Central Exclusive Production of meson pairs in proton-proton collisions at $\sqrt{s} = 200$ GeV in the STAR experiment at RHIC

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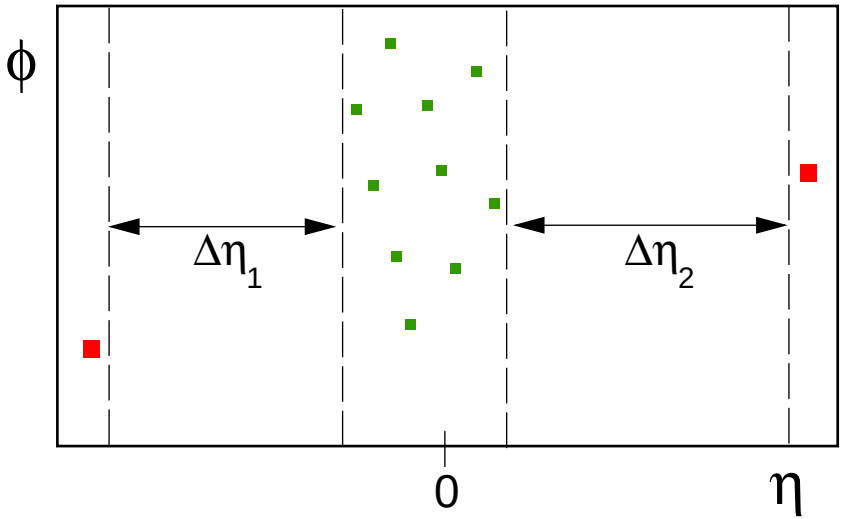
Outline

Central Exclusive Production (CEP)

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

- colliding particles A and B emerge intact
- central state X is fully measured
- state X is well separated from A and B (rapidity gaps become larger as $\sqrt{s}$ grows)



Production mechanisms:

1. $\gamma + \gamma \to l^+ l^-$
2. $\gamma + \mathbb{P} \to$ vector mesons
3. $\mathbb{P}(\mathbb{R}) + \mathbb{P}(\mathbb{R}) \to$ hadrons

$\sigma_{\mathbb{R}\mathbb{R}} \sim s^{-1}$
$\sigma_{\mathbb{P}\mathbb{R}} \sim s^{-0.5}$ → At RHIC energies Double Pomeron Exchange expected to be dominant
$\sigma_{\mathbb{P}\mathbb{P}} \sim$ const

Properties of the central state X:

$$M_X^2 = s\left(\xi_A\,\xi_B \sin^2\frac{\alpha}{2} - \left(1-\xi_A-\xi_B\right)\cos^2\frac{\alpha}{2}\right)$$

$$\overset{\alpha=\pi}{=} s\,\xi_A\,\xi_B, \qquad \alpha = \measuredangle\left(\vec{p}\,'_A, \vec{p}\,'_B\right), \qquad \xi = \frac{p_{beam} - p}{p_{beam}}$$

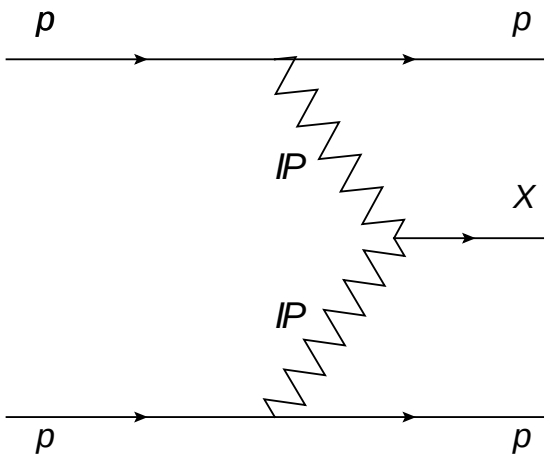
Rapidity of state X: $y_X = \frac{1}{2}\ln\frac{\xi_A}{\xi_B}$

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

Double ℙomeron Exchange (DℙE)

Non perturbative QCD (Regge picture):

1. Each proton emits ℙomeron
2. Two ℙomerons fuse and produce neutral central state X

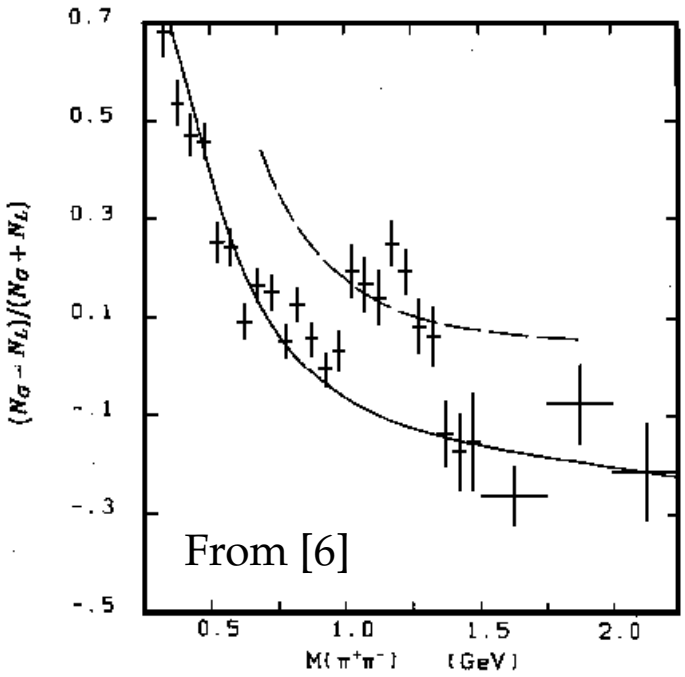


DℙE is isospin and G-parity filter: $I^G = 0^+$

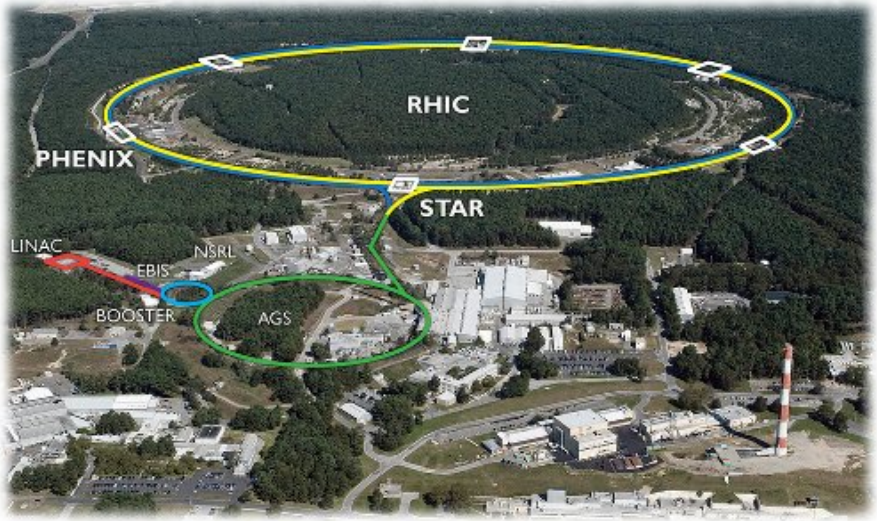
If ℙ carries vacuum quantum numbers: $J^{PC} = 0^{++}, 2^{++}, \ldots$

Related questions/problems pending solution:

- What is the $\sigma_{\mathbb{PP}}$? Current data: [1]
- What is the contribution of resonant and non-resonant production in DℙE? Which models are correct? [2, 3]
- pQCD image of ℙomeron implies that DℙE is gluon-rich process → gluon bound states ("glueballs") could be preferentially produced [4, 5] - are they? Most promising candidates: $f_0(1500)$ and $f_0(1710)$
- Is DℙE the only production mechanism at high $\sqrt{s}$? Possible alternative: $g + g \to X$ with simultaneous g exchange between protons - hints at ISR [6]. Can be verified by asymmetry in central mass distribution between collinear and non-collinear protons (RHS plot)



STAR detector at RHIC

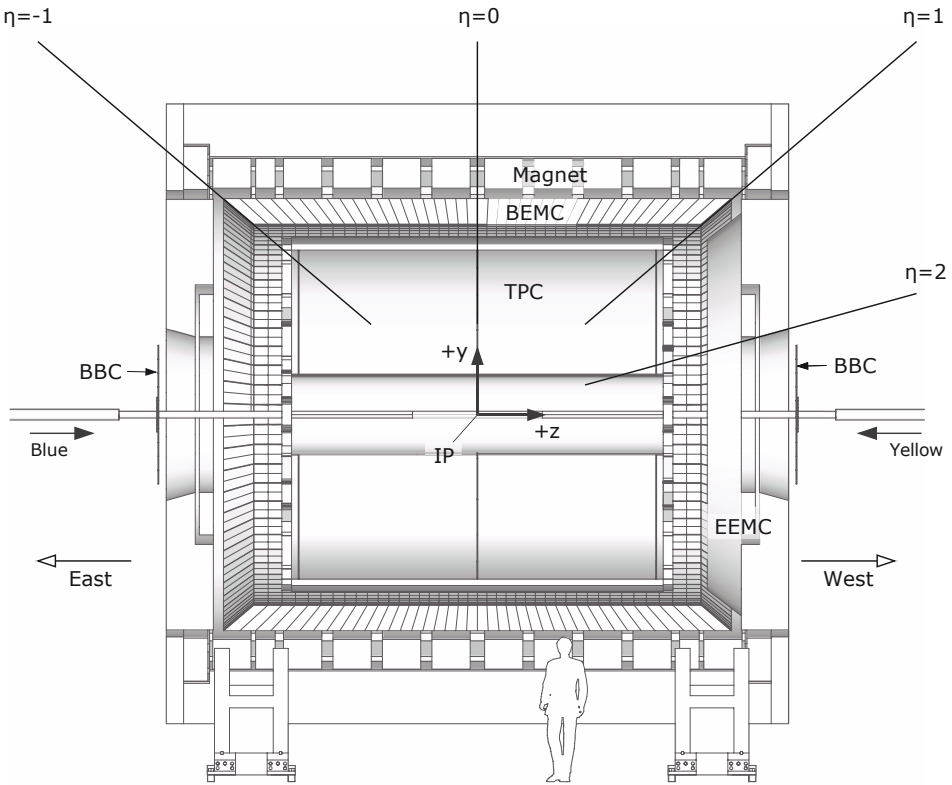


Relativistic Heavy Ion Collider:

- Circumference of 3.8 km
- Unique ability to collide **polarized protons** (transversely and longitudinally)
- Collides also Cu, Au, U, Al, d (deuteron), h (helion) in some combinations
- Center-of-mass energy up to $\sqrt{s} = 510$ GeV

STAR has great capabilities for CEP study:

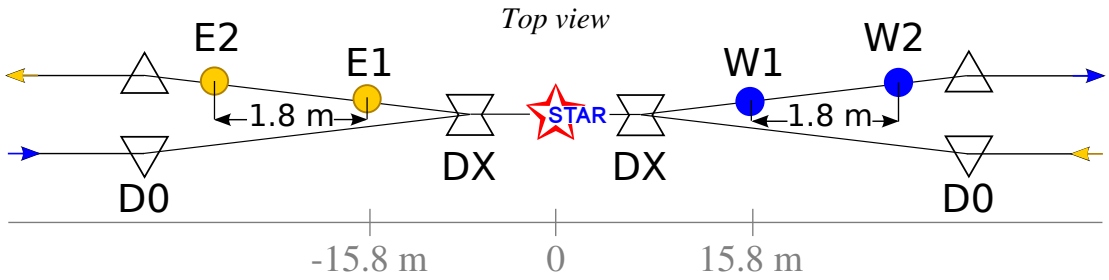
- High-resolution tracking of charged particles by Time Projection Chamber (TPC) covering $|\eta| < 1$, $0 < \phi < 2\pi$
- Precise particle identification through dE/dx and Time-of-Flight (ToF)
- Forward rapidity $2.1 < |\eta| < 5.0$ covered by Beam-Beam Counters (BBC) to ensure rapidity gap
- **Equipped with Silicon Strip Detectors in Roman Pots for measurement of forward protons** (next slide)

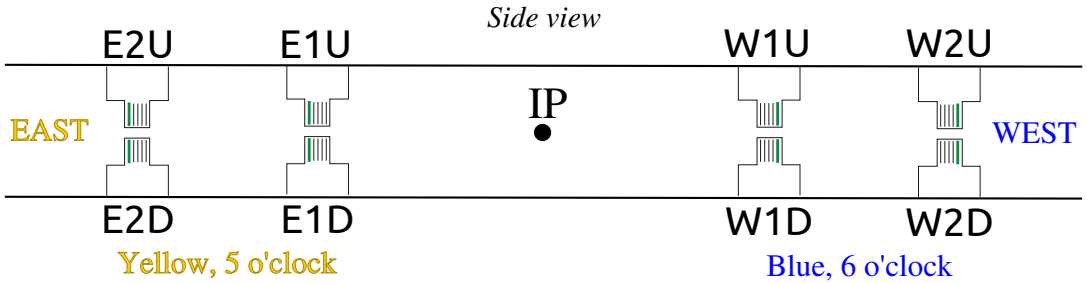


Forward proton detectors

Roman Pot Phase II* (operating since 2015):

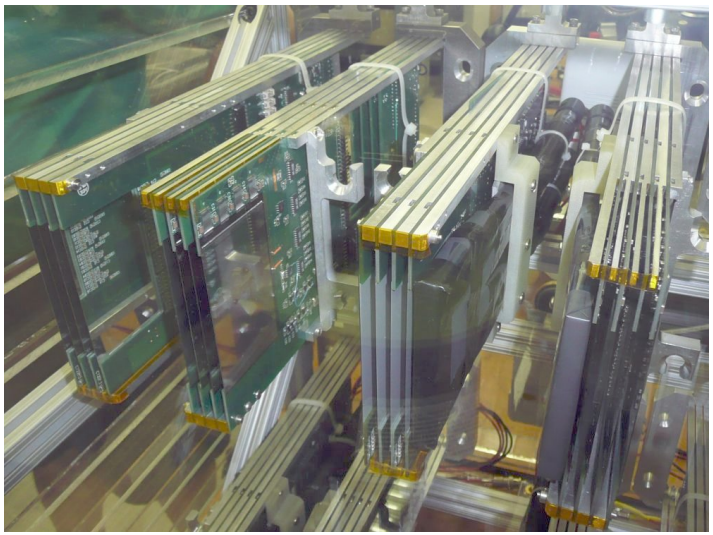
- 8 Silicon Strip Detector (SSD) packages (active area $\approx$ 79 mm $\times$ 49 mm) installed in Roman Pot vessels
- Package contains 4 SSDs (2 x-type + 2 y-type) with spatial resolution $\approx$ 30 μm
- Detectors are mounted in 4 stations (2 stations on each side of STAR central detector, 15.8 m and 17.6 m from IP) placed downstream the DX bending dipoles
- Each station composed of 2 vertically-oriented Roman Pots (above and below the beamline)





Roman Pot vessel:

Silicon Strip Detector packages:



- **Presented setup of Roman Pot detectors does not require dedicated runs/special beam optics $\rightarrow$ continuous data-taking and collecting large data samples is enabled**
- Minimum beam-detector distance at operation ~20 mm
- Approximate acceptance (at $\sqrt{s} = 200$ GeV)

$$0.03 < -t < 0.3\ \mathrm{GeV}^2/c^2$$

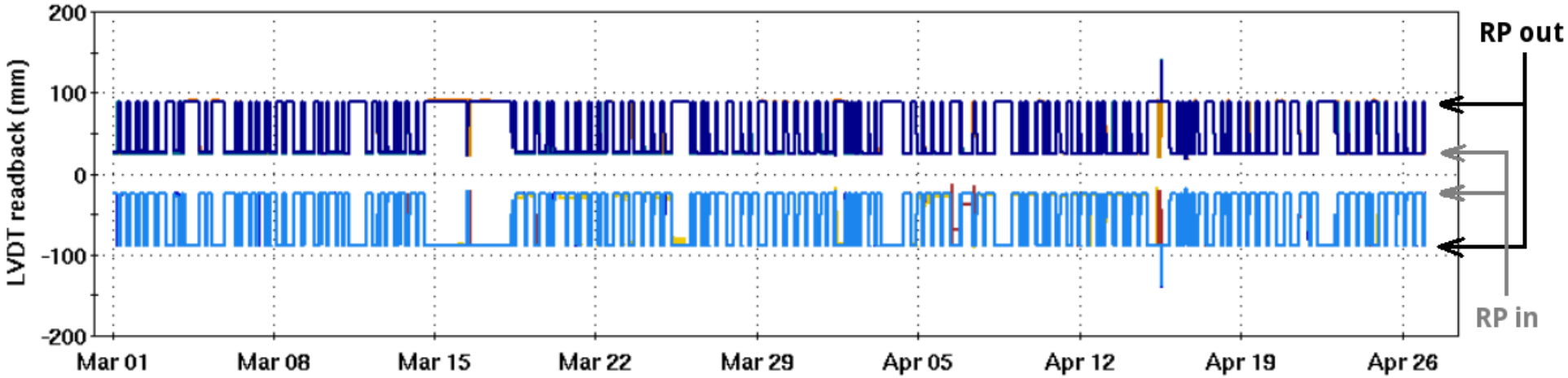
$$\frac{3}{4}\pi \lessapprox |\phi| \lessapprox \frac{1}{4}\pi \qquad \xi < 0.6$$

- Full reconstrucion of proton four-momentum possible

Roman Pots operation during RHIC run 2015

Zero-Degree Calorimeter coincidence rate vs. time:

Approximate Roman Pot distance from the beam vs. time:



- routine operation of Roman Pot system throughout whole RHIC run 2015 at the distance of approximately $8\sigma_y^{beam}$ from the beamline

Central Diffraction trigger and events selection

Trigger definition:

1. At least 2 hits in Time-of-Flight detector (to ensure presence of charged tracks in TPC)
2. Signal in trigger counters in at least 1 Roman Pot at both STAR sides (detecting diffractive protons)
3. Veto on signal in small BBC tiles covering $3.3 < |\eta| < 5.0$ (rapidity gap)

Summary of CEP data from run 2015:

- Collected 6×10^8 CEP triggers in pp collisions with transverse and longitudinal protons polarization
- Integrated luminosity $\int\mathcal{L} \approx 18\,\mathrm{pb}^{-1}$

CEP analysis of two charged mesons - events selection:

- Exactly 2 opposite-sign tracks in TPC matched with hits in Time-of-Flight detector (to discriminate tracks originating from expected bunch crossing)
- Consistence between z-component of vertex measured in TPC and through time of protons detection in Roman Pots (to remove overlap of elastic scattering with minimum-bias events)

$$\left|z_{vx}^{\mathrm{TPC}} - z_{vx}^{\mathrm{RP}}\right| < 3\sigma$$

- Protons (consistent with $\xi = 0$) not collinear (to remove elastic events as described above)

$$\left(\vec{p}_1 + \vec{p}_2\right)_T > 60\ \mathrm{MeV/c}$$

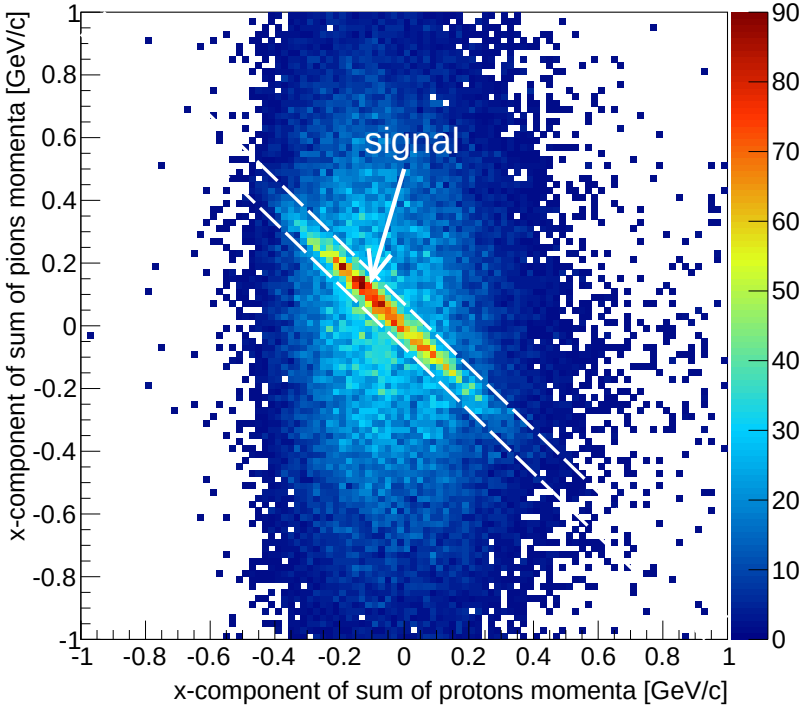
- Lack of significant signal in large BBC tiles (covering $2.1 < |\eta| < 3.3$)
- Particle ID determined by

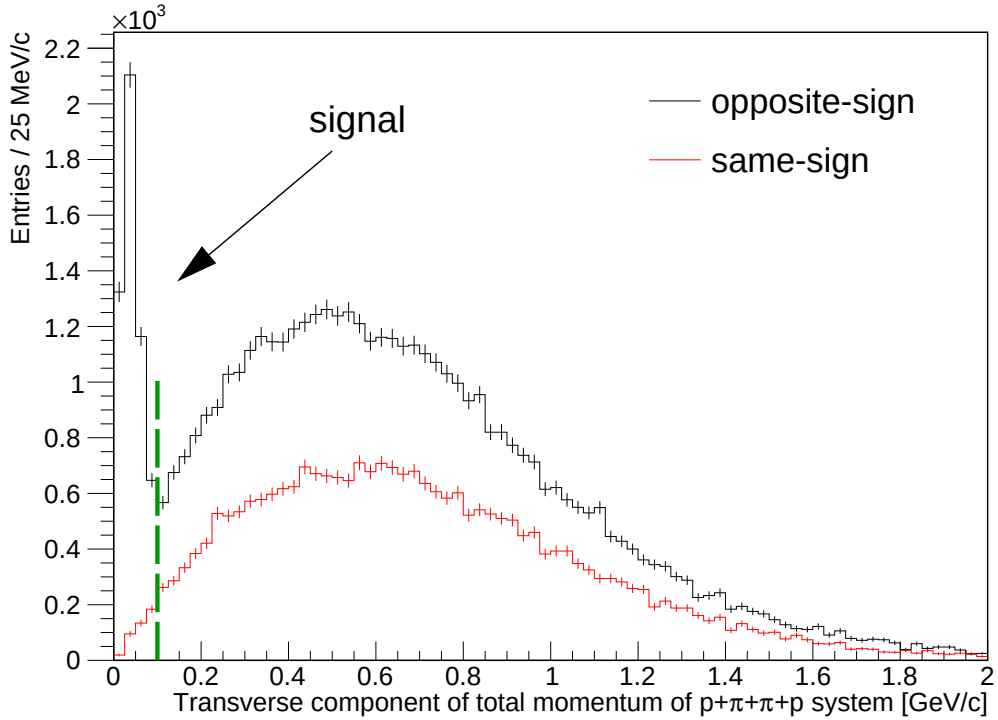
$$\left|dE/dx - dE/dx|_q\right| < 3\sigma, \qquad q = \pi, K, \ldots$$

Preliminary results from RHIC run 2015 are obtained with 2.5% of whole collected data sample → final STAR results will be based on 40 times larger statistics

Exclusivity determination

Detection and momentum reconstruction of all final state particles provides the ability to ensure exclusivity of the system via momentum balance check





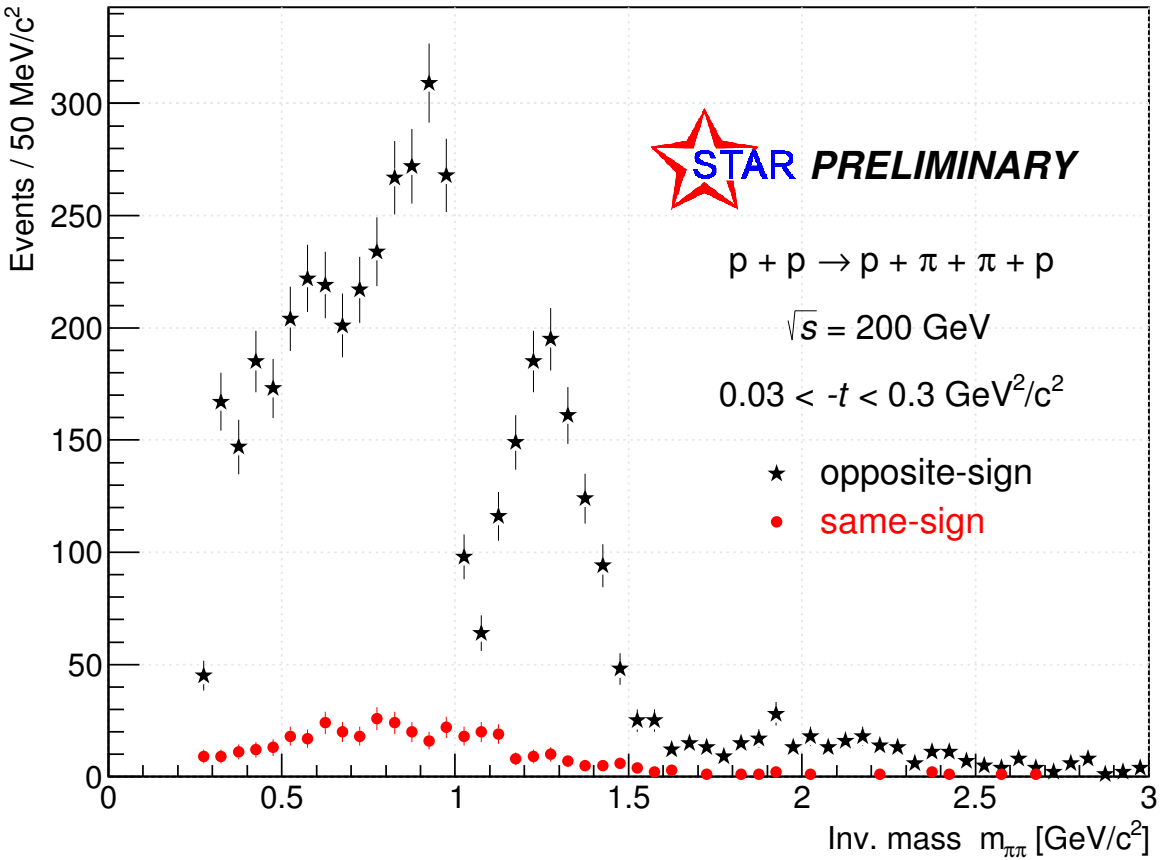
- LHS: Signal visible as strong anticorrelation of protons momentum and central tracks momentum
- RHS: Small total(missing) momentum of fully measured p + X + p system is an excellent exclusivity determinant (width of signal peak dominated by the angular beam divergence)

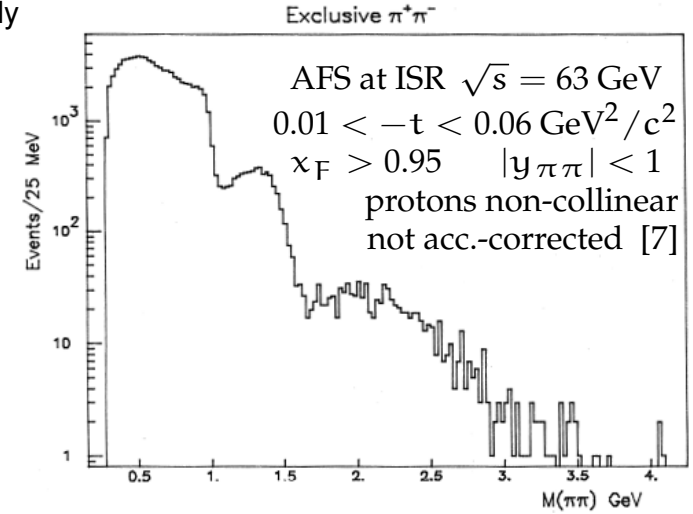
$$p_T^{miss} = \left| \left(\vec{p}_1 + \vec{p}_2 + \vec{q}_1 + \vec{q}_2 \right)_T \right|, \qquad q = \pi, K, \ldots$$

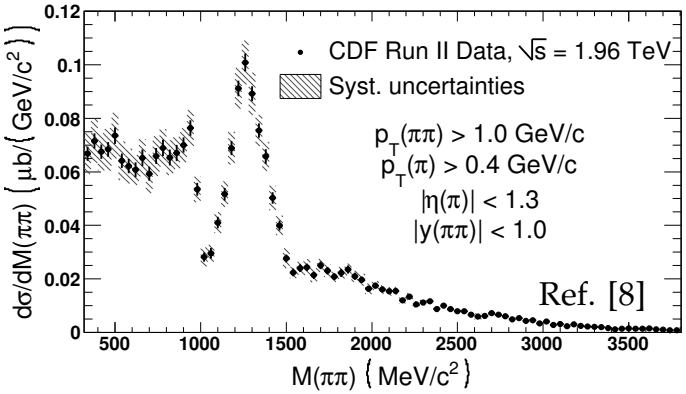
Transverse momentum balance cut: $p_T^{miss} < 0.1\,\mathrm{GeV}/c$

Mass spectrum of exclusive $\pi^+\pi^-$

Invariant mass of $\pi\pi$, $p_T^{miss} < 0.1$ GeV/c, not acceptance-corrected, statistical errors only

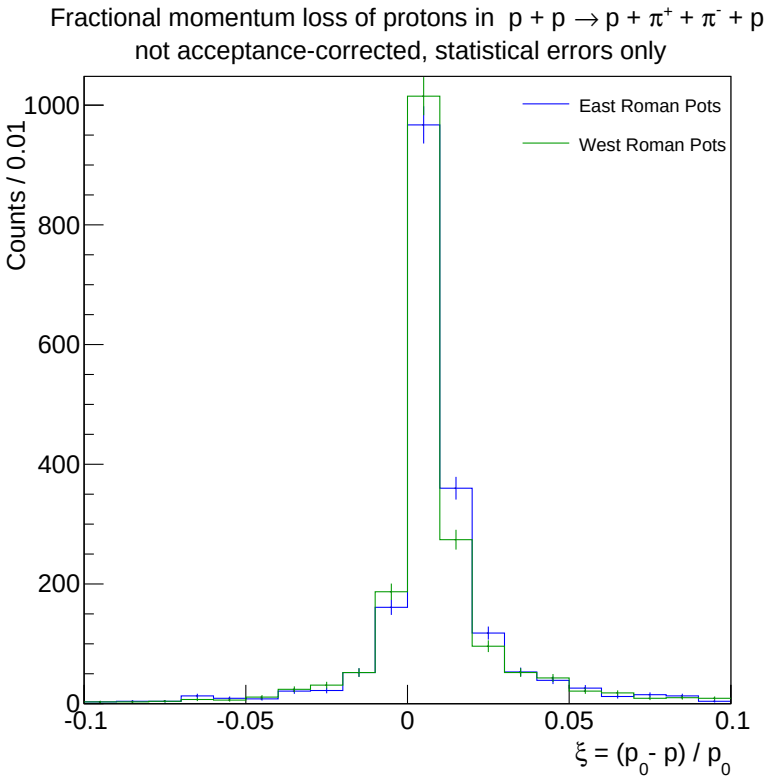


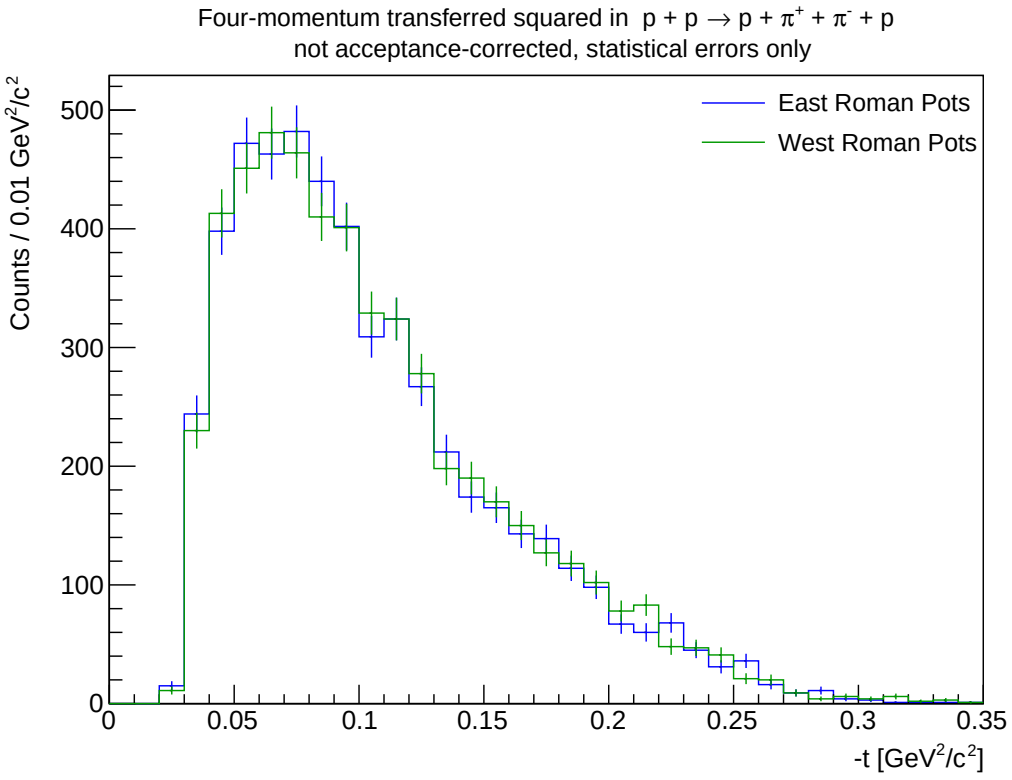




- Features of two-pion mass spectrum:
  - broad structure extending from $\pi^+\pi^-$ threshold to approximately 1 GeV/c^2
  - sharp drop around 1 GeV/c^2 (at K^+K^- threshold $\approx$ $f_0(980)$)
  - resonance-like structure between 1-1.5 GeV/c^2
- Similar spectrum found by AFS (pp) and CDF ($p\bar{p}$, no proton tagging $\rightarrow$ rapidity gap method)
- Expect $\sim 2\times10^5$ exclusive $\pi^+\pi^-$ events at full statistics $\rightarrow$ measurement of cross-section and Partial Waves Analysis

Exclusive $\pi^+\pi^-$ production - proton kinematics





- Majority of protons in exclusive $\pi^+\pi^-$ production have very low momentum loss $\xi \lesssim 0.05$
- Acceptance in $-t \sim [0.03,\ 0.3]\ \mathrm{GeV}^2/c^2$
- Measurements possible with tagged protons:
  - $d\sigma/dt$ (diffractive slope, ...)
  - $d^2\sigma/d\xi_1 d\xi_2$
  - angular correlations
  - ...

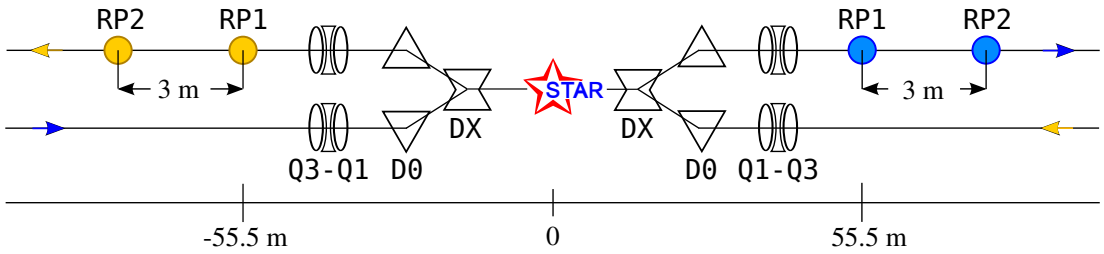
Results on exclusive $\pi^+\pi^-$ production from Roman Pot Phase I

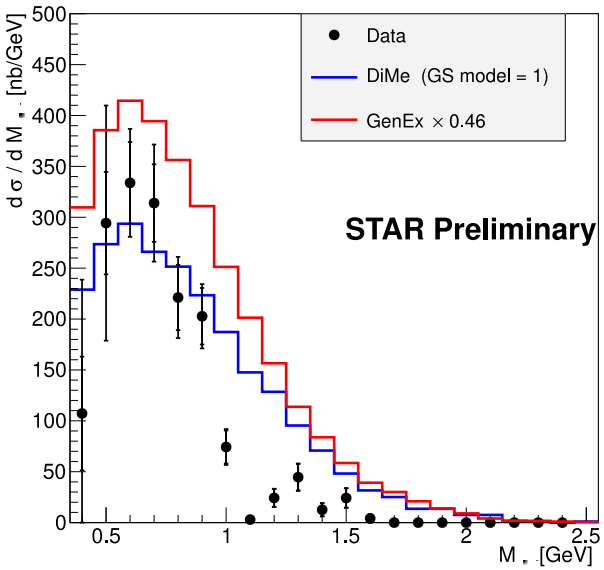
Kinematic coverage:

$$0.005 < -t < 0.03\ \mathrm{GeV}^2/c^2$$

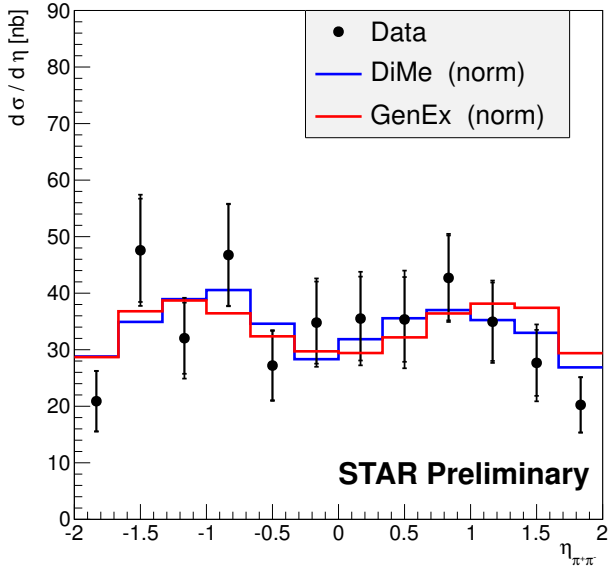
$$0 < \phi < 2\pi \quad |\eta_\pi| < 1 \quad |\eta_{\pi\pi}| < 2$$

Detector layout description: [9]



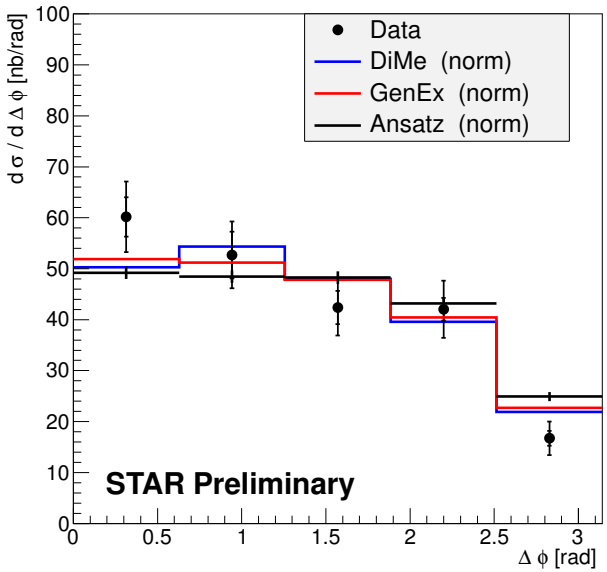


Models of non-resonant $\pi^+\pi^-$ production [2, 3] agree with STAR data up to $\approx 1\ \mathrm{GeV}/c^2$



Preliminary cross section in given kinematic range at $\sqrt{s} = 200$ GeV

$\sigma^{\pi\pi}_{\mathrm{CEP}} = 133 \pm 8(\mathrm{stat}) \pm 12(\mathrm{sys})$ nb

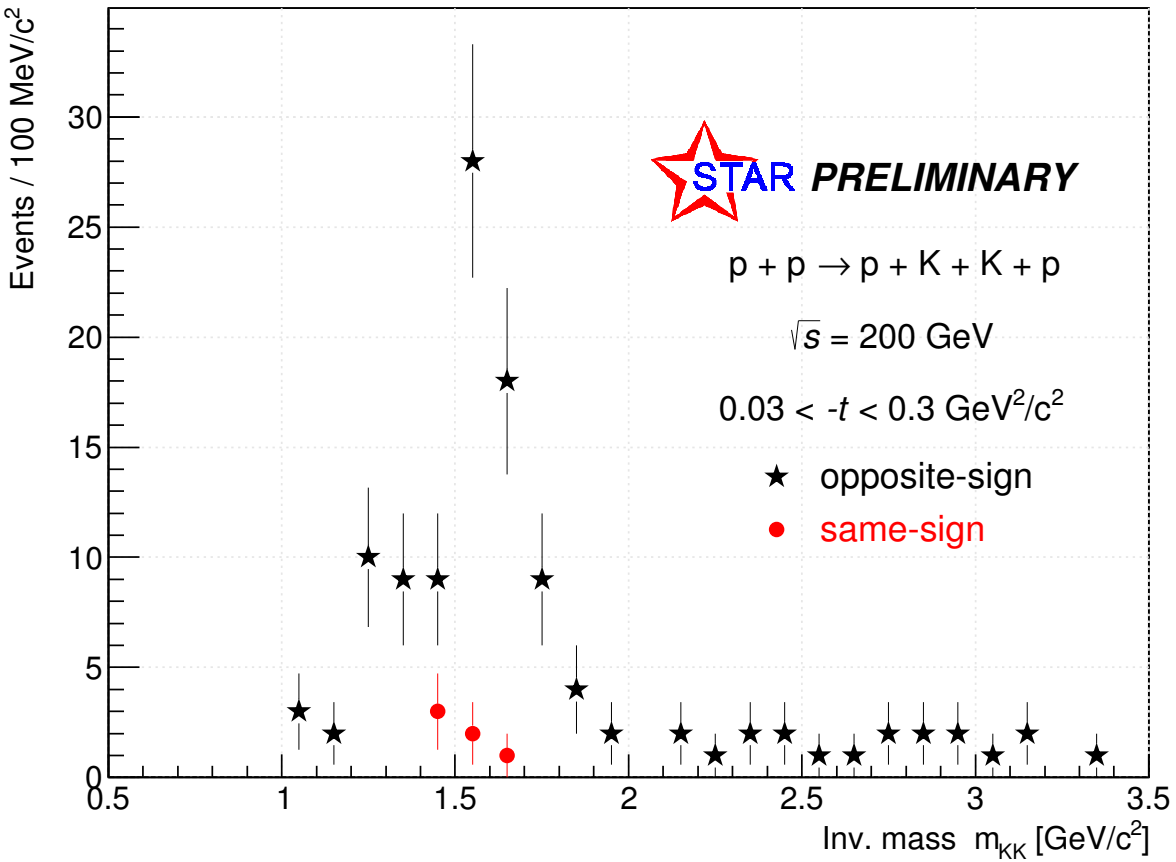


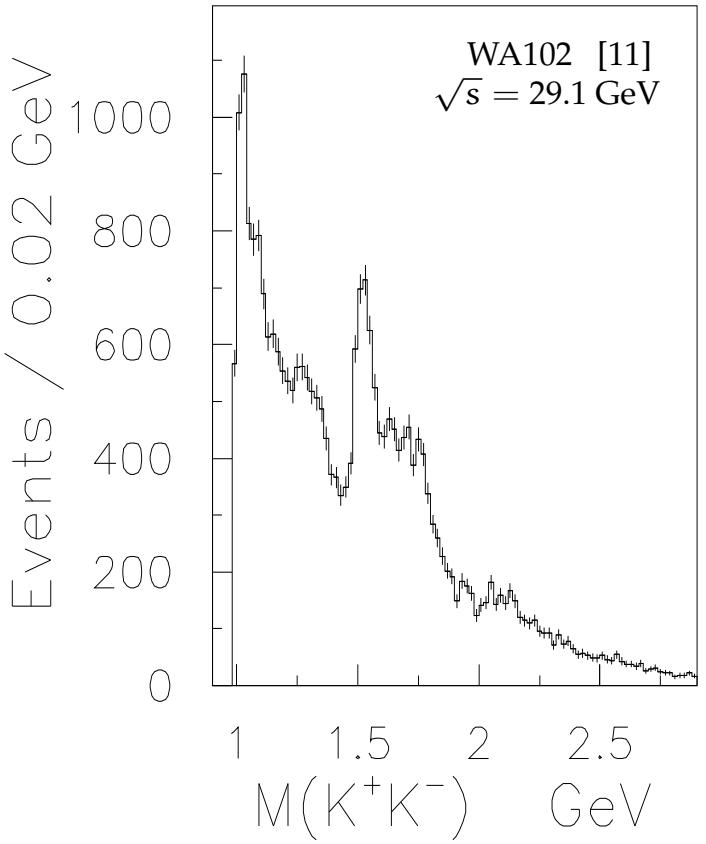
No significant (unexpected) correlation between scattered protons has been found

Details about the results can be found in [10]

Mass spectrum of exclusive K^+K^-

Invariant mass of KK, $p_T^{miss} < 0.1$ GeV/c, not acceptance-corrected, statistical errors only





- Features of two-kaon mass spectrum:
  - prominent peak around 1.5-1.6 GeV/c^2
  - some enhancement at $f_2(1270)/f_0(1370)$ region
- In spectrum measured by WA102 (fixed target) there is significant contribution from $f_0(980)$ not seen by STAR (most probably an effect of limited acceptance at low masses (low kaon p_T))
- Expect $\sim 10^4$ exclusive K^+K^- events at full statistics $\rightarrow$ measurement of cross-section and Partial Waves Analysis

Summary

- STAR experiment at RHIC has suitable conditions to study diffractive physics, which has been demonstrated i.a. by CEP measurement with Roman Pot Phase I.
- In 2015 STAR collected large sample of high quality CEP-dedicated data, whose 2.5% sub-sample was used to prepare presented preliminary mass distributions of exlusively produced pion and kaon pairs.
- Expected number of reconstructed exclusive events allows precise partial wave decomposition in $\pi^+\pi^-$ and K^+K^- channels, also other channels e.g. $\pi^+\pi^-\pi^+\pi^-$ are studied.
- Many aspects of DIPE are not well established thus new measurements are required in this field.
- In 2017 proton-proton data at $\sqrt{s} = 510$ GeV will be collected (larger kinematic region) hence comparison of results from two energy regimes will be possible.

References

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