Single-Spin Asymmetry in J/ψ production in $pp^{\uparrow}$ collision

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Outline

Introduction to TMDs

Quarkonium Models

Single spin asymmetry in $pp^{\uparrow}$ collision

Unpolarized differential cross section in the low P_T region

Results and Summary

TMDs

- In spite of 50 years study, we do not really know the 3D nucleon structure in momentum space.
- TMDs map the 3D structure of the nucleon in terms of partons

At leading twist, we have 8 gluon TMDs

Gluons **Target**	**Unpolarized**	**Circularly**	**Linearly**
Unpolarized	f_1^g		$h_1^{\perp g}$
Longitudinal		g_{1L}^g	$h_{1L}^{\perp g}$
Transverse	$f_{1T}^{\perp g}$	g_{1T}^g	$h_{1T}^g, h_{1T}^{\perp g}$

Boer-Mulders

Kotzinian-Mulders

Pretzelosity

Sivers

Helicity

Worm-gear

R. Angeles-Martinez et al, APhyPolB.46.2501 (2015)

Sivers function

- Sivers function is one of the TMD, which describes the probability to find the unpolarized partons inside a transversely polarized nucleon.

Non-universal property: QCD predicts that

$$\Delta^N f_{a/p^\uparrow}(x, \mathbf{k}_\perp)|_{\rm DY} = -\Delta^N f^\perp_{a/p^\uparrow}(x, \mathbf{k}_\perp)|_{\rm SIDIS}$$

Not yet conformed!

- This kind of non-universal property of Sivers function can be tested and lot of work has been going on from several years.
- SIDIS data come from HERMES, COMPASS and JLab experiments in pion and kaon production. Global analysis has been done to extract the quark and anti quark Sivers functions. PRL. 103 (2009) 152002, PLB. 673 (2009) 127, PLB 744 (2015) 250, PRL 107 (2011) 072003

  JHEP 1704 (2017) 046

- We have Drell-Yan data in W^+, W^- and Z_0 production at RHIC $\sqrt{s} = 500$ GeV. C. Aidala et al, PRL 116 (2016) 132301
- However, gluon Sivers function (GSF) is not known fully, though attempts have been made D'Alesio et al, PRD 96 (2017), PRD 99 (2019)

Probing TMDs

- J/ψ production has been advertised to probe the gluon TMDs

For linearly polarized gluon TMD (Boer-Mulders)

Quarkonium pair production $pp \rightarrow J/\psi + J/\psi + X$ at LHC

Lansberg et al, PLB 791 (2019), NPB920 (2017)

Quarkonium-dilepton production $pp \rightarrow J/\psi + l\bar{l} + X$ at LHC

In ep collision $ep \rightarrow e + J/\psi + X$ at EIC

Mukhejee and SR, EPJC 77(2017), Bachetta et al, arXiv:1809.02056

For Sivers function

$pp^{\uparrow} \rightarrow J/\psi + X$ (in CSM)

D'Alesio et al, PRD 96 (2017)

$pp^{\uparrow} \rightarrow p + J/\psi + X$

V.P. Gonclaves, PRD 97 (2018)

Other processes like, $pp^{\uparrow} \rightarrow D + X$, $pp^{\uparrow} \rightarrow \gamma + X$

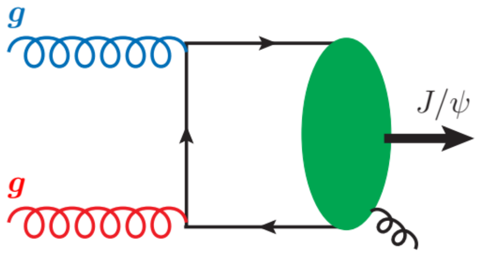
D'Alesio et al, PRD 99 (2019)

$ep^{\uparrow} \rightarrow e + J/\psi + X$

Mukhejee and SR, EPJC 77(2017)

Quarkonium Production

Quarkonium is a bound state of $Q\bar{Q}$



Color Singlet Mechanism (CSM)

Color Evaporation Mechanism (CEM)

NRQCD factorization framework

- In quarkonium production, a heavy quark pair initially is produced in a definite quantum state which can be calculated using perturbation theory.

- Later, the produced heavy quark pair transform into physical quarkonium state by emitting or absorbing soft gluons which happens at the scale below Λ_{QCD} .

NRQCD factorization

LDME

$$d\sigma^{ab\to J/\psi} = \sum_n d\hat{\sigma}[ab \to c\bar{c}(n)]\langle 0 \mid \mathcal{O}_n^{J/\psi} \mid 0\rangle$$

G. T. Bodwin et al, PRD51 (1995)

n is the color, spin and total angular momentum quantum number

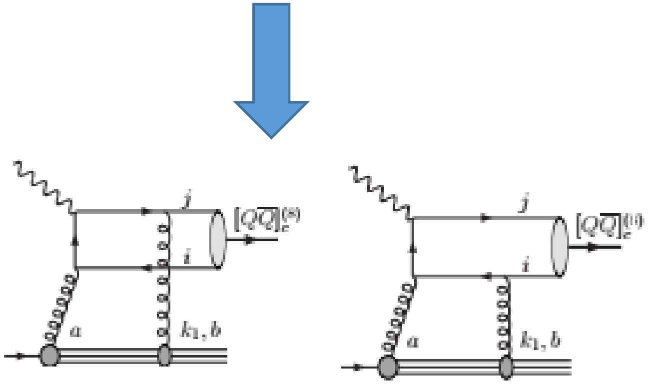
Process Dependence of GSF

- GSF depends on the process under considered and it can be written in terms of two independent Sivers functions f (C-even) and d (C-odd) GSF

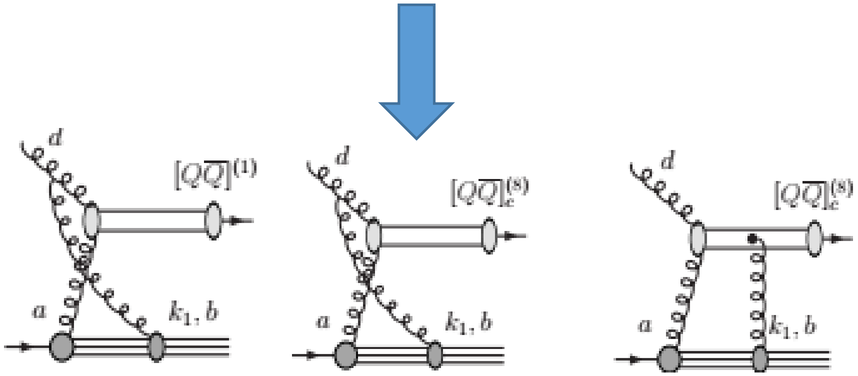
- F. Yuan pointed that under consideration of one gluon exchange approximation

F. Yuan, PRD78 (2008)

A_N^{ep}=0 ($Q\bar{Q}$ in CS)



A_N^{pp}=0 ($Q\bar{Q}$ in CO)



- However, this is true at LO but not valid at NLO in pp collision
- The CO states can contribute to the SSA in pp collision: **On going work**

SSA in $pp^{\uparrow} \rightarrow J/\psi + X$

The SSA is defined as $A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} = \frac{d\Delta\sigma}{2d\sigma}$

- Assuming that TMD factorization holds in the GPM model

- The numerator of the asymmetry is sensitive to the Sivers function

$$d\Delta\sigma = \frac{1}{2(2\pi)^2}\frac{1}{2s}\int \frac{dx_a}{x_a}\frac{dx_b}{x_b} d^2\boldsymbol{k}_{\perp a} d^2\boldsymbol{k}_{\perp b} \Delta\hat{f}_{a/p^{\uparrow}}(x_a, \boldsymbol{k}_{\perp a}) f_{b/p}(x_b, k_{\perp b}) \delta(\hat{s} + \hat{t} + \hat{u} - M^2) |\mathcal{M}_{ab \rightarrow J/\psi c}|^2$$

- The unpolarized differential cross section

$$\frac{d\sigma}{dy d^2\boldsymbol{P}_T} = \frac{1}{2(2\pi)^2}\frac{1}{2s}\int \frac{dx_a}{x_a}\frac{dx_b}{x_b} d^2\boldsymbol{k}_{\perp a} d^2\boldsymbol{k}_{\perp b} f_{a/p}(x_a, k_{\perp a}) f_{b/p}(x_b, k_{\perp b}) \delta(\hat{s} + \hat{t} + \hat{u} - M^2) |\mathcal{M}_{ab \rightarrow J/\psi c}|^2$$

$\Delta\hat{f}_{a/p^{\uparrow}}(x_a, \boldsymbol{k}_{\perp a}) \rightarrow$ Sivers function

$f_{b/p}(x_b, k_{\perp b}) \rightarrow$ Unpolarized TMD

SSA in $pp^{\uparrow} \rightarrow J/\psi + X$

- We have $2 \rightarrow 1$ subprocesses like $gg \rightarrow J/\psi$ and $q\bar{q} \rightarrow J/\psi$
- For $2 \rightarrow 2$ subprocesses like $gg \rightarrow J/\psi g$, $gq \rightarrow J/\psi q$ and $q\bar{q} \rightarrow J/\psi g$
- There are 30 Feynman diagrams over all
- We use the NRQCD framework to calculate the amplitude squares

NRQCD framework

P. L Cho et al, Phys. Rev. **D53**, 6203 (1996)

- The amplitude for quarkonium production is given by

$$\mathcal{M} = \sum_{L_z S_z} \int \frac{d^3\boldsymbol{k}'}{(2\pi)^3} \Psi_{LL_z}(\boldsymbol{k}') \langle LL_z; SS_z | JJ_z \rangle \sum_{ij} \langle 3i; \bar{3}j | 8a \rangle \mathrm{Tr}[O(q, k, P_h, k') \mathcal{P}_{SS_z}(P_h, k')]$$

- $\Psi_{LL_z}(\boldsymbol{k}')$ is the eigenfunction with orbital angular momentum *L*

- $\langle LL_z; SS_z | JJ_z \rangle$ Clebsch-Gordan coefficient projects the orbital angular momentum

- The SU(3) Clebsch-Gordan coefficient projects out the color state of heavy quark pair either in color singlet or octet state $\langle 3i; \bar{3}j | 1 \rangle = \frac{\delta^{ij}}{\sqrt{N_c}}$, $\langle 3i; \bar{3}j | 8a \rangle = \sqrt{2}(T^a)^{ij}$

- Spin projection operator $\mathcal{P}_{SS_z}(P_h, k') = \frac{1}{4M^{3/2}}(-\not{P}_h + 2\not{k}' + M)\Pi_{SS_z}(\not{P}_h + 2\not{k}' + M)$
  with $\Pi_{SS_z} = \gamma^5$ for singlet (S=0) and $\Pi_{SS_z} = \not{\epsilon}_{s_z}(P_h)$ for triplet state (S=1)

- The O is the amplitude for the above Feynman diagrams without the external heavy quark legs

${}^3S_1,\ {}^1S_0,\ {}^3P_0,\ {}^3P_1$ and ${}^3P_2$ CS and CO states are considered

TMDs Parametrization

- First time gluon Sivers function has been extracted form pion data by D' Alesio et al. PRD 99 (2019), 036013

- Gaussian ansatz

$$f(x_a, \mathbf{k}_{\perp a}^2, \mu) = f(x_a, \mu) \frac{1}{\pi \langle k_{\perp a}^2 \rangle} e^{-\mathbf{k}_{\perp a}^2 / \langle k_{\perp a}^2 \rangle}$$

$$\Delta^N f_{a/p^\uparrow}(x_a, k_{\perp a}, \mu) = 2\mathcal{N}_a(x_a) f_{a/p}(x_a, \mu) \frac{\sqrt{2e}}{\pi} \sqrt{\frac{1-\rho}{\rho}} k_{\perp g} \frac{e^{-k_{\perp a}^2 / \rho \langle k_{\perp a}^2 \rangle}}{\langle k_{\perp a}^2 \rangle^{3/2}}$$

$$\mathcal{N}_a(x_a) = N_a x_a^\alpha (1 - x_a)^\beta \frac{(\alpha + \beta)^{(\alpha+\beta)}}{\alpha^\alpha \beta^\beta}$$

Best fit parameters

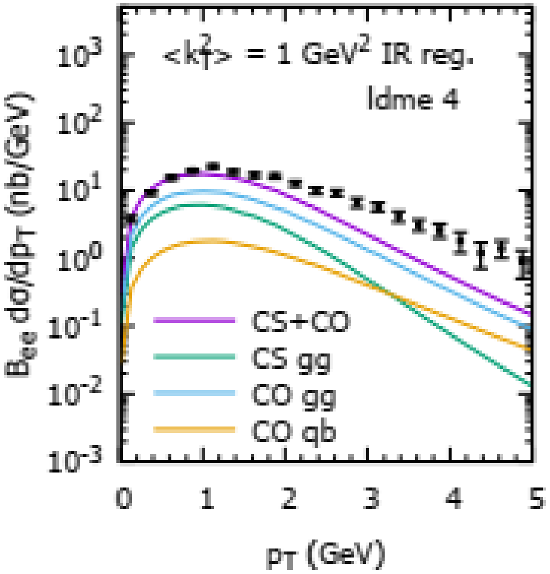
$$N_g = 0.25,\ \alpha = 0.6,\ \beta = 0.6,\ \rho = 0.1,\ \langle k_{\perp a}^2 \rangle = 1.0\ \mathrm{GeV}^2$$

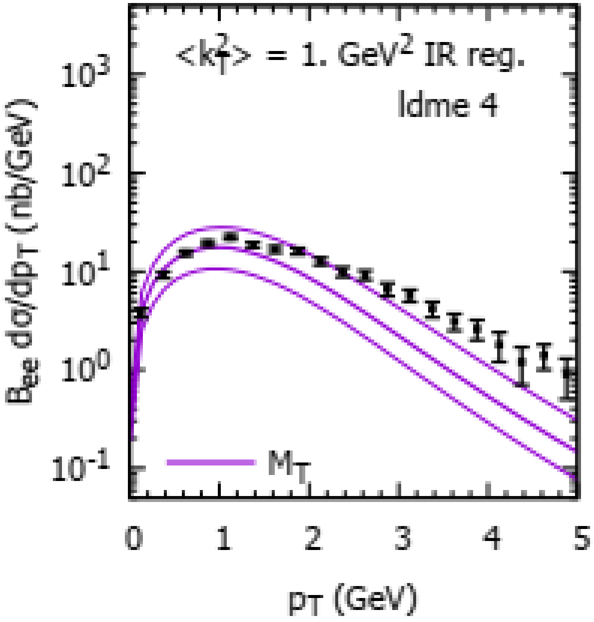
Unpolarized cross section

- The validation of NRQCD factorization has been debatable in low P_T region
- At $P_T = 0$, the final gluon becomes soft which leads to the infrared divergences
- As a result the cross section diverges in collinear factorization approach
- In order to address the issue, resummation and k_T factorization has been used
- In GPM model, the infrared singularities at $P_T = 0$ can be regulated by considering the intrinsic transverse momentum of the parton in the hard part

Unpolarized cross section

$\sqrt{s} = 200$ GeV RHIC





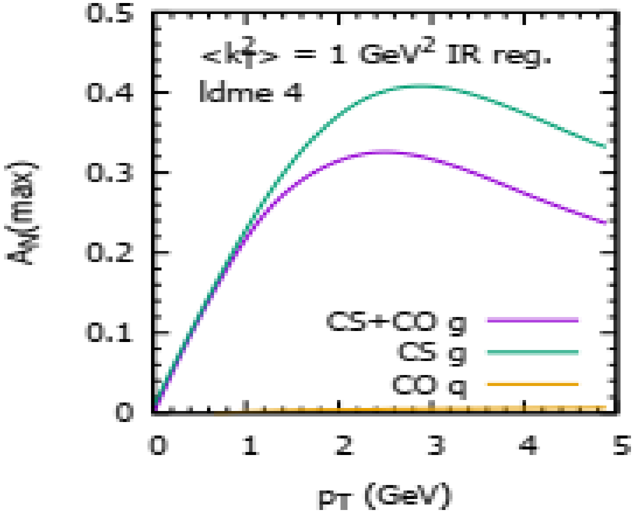
- The contribution of color octet states is needed to match the data along with color singlet states and, the contribution is sizable

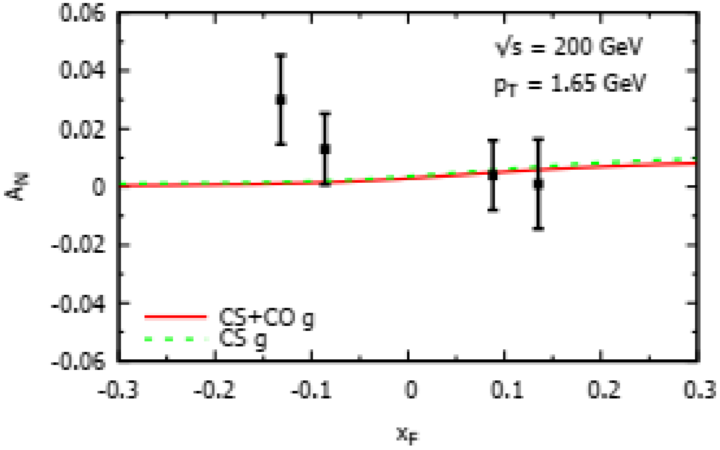
- The higher value for Gaussian width is needed to fit the CDF data

- The values of long distance matrix elements (LDMEs) are taken from M.Butenschoen and Kniehl PRD84 (2008)

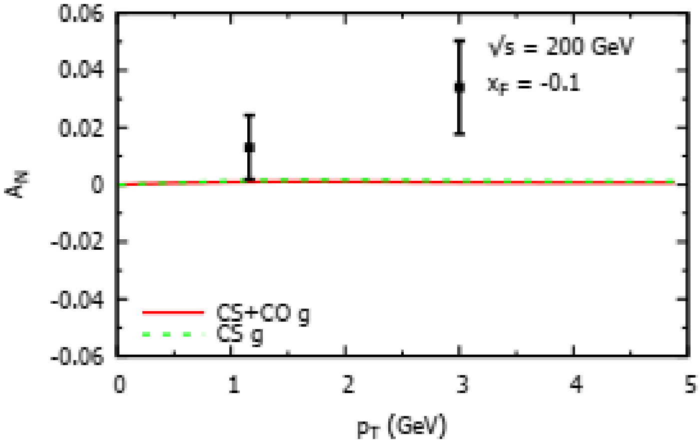
SSA Results for RHIC

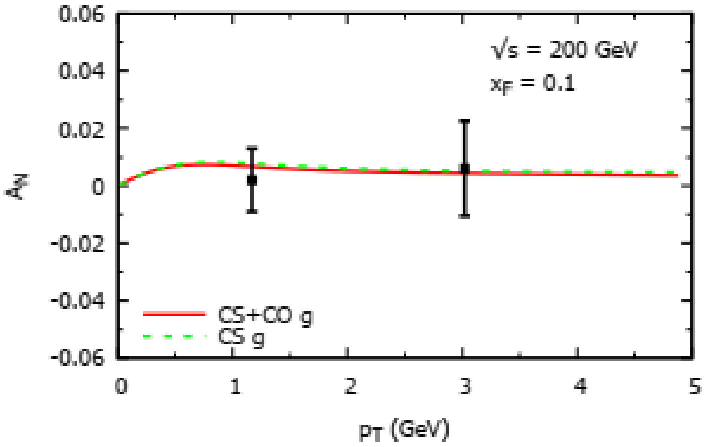
$\sqrt{s} = 200$ GeV RHIC





Data are from C. Aidala et al, PRD 98 (2018) 012006

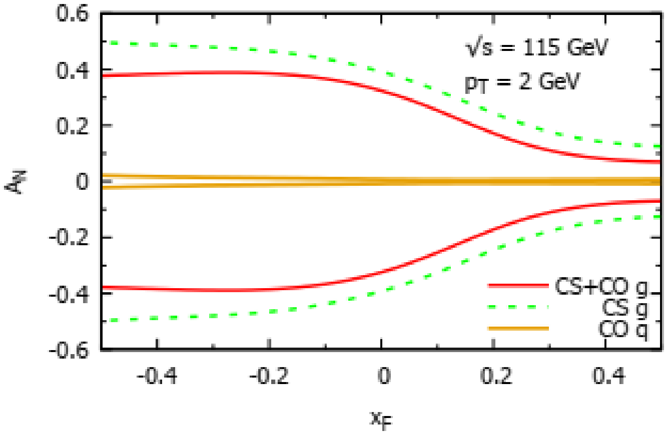


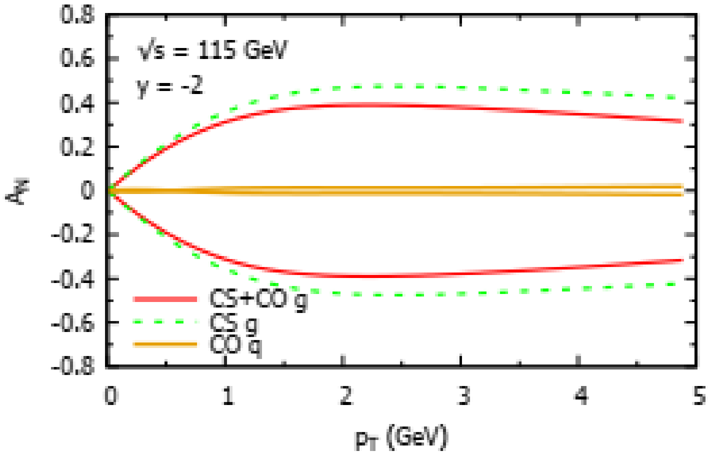


Using GSF parametrization from D’Alesio et al, PRD 99 (2019)

SSA Results for LHC

- The maximum asymmetry by saturating the GSF





Summary

- The SSA is estimated in pp within the GPM including the CS and CO states.

- The estimation of SSA is in good agreement with PHENIX data at forward rapidity region and is compatible with zero

- The prediction of SSA for the process $pp^{\uparrow} \to J/\psi + X$ at LHC is presented

- The unpolarized differential cross section of the J/ψ production in the low P_T region is in good agreement with the PHENIX data

What Next?

- Studying the SSA in CGI-GPM model. Phenomenology part is not yet completed


Thank you