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

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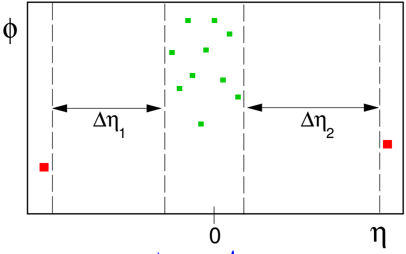
Central Exclusive Production (CEP)

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



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

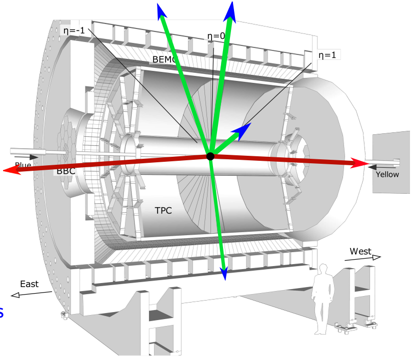
$$M_X \approx \sqrt{\xi_A \xi_B s} \qquad y_X \approx \frac{1}{2} \ln \frac{\xi_A}{\xi_B} \qquad \xi \equiv \frac{p_0 - p}{p_0}$$

Production mechanisms (in general):

- Double Photon Exchange
  $\gamma + \gamma \rightarrow \gamma\gamma,\ l^+l^-,\ W^+W^-$
- photon-Pomeron/Regeon
  $\gamma + \mathbb{P}/\mathbb{R}(\rho, \omega) \rightarrow$ (pseudo)vector mesons, continuum
- $\mathbb{R}+\mathbb{R}$, $\mathbb{P}+\mathbb{R}$, $\mathbb{P}+\mathbb{P}$ (Double Pomeron Exchange, DPE)
  $\mathbb{P} + \mathbb{P} \rightarrow$ scalar/tensor mesons, continuum

$$\sigma_{\mathbb{RR}} \sim s^{-1}$$
$$\sigma_{\mathbb{PR}} \sim s^{-0.5} \quad \rightarrow$$
$$\sigma_{\mathbb{PP}} \sim \text{const}$$

At RHIC energies Double Pomeron Exchange expected to be dominant



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

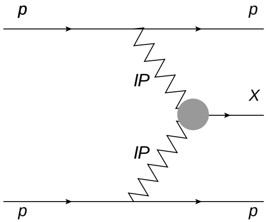
Double IPomeron Exchange (DIPE)

Non perturbative QCD (Regge picture):

1. Each proton "emits" a IPomeron
2. Two IPomerons fuse and produce neutral central state X

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

If IP carries vacuum quantum numbers: $J^{PC} = 0^{++}, 2^{++}, ...$

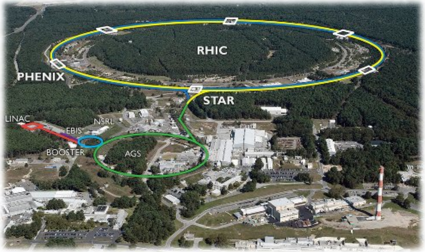


Physics motivation for DIPE study:

- Modeling of the process:
  - Precise cross-section determination (especially w.r.t. proton kinematics)
  - Size of absorptive corrections
  - Contribution of resonant and non-resonant production in DIPE
- pQCD image of IPomeron implies that DIPE is gluon-rich process → gluon bound states ("glueballs") could be preferentially produced. Most promising candidates: $f_0(1500)$ and $f_0(1710)$

Many unresolved questions pending answers

STAR detector at RHIC

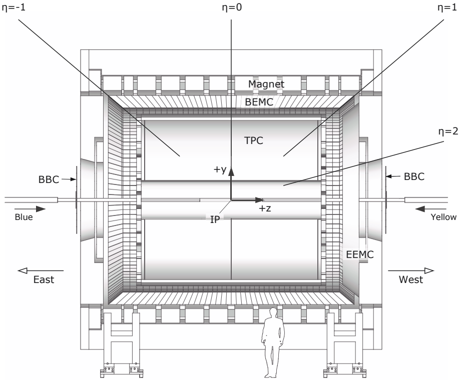


STAR has great capabilities for CEP study:

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

Relativistic Heavy Ion Collider:

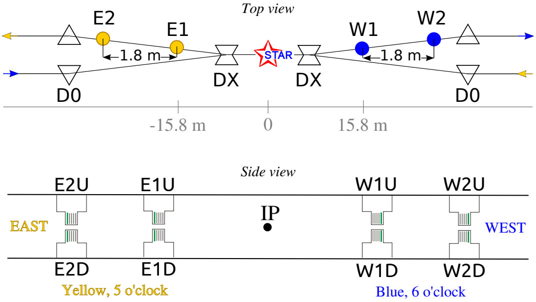
- Circumference of 3.8 km
- Unique ability to collide **polarized protons** (transversely and longitudinally)
- Collides also Cu, Au, U, Al, ^2H (deuteron), ^3He (helion) in some combinations
- CMS energy in pp up to $\sqrt{s} = 510$ GeV



Forward proton detectors

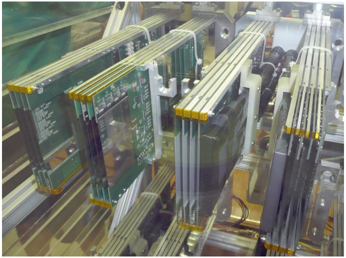
Roman Pot Phase II* (operating since 2015):

- 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**
- Routine operation at beam-detector distance of $8\sigma_{\text{beam}}$, the closest approach ~20 mm
- Approximate acceptance (at $\sqrt{s} = 200$ GeV)

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

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

- Full reconstrucion of proton four-momentum possible

Central Diffraction trigger and event 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 MIP signal in small BBC tiles covering $3.3 < |\eta| < 5.0$ (rapidity gap)

Summary of CEP data from run 2015:

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

CEP analysis of two charged mesons - event 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)

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

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

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

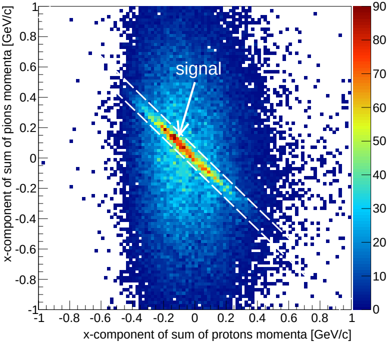
- Lack of significant signal in large BBC tiles (covering $2.1 < |\eta| < 3.3$)
- Particle ID determined by

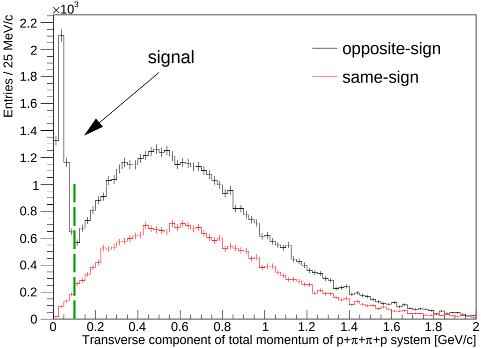
$$\left| dE/dx - dE/dx|_q \right| < 3\sigma, \qquad q = \pi, K, \ldots$$

Preliminary results from RHIC run 2015 are obtained with 2.5% of the whole collected data sample

Exclusivity determination

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





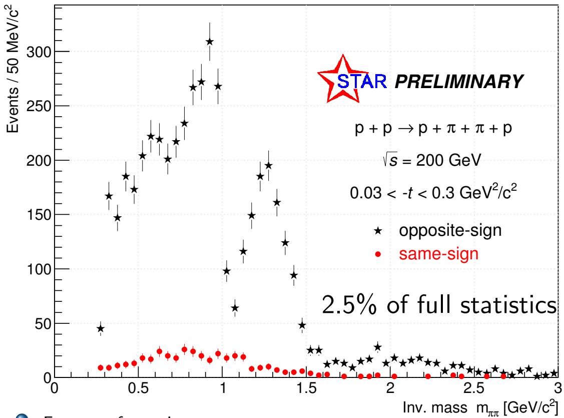
- LHS: Signal visible as strong anticorrelation of protons momentum and central tracks momentum
- RHS: Small total(missing) momentum of fully measured $p + X + p$ system is an excellent exclusivity determinant (width of signal peak dominated by the angular beam divergence)

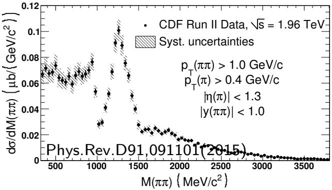
$$p_T^{\text{miss}} = \left| \left(\vec{p}_1 + \vec{p}_2 + \vec{q}_1 + \vec{q}_2 \right)_T \right|, \qquad q = \pi, K, \ldots$$

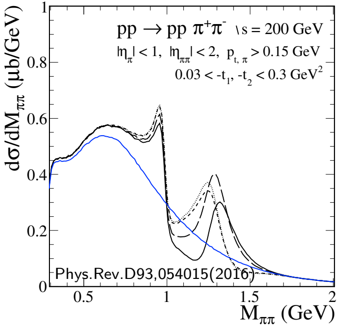
Transverse momentum balance cut: $p_T^{\text{miss}} < 0.1$ GeV$/c$

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

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

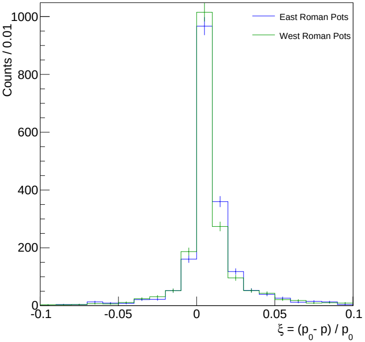


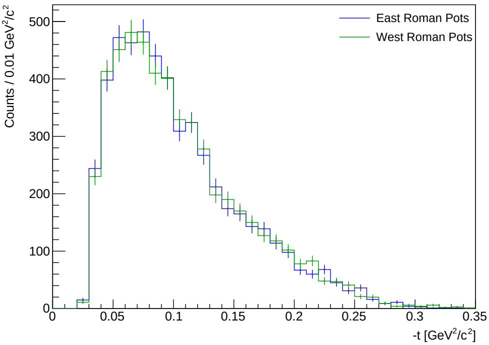




- Features of two-pion mass spectrum:
  - broad structure extending from $\pi^+\pi^-$ threshold to $\approx$1 GeV$/c^2$
  - sharp drop around 1 GeV$/c^2$ (at K^+K^- threshold $\approx$ $f_0(980)$)
  - resonance-like structure between 1-1.5 GeV$/c^2$
- Similar spectrum found e.g. by CDF ($p\bar{p}$, no proton tagging $\rightarrow$ rapidity gap method)
- Theoretical models predict observed shape (blue - continuum, black - coherent sum of continuum, $f_0(980)$ and $f_2(1270)$)
- Expect $\sim 1.5\times10^5$ exclusive $\pi^+\pi^-$ events at full statistics $\rightarrow$ measurement of cross-section and Partial Waves Analysis

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





- Acceptance in $-t \sim [0.03,\ 0.3]$ GeV$^2/c^2$
- Measurements capable only with detected forward protons:
  - $d\sigma/dt$ (diffractive slope), $d^2\sigma/dt_1dt_2$
  - $d\sigma/d\xi$
  - $d\sigma/d\Delta\phi_{pp}$, $d\sigma/d\Delta p_{\mathrm{T}}^{\mathbf{PP}}$
  - $d^2\sigma/d\cos\theta d\phi \quad \rightarrow$ Partial Wave Analysis

$$\Delta\phi_{pp} = \measuredangle\{(p_x'^{\,1}, p_y'^{\,1}), (p_x'^{\,2}, p_y'^{\,2})\}$$

$$\Delta p_{\mathrm{T}}^{\mathbf{PP}} = \left(\vec{\mathbb{P}}^W - \vec{\mathbb{P}}^E\right)_{\mathrm{T}}$$

Phys.Lett. B397 (1997) 333-338

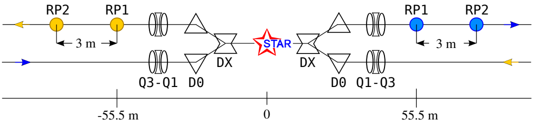
Wealth of possibilities having forward system of detectors

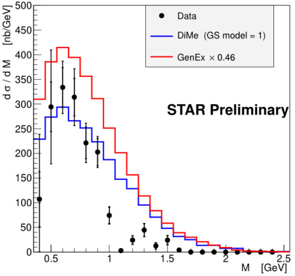
Results on exclusive $\pi^+\pi^-$ production from Roman Pot Phase I

Kinematic coverage:

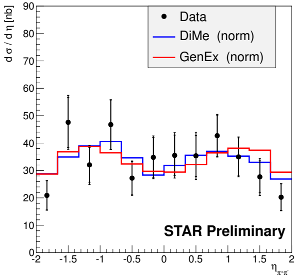
$$0.005 < -t < 0.03\ \text{GeV}^2/c^2$$

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



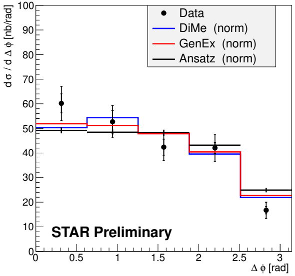


Models of non-resonant $\pi^+\pi^-$ production agree with STAR data up to $\approx 1\ \text{GeV}/c^2$



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

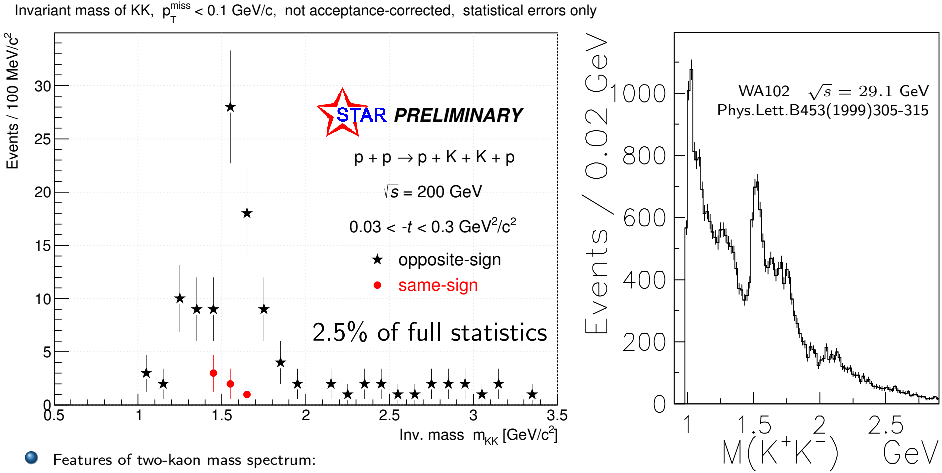
$\sigma^{\pi\pi}_{\text{CEP}} = 133 \pm 8(\text{stat}) \pm 12(\text{sys})$ nb



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

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

Mass spectrum of exclusive K^+K^-



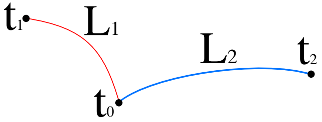
- Features of two-kaon mass spectrum:
  - prominent peak around 1.5-1.6 GeV$/c^2$
  - some enhancement at $f_2(1270)/f_0(1370)$ region
- Difference with the spectrum measured by WA102 (fixed target) arises mostly from lack of acceptance correction applied to the STAR spectrum
- $\sim 2{\times}10^3$ exclusive K^+K^- events at full statistics → measurement of cross-section and Partial Waves Analysis

Status and plans

- Analysis of exclusive $\pi^+\pi^-$, K^+K^-, $p\bar{p}$ and $\pi^+\pi^-\pi^+\pi^-$ production has reached a mature stage:
  - some analysis cuts have been removed/addded/tuned which led to satisfyingly low backround level (a few %),
  - particle identification method has been extended to enhance purity (next slide),
  - efficiency corrections are being determined,
  - study of systematic uncertainties is being performed.

- We plan to publish results of CEP analysis in steps:
  - invariant mass spectra (also with respect to forward proton observables),
  - partial wave decomposition in $\pi^+\pi^-$ (K^+K^-),
  - ...

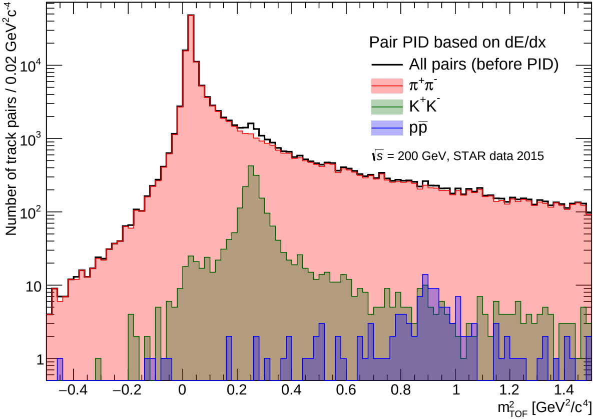
Improved Particle identification - $dE/dx + m^2$



$$\begin{cases} t_1 - t_0 = L_1\sqrt{1 + \frac{m_1^2}{p_1^2}} \\ t_2 - t_0 = L_2\sqrt{1 + \frac{m_2^2}{p_2^2}} \end{cases}$$

$$t_1 - t_2 = L_1\sqrt{1 + \frac{m_1^2}{p_1^2}} - L_2\sqrt{1 + \frac{m_2^2}{p_2^2}}$$

$m_1 = m_2 = m \quad \rightarrow \quad m^2$ from quadratic eq.



Process of determination of the type of particles in a pair relies on two measurements:

- dE/dx of each TPC track: it is checked whether it is consistent with dE/dx of a particle of given ID carrying the track momentum
- m^2: assuming that two particles have the same mass, based on measured times of hit in TOF modules and track lengths and momenta, it is checked whether resulting squared mass is consistent with the mass of partile of given ID

Use of two inputs in particle identification allows efficient selection of exclusive event samples of high purity.

Summary

- STAR experiment at RHIC has suitable conditions to study diffractive physics, which has been demonstrated i.e. 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.

- Number of reconstructed exclusive events with full available statistics will allow precise partial wave decomposition in $\pi^+\pi^-$ and K^+K^- channels. Also other channels as $p\bar{p}$ and $\pi^+\pi^-\pi^+\pi^-$ 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.