Transverse Single Spin Asymmetry in $e + p^{\uparrow} \rightarrow e + J/\psi + X$

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- Single spin asymmetry
- Model for J/ψ production
- Formalism for calculating the asymmetry
- Models for the Sivers function used
- Results
- Conclusion

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In collaboration with R. Godbole (IISc, Bangalore), A. Misra (Mumbai U.), V. Rawoot (Mumbai U.) (arXiv : 1201.1066 [hep-ph])

Single Spin Asymmetry in J/ψ production

- Aim is to study the asymmetry in photoproduction (i.e. low virtuality electroproduction) of charmonium by scattering unpolarized electrons off transversely polarized proton

- Transverse momentum dependent Sivers function describes the probability of finding an unpolarized parton inside a transversely polarized hadron : correlation between transverse momentum of the unpolarized quarks and gluons and the nucleon spin related to orbital angular momentum : Sivers asymmetry gives access to the orbital angular momentum of the partons

- SSAs involving the transverse momentum dependent pdfs and fragmentation functions: very often two or more of these functions contribute to the same physical observable

- In this process that we are considering, at LO, there is contribution only from a single partonic subprocess $\gamma g \longrightarrow c\bar{c}$: can be used as a clean probe of gluon Sivers function

- May throw some light on the charmonium production mechanism as well

Model for charmonium production that we consider

Color evaporation model : first proposed by

Halzen and Matsuda (1978), H. Fritsch (1977)

CEM predicts a cross section for the J/ψ production from the cross section of the $c\bar{c}$ pair

Statistical treatment of color : color can 'evaporate' by multiple soft gluon emission

Cross section for charmonium production is proportional to the rate of production of $c\bar{c}$ pair integrated over the mass range $2m_c$ to $2m_D$

$$\sigma = \frac{1}{9}\int_{2m_c}^{2m_D} dM_{c\bar{c}} \frac{d\sigma_{c\bar{c}}}{dM_{c\bar{c}}}$$

where m_c is the charm quark mass and $2m_D$ is the $D\bar{D}$ threshold; $1/9$ is the statistical probability for the production of a color singlet state; $M^2_{c\bar{c}}$ is the squared invariant mass of $c\bar{c}$

In later versions data are better fitted by the inclusion of a phenomenological factor in differential cross section formula, which depends on a Gaussian distribution of the transverse momentum of the charmonium

Eboli, Gregores, Halzen (2003)

Cross section for charmonium production

Cross section for low-virtuality electroproduction of J/ψ :

$$\sigma^{ep\to e+J/\psi+X} = \int_{4m_c^2}^{4m_D^2} dM_{c\bar{c}}^2 \int dy\, dx\, f_{\gamma/e}(y)\, f_{g/p}(x)\, \frac{d\hat{\sigma}^{\gamma g\to c\bar{c}}}{dM_{c\bar{c}}^2}.$$

The photon flux in the electron is approximated by the distribution (Weizsacker-Williams approximation)

$$f_{\gamma/e}(y,E) = \frac{\alpha}{\pi}\{\frac{1+(1-y)^2}{y}\left(ln\frac{E}{m}-\frac{1}{2}\right)+\frac{y}{2}\left[ln\left(\frac{2}{y}-2\right)+1\right] + \frac{(2-y)^2}{2y}ln\left(\frac{2-2y}{2-y}\right)\}.$$

Kniehl (1991)

where y is the energy fraction of electron carried by the photon, E is the energy of the electron and m is the mass

Single Spin Asymmetry

Generalization of CEM expression by taking into account the transverse momentum dependence

$$\frac{d\sigma^{e+p^\uparrow \to e+J/\psi+X}}{dM^2} = \int dx_\gamma \, dx_g \, [d^2\boldsymbol{k}_{\perp\gamma} d^2\boldsymbol{k}_{\perp g}] \, f_{g/p^\uparrow}(x_g, \boldsymbol{k}_{\perp g}) f_{\gamma/e}(x_\gamma, \boldsymbol{k}_{\perp\gamma}) \frac{d\hat{\sigma}^{\gamma g \to c\bar{c}}}{dM^2}$$

where $M^2 \equiv M^2_{c\bar{c}}$

Single spin asymmetry for a transversely polarized target is defined as

$$A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}$$

Number density of partons inside a proton with transverse polarization $\mathbf{S}$ and momentum $\boldsymbol{P}$ is parameterized as

$$f_{a/p^\uparrow}(x_a, \boldsymbol{k}_{\perp a}, \boldsymbol{S}) \equiv f(x_a, k_{\perp a}) + \frac{1}{2}\Delta^N f_{a/p^\uparrow}(x_a, k_{\perp a}) \, \hat{\boldsymbol{S}} \cdot (\hat{\boldsymbol{P}} \times \hat{\boldsymbol{k}}_{\perp a})$$

$\Delta^N f_{a/p^\uparrow}(x, k_{\perp a})$ is the Sivers function

Single Spin Asymmetry

$$\frac{d^4\sigma^{\uparrow}}{dydM^2d^2\boldsymbol{q}_T} - \frac{d^4\sigma^{\downarrow}}{dydM^2d^2\boldsymbol{q}_T} = \frac{1}{2}\int [dx_\gamma d^2\boldsymbol{k}_{\perp\gamma} dx_g d^2\boldsymbol{k}_{\perp g}]\Delta^N f_{g/p^\uparrow}(x_g, \boldsymbol{k}_{\perp g})$$
$$\times f_{\gamma/e}(x_\gamma, \boldsymbol{k}_{\perp\gamma})\delta^4(p_g + p_\gamma - q)\, \hat{\sigma}_0^{\gamma g\to c\bar{c}}(M^2)$$

where $q = p_c + p_{\bar{c}}$ and the partonic cross section

$$\hat{\sigma_0}^{\gamma g\to c\bar{c}}(M^2) = \frac{1}{2}e_c^2\frac{4\pi\alpha\alpha_s}{M^2}[(1+\gamma-\frac{1}{2}\gamma^2)\ln\frac{1+\sqrt{1-\gamma}}{1-\sqrt{1-\gamma}} - (1+\gamma)\sqrt{1-\gamma}]$$

$\gamma = \frac{4m_c^2}{M^2}$ and $M^2 \equiv \hat{s} = xS$, S is the CM energy squared of the $\gamma - p$ system.
$\Delta^N f_{g/p^\uparrow}(x_g, \boldsymbol{k}_{\perp g})$ is related to the gluon Sivers function $\Delta^N f_{g/p^\uparrow}(x, k_{\perp g})$ by

$$\Delta^N f_{g/p^\uparrow}(x_g, \boldsymbol{k}_{\perp g}) = \Delta^N f_{g/p^\uparrow}(x_g, k_\perp)\, \hat{\boldsymbol{S}}\cdot(\hat{\boldsymbol{P}}\times\hat{\boldsymbol{k}}_{\perp g}).$$

Models for WW Function

For $k_{\perp g}$ dependence of the unpolarized pdf's, we use a simple factorized and Gaussian form

$$f_{g/p}(x_g, k_\perp) = f_{g/p}(x_g) \frac{1}{\pi \langle k_{\perp g}^2 \rangle} e^{-k_{\perp g}^2 / \langle k_{\perp g}^2 \rangle}.$$

we have used two choices for WW function for the photon

1) A simple Gaussian form as above :

$$f_{\gamma/e}(x_\gamma, k_{\perp\gamma}) = f_{\gamma/e}(x_\gamma) \frac{1}{\pi \langle k_{\perp\gamma}^2 \rangle} e^{-k_{\perp\gamma}^2 / \langle k_{\perp\gamma}^2 \rangle}$$

2) Second form :

$$f_{\gamma/e}(x_\gamma, k_{\perp\gamma}) = f_{\gamma/e}(x_\gamma) \, \frac{1}{2\pi} \, \frac{N}{k_{\perp\gamma}^2 + {k_0}^2}$$

Models for Sivers Function

For the Sivers function we use two models

M. Anselmino, M. Boglione, U. D'Alesio, S. Melis, F. Murgia and A. Prokudin (2009)

M. Anselmino, M. Boglione, U. D'Alesio, E. Leader and F. Murgia (2004)

Model I :

$$\Delta^N f_{g/p^\uparrow}(x_g, \boldsymbol{k}_{\perp g}) = \Delta^N f_{g/p^\uparrow}(x_g) \frac{1}{\pi \langle k_{\perp g}^2 \rangle}\, h(k_{\perp g})\, e^{-k_{\perp g}^2/\langle k_{\perp g}^2 \rangle} \cos(\phi_{k_\perp})$$

where the gluon Sivers function, $\Delta^N f_{g/p^\uparrow}(x_g)$ is defined as

$$\Delta^N f_{g/p^\uparrow}(x_g) = 2\,\mathcal{N}_g(x_g)\, f_{g/p}(x_g)$$

$$h(k_{\perp g}) = \sqrt{2e}\, \frac{k_{\perp g}}{M_1}\, e^{-k_{\perp g}^2/M_1^2}$$

Models for Sivers Function

Parametrization for quark Sivers function

$$\mathcal{N}_f(x) = N_f x^{a_f} (1-x)^{b_f} \frac{(a_f + b_f)^{(a_f+b_f)}}{{a_f}^{a_f} {b_f}^{b_f}} \ .$$

For gluons we use (Boer and Vogelsang (2004))

(a) $\mathcal{N}_g(x) = (\mathcal{N}_u(x) + \mathcal{N}_d(x))/2$,

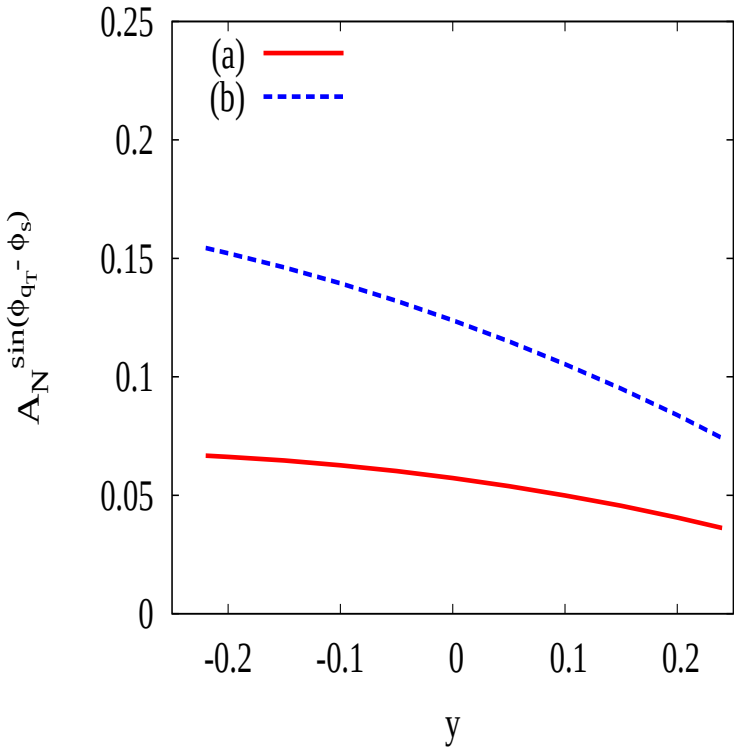
(b) $\mathcal{N}_g(x) = \mathcal{N}_d(x)$.

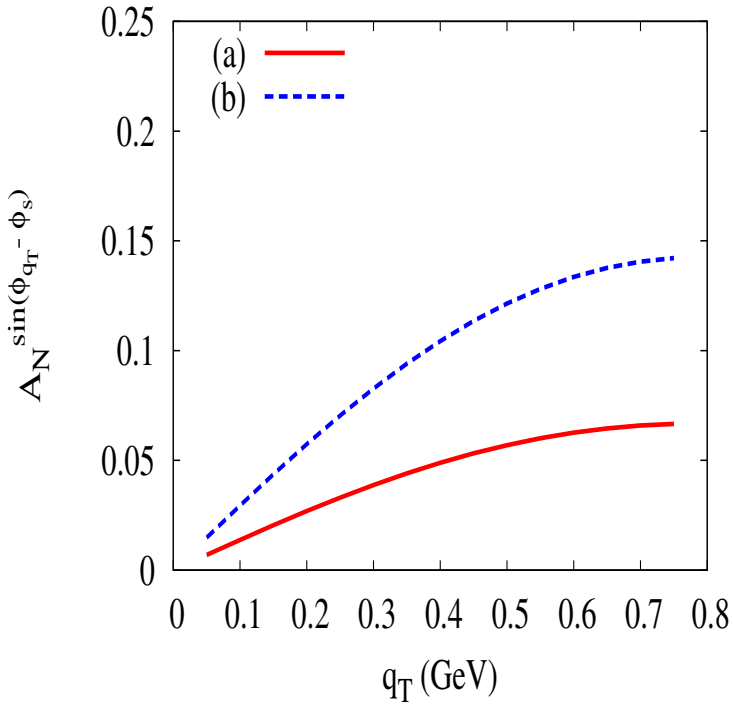
Model II :

$$\Delta^N f_{g/p^\uparrow}(x_g, \boldsymbol{k}_{\perp g}) = \Delta^N f_{g/p^\uparrow}(x_g) \frac{1}{\pi \langle k_{\perp g}^2 \rangle} e^{-k_{\perp g}^2/\langle k_{\perp g}^2 \rangle} \frac{2 k_{\perp g} M_0}{k_{\perp g}^2 + M_0^2} \cos(\phi_{k_\perp}),$$

and $M_0 = \sqrt{\langle k_{\perp g}^2 \rangle}$ where the gluon Sivers function is given as in Model I

SSA for J/ψ production at JLab



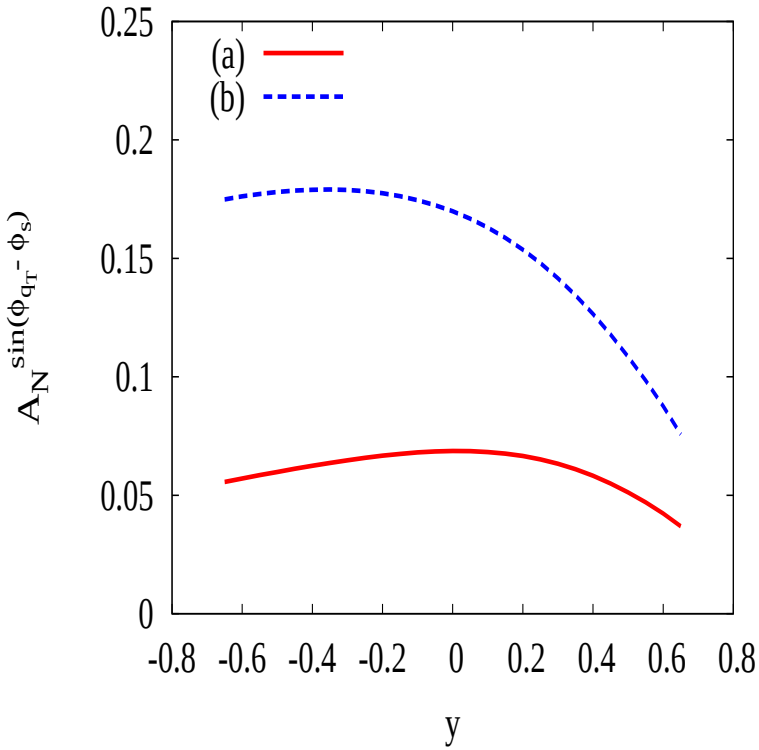


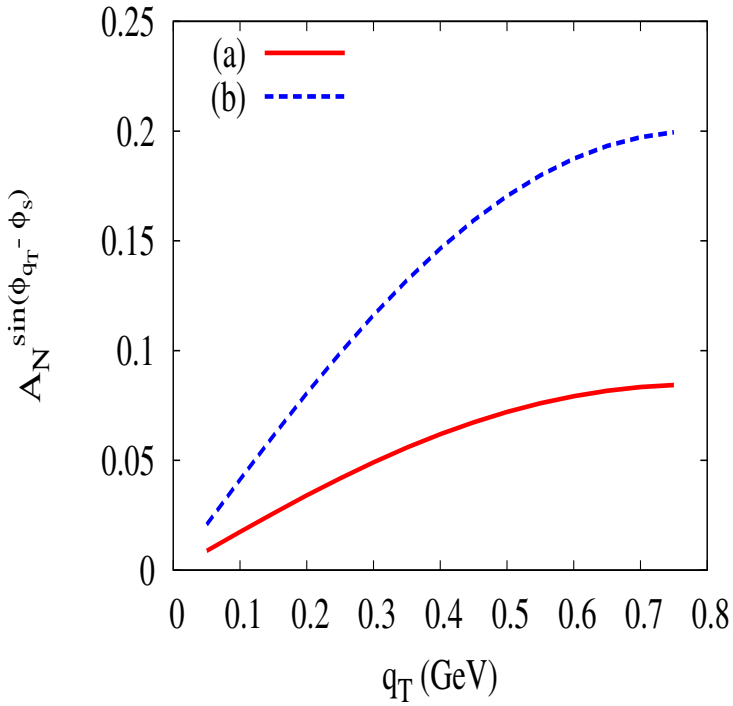
Best fit parameters of Sivers functions (Anselmino et al (2011)

$$N_u = 0.40,\ a_u = 0.35,\ b_u = 2.6\ ,$$
$$N_d = -0.97,\ a_d = 0.44,\ b_d = 0.90\ ,$$
$$M_1^2 = 0.19\ GeV^2.$$

Plot for JLab ($\sqrt{s} = 4.7$ GeV)

SSA for J/ψ production at HERMES



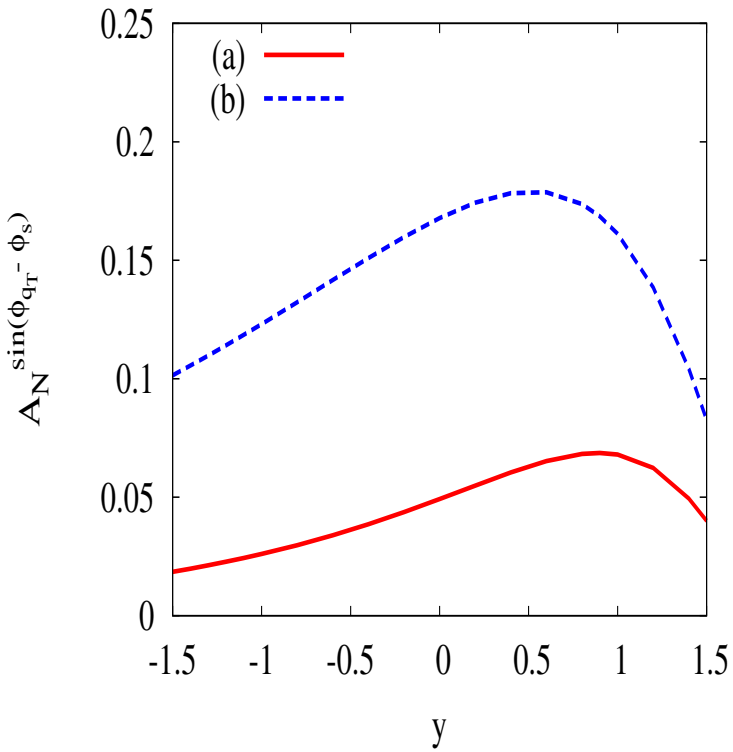


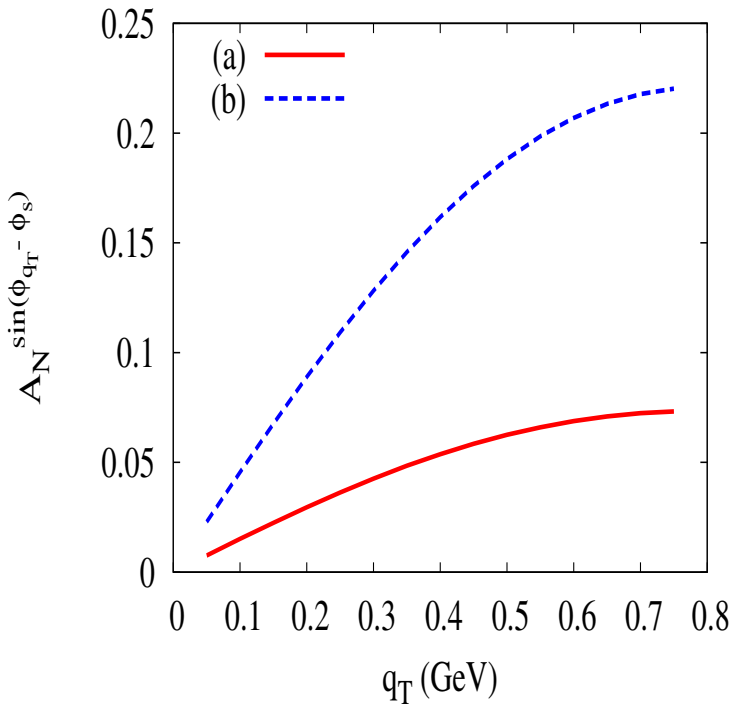
$$\langle k^2_{\perp g} \rangle = \langle k^2_{\perp \gamma} \rangle = 0.25\, GeV^2.$$

Integration ranges are $(0 \leq q_T \leq 1)$ GeV and $(0 \leq y \leq 0.6)$

Plot for HERMES ($\sqrt{s} = 7.2$ GeV)

SSA for J/ψ production at COMPASS

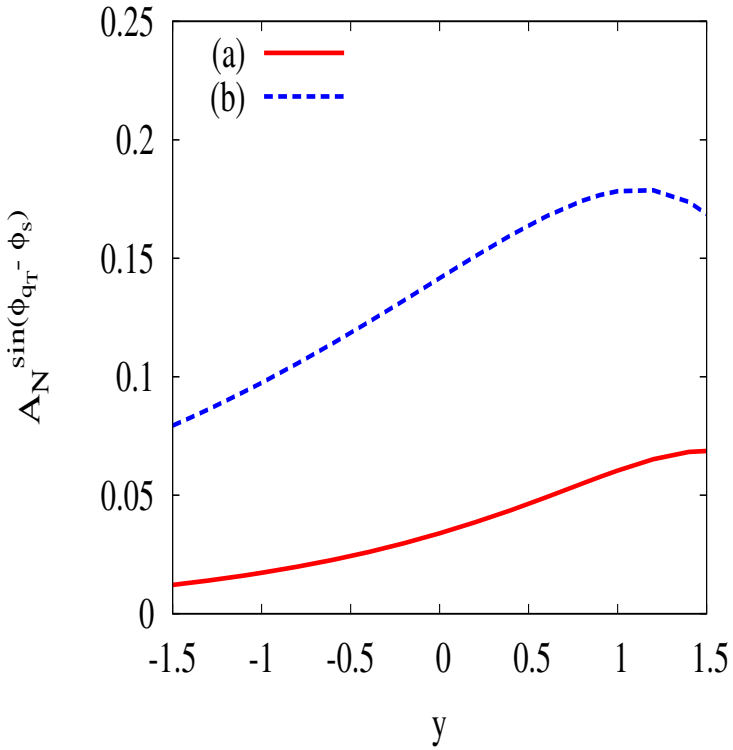


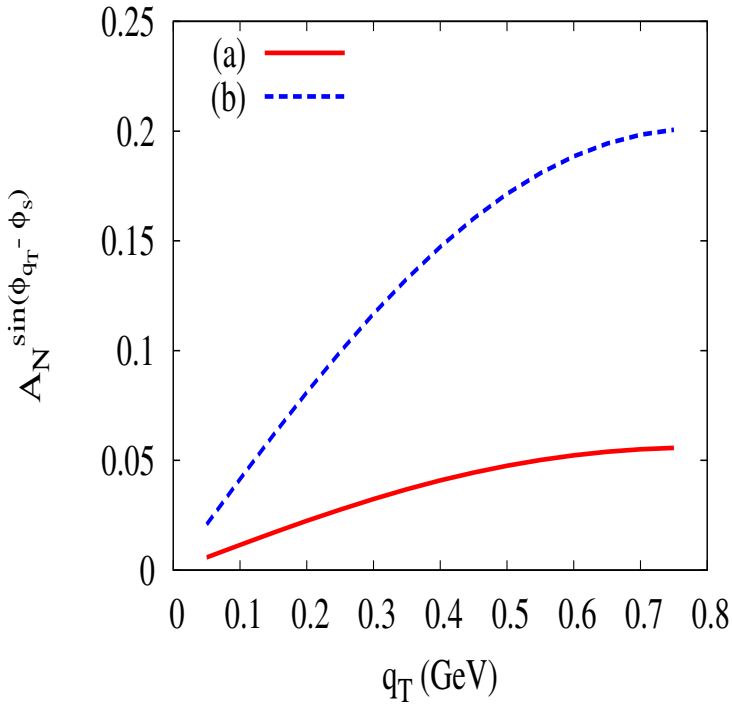


Integration ranges are $(0 \leq q_T \leq 1)$ GeV and $(0 \leq y \leq 1)$

Plot for COMPASS ($\sqrt{s} = 17.33$ GeV)

SSA for J/ψ production at eRHIC

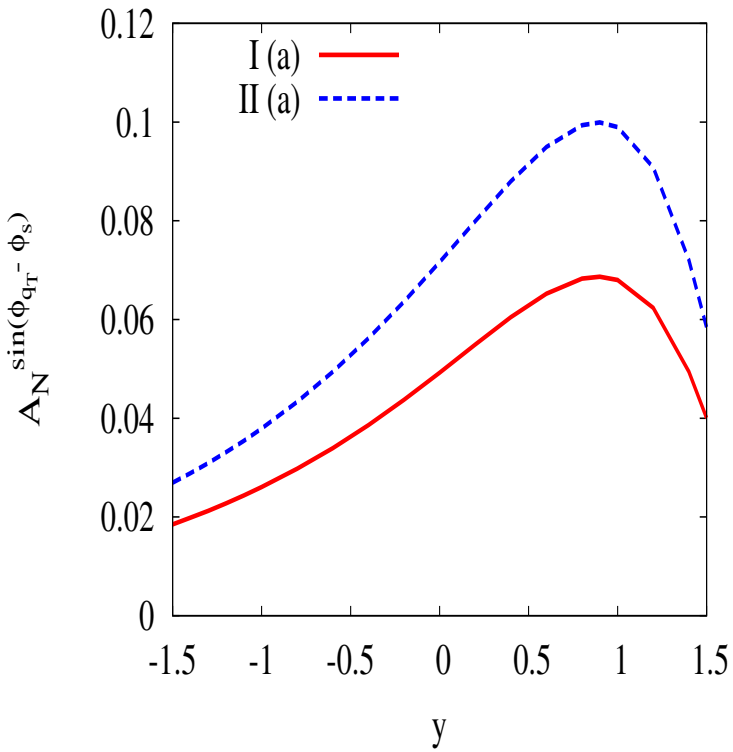


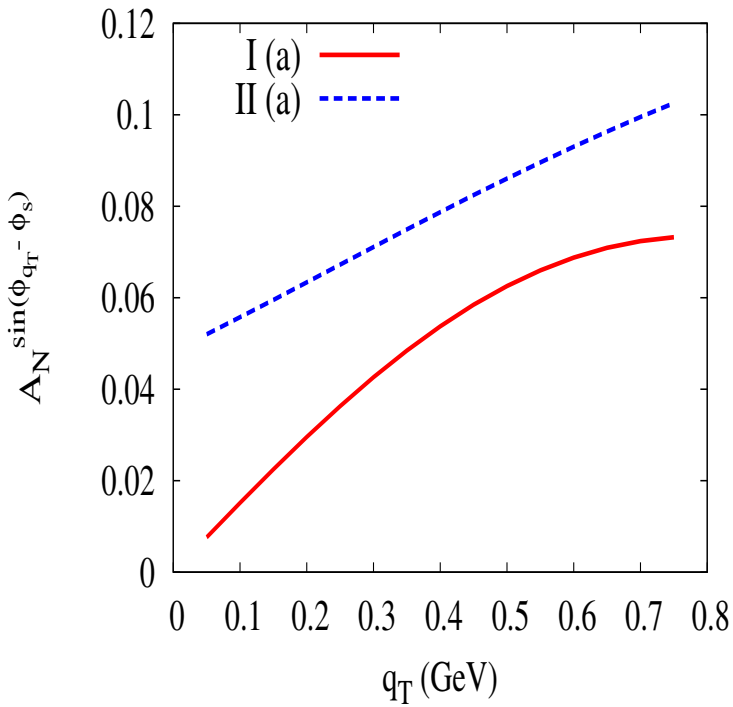


Integration ranges are $(0 \leq q_T \leq 1)$ GeV and $(0 \leq y \leq 1)$

Plot for eRHIC ($\sqrt{s} = 31.6$ GeV)

SSA for J/ψ production at COMPASS

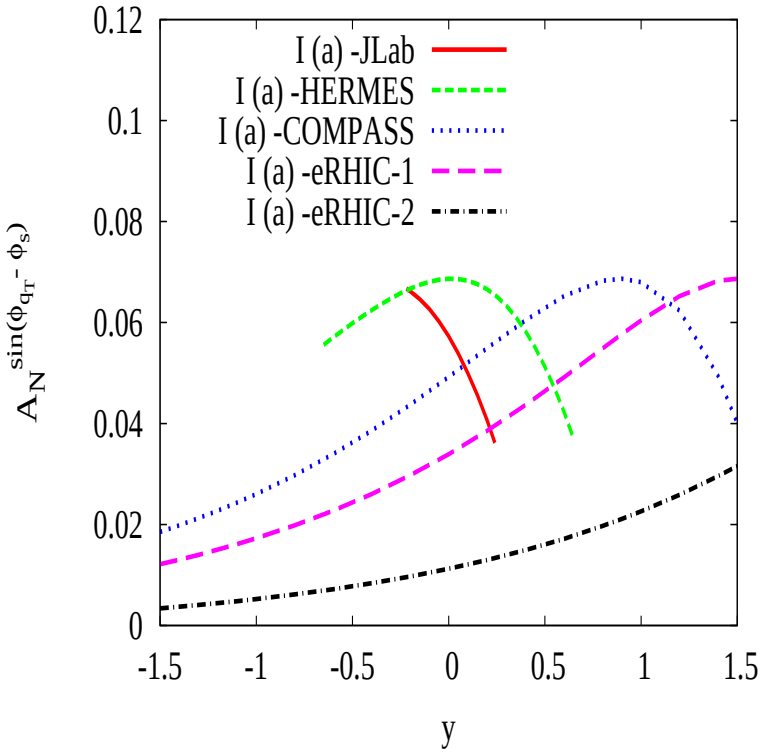


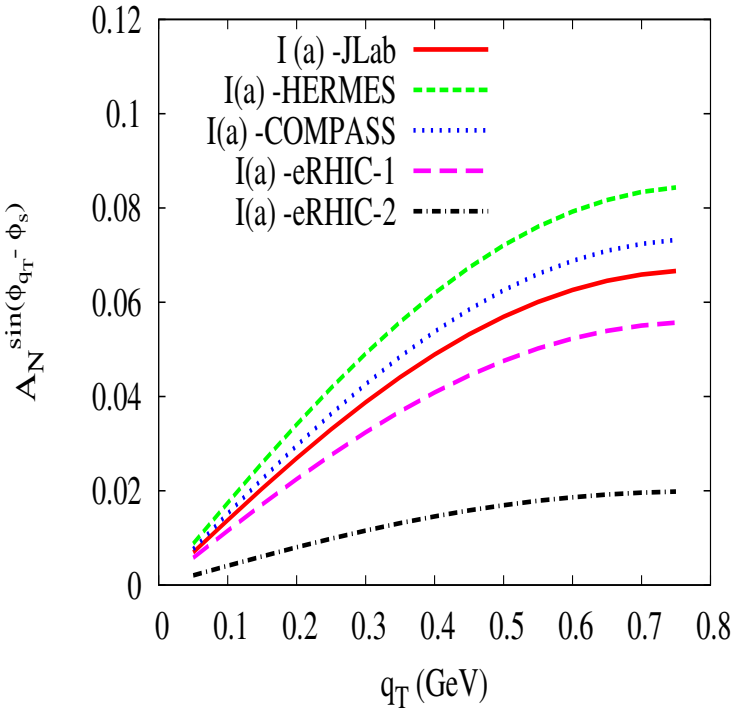


Integration ranges are $(0 \leq q_T \leq 1)$ GeV and $(0 \leq y \leq 1)$

Plot for COMPASS ($\sqrt{s} = 17.33$ GeV) : Comparison of two models

Compare





Asymmetry in model I with parameterization (a) compared for JLab ($\sqrt{s} = 4.7$ GeV) (solid red line), HERMES ($\sqrt{s} = 7.2$ GeV) (dashed green line), COMPASS ($\sqrt{s} = 17.33$ GeV) (dotted blue line), eRHIC-1 ($\sqrt{s} = 31.6$ GeV) (long dashed pink line) and eRHIC-2 ($\sqrt{s} = 158.1$ GeV) (dot-dashed black line)

Conclusion

- Sizable SSA for J/ψ electroproduction : can give information on gluon Sivers function
- SSA does not depend much on the choice of the $k^{\perp}$ dependence of the photon distribution
- Photoproduction : have to consider higher order and resolved photon contributions
- Would be interesting to see how sensitive the SSA is on the charmonium production model
- Also need to investigate how much the scale evolution of the $k^{\perp}$ dependent distributions affect the SSA