Recent results on Central Exclusive Production with the STAR detector at RHIC

Rafał Sikora[†]

for the STAR Collaboration

[†]AGH University of Science and Technology, Kraków, Poland

Diffraction and Low-x 2018

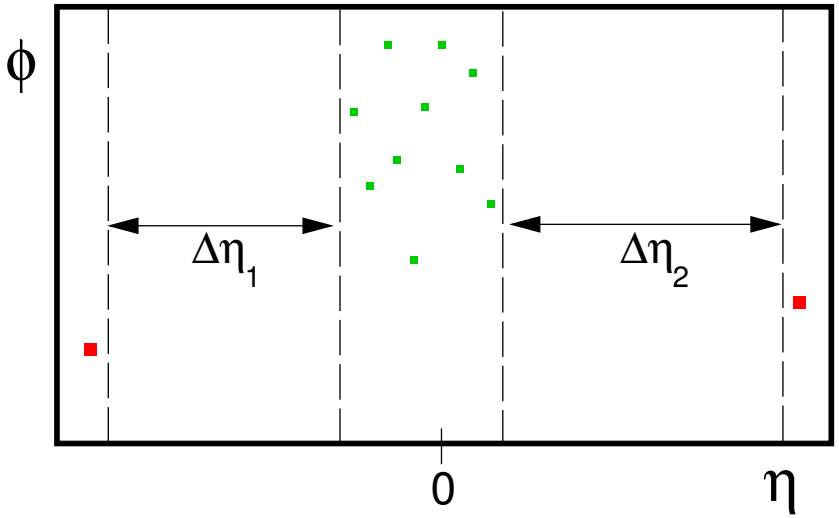
26 August - 1 September 2018, Reggio Calabria, Italy

Central Exclusive Production (CEP)

$$A + B \rightarrow A \overset{\Delta\eta_1}{\oplus} X \overset{\Delta\eta_2}{\oplus} B$$

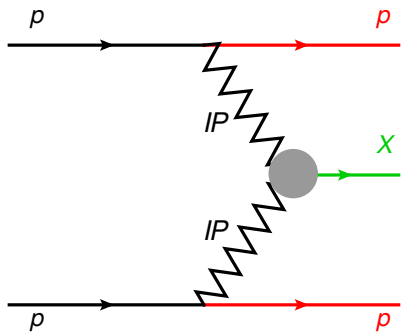
- Colliding particles A and B emerge intact (or excited)
- Central state X is fully measured
- State X is well separated from A and B (size of rapidity gaps increase with increasing $\sqrt{s}$)

$$M_X \approx \sqrt{\xi_A \xi_B s} \qquad y_X \approx \frac{1}{2} \ln \frac{\xi_A}{\xi_B} \qquad \xi \equiv \frac{p_0 - p}{p_0}$$



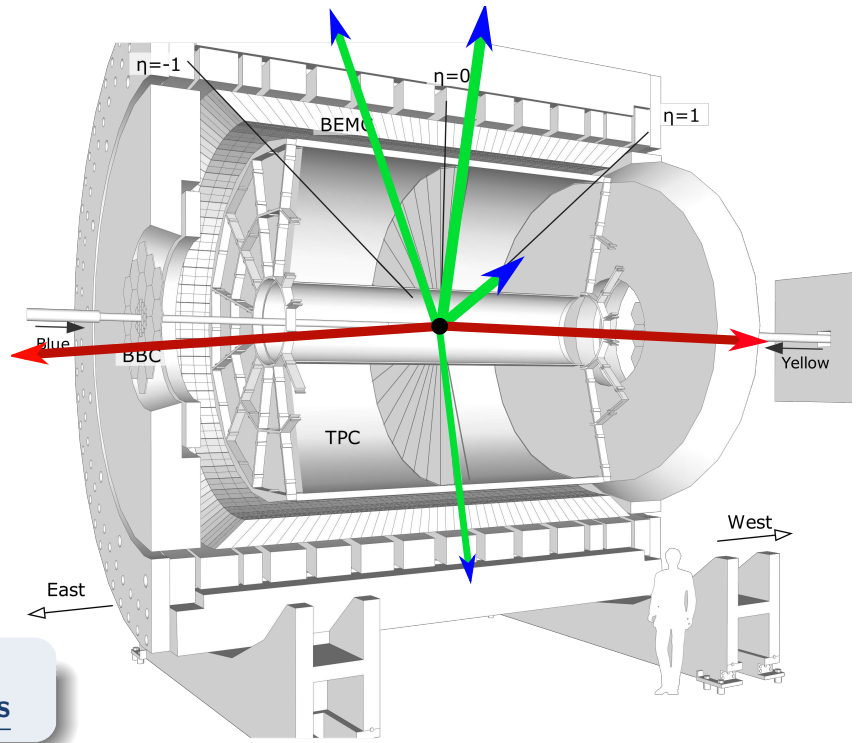
Possible mechanisms of Central Exclusive Production:

- Double Photon Exchange
  $\gamma + \gamma \rightarrow \gamma\gamma,\ l^+l^-,\ W^+W^-$
- Photon-$\mathbb{P}$omeron/$\mathbb{R}$egeon (photoproduction)
  $\gamma + \mathbb{P}/\mathbb{R}(\rho, \omega) \rightarrow$ (pseudo)vector mesons, continuum
- $\mathbb{R}$+$\mathbb{R}$, $\mathbb{P}$+$\mathbb{R}$, $\mathbb{P}$+$\mathbb{P}$ (Double $\mathbb{P}$omeron Exchange, D$\mathbb{P}$E)
  $\mathbb{P} + \mathbb{P} \rightarrow$ continuum, scalar/tensor mesons, glueballs



$$\sigma_{\mathbb{R}\mathbb{R}} \sim (\sqrt{s})^{-2}$$
$$\sigma_{\mathbb{P}\mathbb{R}} \sim (\sqrt{s})^{-1}$$
$$\sigma_{\mathbb{P}\mathbb{P}} \sim \text{const}$$

At RHIC energies D$\mathbb{P}$E is expected to be dominant

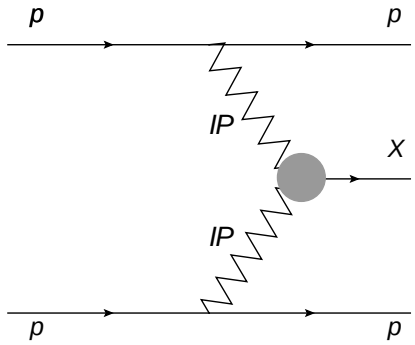


This talk: production and measurement of low-mass central states in diffractive proton-proton interactions with detection of forward protons

Double $\mathbb{P}$omeron Exchange (D$\mathbb{P}$E)

Regge picture:

1. Each proton emits a $\mathbb{P}$omeron
2. Two $\mathbb{P}$omerons fuse and produce neutral central state X



D$\mathbb{P}$E is isospin and G-parity filter: $I^G = 0^+$

If $\mathbb{P}$ carries vacuum quantum numbers: $J^{PC} = 0^{++}, 2^{++}, \ldots$

Motivation for study of low-mass ($\lesssim$3 GeV) Central Exclusive Production via D$\mathbb{P}$E:

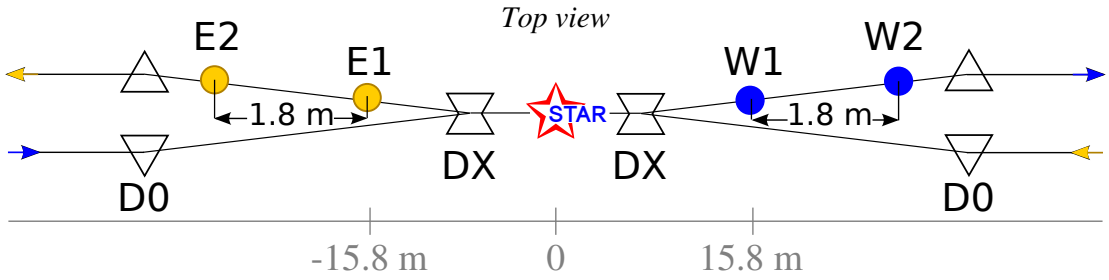
- Lack of hard scale involved = process incalculable within pQCD, only phenomenological models on the market. Need to be experimentally measured and determined:
  - differential cross sections (especially w.r.t. proton kinematical variables)
  - absorption corrections (rapidity gap survival probability S^2)
  - contribution of resonant and non-resonant production
- pQCD image of $\mathbb{P}$omeron implies that D$\mathbb{P}$E is gluon-rich process, therefore gluon bound states (glueballs) are expected to be produced in D$\mathbb{P}$E
  Promising glueball candidates: $f_0(1370)$, $f_0(1500)$, $f_0(1710)$

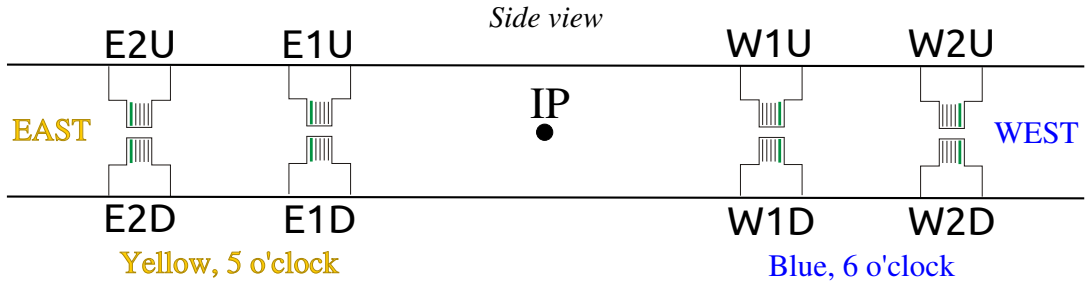
STAR participates in this challenge - it utilizes its unique capabilities:

- High-resolution tracking of charged particles in Time Projection Chamber (TPC) covering $|\eta| < 1$ (full ϕ)
- Precise particle identification through the measurement of $\mathrm{d}E/\mathrm{d}x$ and Time-of-Flight (TOF)
- Forward rapidity $2.1 < |\eta| < 5.0$ covered by Beam-Beam Counters (BBC) to ensure rapidity gap
- **Silicon Strip Detectors in Roman Pots for measurement of forward protons** (next slide)

Forward proton detectors in the STAR experiment - Roman Pot Phase II* (since 2015)

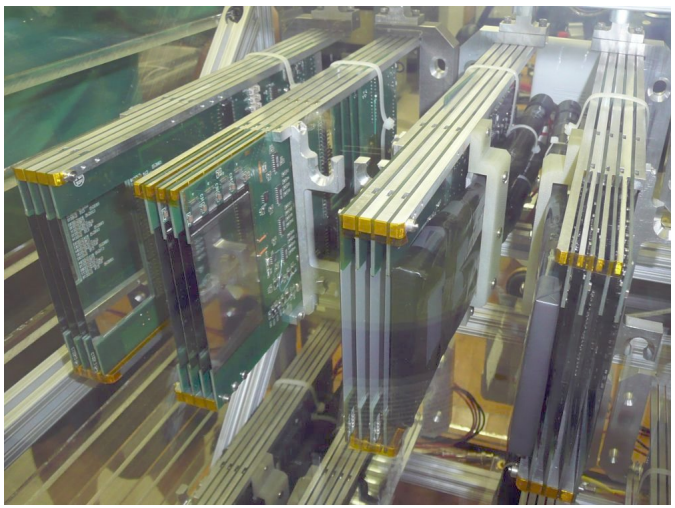
- 8 Silicon Strip Detector (SSD) packages (active area ≈ 79 mm × 49 mm) in Roman Pots
- 4 SSDs/package (2 x-type + 2 y-type), spatial resolution ≈ 30 μm
- 4 detector stations (2 stations/side of central detector) 15.8 m and 17.6 m from IP, downstream the DX dipoles
- station = 2 vertically-oriented Roman Pots (above and below the beamline)





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 $8\sigma_{\text{beam}} \sim 25$ mm
- Acceptance (at $\sqrt{s} = 200$ GeV):

  $0.03 \lesssim -t \lesssim 0.3\ \text{GeV}^2, \quad \frac{1}{4}\pi \lesssim |\phi| \lesssim \frac{3}{4}\pi$
- Full reconstrucion of proton momentum

Central Diffraction trigger definition and event selection

Trigger definition:

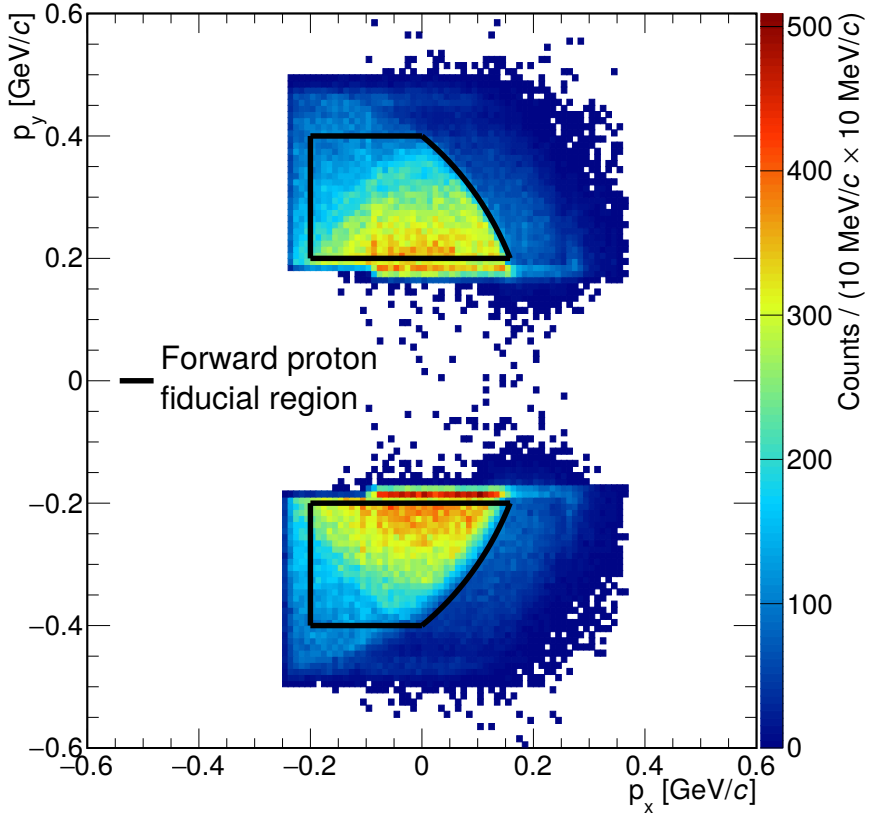
1. $\geq$2 hits in Time-Of-Flight detector
2. Signal in Roman Pots at both STAR sides
3. Veto on MIP signal in small BBC tiles covering $3.3 < |\eta| < 5.0$

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)
- $\left|z_{\text{vtx}}^{\text{TPC}} - z_{\text{vtx}}^{\text{RP}}\right| < 3\sigma \quad (\sigma = 12 \text{ cm})$
- 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^2_{TOF}
- Transverse momentum of all particles balanced within resolution

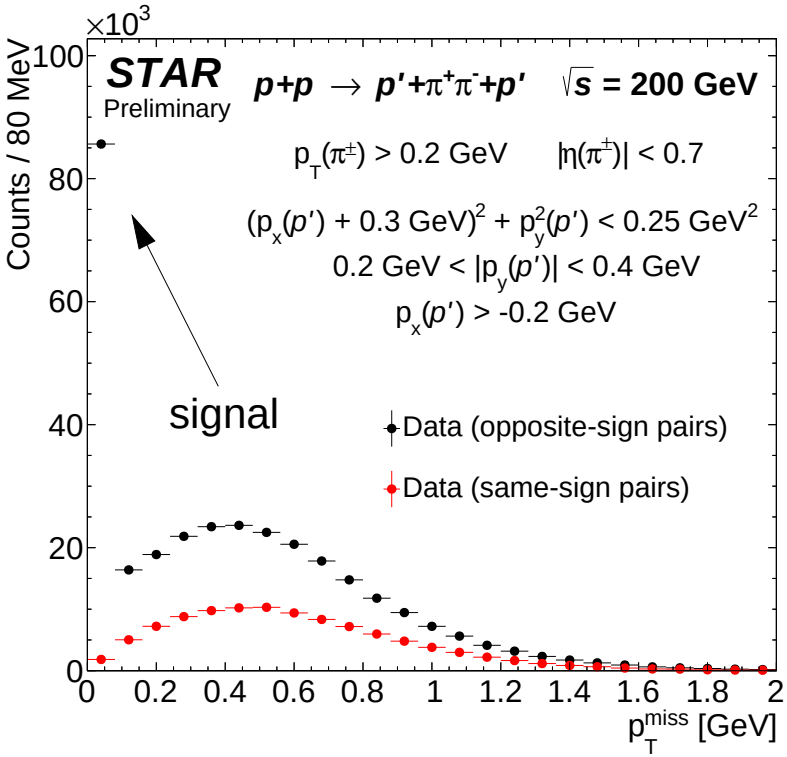
$$p_{\text{T}}^{\text{miss}} = \left(\vec{p}_1 + \vec{p}_2 + \vec{q}_+ + \vec{q}_-\right)_{\text{T}} < 75 \text{ MeV}, \quad q = \pi, K, p$$

6×10^8 CEP triggers were collected in 2015 in p+p collisions with transverse and longitudinal protons polarization, corresponding to $\approx$18 pb^{-1} of integrated luminosity.

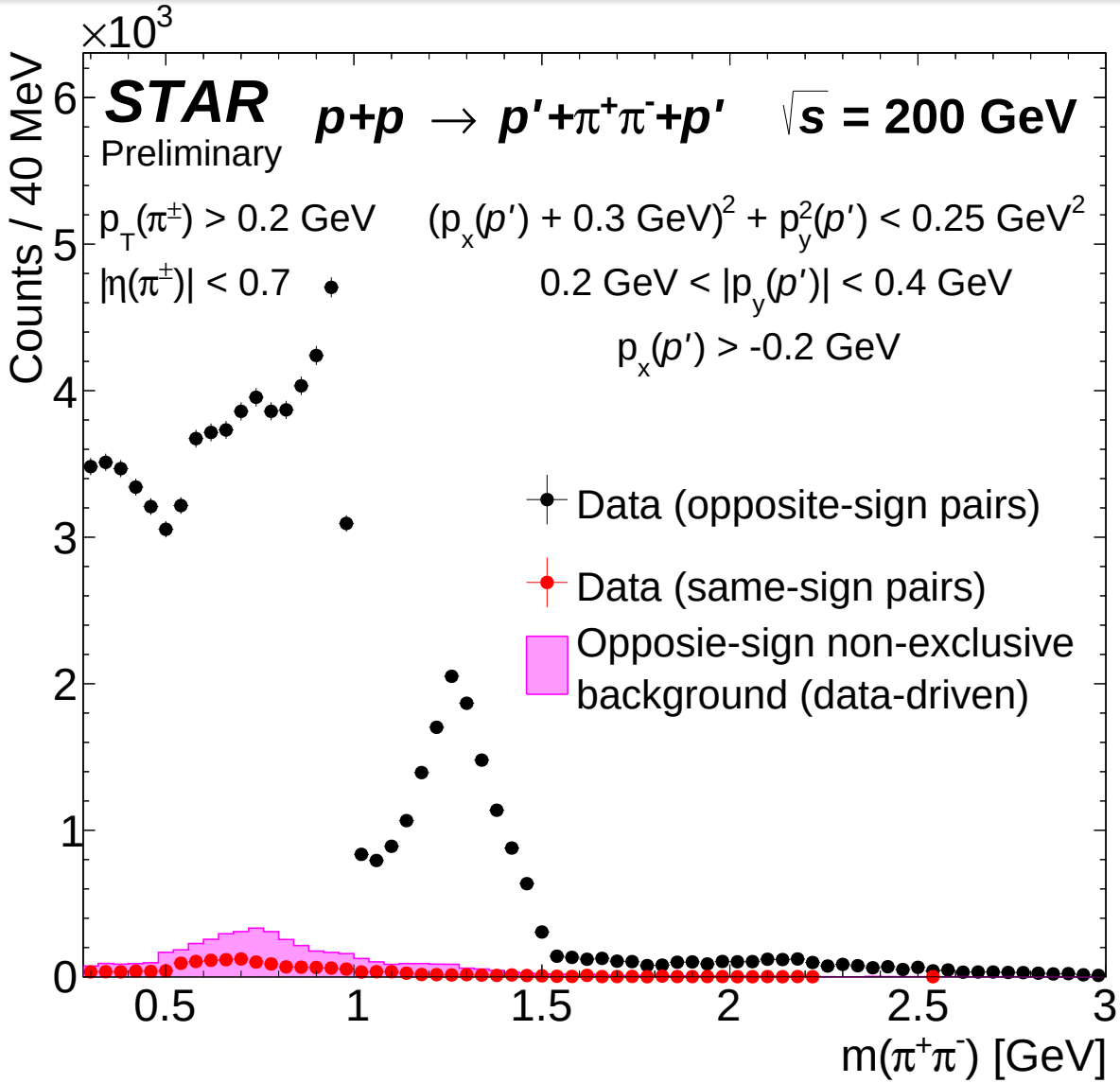


Statistics of selected CEP event candidates:
$\pi^+\pi^-$: **84'000** K^+K^-: **1'000** $p\bar{p}$: **70**

Event selection - momentum balance a key to ensure exclusivity

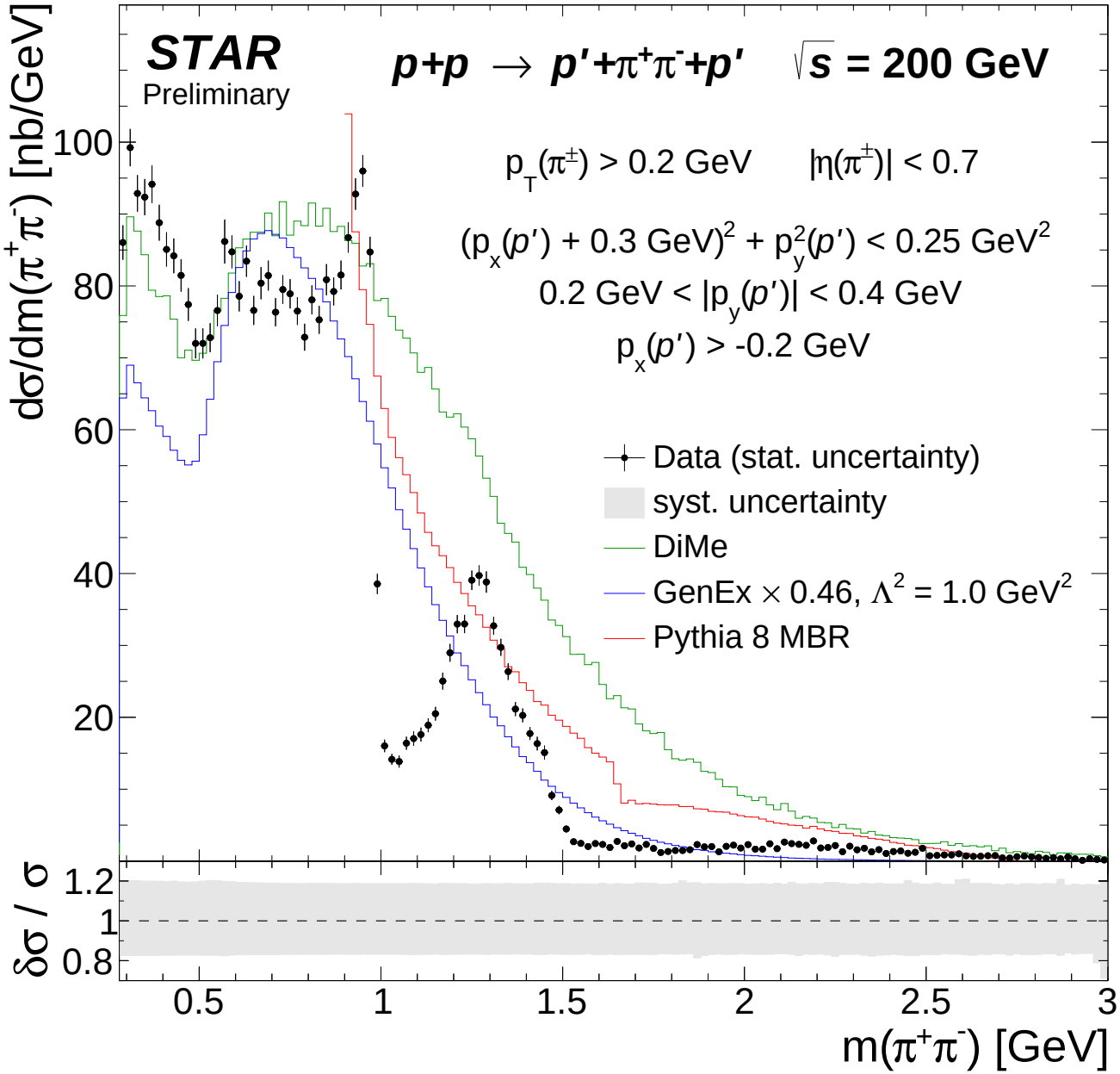


Detection and momentum reconstruction of all final-state particles provides the ability to ensure exclusivity of the system via momentum balance constraint (total transverse momentum is consistent with peak at $p_{\mathrm{T}}^{\mathrm{miss}} = 0$ GeV).



The purity of selected sample of CEP event candidates is $>$ 90%

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

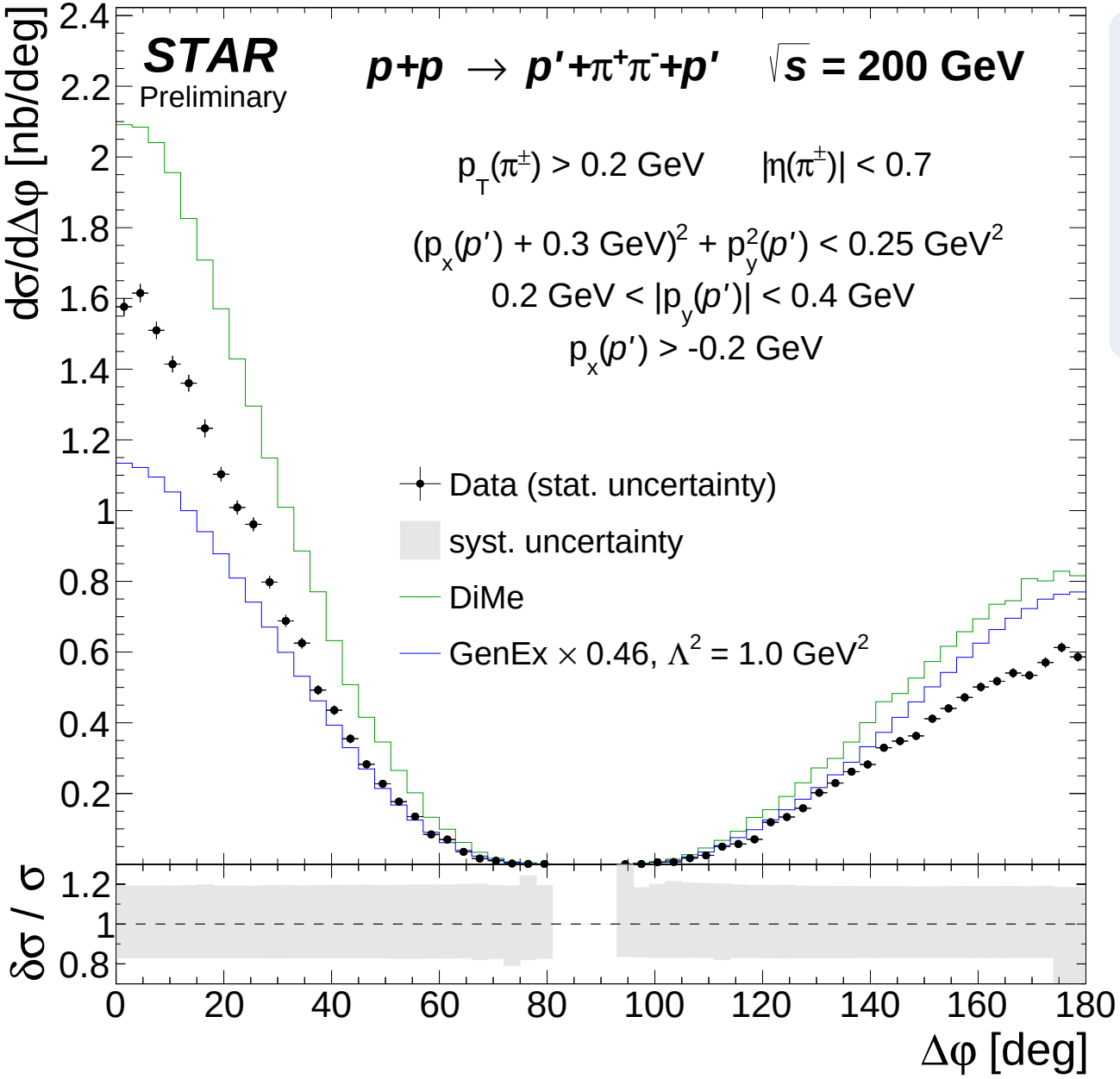


Richness of structures in $d\sigma/dm$:

- Up to ~ 0.7 GeV data is qualitatively described by continuum models (no resonances expected in this mass range)
- Peak below 1 GeV followed by sharp drop of the cross section - presumably $f_0(980)$ opposite in phase to continuum
- Peak between $1 - 1.5$ GeV is probably $f_2(1270)$, maybe with some mixture $f_0(1370)$
- Sharp drop at 1.5 GeV can be due to $f_0(1500)$ interference with the other states

References to continuum models in arXiv:
1312.4553 1411.6035 1205.1446

ℙomeron-ℙomeron impact angle in the transverse plane (CEP of $\pi^+\pi^-$)



Angular separation of diffractively scattered protons in the transverse plane:

$$\Delta\varphi = \measuredangle\{(p_x'^{A}, p_y'^{A}), (p_x'^{B}, p_y'^{B})\}$$

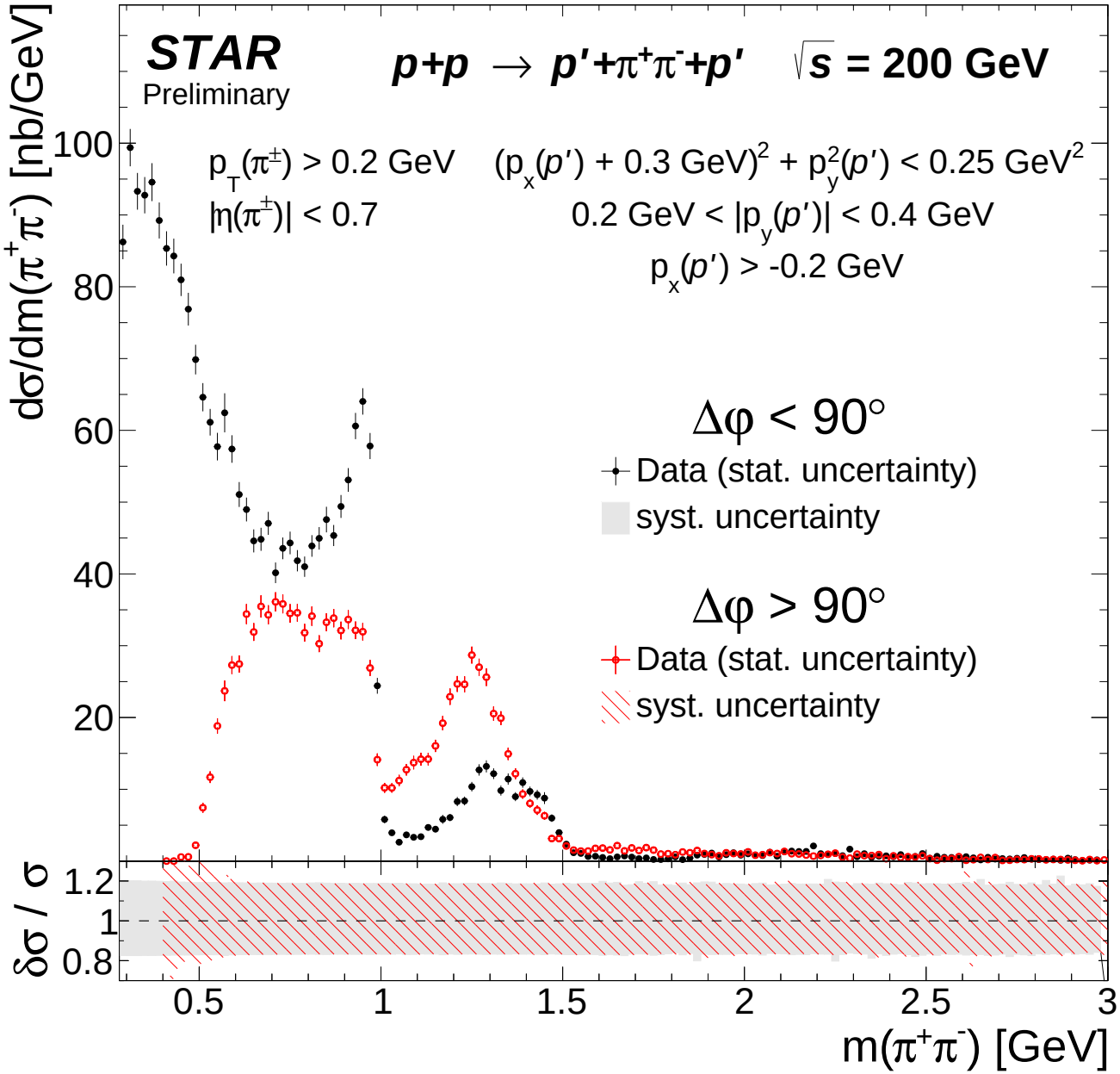
Close relation with the "glueball filter":

$$\Delta p_T^{\mathbb{P}\mathbb{P}} = \left(\vec{\mathbb{P}}^A - \vec{\mathbb{P}}^B\right)_T$$

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

- Data shows large asymmetry in production rate depending on the angle between outgoing protons - partially kinematic effect (different accepted pair p_T at low pair inv. mass)
- Models reproduce the overall trend but none of them correctly describes the relative cross sections for $\Delta\varphi$ below and above 90°
  - resonances are not included
  - absorption is modeled only in DiMe

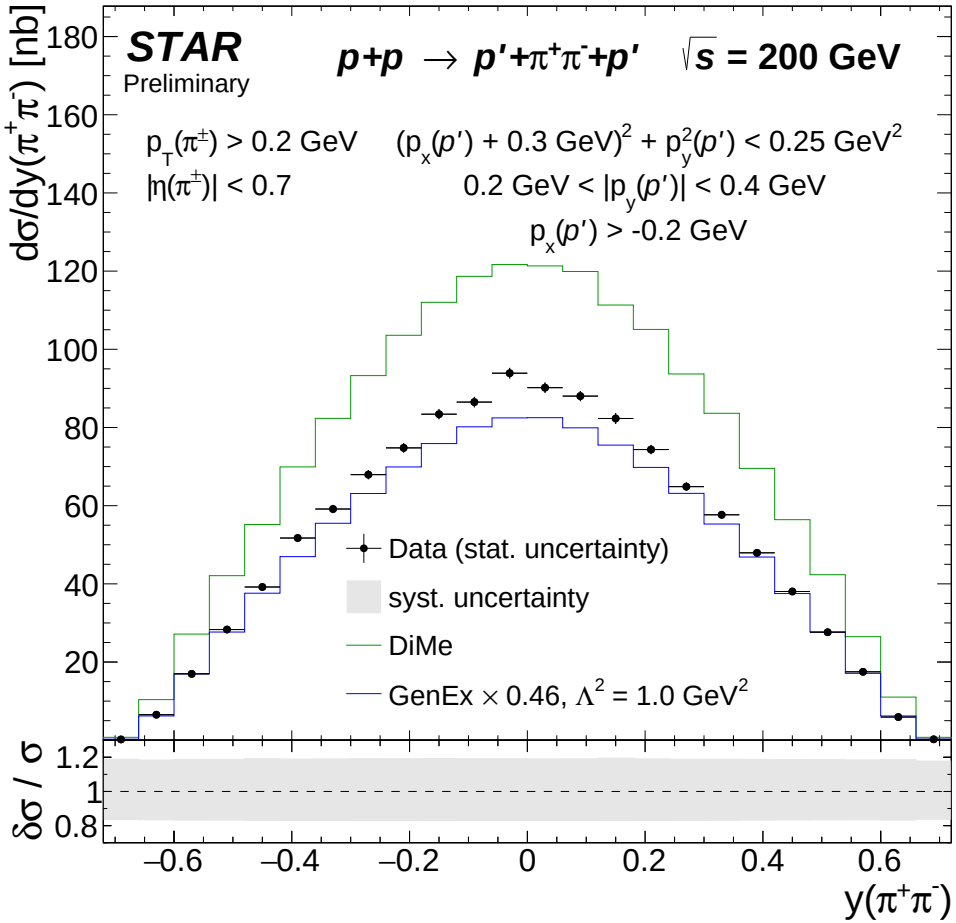
Invariant mass of exclusively produced $\pi^+\pi^-$ vs. azimuthal separation of the diffractive protons

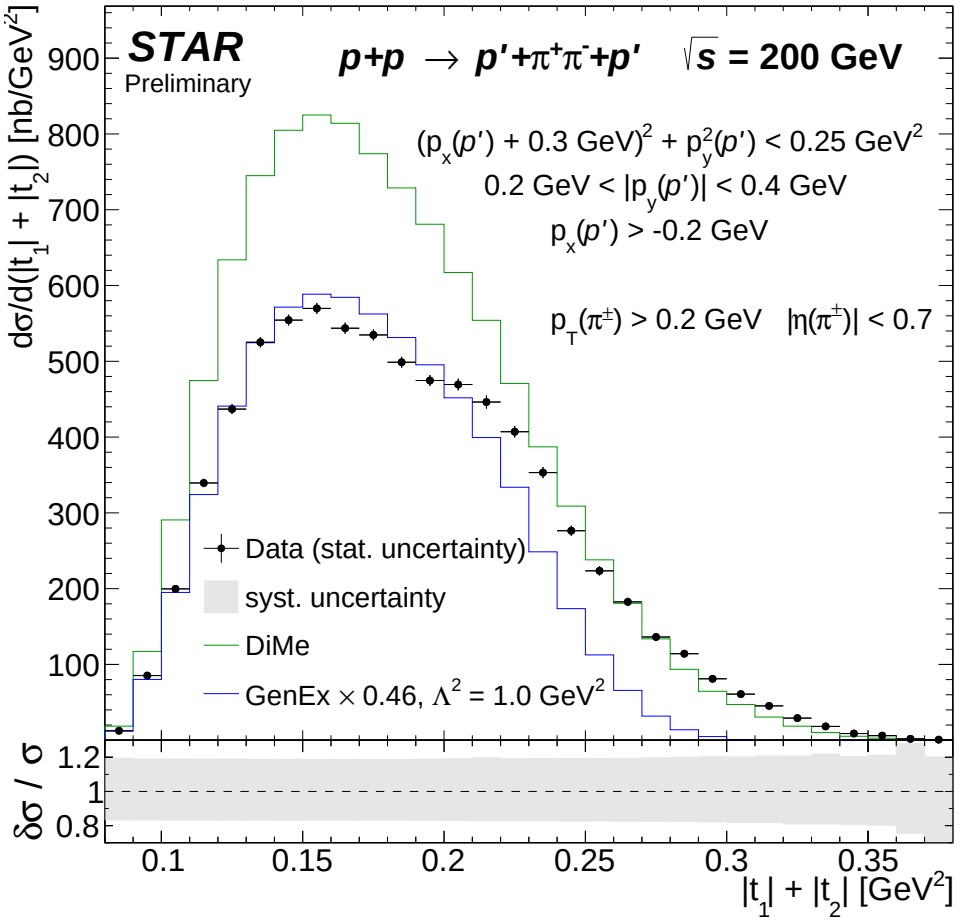


Evident influence of the DIPE dynamics on mass spectrum:

- Below $\sim$ 0.7 GeV large asymmetry in cross section due to the measurement range (kinematic effect)
- Signal from $f_0(980)$ stronger at $\Delta\varphi < 90°$
- Peak of $f_2(1270)$ more pronounced at $\Delta\varphi > 90°$ (undeniable $q\bar{q}$ state)
- Shoulder at 1.45 GeV followed by sharp drop of the cross section more distinct at $\Delta\varphi < 90°$ suggesting larger contribution from $f_0(1500)$ when IPomerons parallel to each other
- Above 1.9 GeV mass spectrum very similiar in both forward proton configurations ($\Delta\varphi < 90°$ and $\Delta\varphi > 90°$)

Rapidity of $\pi^+\pi^-$ and total squared four-momentum transferred by forward protons

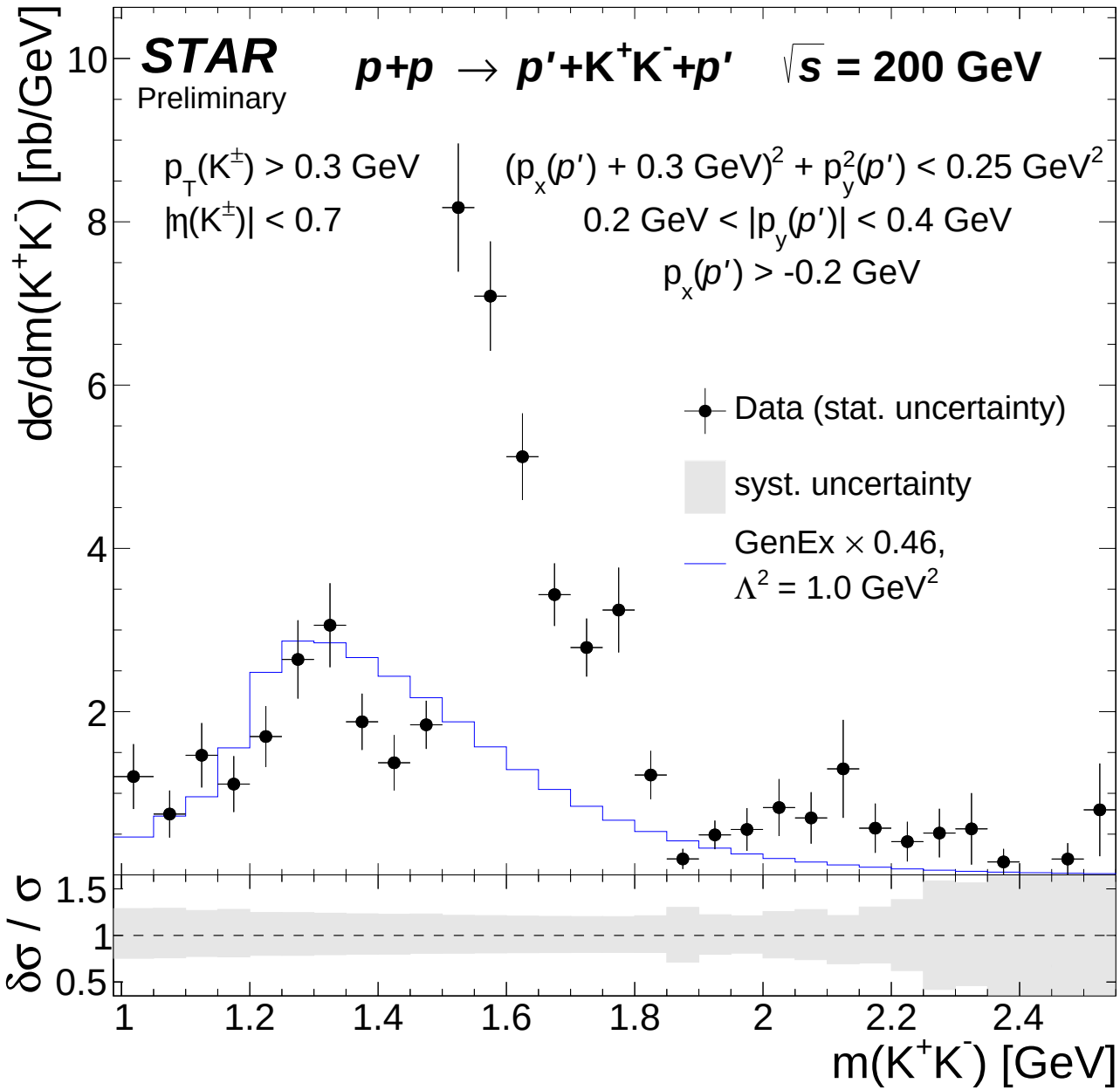




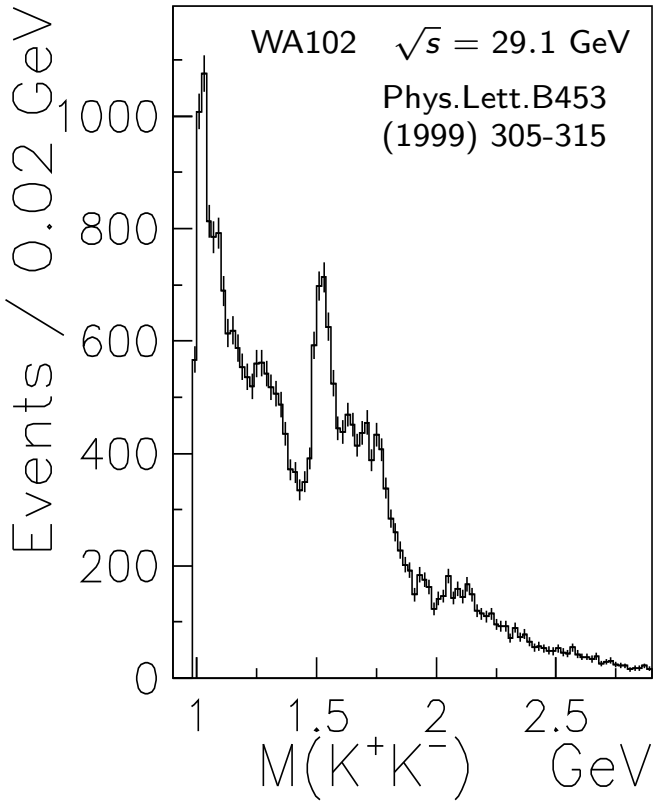
- Models underestimate cross section primarly for the central states produced at rapidities very close to 0 - protons tend to transfer more similiar fractions of its momentum to form the central state
- Measured cross section in the sum of Mandelstam's t variable in proton-$\mathbb{P}$omeron-proton vertices is less steep and indicates higher transfers of four-momenta as compared to model predictions

Discrepancies between data and models may originate from resonances and absorption effects

Invariant mass of exclusively produced K^+K^-



- The most promiment structure: peak between 1.5-1.8 GeV, possibly a $f_0(1500)$ (hints found also in $\pi^+\pi^-$ channel), maybe with $f_2'(1525)$ and $f_0(1710)$
- Peak in mass range of $f_2(1270)$
- Wide enhancement between 1.9-2.4 GeV
- Similiar properties found by WA102 (below) - STAR observes much reduced continuum background thanks to cut on minumum kaon p_T



Summary

- The STAR experiment at RHIC conducts intensive studies of diffractive physics utilizing its rich detector setup, with an emphasis on the forward proton detectors in Roman Pots
- In 2015 STAR collected large sample of high-quality CEP-dedicated data used to prepare presented preliminary differential cross sections of exlusively produced $\pi^+\pi^-$ and K^+K^-
- Even larger dataset was collected in 2017 in proton-proton collisions at $\sqrt{s} = 510$ GeV enabling comparison of the DIPE in different kinematic regimes
- Preliminary CEP differential cross sections measured in STAR indicate high influence of the dynamics of the IPomeron exchange on the properties of the centrally produced system
- Mass spectrum of exclusive $\pi^+\pi^-$ and K^+K^- is rich in structures which might be attributed to resonances with $J^{PC} = 0^{++}$ ($f_0(980), f_0(1500)$) and $2^{++}(f_2(1270))$, of which some are considered to have large gluonic content; no clear signal from states with non-DIPE quantum numbers are observed (e.g. ρ^0)

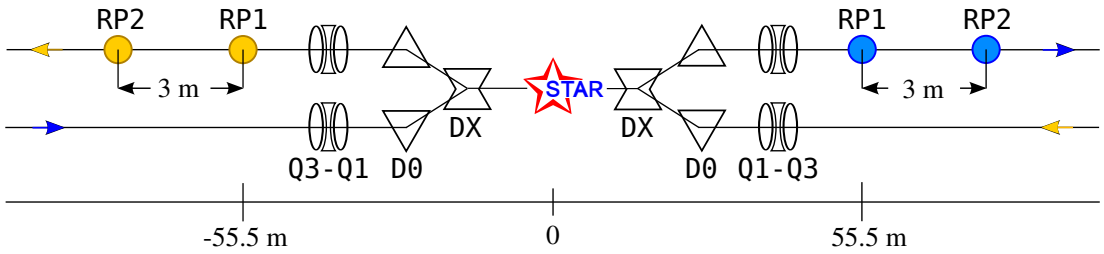
THANK YOU

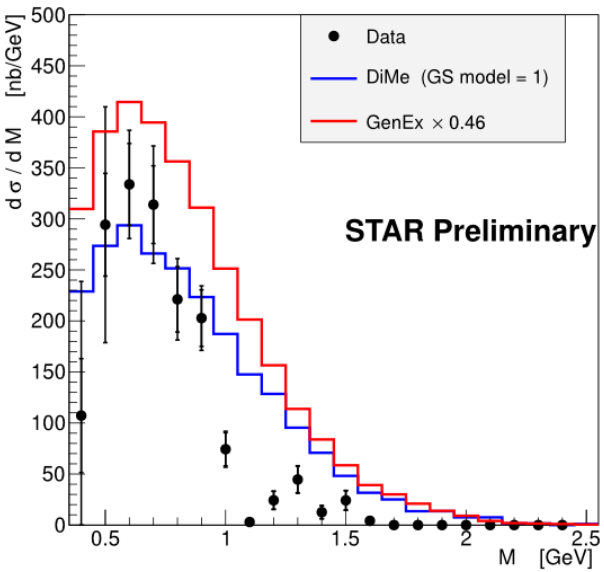
Results on exclusive $\pi^+\pi^-$ production from Roman Pot Phase I

Kinematic coverage:

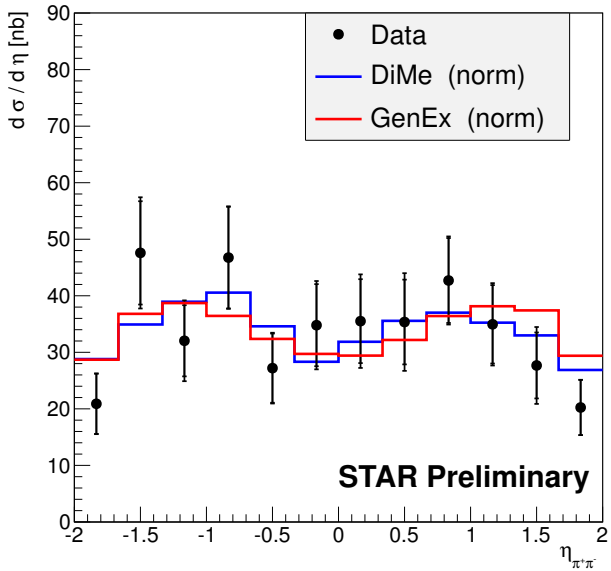
$$0.005 < -t < 0.03 \text{ GeV}^2$$

$$0 < \phi < 2\pi \quad |\eta_\pi| < 1 \quad |\eta_{\pi\pi}| < 2$$

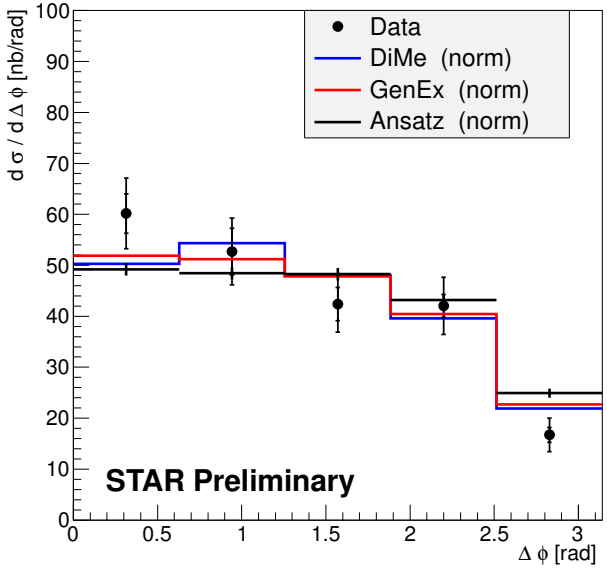




Models of non-resonant $\pi^+\pi^-$ production agree with STAR data up to ≈ 1 GeV



Preliminary cross section in given kinematic range at $\sqrt{s} = 200$ GeV
$\sigma^{\pi\pi}_{\text{CEP}} = 133 \pm 8(\text{stat}) \pm 12(\text{sys})$ nb



No significant (unexpected) correlation between scattered protons has been found

Details about the results can be found in L.Adamczyk et al., Int.J.Mod.Phys. A29, 1446010 (2014)