Central Exclusive Production with forward proton measurement in ATLAS

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Abstract

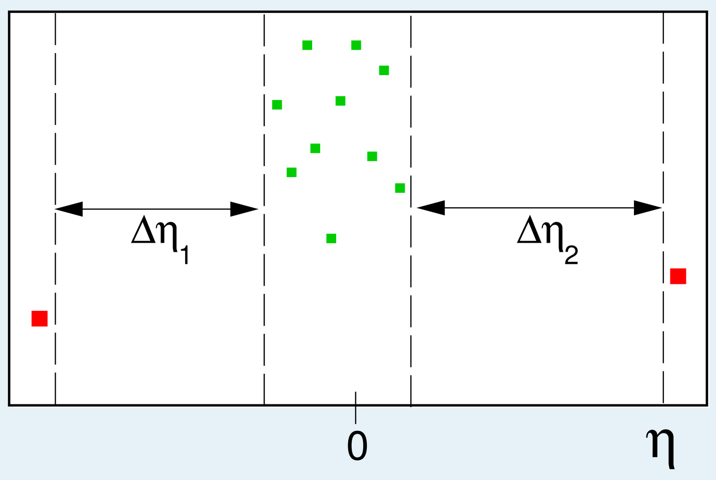
The ATLAS experiment [1] at the LHC shows continuously growing interest in studies of the soft QCD processes e.g. involving intact protons. Capability of measurement of protons scattered in the forward direction is provided by the ALFA sub-detector. It consists of 8 scintillating fiber detectors housed inside Roman Pot vessels, installed approximately 240 meters from the interaction region which enables detection of beam- or near-beam-momentum protons scattered at very small angles with respect to the beamline.

In October 2015, during special LHC runs with $\beta^* = 90$ m and low beams intensity, ATLAS collected nearly 800 nb^{-1} of data from proton-proton collisions at $\sqrt{s} = 13$ TeV dedicated for studies of diffractive Central Exclusive Production (CEP). Mid-rapidity tracks with $|\eta| < 2.5$ and $p_T > 100$ MeV/c were measured in the Inner Detector, whereas forward protons with 0.17 GeV/$c < |p_y| < 0.5$ GeV/c were measured in ALFA on both sides of ATLAS.

We would like to present work-in-progress results of study of the diffractive Central Exclusive Production of low mass systems based on aforementioned dataset. These systems are dominantly produced via the Double IPomeron Exchange (DIPE) [2] mechanism which is recognized as the gluon-rich environment suitable for production of glueballs [3] or hybrid mesons.

Central Exclusive Production - introduction and motivation for measurement

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

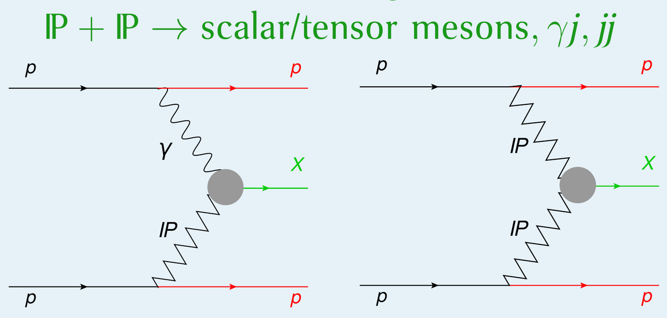


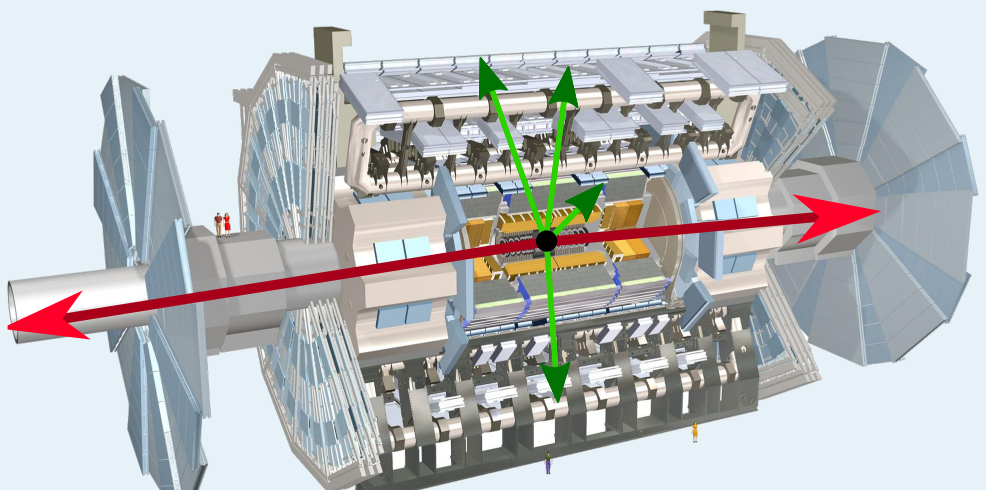
- colliding particles A and B emerge intact (or excited)
- central state X is fully measured
- state X is well separated from A and B (rapidity gaps become larger as $\sqrt{s}$ grows)

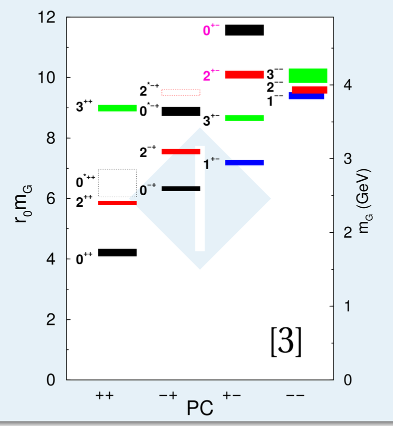
$$M_X \approx \sqrt{\xi_A \xi_B s} \qquad y_X \approx \frac{1}{2} \ln \frac{\xi_A}{\xi_B} \qquad \xi \equiv \frac{p_0 - p}{p_0}$$

Production mechanisms at LHC:

- photon-induced (Double Photon Exchange)
  $\gamma + \gamma \rightarrow \gamma\gamma,\ l^+l^-,\ W^+W^-$
- photoproduction
  $\gamma + \mathbb{P}/\mathbb{R}(\rho, \omega) \rightarrow$ (pseudo)vector mesons
- Double IPomeron Exchange
  $\mathbb{P} + \mathbb{P} \rightarrow$ scalar/tensor mesons, γj, jj







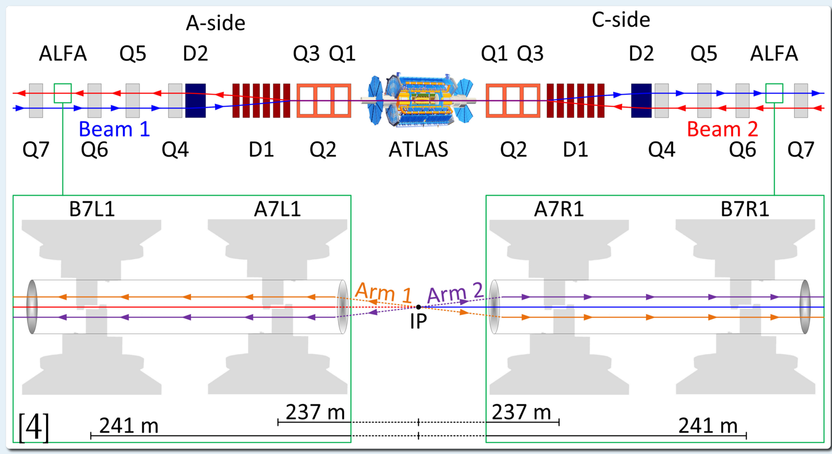
Physics motivation for diffractive CEP mesurement ($\gamma\mathbb{P}$, $\mathbb{P}\mathbb{P}$):

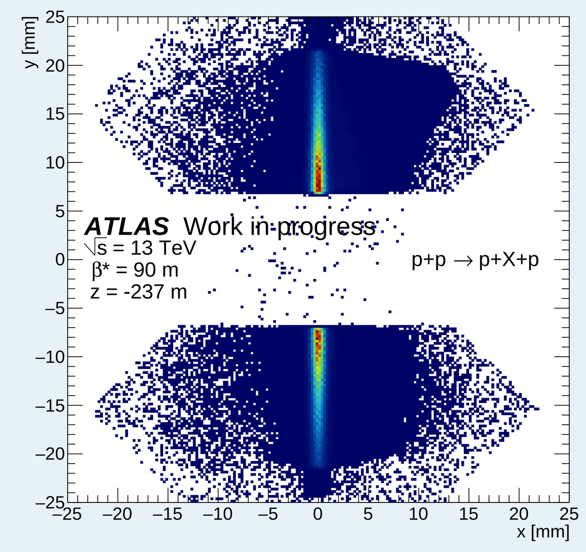
- IPomeron structure - diffractive Parton Density Function (dPDF)
- Double IPomeron Exchange cross-section (differential w.r.t. proton kinematics)
- Size of absorptive corrections (gap survival probability S^2)
- Understanding spectrum of IPIP fusion products, search for scalar glueball

Forward proton measurement in ATLAS

ATLAS has great capabilities for CEP study:

- High-resolution tracking of charged particles in the Inner Detector ($|\eta| < 2.5$, $0 < \phi < 2\pi$)
- Particle identification through dE/dx in the silicon of Inner Detector
- Forward rapidity covered by Minimum Bias Trigger Scintillator (MBTS) to ensure rapidity gap and veto pile-up events (only for low-μ runs)
- **Scintillating Fiber Detectors in ALFA Roman Pots for measurement of forward protons**





Momentum of intact proton detected in ALFA is reconstructed using effective tranport matrix ($\mathbb{T}$) method - an assumption is made that proton has momentum of the beam, which is valid for CEP of low mass states:

$$\begin{bmatrix} x^{RP} \\ \theta_x^{RP} \\ y^{RP} \\ \theta_y^{RP} \\ \xi \end{bmatrix} = \mathbb{T} \begin{bmatrix} x^{IP} \\ \theta_x^{IP} \\ y^{IP} \\ \theta_y^{IP} \\ \xi \end{bmatrix} \quad \xrightarrow{\xi = 0} \quad \begin{bmatrix} x^{IP} \\ \theta_x^{IP} \\ y^{IP} \\ \theta_y^{IP} \end{bmatrix} = \mathbb{T}^{-1} \begin{bmatrix} x^{RP} \\ \theta_x^{RP} \\ y^{RP} \\ \theta_y^{RP} \end{bmatrix}$$

$$p_x = p_0 \cdot \theta_x^{IP} \qquad p_y = p_0 \cdot \theta_y^{IP} \qquad p_z = \sqrt{p_0^2 - p_x^2 - p_y^2}$$

Benefits of detection and reconstruction of forward protons:

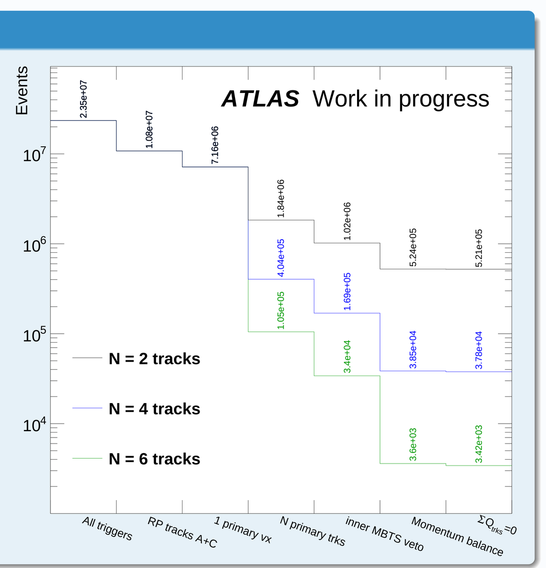
- Cleaner triggers with proton tag requirement
- Rejection of non-exclusive background via momentum balance constraint

$$\vec{p}^A + \vec{p}^C = -\vec{p}_X = -\sum_i \vec{p}_i$$

- Full information about kinematics of interaction:
  - measurement of cross-sections as a function of forward proton observables: t, ξ, etc.
  - enabled spectroscopy and investigation of production mechanism of the central state

CEP event selection

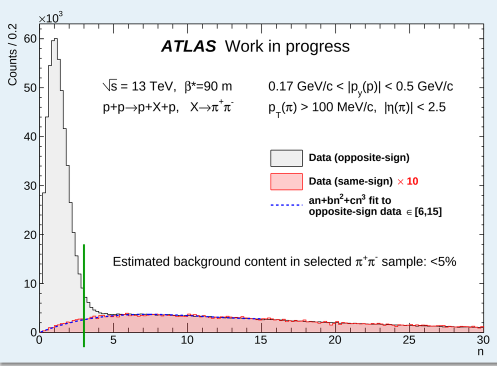
- Trigger: at least 1 track candidate in Inner Detector, activity in ALFA on both sides of ATLAS, at most 1 segment of inner MBTS with signal
- Proton tracks reconstructed in both ALFA stations on A and C side of ATLAS (exactly 1 track per RP, each formed of clusters in 6 (out of 10 maximally possible) scintillating fiber layers in both transverse spatial coordinates)
- Exactly 1 primary vertex reconstructed in Inner Detector
- Exactly 2 (or 4, 6, etc.) primary tracks forming aforementioned vertex of total charge equal 0 (all: $p_T > 100$ MeV, $|\eta| < 2.5$, passing quality requirements)
- Veto on any signal in inner MBTS (lack of charged particles in $2.9 < |\eta| < 3.8$)
- Total momentum of $p + X + p$ balanced within 3σ ($n_{cut} = 3$)



Momentum balance and non-exclusive background estimation

The cut on total transverse momentum of all measured particles (R.H.S.) efficiently separates the signal from non-exclusive background.

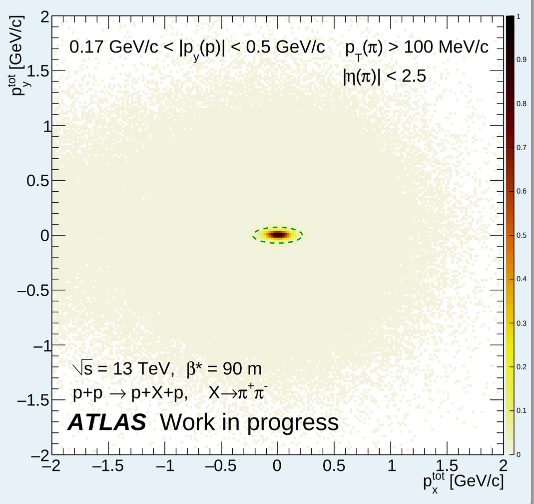
$$\left(\frac{p_x^{tot}}{\sigma_{p_x^{tot}}}\right)^2 + \left(\frac{p_y^{tot}}{\sigma_{p_y^{tot}}}\right)^2 < n_{cut}^2$$



Constrained polynomial fit ($f(0) = 0$) to distribution of variable n:

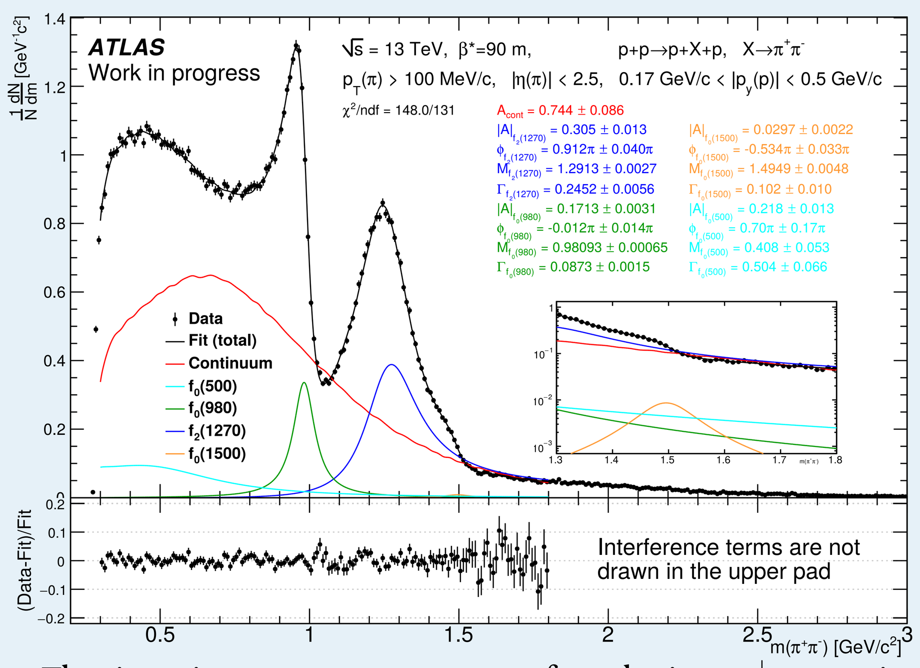
$$n = \sqrt{\left(p_x^{tot}/\sigma_{p_x^{tot}}\right)^2 + \left(p_y^{tot}/\sigma_{p_y^{tot}}\right)^2}$$

in the signal-free region (dashed blue line in L.H.S. figure) gives access to the background yield under the signal peak (also differentially).



Results

NOTE: All distributions are corrected for Inner Detector inefficiency but not for ALFA inefficiency. The latter is expected to have weak/no dependence on physics quantities hence it should not change the shape of distributions.



- The invariant mass spectrum of exclusive $\pi^+\pi^-$ pairs can be successfully described by coherent sum of non-resonant continuum and four resonances
- Study of invariant mass of $\pi^+\pi^-$ system as a function of azimuthal separation between forward scattered protons $\Delta\phi_{pp}$ or transverse difference between exchanged IPomerons momenta Δp_T [6] (R.H.S.) reveals dynamically changing contributions from continuum and resonances
- Partial Wave Analysis will be performed to definitely establish contributions from specific J^{PC} states

Invariant mass distribution of exclusive $\pi^+\pi^-$ pairs with subtracted non-exclusive background (L.H.S.) was fitted with the following function in the range $m \in [0.4, 1.8]$ GeV/c^2:

$$\underbrace{\frac{1}{N}\frac{dN}{dm}}_{model} = \left| A_{cont} \times \sqrt{\frac{1}{N_{cont}}\frac{dN_{cont}}{dm}} + \sum_k A_k \times \mathrm{BW}\left(m; M_k, \Gamma_k\right) \right|^2$$

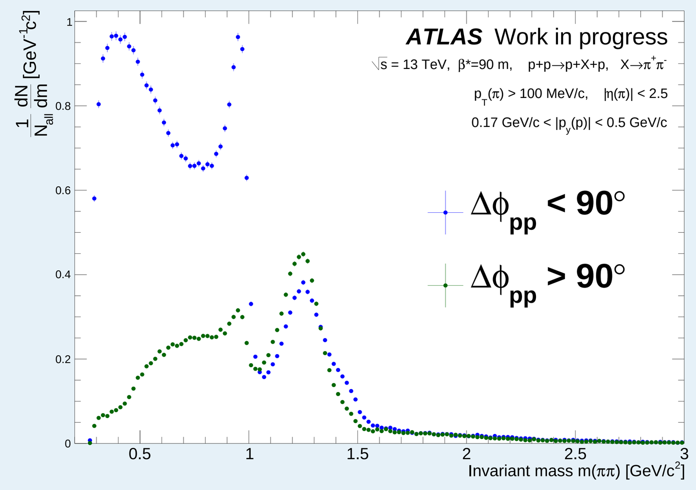
where

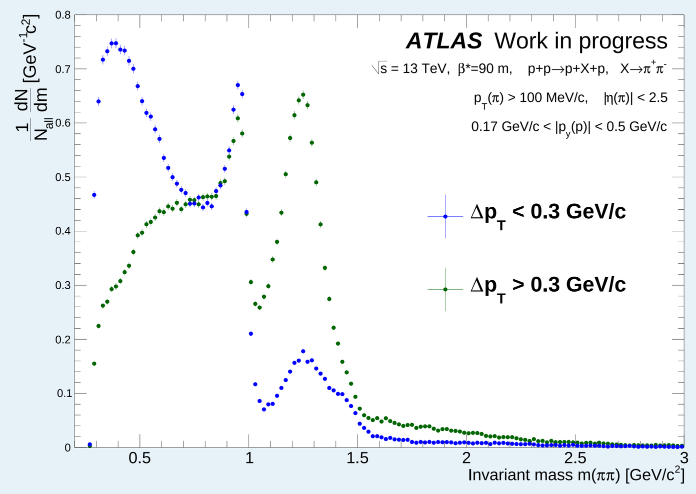
$$k \in \{f_0(500),\ f_0(980),\ f_2(1270),\ f_0(1500)\}, \qquad A_{cont} \in \mathbb{R},\ A_k \in \mathbb{C} \ \rightarrow\ A_k = |A_k| e^{i\phi_k}.$$

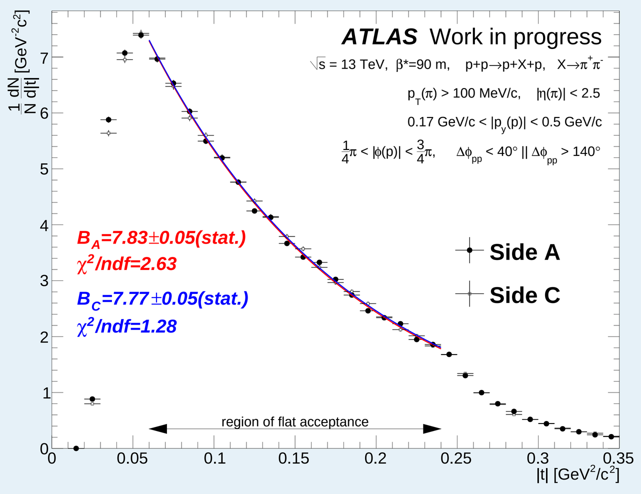
All parameters were free in the fit. The following form of $\mathrm{BW}(m; M, \Gamma_0)$ was used to describe resonances (relativistic Breit-Wigner with mass-dependent width):

$$\mathrm{BW}(m; M, \Gamma_0) = \frac{\sqrt{m M \Gamma(m)}}{m^2 - M^2 + i M \Gamma(m)}, \qquad \Gamma(m) = \Gamma_0 \frac{M}{m}\left(\frac{m^2 - n^2 m_\pi^2}{M^2 - n^2 m_\pi^2}\right)^{\frac{2J+1}{2}}.$$

Shape of continuum was taken from the Lebiedowicz-Szczurek model [5] ($\Lambda_{off} = 1$ GeV).

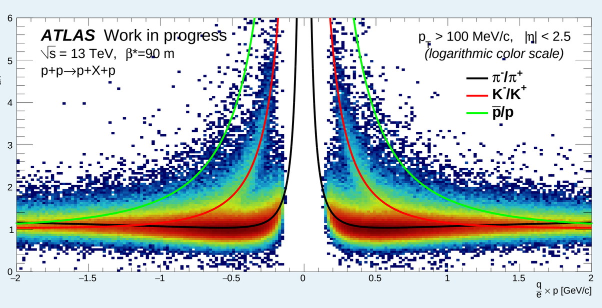


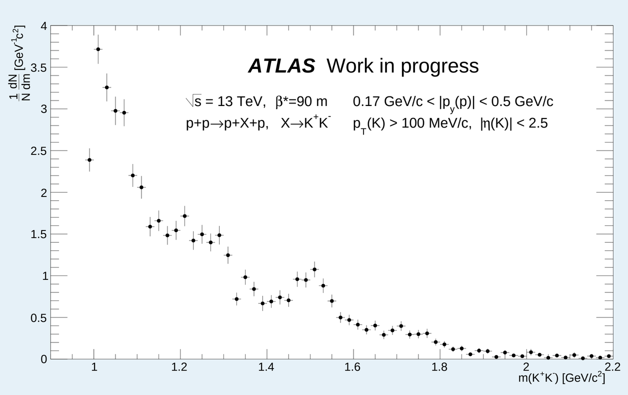


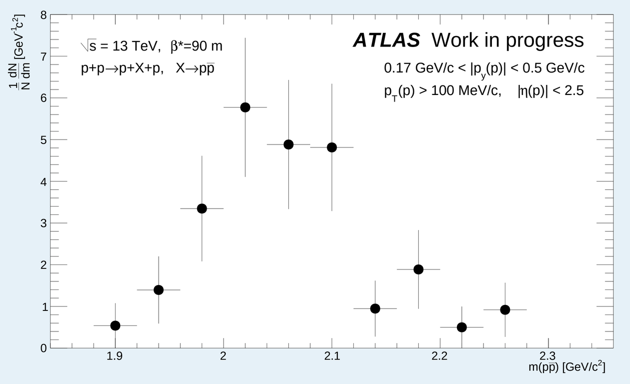


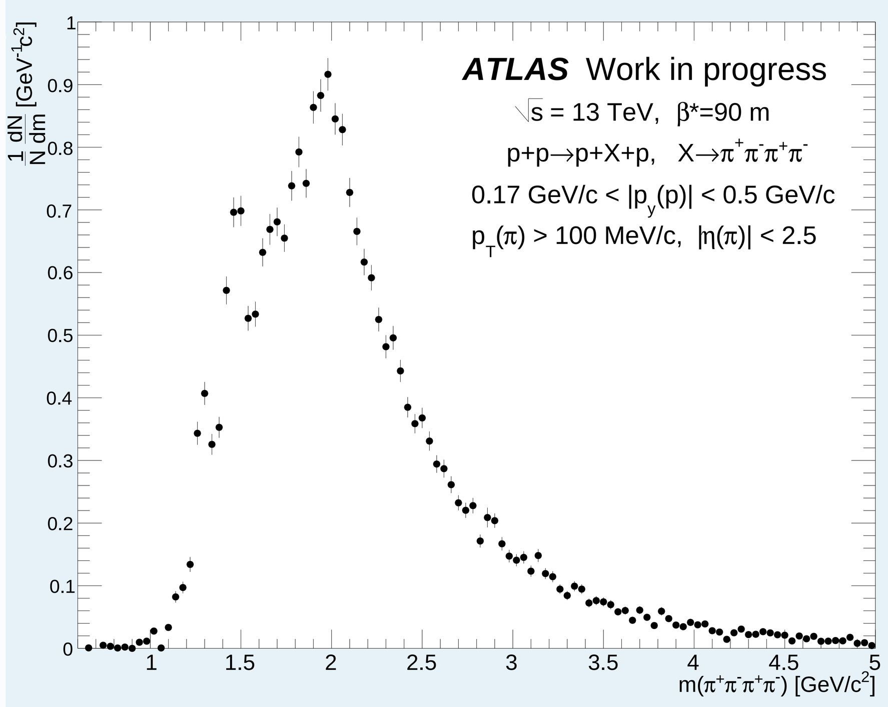
Exponents of the form $\mathcal{A} \times e^{-B|t|}$ were fitted to background-subtracted $|t|$ distributions in range 0.06 GeV$/c^2 < |t| < 0.24$ GeV$/c^2$. As demonstrated, the slope parameter B can be determined with high statistical precision. Values of B obtained from Mandelstam $|t|$ distributions on two sides of ATLAS agree within statistical uncertainties.

Measurement of particle energy loss in the silicon layers of Inner Detector (dE/dx, see R.H.S.) enabled identification of exclusively produced $\pi^+\pi^-$, K^+K^- and $p\bar{p}$ pairs (below) using cut-based and Neural Network approaches.

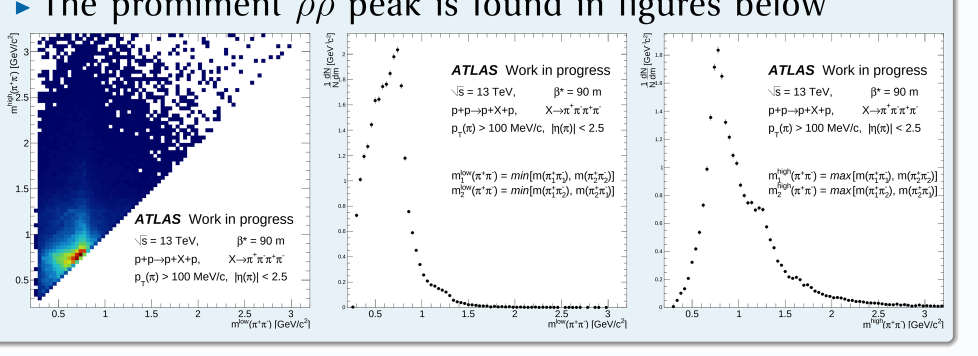








- In the inv. mass spectrum of exclusive $\pi^+\pi^-\pi^+\pi^-$ (L.H.S.) many structures are found below 2 GeV/c^2
- The inv. mass of neutral combinations of pions was studied to reveal dominant production mechanism (possible are: direct production, $R \rightarrow 4\pi$ or $R_1 R_2 \rightarrow [2\pi][2\pi]$). Due to ambiguous choice of two $\pi^+\pi^-$ pairs out of $\pi^+\pi^-\pi^+\pi^-$ bottom plots were filled twice per event
- The promiment $\rho\rho$ peak is found in figures below



Summary

- CEP is particularly interesting class of processes which provides insight to unexplored soft QCD phenomena, where perturbation theory does not apply
- High-β^* data collected by ATLAS in October 2015 allows detailed studies of CEP via DIPE and photoproduction
  - differential cross-sections in $m(X)$, $y(X)$, $\Delta\phi_{pp}$, $|t|$, $\cos\theta^{GJ}$, ..., for $X = \pi^+\pi^-, K^+K^-, p\bar{p}, 4\pi, \ldots$
  - cross-section for production of resonances
  - rapidity gap survival probability
  - diffractive slope extraction

References

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