very forward neutron $A_N$

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Very Forward neutron production in p+p collisions

• Forward neutron production at ISR qualitatively described by one-pion exchange (OPE) model (Regge)

• Also at RHIC in unpolarized cross sections; reasonable consistency with model

PRD 88 (2013) 032006
Transverse Single spin asymmetries (TSSAs)

- First forward neutron asymmetries seen at RHIC
- Existence of nonzero asymmetries requires an extension to OPE model: interference of pion and $a_1$ Regge amplitudes can qualitatively describe $A_{N_s}$

$$A_N = \frac{1}{P} \frac{N^L - N^R}{N^L + N^R}$$


Kopeliovich et al: PRD 84 (2011) 114012
From $p+p$ to $p+A$ neutron asymmetries

- Unexpectedly large $A$ dependence in neutron asymmetries
- Even a sign change seen
- OPE model does not predict such a change in asymmetries
- Are there other sources to the asymmetries?

PRL 120 (2018), 022001
Ultraperipheral collisions in p+A

Mitsuka: EPJC 75 (2015) 614

- When impact parameter too large for nuclear interactions, ultraperipheral collisions still possible with photon field from nucleus
- Especially for forward neutrons at low transverse momenta and high momentum fractions $x_F$, substantial contribution
- $Z^2$ dependence increases relative contribution from Al to Au

STARLIGHT+SOPHIA+DPMJ ET/PYTHIA simulations
Enhance or suppress UPC and hadronic contributions via correlations

PRL 120 (2018), 022001

- Coincidence with charged particle activity in forward and backward region (BBC) enhances hard interactions → asymmetries stay negative
- Veto enhances UPC contribution → p+Al asymmetries already positive

→ study also the actual $x_F$ and $P_T$ dependence for actual interplay
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**PRL 120 (2018), 022001**

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**Mitsuka PRC95 (2017) 044908**
- Qualitative agreement in polarized UPC model (MAID)
Polarized proton beams from $\sqrt{s}$ of 62-510 GeV up to 120 filled bunches, spin orientations alternating bunch-by-bunch in several predefined spin pattern pA, AA collisions up to 200 GeV Spin rotators around PHENIX and STAR to select long. or transversely polarized beams Global (polarized H-jet, C targets) and local (ZDC) polarimetry
The RHIC ring(s) with polarized protons

\[ L_{\text{max}} = 2 \times 10^{32} \text{s}^{-1} \text{cm}^{-2} \]
\[ 50 < \sqrt{s} < 500 \text{ GeV} \]
\[ \sim 70\% \text{ Polarization} \]

\[ 2 \times 10^{11} \text{ Pol. Protons / Bunch} \]
\[ \epsilon = 20 \pi \text{ mm mrad} \]
PHENIX

- main detector:
  - 2 Central arms ($|\eta|<0.35$, 90 degrees each):
  - 2 Muon arms (1.2<$|\eta|<$2.4)
- **BeamBeamCounter** (BBC, 3.1<$|\eta|<$3.9, hard collision/luminosity detectors)
- **ZeroDegreeCalorimeter** ($|\eta|>6.1$):
  - 3 10x10 cm$^2$ modules of 1.7 nuclear interaction lengths each, 20% energy resolution for 100 GeV neutrons
  - ShowerMaxDetector 7 strips horizontally and vertically, 1cm resolution
ZDC running in 2015 p+p and p+A, neutron reconstruction

- In 2015 p+p, p+Al and p+Au collisions at 200 GeV
- For p+A running tilted beam direction compensated by shifting ZDC to nominal beam center

- Total energy in ZDC1+2+3: 40 – 120 GeV
- EM veto: $E_{ZDC2}/E_{tot} > 3\%$
- $0.5 \text{ cm} < r < 4.0 \text{ cm}$ for neutron hits
- >0 SMD Strips horizontal and vertical strips hit
- 4(+2) $P_T$ bins $[0, 0.01, 0.06, 0.11, 0.16, 0.21, 0.4]$ GeV/c
- 4(+2) $x_F$ bins $[0, 0.4, 0.55, 0.7, 0.85, 1., 1.2]$
Unfolding procedure, Systematics, Predictions

• RooUnfold (Bayes) unfolding (iterative unfolding – variation of iterations as one source of systematics) on spin dependent 3D yields → Asymmetry calculation

• Several MC generators + GEANT3 simulations as basis for unfolding: Pythia6/8, DPMJET, OPE motivated (\(\pi+p\) Pythia 8, using measured \(n\) spectra), UPC (STARlight+Sophia+DPMJET) → variation as systematics

• Variation of beam center at ZDC and asymmetry reconstruction method → systematics

• Model calculations from Mitsuka, combining UPC and hadronic \((Kopeliovich et al: PRD 84 (2011) 114012)\) calculations

• For \(p+p\) and \(p+Al\) scaled UPC xsecs by simple \(Z^2\) dependence and OPE xsecs by \(A^{0.42}\) dependence

• UPC model takes into account only \(n+\pi^+\) resonances → sharp \(P_T/x_F\) behavior
Inclusive neutron asymmetries in p+p

**PRD 105 (2022) 032004**

- Magnitude increasing with $P_T$ except for low $x_F$
- Only weak $x_F$ dependence in hadronic events, slightly larger in BBC vetoed events
- Comparable to (OPE dominated) model curves

Dashed areas: best parameterizations of $x_F$ integrated asymmetries using Pol3, Power law or Exponential
Inclusive neutron asymmetries in p+Al

- Cancellation between hadronic and UPC contributions results in very small asymmetries in data and model
- Qualitative agreement of model except at high $x_F$
Inclusive neutron asymmetries in p+Au

- Large, increasing asymmetries seen with likely a hint of decrease at high \( P_T \) for lower \( x_F \)
- Roughly similar behavior in model seen but details shifted – possibly due to inclusion of single pion resonances only
BBC correlated (hits in both BBCs required)

- BBC correlation enhances hadronic interactions $\rightarrow$ p+p and p+Al asymmetries nearly identical, p+Au slightly smaller (some UPC contribution still present)
- Qualitatively consistent with the nearly linear behavior predicted from OPE model
BBC Veto (no hits in either BBC)

• BBC Veto enhances UPC contributions:
  • $p+p$ asymmetries much smaller (but still barely negative)
  • $p+Al$ and $p+Au$ asymmetries larger, reaching up to 40%

• UPC related asymmetries increasing with $P_T$, again suggestion of a reduction at higher $P_T$ at low $x_F$

• Similar rough agreement of model calculations
Summary

• Explicit $x_F$ and $P_T$ dependence of very forward neutron asymmetries studied in $p+p$, $p+Al$ and $p+Au$ collisions

• Generally weak $x_F$ dependence of asymmetries while magnitude increasing with $P_T$

• Interplay between hadronic and UPC interactions studied using correlation studies:
  • BBC tagged asymmetries enhance hadronic interaction and show negative, nearly linear $x_F$ dependence predicted by OPE model
  • BBC vetoed asymmetries enhance UPC interaction and show even larger positive $p+A$ asymmetries, rough model agreement likely limited by included resonances

• Studies of $p+p$ asymmetries at other collisions energies ($\rightarrow$ different reach in $P_T$) ongoing