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

Gluon TMDs

Gluon correlator

$$\Phi_g^{\mu\nu;\rho\sigma}(x,k) = \int \frac{d^4\xi}{(2\pi)^4} e^{ik.\xi} \langle P|\mathrm{Tr}[F^{\mu\nu}(\xi)W[\xi,0]F^{\rho\sigma}(0)W[0,\xi]]|P\rangle$$

Mulders and Rodrigues PRD 63 094021(2001)

Parameterization of gluon correlator at "leading twist "

$$\Phi_{\mathrm{un}}^{\mu\nu} = -\frac{1}{2x}\left\{ g_T^{\mu\nu} f_1^g(x,\mathbf{k}_\perp^2) - \left(\frac{k_\perp^\mu k_\perp^\nu}{M_p^2} + g_T^{\mu\nu}\frac{\mathbf{k}_\perp^2}{2M_p^2}\right) h_1^{\perp g}(x,\mathbf{k}_\perp^2)\right\}$$

$$\Phi_T^{\mu\nu} = -\frac{1}{2x} g_T^{\mu\nu} \frac{1}{M_p} \epsilon_T^{\rho\sigma} k_{\perp\rho} S_{T\sigma} f_{1T}^{\perp g}(x,\boldsymbol{k}_\perp^2) + \ldots.$$

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

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

Gluon Sivers function (GSF)

- GSF describes the density of unpolarized gluons inside a transversely polarized nucleon.

$$\Delta\hat{f}_{g/p^\uparrow}(x,\boldsymbol{k}_\perp) = f_{g/p^\uparrow}(x,\boldsymbol{k}_\perp) - f_{g/p^\downarrow}(x,\boldsymbol{k}_\perp)$$

Trento notation

$$\Delta^N f_{g/p^\uparrow} = -2\frac{k_\perp}{M_p} f_{1T}^{\perp g}$$

Parametrization of polarized TMD is

$$f_{g/p^\uparrow}(x,\mathbf{k}_\perp) = f_{g/p}(x,\mathbf{k}_\perp) + \tfrac{1}{2}\Delta^N f_{g/p^\uparrow}(x,k_\perp)\hat{\mathbf{S}}.(\hat{\mathbf{P}}\times\hat{\mathbf{k}}_\perp)$$

Sivers effect

- Under Time-reversal transformation

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

Not yet conformed!

- This kind of non-universal property of Sivers function can be used as tool to test our understanding of SSA PRL. 103 (2009) 152002, PLB. 673 (2009) 127, PLB 744 (2015) 250
- SIDIS data come from HERMES, COMPASS and JLab experiments in pion and kaon production. Global analysis has been done to extract the quarks and anti quarks Sivers function. Anselmino et al, JHEP 1704 (2017) 046, PRL 107 (2011) 072003
- 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, GSF is not known fully, though attempts have been made D'Alesio et al, PRD 96 (2017), PRD 99 (2019)

Process Dependence of GSF

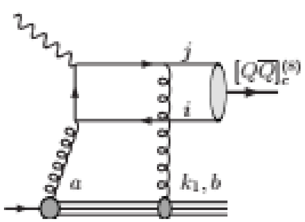
- GSF depends on the process under considered and it can be written in terms of two independent Sivers functions f (C-even) and d (C-odd) GSF

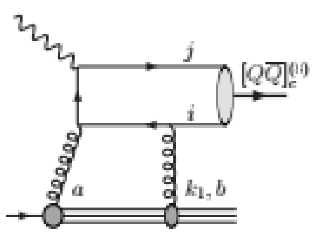
M. Buffing et al, PRD 88 (2013)

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

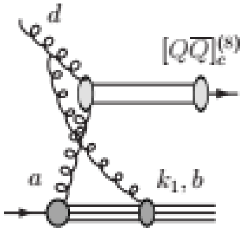
F. Yuan, PRD78 (2008)

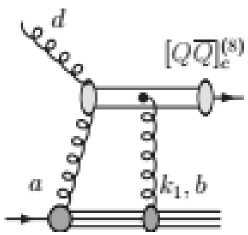
A_N^{ep}=0 ($Q\bar{Q}$ in CS)





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 would contribute to the SSA in pp collision: **On going work**

Probing TMDs

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

For linearly polarized gluon TMD (Boer-Mulders)

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

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

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

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

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

For Sivers function

$pp^{\uparrow} \to J/\psi + X$ (in CSM) D'Alesio et al, PRD 96 (2017)

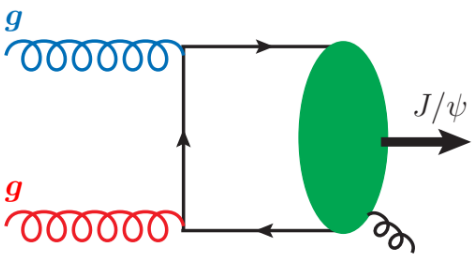
$pp^{\uparrow} \to p + J/\psi + X$ V.P. Gonclaves, PRD 97 (2018)

$ep^{\uparrow} \to e + J/\psi + X$ $ep^{\uparrow} \to J/\psi + X$ Mukhejee and SR, EPJC 77(2017) SR et al, PRD 98(2018)

$ep^{\uparrow} \to e + J/\psi + jet + X$ D'Alesio et al, PRD 100 (2019)

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

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

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

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

- The unpolarized differential cross section

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

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

NRQCD

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

TMDs Parametrization

- First time gluon Sivers function has been extracted using pion data from RHIC

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

- Free parameters in our calculation are: Gaussian width and LDMEs

For Quarks: $<k_\perp^2>= 0.25\ GeV^2$ Anselmino et al JHEP 1704 (2017) 046

Gluons: : $<k_\perp^2>= 1\ GeV^2$ D'Alesio et al, PRD 99 (2019)

- There are several LDME sets in the market (expected to be universal): due to different assumption in the extraction like kinematical cuts on $P_T > 3\ GeV$
- 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 describe low P_T data , resummation, CGC and k_T factorization have been used
- In GPM model, the infrared singularities at $P_T = 0$ can be regulated with the intrinsic transverse momentum of the partons in the hard part
- Two sets of LDMEs are considered

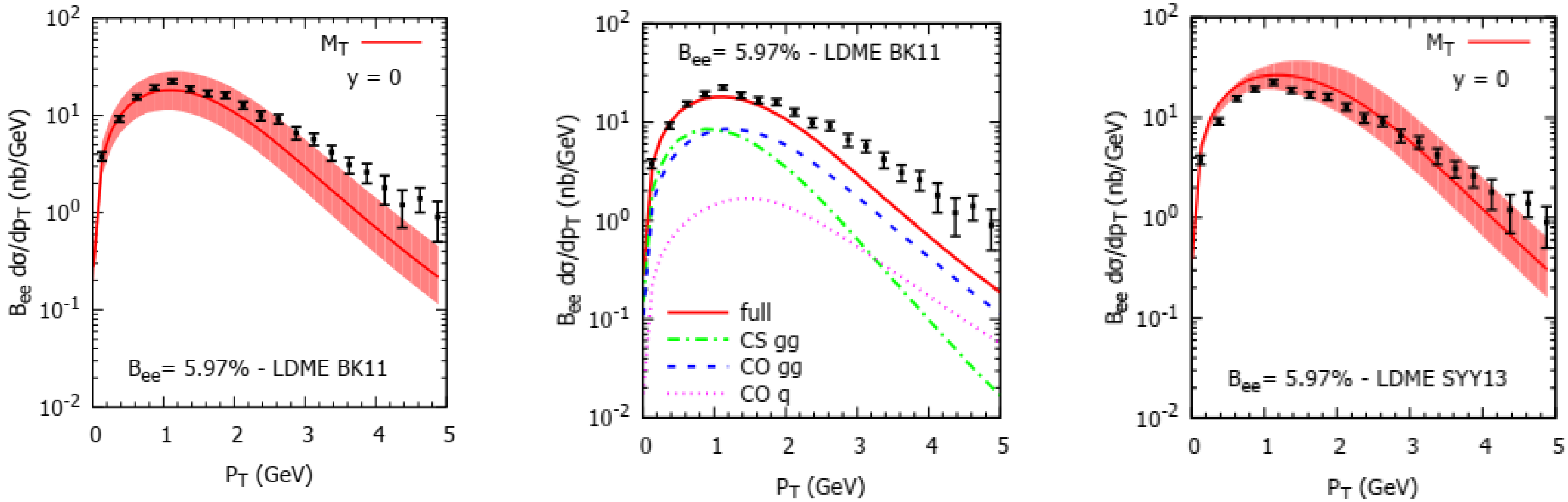
M. Butenschoen and B. Kniehl, PRD84 (2008) 051501 (BK11)

P. Sun, C. Yuan and F. Yuan PRD88 (2013) 054008 (SYY13)

Unpolarized cross section

$\sqrt{s} = 200$ GeV RHIC

Data from A. Adare (PHENIX) et al, PRD 82 (2008) 012001

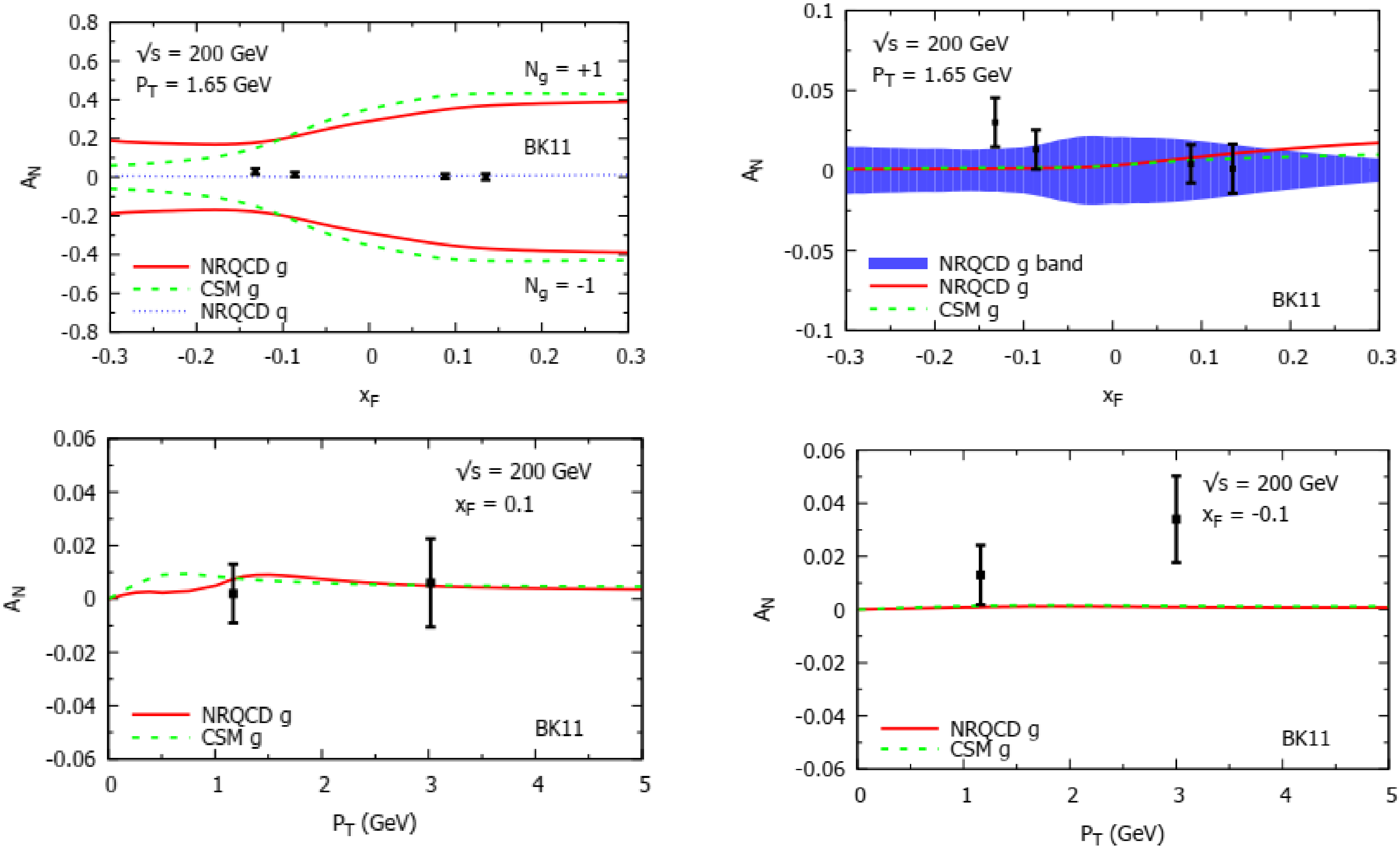


- The contribution of color octet states is needed to match the data along with color singlet states and, the contribution is sizable

U. D' Alesio, F. Murgia, C.Pisano and SR arXiv:1910.09640

SSA Results for RHIC

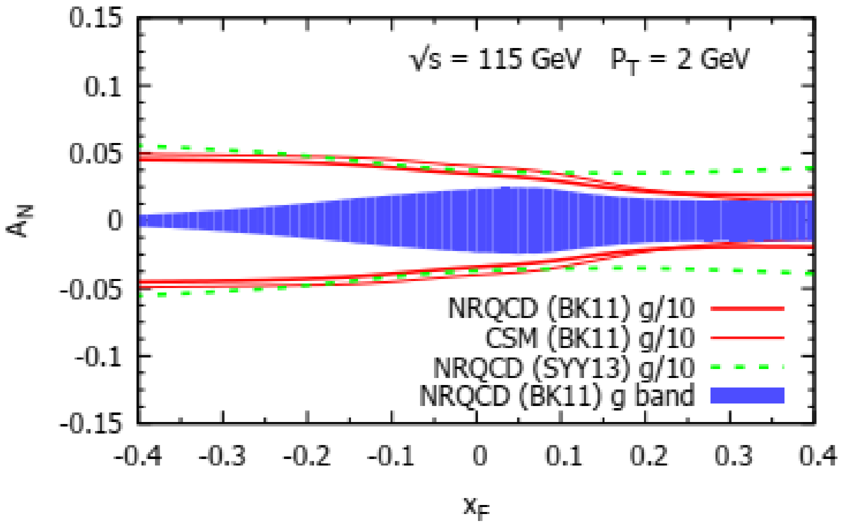
Data from C. Aidala (PHENIX) et al, PRD 98 (2018) 012006

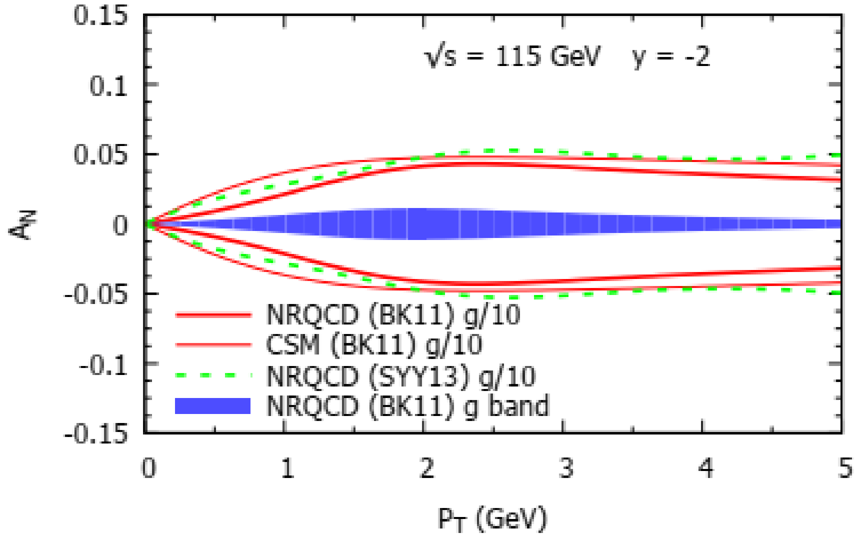


U. D’ Alesio, F. Murgia, C.Pisano and SR arXiv:1910.09640

SSA Results for LHC

- The maximum asymmetry by saturating the GSF





U. D’ Alesio, F. Murgia, C.Pisano and SR arXiv:1910.09640

Summary

- The SSA is estimated in pp within the GPM adopting NRQCD approach.

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

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