Transverse single spin asymmetries for very forward neutrons in ultra-peripheral p-A collisions

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1. Introduction and Physics motivation
   • Large $A_N$ for forward neutrons discovered in pAu collisions
   • Can electromagnetic effects explain positive and large $A_N$?
2. Ultra-peripheral collisions (UPCs)
   • Do $\gamma^*p$ interactions have large $A_N$?
   • MC simulations of $\gamma^*p$ interactions
3. MC simulation results
   • UPCs vs. hadronic interactions
   • MC simulations vs. the PHENIX measurements
4. Summary and Future prospects
1. Introduction and Physics motivations

**Single spin asymmetry \( A_N \) for very forward neutrons in \( pp \)**

\[ A_N \text{ in } pp \text{ at the RHIC energies are well explained by an one-}\pi/\text{Reggeon exchange model with the interference between } \pi \text{ (spin flip) and } a_1 \text{ (nonflip).} \]

Kopeliovich et al.
PRD. 84.114012 (2011)

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**Single spin asymmetry \( A_N \) for very forward neutrons in \( pA \)**

Can \( A_N \) in \( pA \) be successfully explained by the \( \pi \)-\( a_1 \) interference? or by other mechanisms?
→ understand forward neutron production in \( pA \)
1.1 Transversely polarized pA collisions

Run15 pAl/pAu collisions at RHIC
Dedicated run for A_N measurements
Average pol. ~ 0.5-0.6
(syst. uncertainty ~ 3%)

- ZDC (Zero Degree Calorimeter): hadron calorimeter with a 10 x 10 cm² area (ΔE/E ~ 20–30 %)
- SMD (Shower Max Detector): X-Y plastic scintillator hodoscope (Δx, Δy ~ 1 cm)
- Charge veto counter: plastic scintillator pad at front

Nucleus 100 GeV
Proton 100 GeV
1.2 *Inclusive* $A_N$ for forward neutrons

**PHENIX**, arXiv:1703.10941

- **Prediction before the measurement:**
  - Weak $A$-dependence
  - (Reggeon exc. and/or nuclear effects)

Surprisingly strong $A$-dependence

→ What mechanisms do produce such strong $A$-dependence?

→ *Hint: how does $A_N$ behave with the other triggers?*
1.3 **BBC correlated $A_N$ for forward neutrons**

PHENIX, arXiv:1703.10941

**PHENIX**

$p^+ + A \rightarrow n + X$ at $\sqrt{s_{NN}} = 200$ GeV

$0.3 < \theta < 2.2$ mrad

$x_F > 0.5$

3% scale uncertainty not shown

**Particle veto at lower rapidities:** **BBC-VETO**

→ much stronger A-dependence

**BBC**

$(3.0 < \eta < 3.9)$

**Particle hits at lower rapidities:** **BBC-TAG**

→ weak A-dependence
1.3 **BBC correlated** $A_N$ for forward neutrons

- **PHENIX**, arXiv:1703.10941

**Plot:**
- $p + A \rightarrow n + X$ at $\sqrt{s_{NN}} = 200$ GeV
- $x_F > 0.5$, $0.3 < \theta < 2.2$ mrad
- 3% scale uncertainty not shown

**Legend:**
- Red circles: ZDC inclusive
- Green squares: ZDC$\otimes$BBC-tag
- Blue triangles: ZDC$\otimes$BBC-veto

Particle veto at lower rapidities: **BBC-VETO**

- **Large** $A_N$ when **fewer** underlying particles
- **Small** $A_N$ when **ample** underlying particles

Do not only hadronic interactions but also electromagnetic interactions play a crucial role in $pA$?

Particle hits at lower rapidities: **BBC-TAG**

- $\rightarrow$ weak A-dependence

**Diagram:**
- BBC correlated $A_N$ for forward neutrons
- Atomic mass number
- $A (\text{atomic mass number})$
- $A_N$
- Set of nuclei: $p$, Al, Au

**Equations and Formulas:**
- $p + A \rightarrow n + X$
2. Ultra-peripheral collisions (UPCs)

**UPCs (aka Primakoff effects);**
- A collision of a proton with the EM field made by a relativistic nucleus
  when the impact parameter b is larger than \( R_A + R_p \)
- Fewer underlying particles unlike in hadronic interactions → smaller activity at BBC

\[
\frac{d\sigma^4_{\text{UPC}}(p^+ A \rightarrow \pi^+ n)}{dW db^2 d\Omega_n} = \frac{d^3 N_{\gamma^*}}{dW db^2} \frac{d\sigma_{\gamma^* p^+ \rightarrow \pi^+ n (W)}}{d\Omega_n} P_{\text{had}}(b)
\]

GM, EPJ. C 75, 614 (2015)
2. Virtual photon flux

The number of virtual photons per energy and b is formulated by the Weizsacker-Williams approximation (Phys. Rep 364 359’02, NPA 442 739 ’85, etc…):

$$\frac{d^3 N_{\gamma^*}}{d\omega_{\gamma^*} \, db^2} = \frac{Z^2 \alpha}{\pi^2} \frac{x^2}{\omega_{\gamma^*} b^2} \left( K^2_1(x) + \frac{1}{\gamma^2} K^2_0(x) \right)$$

where \( x = \omega_{\gamma^*} b / \gamma \) and \( \omega_{\gamma^*} \) is the virtual photon energy in the proton rest frame. Note that the virtual photon flux depends on the charge of photon source as \( Z^2 \).

- From the virtual photon flux, we see that low-energy photons dominate UPCs.

Photon virtuality is limited by \( Q^2 < \frac{1}{R^2} \). So, \( Q^2 < 10^{-3} \text{ GeV}^2 \)
2.1 Do $\gamma^*p$ interactions have large $A_N$?

Polarized $\gamma^*p$ cross sections

\[
\frac{d\sigma_{\gamma^* p \uparrow \rightarrow \pi + n}}{d\Omega_{\pi}} = \frac{|q|}{\omega_{\gamma^*}} (R_T^{00} + P_y R_T^{0y}) = \frac{|q|}{\omega_{\gamma^*}} R_T^{00} (1 + P_2 \cos \phi_{\pi} T(\theta_{\pi}))
\]

Equivalent to $A_N$

$T(\theta_{\pi})$ is decomposed into multipoles:

\[
T(\theta_{\pi}) \equiv \frac{R_T^{0y}}{R_T^{00}} \propto \text{Im}\{E_0^*(E_{1+} - M_{1+}) - 4\cos \theta_{\pi} (E_1^* M_{1+})\ldots\}
\]

Interference between $E_{0+}$ and $M_{1+}$ leads to large $T(\theta_{\pi})$ in the $\Delta(1232)$ region

MC simulations of the polarized $\gamma^*p$ interactions are developed for testing $T(\theta_{\pi})$, i.e. $A_N$ in pA collisions.
2.2 MC simulations for γ*p interactions

- MC simulations based on the MAID2007 model (Drechsel et al. EPJ A 34, 69 (2007)) are performed for R_{T^{00}} and T(θ_π).
- T(θ_π)~0.8 at Δ(1232), ~-0.5 at N(1680) → large A_N!!

**γ*p center-of-mass system**

transversely polarized proton along 2-axis

Numerical data from MAID 2007 (Q^2 = 0, θπ = 90 degree)

<table>
<thead>
<tr>
<th>W (MeV)</th>
<th>R_{T^{00}}</th>
<th>\frac{R_{T^{0γ}}}{R_{T^{00}}} = T(θ_π)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1100</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>1200</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>1300</td>
<td>0.40</td>
<td>0.40</td>
</tr>
<tr>
<td>1400</td>
<td>0.60</td>
<td>0.60</td>
</tr>
<tr>
<td>1500</td>
<td>0.80</td>
<td>0.80</td>
</tr>
</tbody>
</table>

**Diagram:**

- ZDC
- Au beam (γ*)
- Neutron
- Proton beam
- π^+
- π^-
- Reaction plane
- Scattering plane
- Center-of-mass frame
- Born terms as determined by the Gribov-Glauber model [17, 18].
2.2 MC simulations for γ*p interactions

- MC simulations based on the MAID2007 model (Drechsel et al. EPJ A 34, 69 (2007)) are performed for $R_{T}^{00}$ and $T(\theta_{\pi})$.
- $T(\theta_{\pi}) \sim 0.8$ at $\Delta(1232)$, $\sim 0.5$ at $N(1680) \rightarrow$ large $A_{N}$!!

**γ*p center-of-mass system**

- Transversely polarized proton along 2-axis.
- Solid curves indicate the ZDC acceptance.
- $T(\theta_{\pi})$ with the weight of $\gamma^{*}$ flux = $A_{N}$.
2.2 UPC cross sections as a function of $W$

\[
\frac{d\sigma_{\text{UPC}}^{4}(p^\uparrow A \rightarrow \pi^+ n)}{dW \, dB^2 \, d\Omega_n} = \frac{d^3 N_\gamma^* \, d\sigma_{\gamma^* p^\uparrow \rightarrow \pi^+ n}(W)}{dW \, dB^2 \, d\Omega_n} \frac{1}{P_{\text{had}}(b)}
\]

- $2\pi$ channels are anyway subdominant in UPCs.
- Table I and II show the total cross sections in UPCs and hadronic interactions.

### Table I.
Cross sections for neutron production in ultraperipheral collisions and hadronic interactions at $\sqrt{s_{NN}} = 200$ GeV. Cross sections in parentheses are calculated without $\eta$ and $z$ limits.

<table>
<thead>
<tr>
<th>UPCs</th>
<th>Hadronic interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p^\uparrow A$</td>
<td>$p^\uparrow A$</td>
</tr>
<tr>
<td>$p^\uparrow$Al</td>
<td>$p^\uparrow$Al</td>
</tr>
<tr>
<td>0.7 mb (2.2 mb)</td>
<td>8.3 mb</td>
</tr>
<tr>
<td>19.6 mb (41.7 mb)</td>
<td>19.2 mb</td>
</tr>
</tbody>
</table>

### Table II.
Cross sections in ultraperipheral $pA$ collisions at $\sqrt{s_{NN}} = 200$ GeV.

<table>
<thead>
<tr>
<th>$pA \rightarrow nX$ ($\eta &gt; 6.9$ and $z &gt; 0.4$)</th>
<th>$p^\uparrow A \rightarrow \pi^+ \pi^0 n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt; 1.1$ GeV</td>
<td>0.6 mb</td>
</tr>
<tr>
<td>1.1–2.0 GeV</td>
<td>27.4 mb</td>
</tr>
<tr>
<td>$&gt; 2.0$ GeV</td>
<td>1.8 mb</td>
</tr>
<tr>
<td>1.25–2.0 GeV</td>
<td>6.2 mb</td>
</tr>
</tbody>
</table>
3.1 Hadronic interactions (one-π exchange)

\[ z \frac{d\sigma_{pp \to nX}}{dz dp_T^2} = S^2 \left( \frac{\alpha'_{\pi}}{8} \right)^2 |t| G_{\pi^+ p n}^2(t) |\eta_{\pi}(t)|^2 \times (1 - z)^{1 - 2\alpha_{\pi}(t)} \sigma_{\pi^+ p}^{\text{tot}}(M_X^2), \]

\[ z \frac{d\sigma_{pA \to nX}}{dz dp_T^2} \]

- Kopeliovich et al. propose an interference between π and a₁-Reggeon leading to negative asymmetry in p-p and p-A.
- In this study, due to a technical difficulty, I omit an implementation of the interference. Alternatively, I apply \((1+\cos\Phi A)\) to the differential cross section of unpolarized proton and then effectively obtain the differential cross section of polarized proton.
- The coupling \(G_{\pi^+ p n}\) is chosen so that the calculated \(d\sigma/dz\) gives the best-fit to the PHENIX result.
3.1 UPCs vs. hadronic interactions

- Neutron cross section in pAu UPCs ($\propto Z^2$) is comparable with hadronic interactions, while $\sigma_{UPC} \sim \sigma_{HAD} \times 0.1$ in pAl.
- UPC-induced $A_N$ is positive and large in both pAl and pAu.

Expected $X_F$ and $\Phi$ distributions for forward neutrons in pAu

(a) pAu $\rightarrow$ nX ($\eta>6.8$)
- OPE $\times$ Glauber
- UPC

(OPE is based on Kopeliovich et al. arXiv:1702.07708)

(b) pAu $\rightarrow$ nX ($\eta>6.8$, $z>0.4$)

Positive and large $A_N$ in UPCs

Negative and small $A_N$ in hadronic interactions
3.2 MC sim. vs. the PHENIX measurements

- PHENIX measurements are well explained by the sum of UPCs and hadronic interactions.
- BBC-veto can be reasonably understood by the enhanced UPC fraction.

PHENIX, arXiv:1703.10941
GM, PRC 95, 044908

If we omit an interference between EM and hadronic amplitudes, total $A_N$ can be written as

$$A_N^{UPC+OPE} = \frac{\sigma_{UPC}A_N^{UPC} + \sigma_{OPE}A_N^{OPE}}{\sigma_{UPC} + \sigma_{OPE}}$$

The subtraction of UPCs (sys.$\sim$10%) from the PHENIX measurements enables discussions on

- Nuclear effects to $A_N$
- Coulomb-Nuclear Interference
4. Summary and Future prospects

- Large $A_N$ for forward neutrons in polarized pAu collisions and its $A$-dependence are discovered by PHENIX.

- To compared with the PHENIX data, we developed the MC simulations involving UPCs and hadronic interactions in polarized pA collisions.

- UPCs has large $A_N$ and the cross section is proportional to $Z^2$.

- Simulation results well explain the PHENIX inclusive measurements.
  - Large $A_N$ in pAu collisions originates in UPCs.

- Future prospects:
  - Missing 2π-production will contribute by $\sim$10 % at $W > 1.25$ GeV.
  - Coulomb-Nuclear interference?
Asymmetries for forward $\pi^0$ at FNAL...

$$A_{\text{UPC}}^{\text{UPC}} \sim T(\theta_\pi) \equiv \frac{R_{T}^{0y}}{R_{T}^{00}} \propto \text{Im}\{E_{0+}^{*}(E_{1+} - M_{1+}) - 4 \cos \theta_{\pi}(E_{1+}^{*}M_{1+})\}$$

$(\theta_\pi = 40^\circ \text{ assumed})$

**FIG. 2.** The invariant-mass spectrum of the $\pi^0-p$ system in $p+\text{Pb} \rightarrow \pi^0+p+\text{Pb}$ for $|t'| < 1 \times 10^{-3} \text{ (GeV/c)}^2$. Peaks due to the $\Delta^+(1232)$ and $N^*(1520)$ resonances are shown. Regions I and II are defined in the text.

$I$: $A_N \sim 0$

$II$: $A_N = -0.57$
Asymmetries for forward $\pi^0$ at FNAL...

**FIG. 2.** The invariant-mass spectrum of the $\pi^0$-$p$ system in $p+\text{Pb} \rightarrow \pi^0+p+\text{Pb}$ for $|t'| < 1 \times 10^{-3} \text{ (GeV/c)}^2$. Peaks due to the $\Delta^+(1232)$ and $N^*(1520)$ resonances are shown. Regions I and II are defined in the text.
Backup
UPC formalism

The UPC cross section is factorized as

\[
\frac{d\sigma^4_{\text{UPC}(p^+A \rightarrow \pi^+n)}}{dW db^2 d\Omega_n} = \frac{d^3 N_{\gamma^*}}{dW db^2} \frac{d\sigma_{\gamma^* p^+ \rightarrow \pi^+ n}(W)}{d\Omega_n} \overline{P}_{\text{had}}(b)
\]

- photon flux (N): quasi-real photons produced by a relativistic nucleus
- \(\sigma_{\gamma+p \rightarrow x}\): inclusive cross sections of \(\gamma+p\) interactions
- \(\overline{P}_{\text{had}}\): a probability not having a \(p+A\) hadronic interaction.

- \(\overline{P}_{\text{had}}\) is calculated by using a Glauber MC simulation.
- UPCs occur only if the impact parameter \(b\) is larger than the sum of radii \(R_p\) and \(R_A\).
- \(\overline{P}_{\text{had}}(b)\) distribution is important not only for the cross section but also for the energy distribution.
Inclusive cross sections of $\gamma+p$ interactions

Only $1\pi$ channel is simulated in this study. It is hard to simulate neutron momenta in $2\pi$ channels (future study?).
Photopion production formalism

(Berends et al. NPB 4, 1 '67)

\[ \frac{d\sigma}{d\Omega} = \frac{q}{k} \left| \langle x_f | \mathcal{F} | x_i \rangle \right|^2, \quad (A.1) \]

where

\[ \mathcal{F} = i\sigma \cdot \varepsilon \mathcal{F}_1 + \sigma \cdot \hat{q} \sigma \cdot (\hat{k} \times \varepsilon) \mathcal{F}_2 + i\sigma \cdot \hat{k} \hat{q} \cdot \varepsilon \mathcal{F}_3 + i\sigma \cdot \hat{q} \hat{q} \cdot \varepsilon \mathcal{F}_4. \quad (A.2) \]

\[ \sum \langle x_f | \mathcal{F} | x_i \rangle^\dagger \langle x_f | \mathcal{F} | x_i \rangle = \langle x_i | \mathcal{F}^\dagger \mathcal{F} | x_i \rangle \]

\[ \langle x_1 | \mathcal{F}_\pm \mathcal{F}_\pm | x_i \rangle = (1 \mp \hat{k} \cdot \hat{P}) \alpha + \beta \pm \sin \theta \hat{e}_1 \cdot \hat{P} \gamma + \sin \theta \hat{e}_2 \cdot \hat{P} \delta, \quad (A.7) \]

where

\[ \alpha = | \mathcal{F}_1 |^2 + | \mathcal{F} |^2 - 2 \cos \theta \Re (\mathcal{F}_1^* \mathcal{F}_2) + \sin^2 \theta \Re \{ \mathcal{F}_1^* \mathcal{F}_4 + \mathcal{F}_2^* \mathcal{F}_3 \}, \quad (A.8) \]

\[ \beta = \frac{1}{2} \sin^2 \theta \{ | \mathcal{F}_3 |^2 + | \mathcal{F}_4 |^2 + 2 \cos \theta \Re (\mathcal{F}_3^* \mathcal{F}_4) \}, \quad (A.9) \]

\[ \gamma = \Re \{ \mathcal{F}_1^* \mathcal{F}_3 - \mathcal{F}_2^* \mathcal{F}_4 \} + \cos \theta \Re \{ \mathcal{F}_1^* \mathcal{F}_4 - \mathcal{F}_2^* \mathcal{F}_3 \}, \quad (A.10) \]

\[ \delta = \operatorname{Im} \{ \mathcal{F}_1^* \mathcal{F}_3 - \mathcal{F}_2^* \mathcal{F}_4 \} + \cos \theta \operatorname{Im} \{ \mathcal{F}_1^* \mathcal{F}_4 - \mathcal{F}_2^* \mathcal{F}_3 \} - \sin^2 \theta \operatorname{Im} (\mathcal{F}_3^* \mathcal{F}_4). \quad (A.11) \]

Polarized nucleon, unpolarized photon

\[ \frac{d\sigma(P)}{d\Omega} = \frac{1}{2} \left\{ \frac{d\sigma_+(P)}{d\Omega} + \frac{d\sigma_-(P)}{d\Omega} \right\} \]

\[ = \frac{q}{k} \left\{ \alpha + \beta + \sin \theta \hat{e}_2 \cdot \hat{P} \delta \right\} \rightarrow \frac{d\sigma_0}{d\Omega} = \frac{q}{k} (\alpha + \beta), \quad A_N = \frac{\sin \theta \delta}{\alpha + \beta} \]
Photopion production

(Berends et al. NPB 4, 1 '67)

\[ \tilde{F}(s, t) = \sum_{l=0}^{\infty} \begin{bmatrix} G_l(x) & 0 \\ 0 & H_l(x) \end{bmatrix} \tilde{M}_l(s) , \quad \tilde{M}_l = \begin{bmatrix} E_{l+} \\ E_{l-} \\ M_{l+} \\ M_{l-} \\ S_{l+} \\ S_{l-} \end{bmatrix} \]

\( G_l \) and \( H_l \) are Legendre polynomials, and \( \tilde{M}_l \) are multipoles.

(Drechsel and Tiator, JphysG 18, 449 '92)

Multipole decomposition:

\[
R_T = |E_{0+}|^2 + \frac{1}{2} |2M_{1+} + M_{1-}|^2 + \frac{1}{2} |3E_{1+} - M_{1+} + M_{1-}|^2 \\
+ 2 \cos \Theta \Re \{ E_{0+}^* (3E_{1+} + M_{1+} - M_{1-}) \} \\
+ \cos^2 \Theta (|3E_{1+} + M_{1+} - M_{1-}|^2 - \frac{1}{2} |2M_{1+} + M_{1-}|^2 \\
- \frac{1}{2} |3E_{1+} - M_{1+} + M_{1-}|^2 )
\]

\[
R_T(n_i) = 3 \sin \Theta \Im \{ E_{0+}^* (E_{1+} - M_{1+}) - \cos \Theta (E_{1+}^* (4M_{1+} - M_{1-}) + M_{1+}^* M_{1-}) \}
\]

\[
R_T^{00} \equiv R_T \quad \text{and} \quad R_T^{0y} \equiv R_T(n_i) \quad \frac{d\sigma_{\gamma^* p \rightarrow \pi^+ n}}{d\Omega_\pi} = \frac{|q|}{\omega_{\gamma^*}} (R_T^{00} + P_y R_T^{0y})
\]

\[
pion \text{ and neutron production in UPCs} \quad \frac{d\sigma_{\gamma^* p \rightarrow \pi^+ n}}{d\Omega_\pi} = \frac{|q|}{\omega_{\gamma^*}} R_T^{00} (1 + P_2 \cos \phi_\pi T(\theta_\pi))
\]

Several models provide their predicted multipoles. MAID2007 is available at https://maid.kph.uni-mainz.de.
Multipole decomposition of $T(\theta_\pi)$

\[ A_N^{\text{UPC}} \sim T(\theta_\pi) \equiv \frac{R_{0y}^0}{R_{00}^T} \propto \text{Im}\left\{ E_{0+}^*(E_{1+} - M_{1+}) - 4 \cos \theta_\pi (E_{1+}^* M_{1+}) \right\} \]

**Im\{E_{0+}^*(E_{1+} - M_{1+})\}**

**Im\{4\cos(40)(E_{1+}^* M_{1+})\}**

\begin{align*}
\text{Invariant Mass [MeV]} & \quad \text{Imaginary Amplitude} \\
1100 & \quad 0 \\
1175 & \quad 75 \\
1250 & \quad 150 \\
1325 & \quad 225 \\
1400 & \quad 300
\end{align*}

\begin{align*}
\text{Invariant Mass [MeV]} & \quad \text{Imaginary Amplitude} \\
1100 & \quad 0 \\
1175 & \quad 75 \\
1250 & \quad 150 \\
1325 & \quad 225 \\
1400 & \quad 300
\end{align*}
Target asymmetry as a function of $W$

Osaka-Argonne

MAID 2007

$z$ axis: $T(\theta)$
Hadron interactions (one-π exchange)

(Kopeliovich et al. arXiv:1702.07708)

\[ A_N^{(\pi-\bar{a}_1)}(q_T, z) = q_T \frac{A_{mN} q_L}{|t|^{3/2}} (1 - z)^{\alpha_\pi(t) - \alpha_{\bar{a}_1}(t)} \] (12)

\[ \frac{\text{Im} \eta_\pi^*(t) \eta_{\bar{a}_1}(t)}{|\eta_\pi(t)|^2} \left( \frac{d\sigma_{\pi p \to \bar{a}_1 p}}{d\sigma_{\pi p \to \pi p}} \right)_{M_X^2}^{t=0} \left( \frac{d\sigma_{\pi p \to \pi p}}{d\sigma_{\pi p \to \pi p}} \right)_{M_X^2}^{t=0} \frac{1}{2} \frac{g_{\bar{a}_1}^{++}}{g_{\pi}^{++}}. \]

\[ A_{pA \to nX}^N = A_{pp \to nX}^N \times \frac{R_1}{R_2} R_3 \]

Nuclear effects
A simple OPE model has considered only forward neutrons so far.

Simulation for $\pi+p$ interactions via PYTHIA8 is now implemented to simulate the particles $X$ which may trigger the BBCs.

$dN_{\text{ch}}^{X}/d\eta \sim 1.0 \ (1.3)$ at $3<\eta<4 \ (3<-\eta<4)$. 

Neutral particles

Charged particles