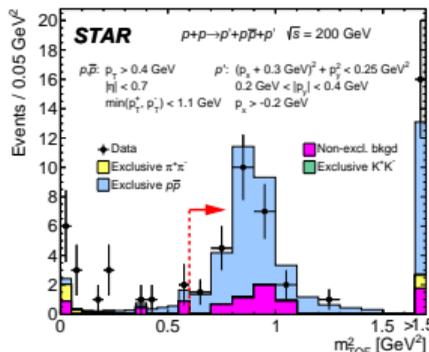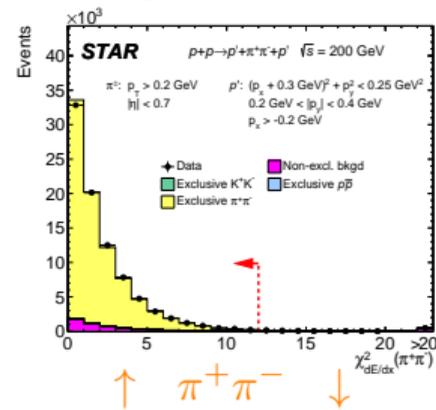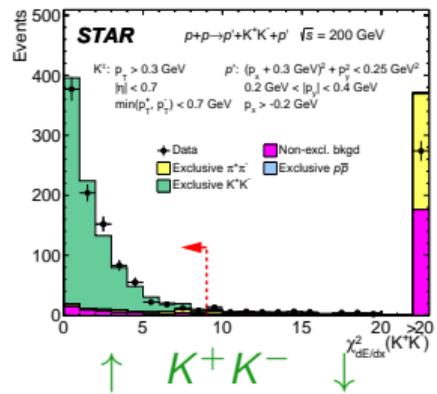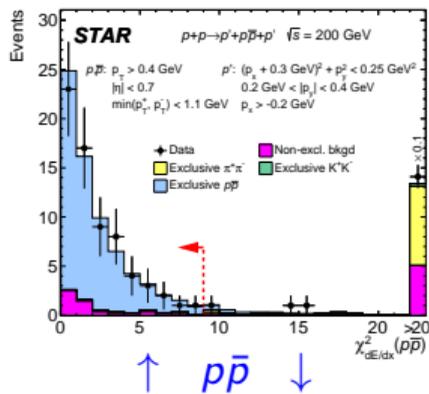
- Pythia8 Minimum Bias (MB) MC embedded into real data (accidentals) normalized to data in the tails of $z_{\mathrm{vtx}}^{\mathrm{RP}} - z_{\mathrm{vtx}}^{\mathrm{TPC}}$.
- Pythia8 CD normalized to data in the signal-free (large) $p_{\mathrm{T}}^{\mathrm{miss}}$ region.

MC describes data well. Non-exclusive background under control.

$$\chi^2_{dE/dx} = (n\sigma_{h,1})^2 + (n\sigma_{h,2})^2 \qquad\qquad \Delta t = L_1\sqrt{1+m^2_{\mathrm{TOF}}/p_1^2} - L_2\sqrt{1+m^2_{\mathrm{TOF}}/p_2^2} \to m^2_{\mathrm{TOF}}$$

$\uparrow \quad p\bar{p} \quad \downarrow$ $\qquad\qquad \uparrow \quad K^+K^- \qquad\qquad \uparrow \quad \pi^+\pi^- \quad \downarrow$

Low misidentifications rate: $< 1\%$ ($\pi^+\pi^-$ and $p\bar{p}$), and $< 3\%$ (K^+K^-)