PROBING GLUON TMDS IN J/ψ PRODUCTION PROCESSES AT THE EIC

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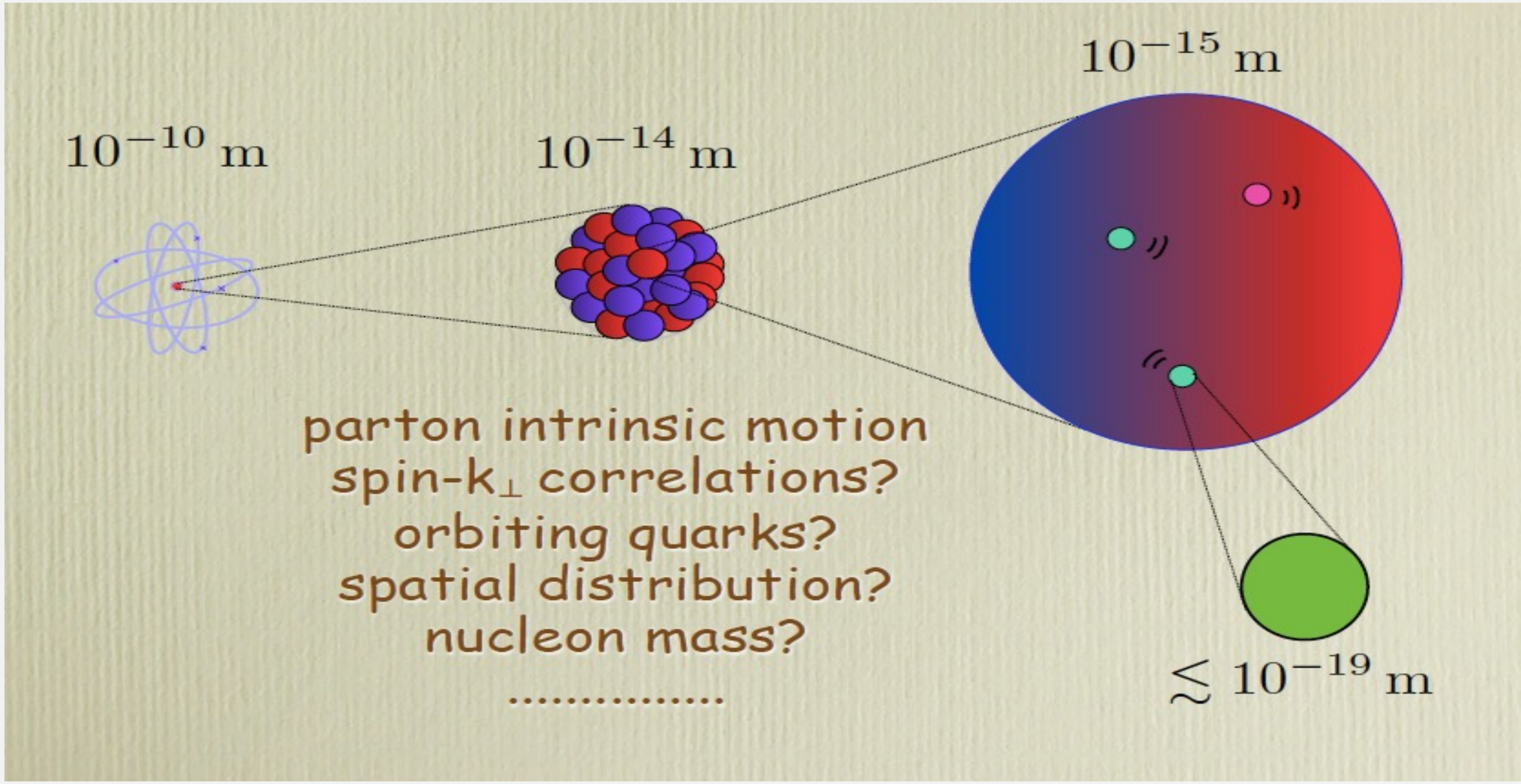
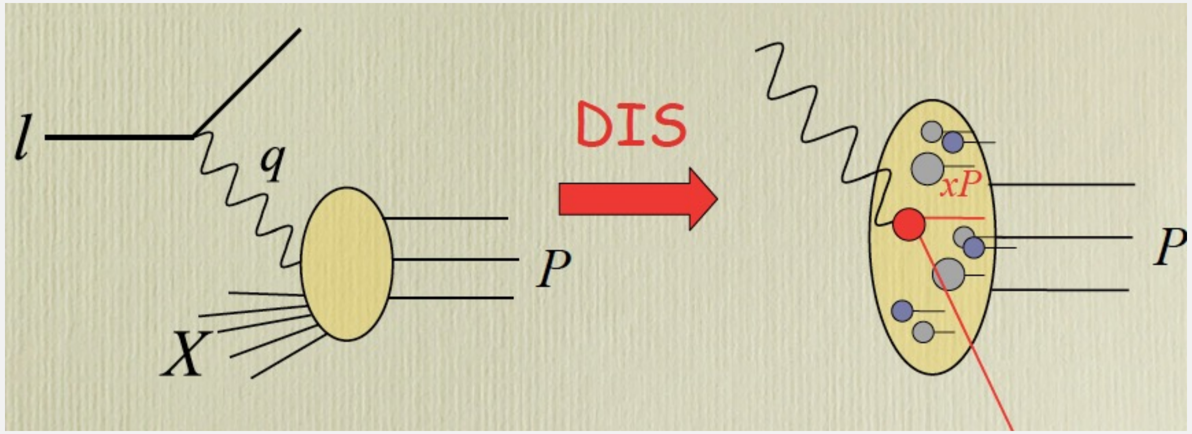
CFNS School, Stony Brook University, June 14 th, 2024

STRUCTURE OF THE NUCLEONS IN TERMS OF QUARKS AND GLUONS : STILL NOT UNDERSTOOD COMPLETELY



Pic : M. Anselmino

NUCLEON STRUCTURE : PROBED THROUGH ELECTRON-PROTON DEEP INELASTIC SCATTERING



$$\ell\, p \to \ell\, X \qquad Q^2 = -q^2 \qquad x = \frac{Q^2}{2P \cdot q}$$

Scattering through a virtual photon

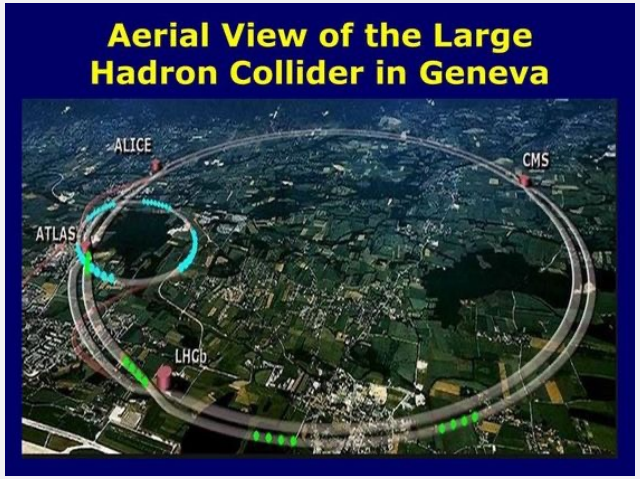
Interacts with the quarks in the nucleon

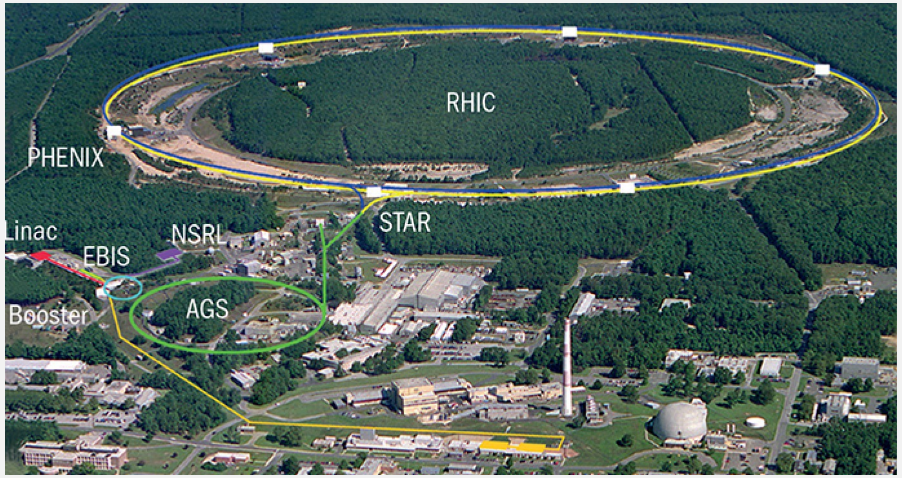
(collinear) parton distributions (pdfs) q(x) ; probability to find a parton in the nucleon with momentum fraction x ; depend also on the momentum scale

Cross section

$$\frac{d\sigma^{\ell p \to \ell X}}{dx\, dQ^2} = \sum_q q(x) \frac{d\hat{\sigma}^{\ell q \to \ell q}}{dQ^2}$$

EXPERIMENTS AROUND THE WORLD





ELECTRON-ION COLLIDER (EIC)

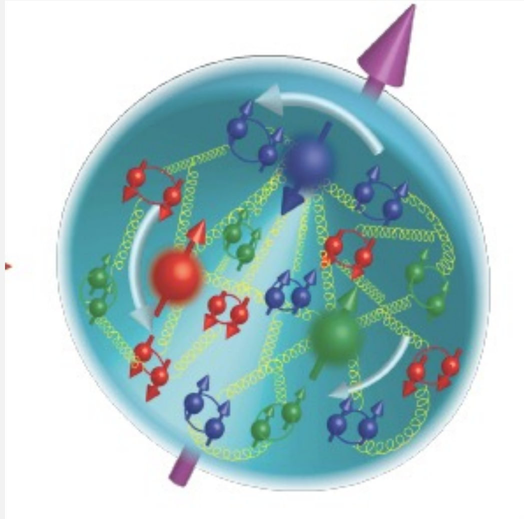
The EIC to be built at Brookhaven National Lab, USA will collide highly energetic electron beam with proton/heavy ion to take 'snapshots' at high accuracy --tomography of the nucleon

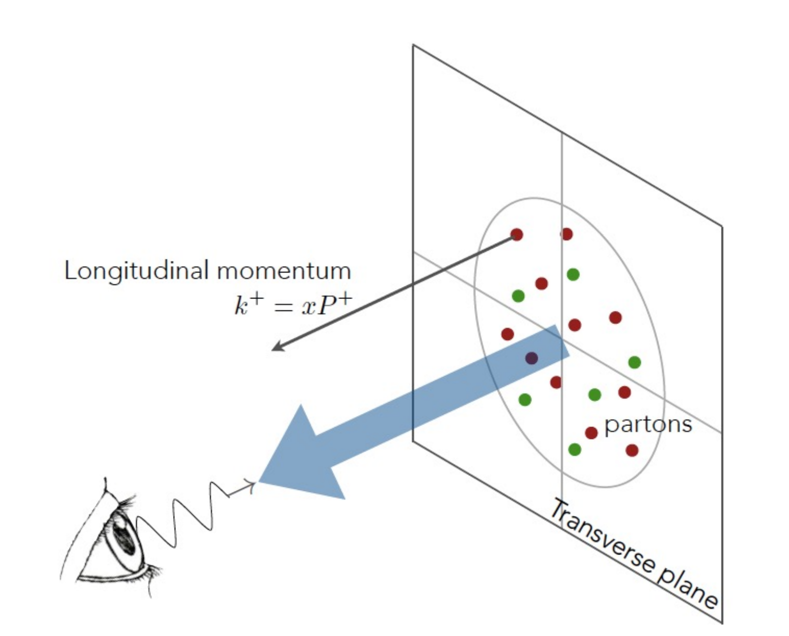
Will try to understand the glue (gluons) that binds us all

Will explore how the spin (1/2) of the proton is made from the spin and orbital angular momentum of the quarks and gluons

Will explore the correlations between spin/OAM and intrinsic transverse momentum

COLLINEAR PDFS : NUCLEON STRUCTURE IN 1-D





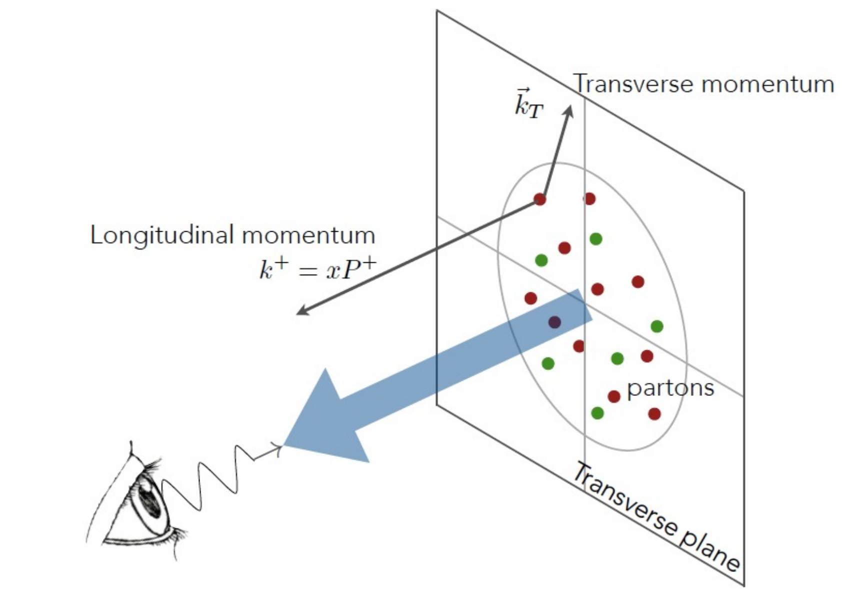
Motion of quarks in the transverse plane ignored

Non-perturbative : Is extracted by fitting experimental data

Scale evolution of pdfs can be calculated

Independent of process : once extracted can be used to predict cross section of another process as the scale evolution is known

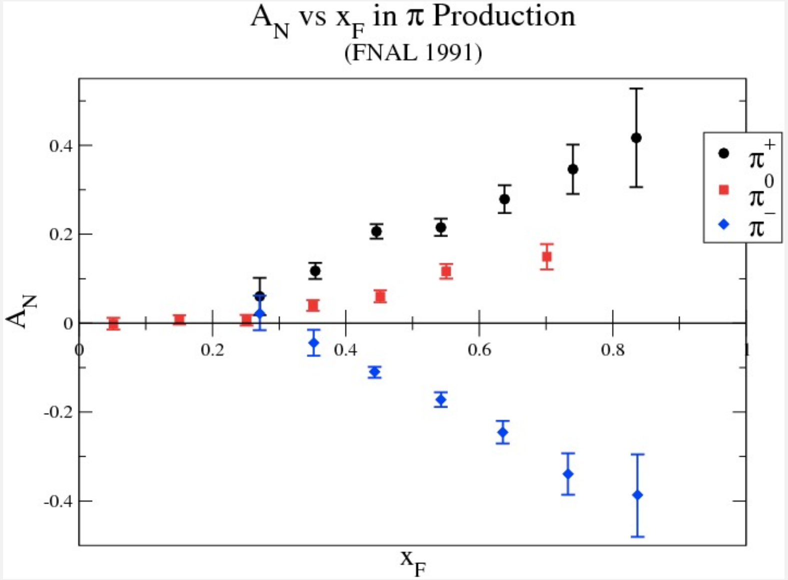
TRANSVERSE MOMENTUM DEPENDENT PARTON DISTRIBUTIONS (TMDS)



Large (30-40%) Single transverse spin asymmetries were seen at FermiLab and RHIC experiments

Such large asymmetries cannot be explained in terms of collinear leading twist pdfs : need TMDs, or twist three pdfs

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

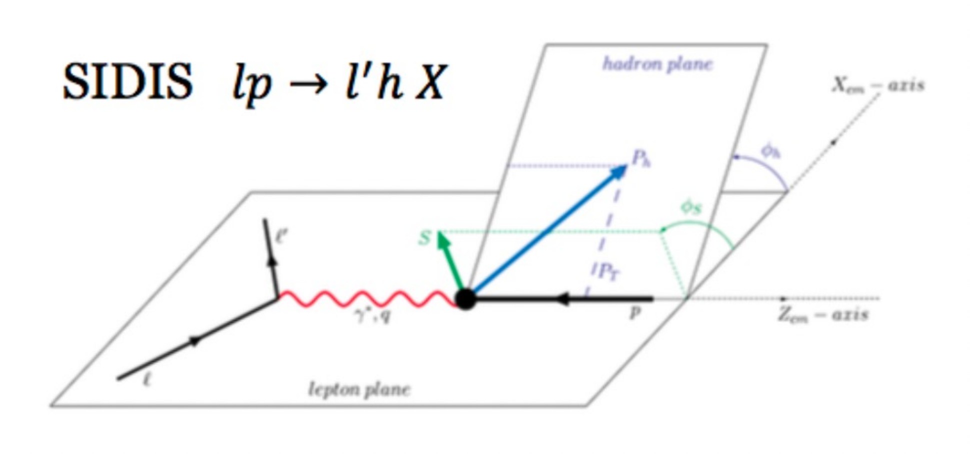


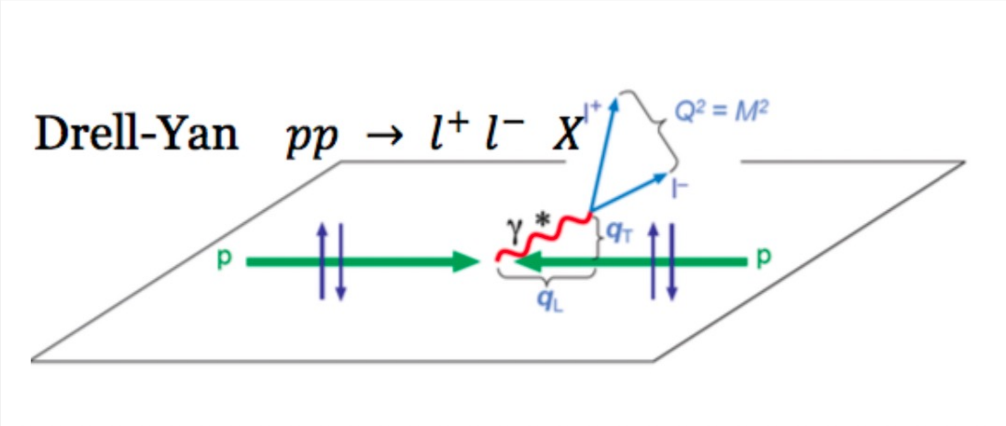
TMDs : functions of x and intrinsic transverse momentum : Gives a 3 D picture of the nucleon in momentum space

Correlations of spin, OAM and k_T : in terms of TMDs

TRANSVERSE MOMENTUM DEPENDENT PDFS (TMDS)

TMDs play a role in processes where two scales are present $Q^2 >> q_T^2$





For SIDIS and DY, TMD factorization is proven to all orders in α_s and leading twist

Collins, Cambridge University Press (2011)
Boussarie et al, TMD handbook 2304.03302

For some processes, attempts have been made to prove TMD factorization at one loop and beyond leading twist

TRANSVERSE MOMENTUM DEPENDENT PDFS (TMDS)

TMD-PDFs hard scattering TMD-FFs

$$d\sigma^{\ell p\to\ell hX} = \sum_q f_q(x, \boldsymbol{k}_\perp; Q^2) \otimes d\hat{\sigma}^{\ell q\to\ell q}(y, \boldsymbol{k}_\perp; Q^2) \otimes D_q^h(z, \boldsymbol{p}_\perp; Q^2)$$

TMDs play an important role in single spin and azimuthal asymmetries

Process dependent due to the gauge link or Wilson line in the operator

Gauge invariant definition of Φ (not unique)

$$\Phi^{[\mathcal{U}]} \propto \left\langle P, S \left| \overline{\psi}(0)\, \mathcal{U}^{\mathcal{C}}_{[0,\xi]}\, \psi(\xi) \right| P, S \right\rangle \qquad \mathcal{U}^{\mathcal{C}}_{[0,\xi]} = \mathcal{P}\exp\left(-ig \int_{\mathcal{C}[0,\xi]} ds_\mu A^\mu(s)\right)$$

Φ : quark correlator, parametrized in terms of TMDs

Gauge link : resummation of initial and/or final state gluon exchanges : process dependent

QUARK TMDS

QUARKS	*unpolarized*	*chiral*	*transverse*
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_{1T}, h_{1T}^\perp$

Angeles-Martinez *et al.*, Acta Phys, Pol. B46 (2015)
Mulders, Rodrigues, PRD 63 (2001)
Meissner, Metz, Goeke, PRD 76 (2007)

There are eight quark TMDs at leading twist

Only three of them survive after transverse momentum integration

Two TMDs, Sivers function and Boer-Mulders function are odd under time reversal

TMDs contribute in different azimuthal angle asymmetries

Extraction of unpolarized TMD as well as the Sivers function Upto N^3LL

Pavia 2017, JHEP 06 (2017)
Scimemi, Vladimirov, JHEP 06 (2020)
MAP Collaboration, JHEP (2022)

Bury, Prokudin, Vladimirov, PRL 126 (2021)
Echevarria, Kang, Terry, JHEP 01 (2021)
Bacchetta, Delcarro, Pisano, Radici, CP, PLB 827 (2022)

GLUON TMDS

GLUONS	*unpolarized*	*circular*	*linear*
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	$h_{1T}^g,\ h_{1T}^{\perp g}$

$h_1^{\perp g}$: Linearly polarized gluon distribution in unpolarized hadron; T even

$f_{1T}^{\perp g}$ Gluon Sivers function in Transversely polarized proton

Angeles-Martinez *et al.*, Acta Phys, Pol. B46 (2015)
Mulders, Rodrigues, PRD 63 (2001)
Meissner, Metz, Goeke, PRD 76 (2007)

$$h_1^g \equiv h_{1T}^g + \frac{\boldsymbol{p}_T^2}{2M_p^2}\, h_{1T}^{\perp g}$$

Vanish under p_T integration

In contrast to quark TMDs, very little is known about gluon TMDs

$$\Gamma^{[\mathcal{U},\mathcal{U}']\mu\nu} \propto \langle P,S|\,\mathrm{Tr}_c\left[\,F^{+\nu}(0)\,\mathcal{U}^{\mathcal{C}}_{[0,\xi]}\,F^{+\mu}(\xi)\,\mathcal{U}^{\mathcal{C}'}_{[\xi,0]}\,\right]|P,S\rangle$$

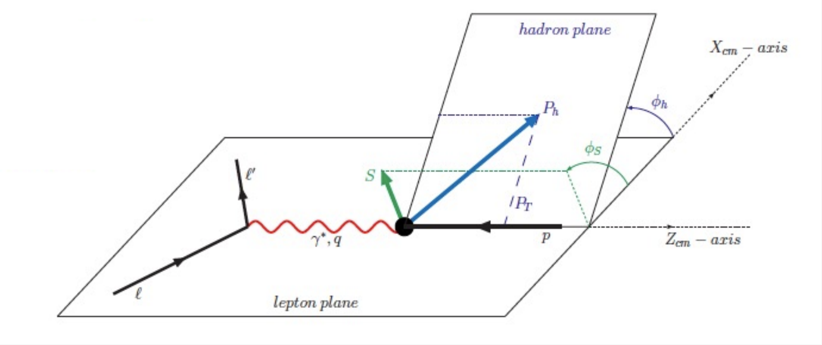
Gluon TMDs need two gauge links for gauge invariance

Mulders, Rodrigues, PRD 63 (2001)
Buffing, Mukherjee, Mulders, PRD 88 (2013)
Boer, Cotogno, Van Daal, Mulders, Signori, Zhou, JHEP 1610 (2016)

SIMPLE EXAMPLE OF PROCESS DEPENDENCE OF TMDS : SIVERS EFFECT

Diff cross section for SIDIS with transversely polarized proton can be written as

$$
\begin{aligned}
&\frac{d\sigma^{\ell+p(S_T)\to\ell' hX}}{dx_B\, dQ^2\, dz_h\, d^2\boldsymbol{P}_T\, d\phi_S} = \frac{2\,\alpha^2}{Q^4} \times \\
&\left\{ \frac{1+(1-y)^2}{2} F_{UU} + (2-y)\sqrt{1-y}\,\cos\phi_h\, F_{UU}^{\cos\phi_h} + (1-y)\,\cos 2\phi_h\, F_{UU}^{\cos 2\phi_h} \right. \\
&+ \left[\frac{1+(1-y)^2}{2}\, \sin(\phi_h-\phi_S)\, F_{UT}^{\sin(\phi_h-\phi_S)} + (1-y)\,\sin(\phi_h+\phi_S)\, F_{UT}^{\sin(\phi_h+\phi_S)} \right. \\
&+ \quad (1-y)\,\sin(3\phi_h-\phi_S)\, F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&+ \quad \left.\left. (2-y)\sqrt{1-y}\left(\sin\phi_S\, F_{UT}^{\sin\phi_S} + \sin(2\phi_h-\phi_S)\, F_{UT}^{\sin(2\phi_h-\phi_S)} \right) \right] \right\}
\end{aligned}
$$

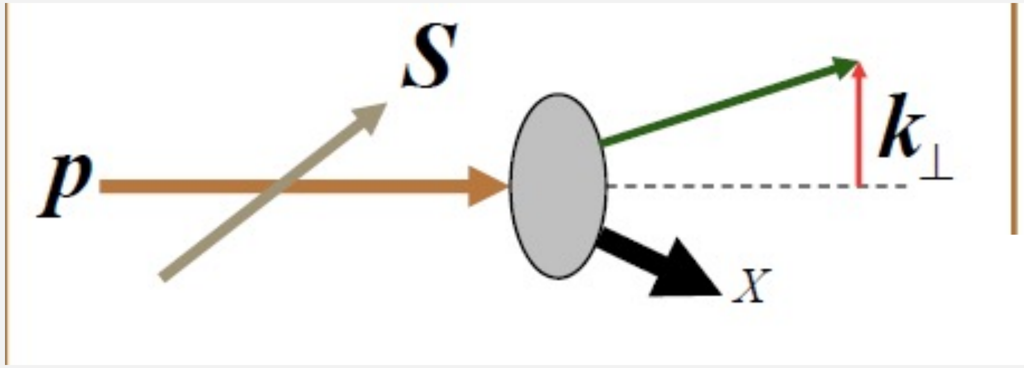


$$
F_{UT}^{\sin(\phi-\phi_S)} \sim \sum e_a^2\, f_{1T}^{\perp a} \otimes D_1^a
$$

F functions contain different TMDs : each come with a different azimuthal modulation

Sivers Function

SIVERS FUNCTION



$$f_{q/p,S}(x,k_\perp) = f_{q/p}(x,k_\perp) + \frac{1}{2}\Delta^N f_{q/p^\uparrow}(x,k_\perp)\, \boldsymbol{S}\cdot(\hat{\boldsymbol{p}}\times\hat{\boldsymbol{k}}_\perp)$$

$$= f_{q/p}(x,k_\perp) - \frac{k_\perp}{M} f_{1T}^{\perp q}(x,k_\perp)\, \boldsymbol{S}\cdot(\hat{\boldsymbol{p}}\times\hat{\boldsymbol{k}}_\perp)$$

Sivers function TMD (D. Sivers; PRD (1990)) is related to the probability to find an unpolarized quark inside a transversely polarized nucleon

It includes the correlation between the quark intrinsic transverse momentum and the transverse spin of the proton

In some models it is related to the orbital angular momentum of the quarks

Meissner, Metz, Goeke, PRD 76 (2007), 034002

T-odd function ; depends on gauge link

PROCESS DEPENDENCE OF TMDS

Gauge link is also present in collinear pdfs : but it is possible to choose a gauge (light-front gauge) where the gauge link becomes unity.

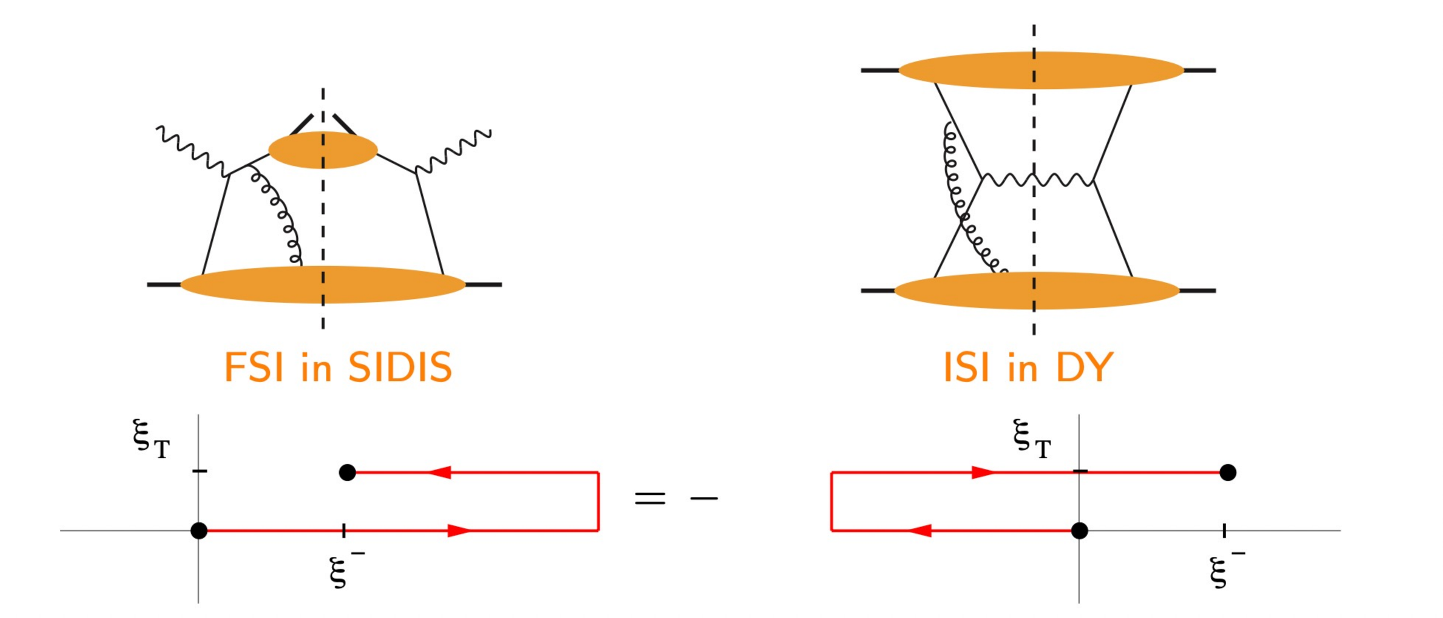
This is because the collinear pdf operator is bilocal only in the longitudinal direction but TMD operator is bilocal both in longitudinal and transverse direction

$\bar{\psi}(y^-)\Gamma\psi(0)$ $\bar{\psi}(y^-, y^\perp)\Gamma\psi(0)$ $y^- = y^0 - y^3$

For TMDs, even if one chooses the light cone gauge the effect of the gauge link remains and in fact plays a very important role for the T-odd TMDs like Sivers function.
Such TMDs would be zero if the gauge link is not taken into account

J. C. Collins, Phys. Lett. B 536 (2002) 43

SIVERS FUNCTION : PROCESS DEPENDENCE



Gauge link : depends on specific process . Example : SIDIS (final state interaction, future pointing gauge link) and Drell Yan (initial state interaction, past pointing gauge link)

Sivers function in Drell-Yan process is same in magnitude but opposite in sign compared to the Sivers function probed in semi-inclusive DIS

$$f_{1T}^{\perp\,[DY]}(x, \boldsymbol{k}_\perp^2) = -f_{1T}^{\perp\,[SIDIS]}(x, \boldsymbol{k}_\perp^2)$$

Collins, PLB (2002); Boer, Mulders, Pijlman, Nucl. Phy. B (2003)

However, more complex processes have complex gauge link structure, and factorization is not always guaranteed

LINEARLY POLARIZED GLUON DISTRIBUTIONS

Linearly polarized gluon distributions were first introduced in

Mulders and Rodrigues, PRD 63, 094021 (2001)

Operator structure of unintegrated gluon distributions can be different in different processes. In the literature, at small x, Weizsacker-Williams (WW) gluon distribution contains both past or both future pointing gauge links and dipole distributions contain one past and one future pointing gauge link. These are also called f and d type distributions, contribute in different processes

Extensive literature on unintegrated gluon distributions.

Linearly polarized gluon TMD : Measures an interference between an amplitude when the active gluon is polarized along x (or y) direction and a complex conjugate amplitude with the gluon polarized in y (or x) direction in an unpolarized hadron

Affects unpolarized cross section as well as generates a cos 2ϕ asymmetry

GLUON SIVERS FUNCTION (GSF)

Distribution of quarks and gluons in a transversely polarized proton is not left-right symmetric with respect to the plane formed by the momentum and spin directions – this generates an asymmetry called Sivers effect

D. Sivers, PRD 41, 83 (1990)

Highly sensitive to the color flow of the process and on initial/final state interactions (T-odd)

In some models, the Sivers function TMD is related to the orbital angular momentum of the quarks

Very little is known about GSF apart from a positivity bound

Depending on the gauge link in the operator structure there can be two different gluon Sivers function, f-type and d-type

Bomhof and Mulders, JHEP 02, 029 (2007),
Buffing, AM, Mulders, PRD 88, 054027 (2013)

Burkardt's sum rule, which states that the total transverse momentum of all quarks and gluon in a transversely polarized proton is zero, still leaves some room for GSF (30 %), moreover d type GSF is not constrained by it.

M. Burkardt, Phys. Rev. D 69, 091501 (2004)

Back-to-back J/ψ-photon/jet/pion production processes in eP collision are effective ways to probe the gluon TMDs : expect TMD factorization. Only f-type gluon TMDs contribute

GLUON TMDS IN J/ψ PRODUCTION PROCESSES

Semi-inclusive J/ψ production in eP collision is a good cannel to probe gluon TMDs

Godbole, Misra, AM, Rawoot, PRD (2012); AM and Rajesh EPJC (2017)

For low transverse momentum region, TMD factorization is expected to hold and for large transverse momentum collinear factorization is applicable. In the intermediate region, results from these two formalisms should match

TMD factorized description of the process needs smearing effects to be taken into account in the form of TMD shape functions. The perturbative tail of the shape function can be obtained through a matching procedure.

M. G. Echevarria, JHEP (2019), Boer et al, JHEP (2023)

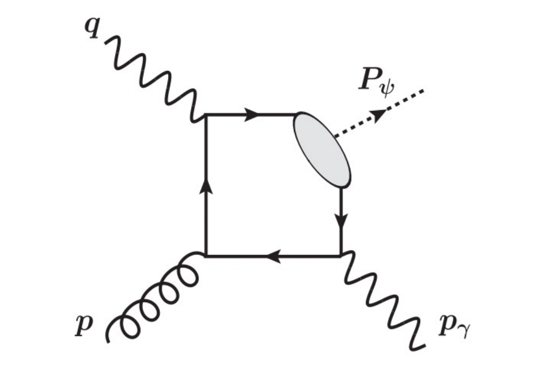
Also gluon TMDs can be probed in back-to-back production of J/ψ and photon/jet/pion, TMD factorization is expected to be valid. The small scale is provided by the transverse momentum of the pair. By varying the invariant mass of the pair scale evolution of the TMDs can be studied

So far the smearing effects and the shape functions are not calculated by matching procedure

GLUON TMDS IN J/ψ AND PHOTON PRODUCTION

We consider the following process where the proton can be unpolarized or transversely polarized

$$e(l) + p^{\uparrow}(P) \to e(l') + J/\psi(P_\psi) + \gamma(p_\gamma) + X,$$



$$P^\mu = n_-^\mu + \frac{M_p^2}{2} n_+^\mu \approx n_-^\mu,$$

$$q^\mu = -x_B n_-^\mu + \frac{Q^2}{2x_B} n_+^\mu \approx -x_B P^\mu + (P \cdot q) n_+^\mu,$$

$$l^\mu = \frac{1-y}{y} x_B n_-^\mu + \frac{1}{y} \frac{Q^2}{2x_B} n_+^\mu + \frac{\sqrt{1-y}}{y} Q \hat{l}_\perp^\mu,$$

$$Q^2 = x_b y S \qquad S = (P+l)^2$$

$$y = \frac{P \cdot q}{P \cdot l} \qquad x_B = \frac{Q^2}{2P \cdot q}$$

$$\mathrm{d}\sigma = \frac{1}{2S} \frac{\mathrm{d}^3 \boldsymbol{l}'}{(2\pi)^3 2E_{l'}} \frac{\mathrm{d}^3 \boldsymbol{P}_\psi}{(2\pi)^3 2E_\psi} \frac{\mathrm{d}^3 \boldsymbol{p}_\gamma}{(2\pi)^3 2E_\gamma} \times \int \mathrm{d}x \mathrm{d}^2 \boldsymbol{p}_T (2\pi)^4 \delta^4(q + p - P_\psi - p_\gamma) \times \frac{1}{Q^4} L^{\mu\nu}(l, q) \Phi_g^{\rho\sigma}(x, \boldsymbol{p}_T) H_{\mu\rho} H_{\nu\sigma}^*.$$

Partonic subprocess : virtual photon-gluon fusion

J/ψ production in color singlet channel in virtual photon-photon fusion is suppressed due to a larger gluon density

Use TMD factorization

D. Chakrabarti, R. Kishore, AM, S. Rajesh, *Phys.Rev.D* 107 (2023) 1, 014008

PRODUCTION OF J/Ψ IN NRQCD

In NRQCD the heavy quark pair is produced in the hard process either in color octet or in color singlet configuration

Then they hadronize to form a color singlet quarkonium state of given quantum numbers through soft gluon emission

Hard process is calculated perturbatively and soft process is given in terms of long distance matrix elements (LDMEs) that are determined from data

The LDMEs are categorized by performing an expansion in terms of the relative velocity of the heavy quark v in the limit $v \ll 1$

The theoretical predictions are arranged as double expansions in terms of v as well as α_s.

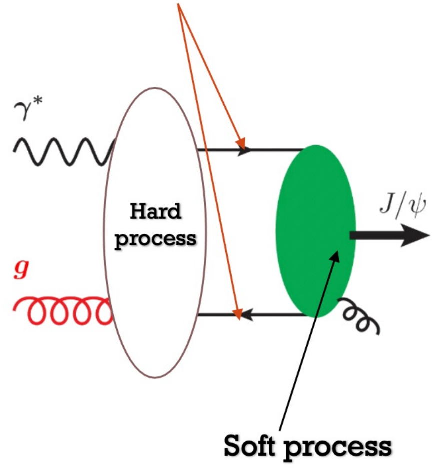
C. E. Carlson and R. Suaya, Phys. Rev. D 14, 3115 (1976).
E. L. Berger and D. L. Jones, Phys. Rev. D 23, 1521 (1981).
R. Baier and R. Ruckl, Phys. Lett. B 102B, 364 (1981).
R. Baier and R. Ruckl, Nucl. Phys. B201, 1 (1982).
E. Braaten and S. Fleming, Phys. Rev. Lett. 74, 3327 (1995).
P. L. Cho and A. K. Leibovich, Phys. Rev. D 53, 150 (1996).

G. T. Bodwin, E. Braaten, and G. P. Lepage, Phys. Rev. D 51, 1125 (1995); 55, 5853(E) (1997).

PRODUCTION OF J/Ψ IN NRQCD

J/ψ is a bound state of charm quark and anti-quark ($Q\bar{Q}$)

$Q\bar{Q}$ pair with $[^{2S+1}L_J^{(1,8)}]$ quantum number



Long distance matrix elements (LDMEs) : Describes hadronization of of $Q\bar{Q}[n]$ states into final quarkonium state

NRQCD factorization

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

Perturbative short distance coefficient

Subprocess cross section for formation of heavy quark pair in particular color, angular momentum and spin state "n" : $^{2S+1}L_J$, calculated by perturbative QCD

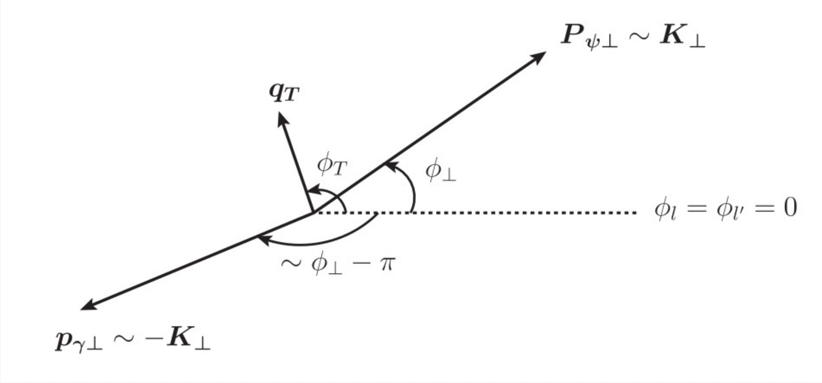
G.T. Bodwin et al, PRD51 (1995), Lepage 95

GLUON TMDS IN J/ψ AND PHOTON PRODUCTION

J/ψ and photon almost back to back

$$\boldsymbol{q}_T \equiv \boldsymbol{P}_{\psi\perp} + \boldsymbol{p}_{\gamma\perp}, \qquad \boldsymbol{K}_\perp \equiv \frac{\boldsymbol{P}_{\psi\perp} - \boldsymbol{p}_{\gamma\perp}}{2}.$$

$$q_T \ll K_\perp$$



We use NRQCD to calculate J/ψ production. At leading order only one CO state $^3S_1^{(8)}$ contributes

Cross section depends on only one LDME at LO , and the asymmetry becomes independent of the LDME

$$\Phi_U^{\mu\nu}(x,\boldsymbol{p}_T) = \frac{1}{2x}\left\{-g_T^{\mu\nu} f_1^g(x,\boldsymbol{p}_T^2) + \left(\frac{p_T^\mu p_T^\nu}{M_p^2} + g_T^{\mu\nu}\frac{\boldsymbol{p}_T^2}{2M_p^2}\right) h_1^{\perp g}(x,\boldsymbol{p}_T^2)\right\}$$

$$\Phi_T^{\mu\nu}(x,\boldsymbol{p}_T) = \frac{1}{2x}\left\{-g_T^{\mu\nu}\frac{\epsilon_T^{\rho\sigma} p_{T\rho} S_{T\sigma}}{M_p} f_{1T}^{\perp g}(x,\boldsymbol{p}_T^2) + i\epsilon_T^{\mu\nu}\frac{\boldsymbol{p}_T\cdot \boldsymbol{S}_T}{M_p} g_{1T}^g(x,\boldsymbol{p}_T^2) + \frac{p_{T\rho}\epsilon_T^{\rho\{\mu} p_T^{\nu\}}}{2M_p^2}\frac{\boldsymbol{p}_T\cdot \boldsymbol{S}_T}{M_p} h_{1T}^{\perp g}(x,\boldsymbol{p}_T^2) - \frac{p_{T\rho}\epsilon_T^{\rho\{\mu} S_T^{\nu\}} + S_{T\rho}\epsilon_T^{\rho\{\mu} p_T^{\nu\}}}{4M_p} h_{1T}^g(x,\boldsymbol{p}_T^2)\right\}$$

In the back-to-back kinematics, we approximate

$$\boldsymbol{P}_{\psi\perp} \simeq -\boldsymbol{p}_{\gamma\perp} \simeq \boldsymbol{K}_\perp.$$

Mulders and Rodrigues, PRD 63, 094021 (2001)

CROSS SECTION AND ASYMMETRY

$$\frac{\mathrm{d}\sigma}{\mathrm{d}z\mathrm{d}y\mathrm{d}x_B\mathrm{d}^2\boldsymbol{q}_T\mathrm{d}^2\boldsymbol{K}_\perp} \equiv \mathrm{d}\sigma(\phi_S,\phi_T,\phi_\perp) = \mathrm{d}\sigma^U(\phi_T,\phi_\perp) + \mathrm{d}\sigma^T(\phi_S,\phi_T,\phi_\perp).$$

$$\mathrm{d}\sigma^U = \mathcal{N}\Big[(\mathcal{A}_0 + \mathcal{A}_1\cos\phi_\perp + \mathcal{A}_2\cos 2\phi_\perp) f_1^g(x,\boldsymbol{q}_T^2) + (\mathcal{B}_0\cos 2\phi_T + \mathcal{B}_1\cos(2\phi_T-\phi_\perp)$$
$$+ \mathcal{B}_2\cos 2(\phi_T-\phi_\perp) + \mathcal{B}_3\cos(2\phi_T-3\phi_\perp) + \mathcal{B}_4\cos(2\phi_T-4\phi_\perp))\frac{\boldsymbol{q}_T^2}{M_p^2} h_1^{\perp g}(x,\boldsymbol{q}_T^2)\Big],$$

Unpolarized proton

$$\mathrm{d}\sigma^T = \mathcal{N}|\boldsymbol{S}_T|\Big[\sin(\phi_S-\phi_T)(\mathcal{A}_0 + \mathcal{A}_1\cos\phi_\perp + \mathcal{A}_2\cos 2\phi_\perp)\frac{|\boldsymbol{q}_T|}{M_p} f_{1T}^{\perp g}(x,\boldsymbol{q}_T^2)$$
$$+ \cos(\phi_S-\phi_T)(\mathcal{B}_0\sin 2\phi_T + \mathcal{B}_1\sin(2\phi_T-\phi_\perp) + \mathcal{B}_2\sin 2(\phi_T-\phi_\perp)$$
$$+ \mathcal{B}_3\sin(2\phi_T-3\phi_\perp) + \mathcal{B}_4\sin(2\phi_T-4\phi_\perp))\frac{|\boldsymbol{q}_T|^3}{M_p^3} h_{1T}^{\perp g}(x,\boldsymbol{q}_T^2)$$
$$+ (\mathcal{B}_0\sin(\phi_S+\phi_T) + \mathcal{B}_1\sin(\phi_S+\phi_T-\phi_\perp) + \mathcal{B}_2\sin(\phi_S+\phi_T-2\phi_\perp)$$
$$+ \mathcal{B}_3\sin(\phi_S+\phi_T-3\phi_\perp) + \mathcal{B}_4\sin(\phi_S+\phi_T-4\phi_\perp))\frac{|\boldsymbol{q}_T|}{M_p} h_{1T}^{g}(x,\boldsymbol{q}_T^2)\Big],$$

Transversely polarized proton

Weighted asymmetry :

$$A^{W(\phi_S,\phi_T)} \equiv 2\frac{\int \mathrm{d}\phi_S\mathrm{d}\phi_T\mathrm{d}\phi_\perp W(\phi_S,\phi_T)\mathrm{d}\sigma(\phi_S,\phi_T,\phi_\perp)}{\int \mathrm{d}\phi_S\mathrm{d}\phi_T\mathrm{d}\phi_\perp \mathrm{d}\sigma(\phi_S,\phi_T,\phi_\perp)},$$

Using the weight factors, specific azimuthal modulations are isolated.

C. Pisano, D. Boer, S. J. Brodsky, M. G. A. Buffing, and P. J. Mulders, J. High Energy Phys. 10 (2013) 024.

ASYMMETRY

$$A^{\cos 2\phi_T} = \frac{\boldsymbol{q}_T^2}{M_p^2} \frac{\mathcal{B}_0}{\mathcal{A}_0} \frac{h_1^{\perp g}(x, \boldsymbol{q}_T^2)}{f_1^g(x, \boldsymbol{q}_T^2)},$$

$$A^{\cos 2(\phi_T - \phi_\perp)} = \frac{\boldsymbol{q}_T^2}{M_p^2} \frac{\mathcal{B}_2}{\mathcal{A}_0} \frac{h_1^{\perp g}(x, \boldsymbol{q}_T^2)}{f_1^g(x, \boldsymbol{q}_T^2)}.$$

$$A^{\sin(\phi_S - \phi_T)} = \frac{|\boldsymbol{q}_T|}{M_p} \frac{f_{1T}^{\perp g}(x, \boldsymbol{q}_T^2)}{f_1^g(x, \boldsymbol{q}_T^2)},$$

$$A^{\sin(\phi_S + \phi_T)} = \frac{|\boldsymbol{q}_T|}{M_p} \frac{\mathcal{B}_0}{\mathcal{A}_0} \frac{h_1^g(x, \boldsymbol{q}_T^2)}{f_1^g(x, \boldsymbol{q}_T^2)}$$

$$h_1^g \equiv h_{1T}^g + \frac{\boldsymbol{p}_T^2}{2M_p^2} h_{1T}^{\perp g},$$

$$A^{\sin(\phi_S - 3\phi_T)} = -\frac{|\boldsymbol{q}_T|^3}{2M_p^3} \frac{\mathcal{B}_0}{\mathcal{A}_0} \frac{h_{1T}^{\perp g}(x, \boldsymbol{q}_T^2)}{f_1^g(x, \boldsymbol{q}_T^2)}.$$

The coefficients A and B are calculated in NRQCD. Only one CO state contributes in the cross section namely

$$\langle 0|\mathcal{O}^{J/\psi}({}^3S_1^{(8)})|0\rangle$$

Using cross section data one can fit the LDME

The LDME cancels in the asymmetries : clean probe of gluon TMDs

Positivity constraints :

$$\frac{|\boldsymbol{q}_T|}{M_p} |f_{1T}^{\perp g}(x_g, \boldsymbol{q}_T^2)| \leq f_1^g(x_g, \boldsymbol{q}_T^2),$$

$$\frac{\boldsymbol{q}_T^2}{2M_p^2} |h_1^{\perp g}(x_g, \boldsymbol{q}_T^2)| \leq f_1^g(x_g, \boldsymbol{q}_T^2),$$

$$\frac{|\boldsymbol{q}_T|}{M_p} |h_1^g(x_g, \boldsymbol{q}_T^2)| \leq f_1^g(x_g, \boldsymbol{q}_T^2),$$

$$\frac{|\boldsymbol{q}_T|^3}{2M_p^3} |h_{1T}^{\perp g}(x_g, \boldsymbol{q}_T^2)| \leq f_1^g(x_g, \boldsymbol{q}_T^2).$$

GAUSSIAN PARAMETRIZATION OF THE TMDS

Numerical estimate of the asymmetries are dependent on the TMD parametrization. We have used a Gaussian parametrization

$$f_1^g(x, \boldsymbol{q}_T^2) = f_1^g(x, \mu) \frac{e^{-\boldsymbol{q}_T^2/\langle q_T^2 \rangle}}{\pi \langle q_T^2 \rangle}$$

$f_1^g(x, \mu)$ Is the collinear unpolarized pdf at a scale $\langle q_T^2 \rangle = 1 \text{ GeV}^2$

$$\mu = \sqrt{M_\psi^2 + Q^2}$$

M. Anselmino, U. D'Alesio, and F. Murgia, Phys. Rev. D 67 (2003).

$$h_1^{\perp g}(x, \boldsymbol{q}_T^2) = \frac{M_p^2 f_1^g(x, \mu)}{\pi \langle q_T^2 \rangle^2} \frac{2(1-r)}{r} e^{1 - \frac{q_T^2}{r \langle q_T^2 \rangle}}$$

M_p is the proton mass, r=1/3

D. Boer et al, PRL 108 (2012), Boer and Pisano, PRD 86 (2012)

$$\Delta^N f_{g/p^\uparrow}(x, q_T) = \left(-\frac{2|\boldsymbol{q}_T|}{M_P} \right) f_{1T}^{\perp g}(x, q_T)$$

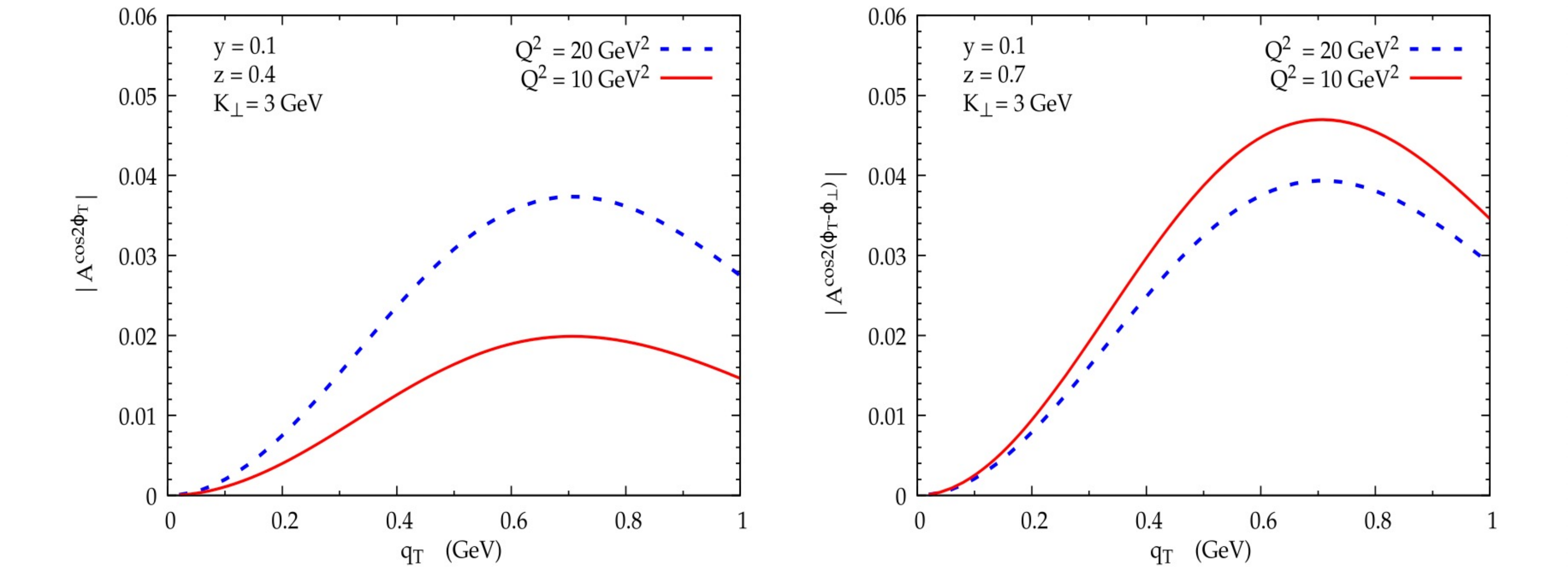
$$= 2\frac{\sqrt{2e}}{\pi} \mathcal{N}_g(x) f_{g/p}(x) \sqrt{\frac{1-\rho}{\rho}} q_T \frac{e^{-\boldsymbol{q}_T^2/\rho \langle q_T^2 \rangle}}{\langle q_T^2 \rangle^{3/2}}$$

$$\mathcal{N}_g(x) = N_g x^\alpha (1-x)^\beta \frac{(\alpha+\beta)^{(\alpha+\beta)}}{\alpha^\alpha \beta^\beta}$$

$$N_g = 0.25, \qquad \alpha = 0.6, \qquad \beta = 0.6, \qquad \rho = 0.1.$$

U. D'Alesio, C. Flore, F. Murgia, C. Pisano, and P. Taels, Phys. Rev. D 99 (2019)

ASYMMETRY WITH GAUSSIAN PARAMETRIZATION OF TMDS



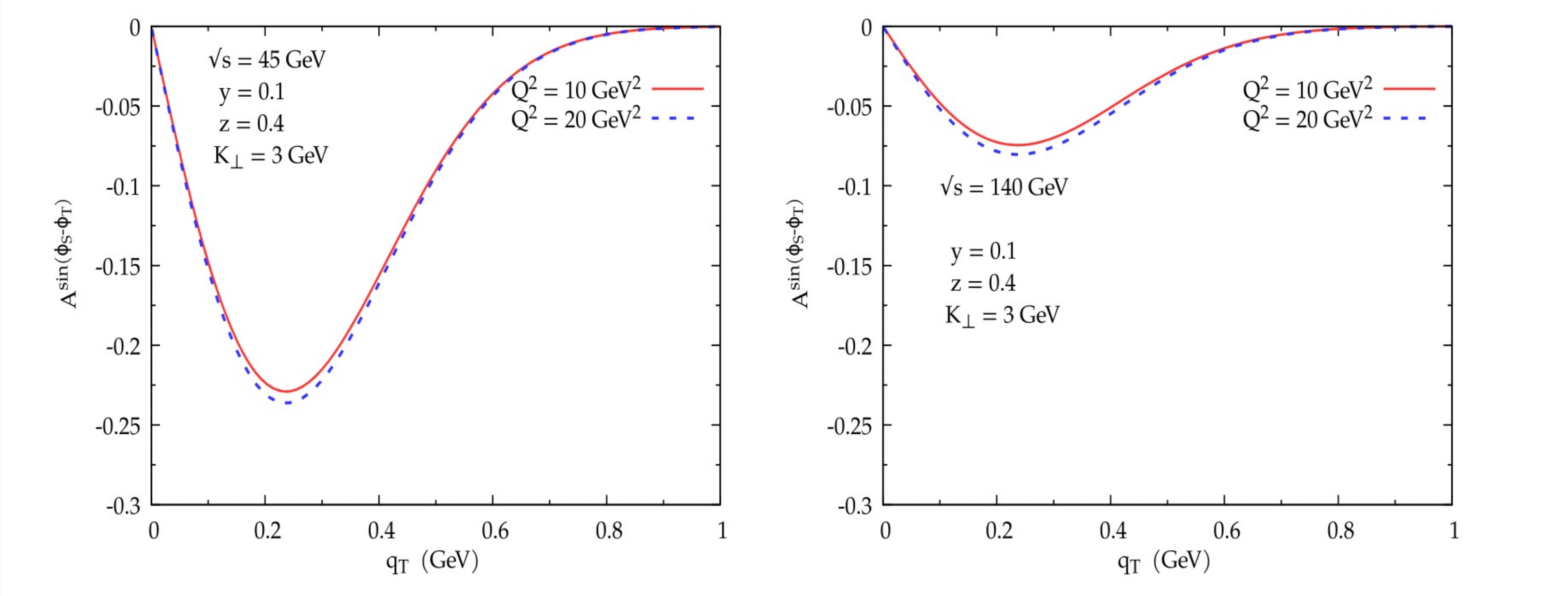
Asymmetry does not depend that much on CMS energy

Has peak value around q_T =0.7 GeV

kinematics chosen for back-to-back configuration

D. Chakrabarti, R. Kishore, AM, S. Rajesh, Phys. Rev D *Phys.Rev.D* 107 (2023) 1, 014008

SIVERS ASYMMETRY



Sivers asymmetry is negative, depends on the CMS energy

Does not depend much on the photon virtuality

Sivers asymmetry quite sizable at EIC kinematics and using Gaussian parametrization of the TMDs

D. Chakrabarti, R. Kishore, AM, S. Rajesh, Phys. Rev D *Phys.Rev.D* 107 (2023) 1, 014008

BACK-TO BACK PRODUCTION OF J/ψ AND JET

$$e^-(l) + p(\mathrm{P}) \to e^-(l') + J/\psi(\mathrm{P}_\psi) + \mathrm{jet}(\mathrm{P}_j) + X,$$

$$Q^2 = -q^2, \qquad s = (P+l)^2, \qquad W^2 = (P+q)^2,$$

$$x_B = \frac{Q^2}{2P \cdot q}, \qquad y = \frac{P \cdot q}{P \cdot l}, \qquad z = \frac{P \cdot \mathrm{P}_\psi}{P \cdot q}.$$

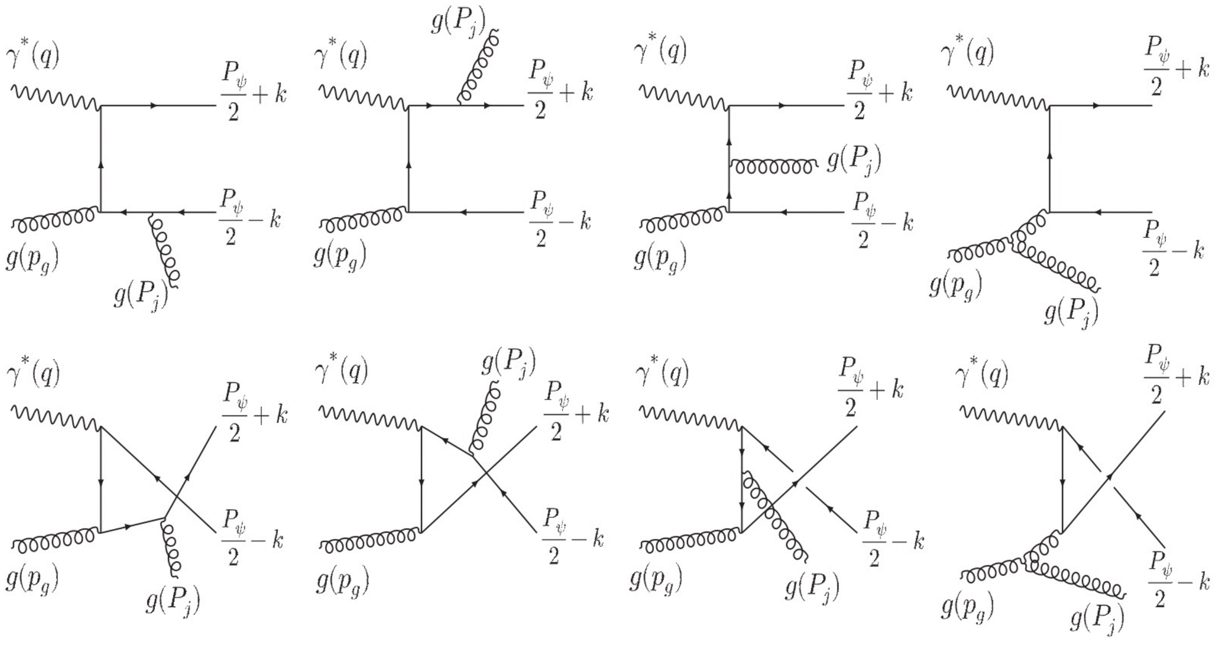


FIG. 1. Feynman diagrams for the partonic process $\gamma^*(q) + g(p_g) \to J/\psi(\mathrm{P}_\psi) + g(\mathrm{P}_j)$.

Use TMD factorization in the kinematics where the outgoing J/ψ and (gluon) jet are almost back-to back

Use NRQCD to calculate the J/ψ production

Also compare with the color singlet (CS) model result

Raj Kishore, AM, Amol Pawar, M. Siddiqah, *Phys.Rev.D* 106 (2022) 3, 034009

CALCULATION OF AMPLITUDE USING NRQCD

The amplitude can be written as

D. Boer and C. Pisano (2012)

$$M(\gamma^* g \to Q\bar{Q}[^{2S+1}L_J^{(1,8)}](P_\psi) + g)$$
$$= \sum_{L_z S_z} \int \frac{d^3k}{(2\pi)^3} \Psi_{LL_z}(k) \langle LL_z ; SS_z | JJ_z \rangle \mathrm{Tr}[\mathcal{O}(q,p,P_\psi,k)\mathcal{P}_{SS_z}(P_\psi,k)]$$

Amplitude for production of $Q\bar{Q}$ pair : $\mathcal{O}(q,p,P_\psi,k) = \sum_{m=1}^{8} C_m \mathcal{O}_m(q,p,P_\psi,k)$

The spin projection operator, $\mathcal{P}_{SS_z}(P_\psi,k)$, projects the spin triplet and spin singlet states of $Q\bar{Q}$ pair

$$\mathcal{P}_{SS_z}(P_\psi,k) = \sum_{s_1 s_2} \left\langle \frac{1}{2} s_1 ; \frac{1}{2} s_2 \middle| SS_z \right\rangle v\left(\frac{P_\psi}{2} - k, s_1\right) \bar{u}\left(\frac{P_\psi}{2} + k, s_2\right)$$
$$= \frac{1}{4M_\psi^{3/2}} (-P_\psi + 2k + M_\psi) \Pi_{SS_z} (P_\psi + 2k + M_\psi) + O(k^2)$$

$\Pi_{SS_z} = \gamma^5$ for spin singlet ($S = 0$)

$\Pi_{SS_z} = \epsilon_{S_z}^{\mu}(P_\psi)\gamma_\mu$ for spin triplet ($S = 1$)

BACK-TO-BACK PRODUCTION OF J/Ψ AND JET

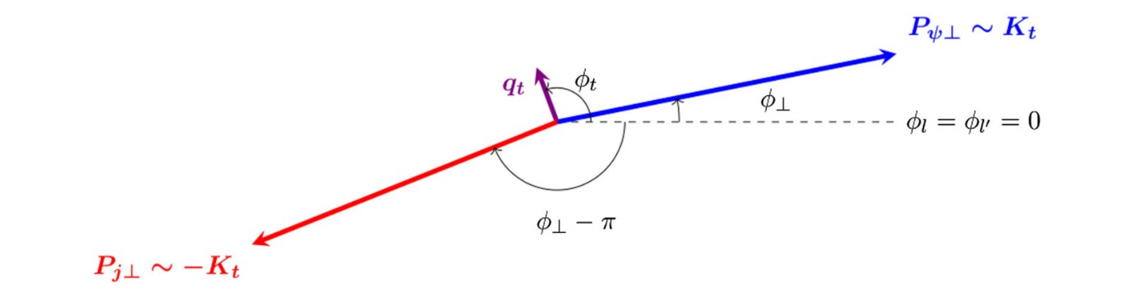
$$d\sigma=\frac{1}{2s}\frac{d^3l'}{(2\pi)^3 2E_{l'}}\frac{d^3P_\psi}{2E_\psi(2\pi)^3}\frac{d^3P_j}{2E_j(2\pi)^3}$$
$$\times\int dx d^2\mathbf{p}_T(2\pi)^4\delta^4(q+p_g-P_j-P_\psi)$$
$$\times\frac{1}{Q^4}L^{\mu\mu'}(l,q)\Phi_g^{\nu\nu'}(x,\mathbf{p}_T^2)\mathcal{M}_{\mu\nu}^{g\gamma^*\to J/\psi g}\mathcal{M}_{\mu'\nu'}^{*g\gamma^*\to J/\psi g}.$$

$$\mathcal{M}(\gamma^* g\to Q\bar{Q}[^{2S+1}L_J^{(1,8)}]g)$$
$$=\sum_{L_zS_z}\int\frac{d^3\mathbf{k}}{(2\pi)^3}\Psi_{LL_z}(\mathbf{k})\langle LL_z;SS_z|JJ_z\rangle$$
$$\times\mathrm{Tr}[O(q,p_g,P_\psi,k)\mathcal{P}_{SS_z}(P_\psi,k)],$$

Contribution comes from the color singlet state $({}^3S_1^{(1)})$ And color octet states $({}^3S_1^{(8)},{}^1S_0^{(8)},{}^3P_{J(0,1,2)}^{(8)})$

In NRQCD, k, the relative momentum of the charm quark is small.
We have Taylor expanded the amplitude about k=0. The first term gives the S wave contribution and second term the p wave contribution

Formation of the bound state J/ψ from the heavy quark pair is encoded in the non-perturbative long distance matrix elements (LDMEs). These are obtained by fitting data



Upper bound of the asymmetries : U. D'Alesio, F. Murgia, C. Pisano, and P. Taels *Phys.Rev.D* 100 (2019) 9, 094016

ASYMMETRY

$$\mathbf{q}_t \equiv \mathbf{P}_{\psi\perp} + \mathbf{P}_{j\perp}, \qquad \mathbf{K}_t \equiv \frac{\mathbf{P}_{\psi\perp} - \mathbf{P}_{j\perp}}{2}.$$

$$|\mathbf{q}_t| \ll |\mathbf{K}_t|.$$

$$\frac{d\sigma}{dz dy dx_B d^2\mathbf{q}_t d^2\mathbf{K}_t} = \frac{1}{(2\pi)^4}\frac{1}{16sz(1-z)Q^4}\Big\{(\mathbb{A}_0 + \mathbb{A}_1\cos\phi_\perp + \mathbb{A}_2\cos 2\phi_\perp) f_1^g(x,\mathbf{q}_t^2) + \frac{\mathbf{q}_t^2}{M_P^2} h_1^{\perp g}(x,\mathbf{q}_t^2)(\mathbb{B}_0\cos 2\phi_t + \mathbb{B}_1\cos(2\phi_t - \phi_\perp) + \mathbb{B}_2\cos 2(\phi_t - \phi_\perp) + \mathbb{B}_3\cos(2\phi_t - 3\phi_\perp) + \mathbb{B}_4\cos(2\phi_t - 4\phi_\perp))\Big\}.$$

$$\langle\cos 2\phi_t\rangle \equiv A^{\cos 2\phi_t} = \frac{\int q_t dq_t \frac{\mathbf{q}_t^2}{M_p^2}\mathbb{B}_0 h_1^{\perp g}(x,\mathbf{q}_t^2)}{\int q_t dq_t \mathbb{A}_0 f_1^g(x,\mathbf{q}_t^2)}.$$

Gaussian parametrization of TMDs :

$$f_1^g(x,\mathbf{q}_t^2) = f_1^g(x,\mu)\frac{1}{\pi\langle\mathbf{q}_t^2\rangle}e^{-\mathbf{q}_t^2/\langle\mathbf{q}_t^2\rangle},$$

$$h_1^{\perp g}(x,\mathbf{q}_t^2) = \frac{M_p^2 f_1^g(x,\mu)}{\pi\langle\mathbf{q}_t^2\rangle^2}\frac{2(1-r)}{r}e^{1-\frac{\mathbf{q}_t^2}{r\langle\mathbf{q}_t^2\rangle}},$$

Boer and Pisano, PRD, 2012

$\langle\mathbf{q}_t^2\rangle = 0.25\ \mathrm{GeV}^2.$ r=1/3

Spectator model :

$$F^g(x,\mathbf{q}_t^2) = \int_M^\infty dM_X\rho_X(M_X)\hat{F}^g(x,\mathbf{q}_t^2;M_X).$$

Spectral function

$$\rho_X(M_X) = \mu^{2a}\left[\frac{A}{B+\mu^{2b}} + \frac{C}{\pi\sigma}e^{-\frac{(M_X-D)^2}{\sigma^2}}\right],$$

M_X : mass of spectator : continuous

$$L_X^2(\Lambda_X^2) = xM_X^2 + (1-x)\Lambda_X^2 - x(1-x)M^2.$$

$$\begin{aligned}\hat{f}_1^g(x,\mathbf{q}_t^2;M_X) &= -\frac{1}{2}g^{ij}[\Phi^{ij}(x,\mathbf{q}_t,S) + \Phi^{ij}(x,\mathbf{q}_t,-S)] \\ &= [(2Mxg_1 - x(M+M_X)g_2)^2[(M_X - M(1-x))^2 + \mathbf{q}_t^2] \\ &\quad + 2\mathbf{q}_t^2(\mathbf{q}_t^2 + xM_X^2)g_2^2 + 2\mathbf{q}_t^2M^2(1-x)(4g_1^2 - xg_2^2)][(2\pi)^3 4xM^2(L_X^2(0) + \mathbf{q}_t^2)^2]^{-1},\end{aligned}$$

$$\begin{aligned}\hat{h}_1^{\perp g}(x,\mathbf{q}_t^2;M_X) &= \frac{M^2}{\varepsilon_t^{ij}\delta^{jm}(p_t^j p_t^m + g^{jm}\mathbf{q}_t^2)}\varepsilon_t^{ln}\delta^{nr}[\Phi^{nr}(x,\mathbf{q}_t,S) + \Phi^{nr}(x,\mathbf{q}_t,-S)] \\ &= [4M^2(1-x)g_1^2 + (L_X^2(0) + \mathbf{q}_t^2)g_2^2] \times [(2\pi)^3 x(L_X^2(0) + \mathbf{q}_t^2)^2]^{-1}.\end{aligned}$$

A. Bacchetta, F. G. Celiberto, M. Radici, and P. Taels, Eur. Phys. J. C 80, 733 (2020).

TMD EVOLUTION

Also incorportated TMD evolution in the asymmetry

TMD evolution is done in impact parameter space

$$\hat{f}(x, \mathbf{b}_t^2, Q_f^2) = \frac{1}{2\pi} \sum_{p=q,\bar{q},g} (C_{g/p} \otimes f_1^p)(x, Q_i^2) \times e^{-\frac{1}{2}S_A(\mathbf{b}_t^2, Q_f^2, Q_i^2)} e^{-S_{np}(\mathbf{b}_t^2, Q_f^2)},$$

Boer, D'Alesio, Murgia, Pisano, and Taels, JHEP (2020) 40.

Aybat and Rogers, PRD 83, 114042 (2011)

S_A and S_{np} are perturbative and non-perturbative Sudakov factors

$$S_A(\mathbf{b}_t^2, Q_f^2, Q_i^2) = \frac{C_A}{\pi} \int_{Q_i^2}^{Q_f^2} \frac{d\eta^2}{\eta^2} \alpha_s(\eta) \left(\log \frac{Q_f^2}{\eta^2} - \frac{11 - 2n_f/C_A}{6} \right) = \frac{C_A}{\pi} \alpha_s \left(\frac{1}{2} \log^2 \frac{Q_f^2}{Q_i^2} - \frac{11 - 2n_f/C_A}{6} \log \frac{Q_f^2}{Q_i^2} \right).$$

$$S_{np} = \frac{A}{2} \log\left(\frac{Q_f}{Q_{np}}\right) \mathrm{b}_c^2, \qquad Q_{np} = 1\ \mathrm{GeV}.$$

Scarpa, Boer, Echevarria, Lansberg, Pisano, Schlegel, EPJC(2020)

$$Q_f = \sqrt{M_\psi^2 + \mathrm{K}_t^2}.$$

$$A = 2.3\ \mathrm{GeV}^2$$

$$Q_i = 2e^{-\gamma_E}/\mathrm{b}_t$$

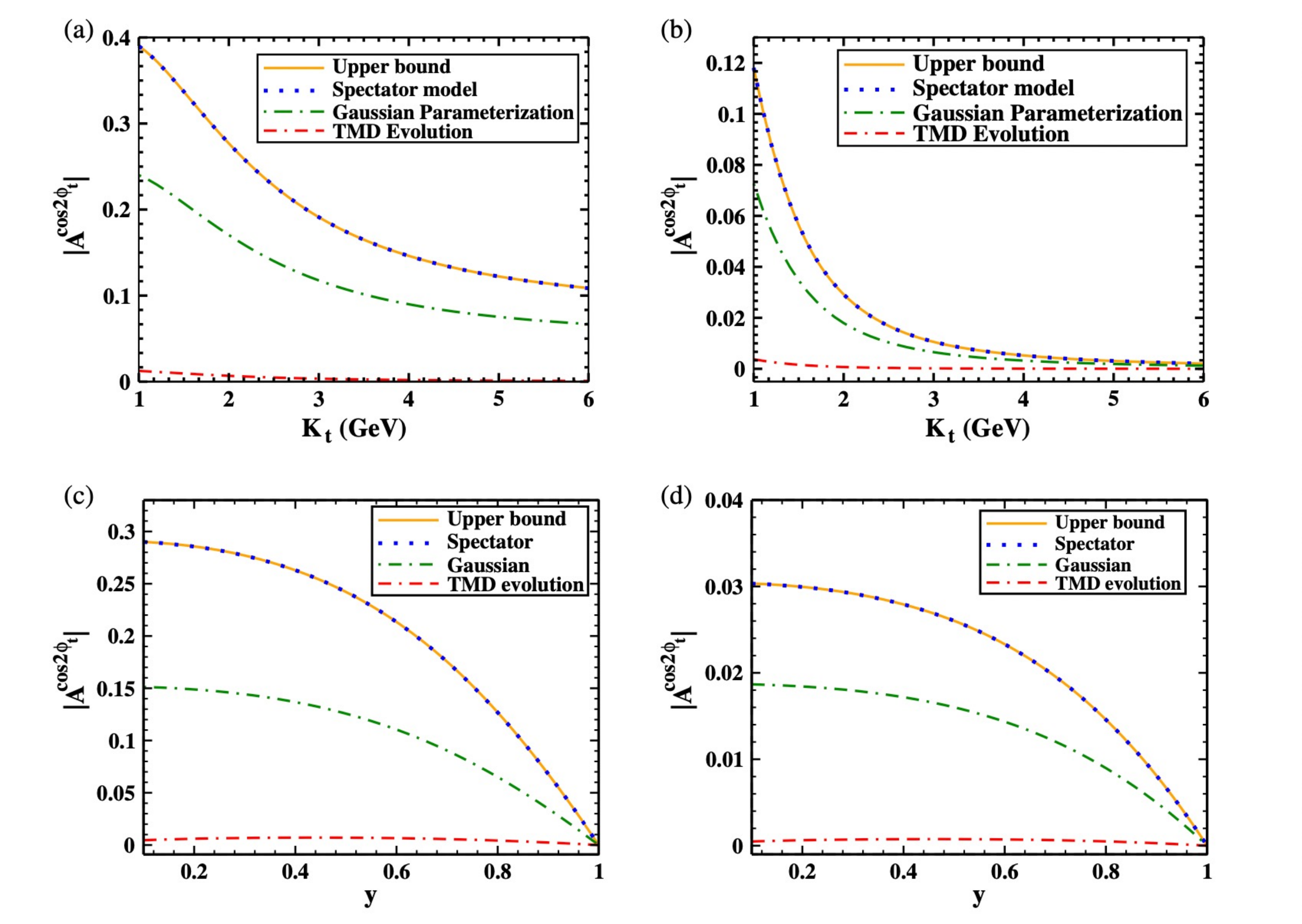
Used b_{t*} prescription to prevent Q_i larger than Q_f for low b_t

Final expressions are :

$$f_1^g(x, \mathbf{q}_t^2) = \frac{1}{2\pi} \int_0^\infty \mathrm{b}_t d\mathrm{b}_t J_0(\mathrm{b}_t \mathrm{q}_t) \left\{ f_1^g(x, Q_f^2) - \frac{\alpha_s}{2\pi} \left[\left(\frac{C_A}{2} \log^2 \frac{Q_f^2}{Q_i^2} - \frac{11C_A - 2n_f}{6} \log \frac{Q_f^2}{Q_i^2} \right) f_1^g(x, Q_f^2) + (P_{gg} \otimes f_1^g + P_{gi} \otimes f_1^i)(x, Q_f^2) \log \frac{Q_f^2}{Q_i^2} - 2 f_1^g(x, Q_f^2) \right] \right\} \times e^{-S_{np}(\mathbf{b}_t^2)}.$$

$$\frac{\mathbf{q}_t^2}{M_p^2} h_1^{\perp g(2)}(x, \mathbf{q}_t^2) = \frac{\alpha_s}{\pi^2} \int_0^\infty d\mathrm{b}_t \mathrm{b}_t J_2(\mathrm{q}_t \mathrm{b}_t) \left[C_A \int_x^1 \frac{d\hat{x}}{\hat{x}} \left(\frac{\hat{x}}{x} - 1 \right) f_1^g(\hat{x}, Q_f^2) + C_F \sum_{p=q,\bar{q}} \int_x^1 \frac{d\hat{x}}{\hat{x}} \left(\frac{\hat{x}}{x} - 1 \right) f_1^p(\hat{x}, Q_f^2) \right] \times e^{-S_{np}(\mathbf{b}_t^2)}.$$

UPPER BOUND OF THE ASYMMETRY COMPARED WITH DIFFERENT RESULTS



NRQCD

CS

$y = 0.3$ In upper panels $\sqrt{s} = 140\ GeV$

$K_t = 0.2\ GeV$ In lower panels

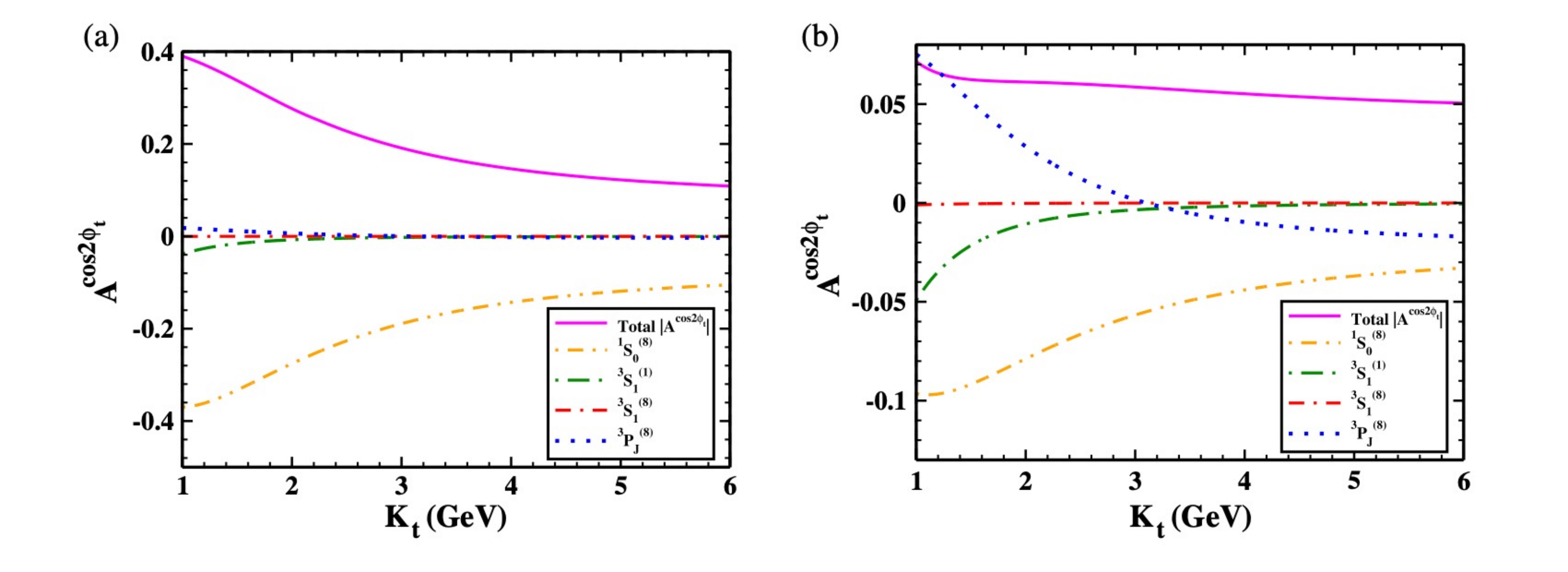
Result in spectator model in the kinematics considered overlaps with the upper bound saturating the positivity bound

Result is Gaussian parametrization lower than in spectator model

Asymmetries in CS smaller than in NRQCD

Raj Kishore, AM, Amol Pawar, M. Siddiqah, *Phys.Rev.D* 106 (2022) 3, 034009

CONTRIBUTION TO ASYMMETRY FROM DIFFERENT STATES



$$\sqrt{s} = 140\ GeV$$

$$Q = \sqrt{M_\psi^2 + K_t^2},$$

y=0.3

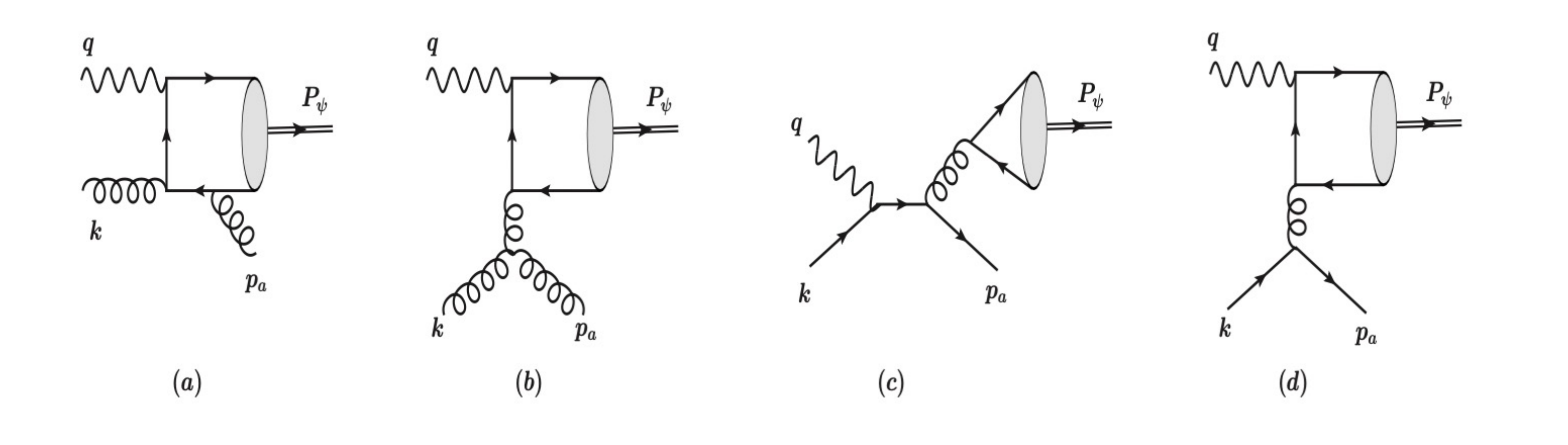
(a) LDMEs from K.T. Chao et al, Phys. Rev. Lett. 108, 242004 (2012).

(b) LDMEs from Sharma and Vitev, Phys. Rev. C 87, 044905 (2013)

In (a) dominating contribution come from a single state whereas in (b) contributions come from several states

Raj Kishore, AM, Amol Pawar, M. Siddiqah *Phys.Rev.D* 106 (2022) 3, 034009

J/ψ AND PION PRODUCTION



Fragmentation of the outgoing gluon into pion

$$\gamma^*(q) + a(k) \to J/\psi(P_\psi) + a(P_a)$$

Back-to-back J/ψ and pion : transverse momentum of each large.
Treated fragmentation of final state parton into pion as collinear

Contributions from both quark and gluon channels estimated

$$P_\pi^\mu = z_\pi (P\cdot q) n_+^\mu + \frac{M_\pi^2 + \boldsymbol{P}_{\pi\perp}^2}{2 z_\pi P\cdot q} P^\mu + P_{\pi\perp}^\mu \,,$$

$$P_{a\perp}^\mu = \frac{1}{z} P_\pi^\mu .$$

$$P_a^\mu = \frac{1}{z} P_\pi^\mu - \frac{1}{2P\cdot P_\pi}\left(\frac{M_\pi^2}{z}\right) P^\mu .$$

$$z = \frac{P\cdot P_\pi}{P\cdot P_a} = \frac{z_\pi}{z_a}$$

$$z_\pi = \frac{P\cdot P_\pi}{P\cdot q}$$

Khatiza Sheikh, Amol Pawar, AM, Sangem Rajesh, 2406.00271 [hep-ph]

CROSS SECTION AND ASYMMETRIES

$$\mathrm{d}\sigma^{ep\to e+J/\psi+\pi^{\pm}+X} = \frac{1}{2s}\frac{\mathrm{d}^3\boldsymbol{l}'}{(2\pi)^3 2E_{l'}}\frac{\mathrm{d}^3\boldsymbol{P}_\psi}{(2\pi)^3 2E_\psi}\frac{\mathrm{d}^3\boldsymbol{P}_\pi}{(2\pi)^3 2E_\pi}\int \mathrm{d}x_a\,\mathrm{d}^2\boldsymbol{k}_{\perp a}\,\mathrm{d}z\,(2\pi)^4\,\delta^4(q+k-P_\psi-P_a)$$
$$\times\frac{1}{Q^4}L^{\mu\mu'}(l,q)\,\Phi_a^{\alpha\alpha'}(x,\boldsymbol{k}_{\perp a})\,\mathcal{M}_{\mu\alpha}^{\gamma^* a\to J/\psi+a}\mathcal{M}_{\mu'\alpha'}^{*;\gamma^* a\to J/\psi+a}\,D(z)J(z).$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2\mathrm{d}y\mathrm{d}z_\psi\mathrm{d}^2\boldsymbol{q}_T\mathrm{d}^2\boldsymbol{K}_\perp} \equiv \mathrm{d}\sigma(\phi_S,\phi_T) = \mathrm{d}\sigma^U(\phi_T,\phi_\perp) + \mathrm{d}\sigma^T(\phi_S,\phi_T)\,.$$

$$\mathrm{d}\sigma^U = \mathcal{N}\int\mathrm{d}z\Big[\big(\mathcal{A}_0+\mathcal{A}_1\cos\phi_\perp+\mathcal{A}_2\cos 2\phi_\perp\big)f_1^g(x_g,\boldsymbol{q}_T^2)+\big(\mathcal{B}_0\cos 2\phi_T+\mathcal{B}_1\cos(2\phi_T-\phi_\perp)$$
$$+\mathcal{B}_2\cos 2(\phi_T-\phi_\perp)+\mathcal{B}_3\cos(2\phi_T-3\phi_\perp)+\mathcal{B}_4\cos(2\phi_T-4\phi_\perp)\big)\frac{\boldsymbol{q}_T^2}{M_p^2}h_1^{\perp g}(x_g,\boldsymbol{q}_T^2)\Big]D(z)\,.$$

Calculate coefficients in NRQCD

$$\mathrm{d}\sigma^T = \mathcal{N}|\boldsymbol{S}_T|\int\mathrm{d}z\Big[\sin(\phi_S-\phi_T)\big(\mathcal{A}_0+\mathcal{A}_1\cos\phi_\perp+\mathcal{A}_2\cos 2\phi_\perp\big)\frac{|\boldsymbol{q}_T|}{M_p}f_{1T}^{\perp g}(x_g,\boldsymbol{q}_T^2)$$
$$+\cos(\phi_S-\phi_T)\big(\mathcal{B}_0\sin 2\phi_T+\mathcal{B}_1\sin(2\phi_T-\phi_\perp)+\mathcal{B}_2\sin 2(\phi_T-\phi_\perp)$$
$$+\mathcal{B}_3\sin(2\phi_T-3\phi_\perp)+\mathcal{B}_4\sin(2\phi_T-4\phi_\perp)\big)\frac{|\boldsymbol{q}_T|^3}{M_p^3}h_{1T}^{\perp g}(x_g,\boldsymbol{q}_T^2)$$
$$+\big(\mathcal{B}_0\sin(\phi_S+\phi_T)+\mathcal{B}_1\sin(\phi_S+\phi_T-\phi_\perp)+\mathcal{B}_2\sin(\phi_S+\phi_T-2\phi_\perp)$$
$$+\mathcal{B}_3\sin(\phi_S+\phi_T-3\phi_\perp)+\mathcal{B}_4\sin(\phi_S+\phi_T-4\phi_\perp)\big)\frac{|\boldsymbol{q}_T|}{M_p}h_{1T}^{g}(x_g,\boldsymbol{q}_T^2)\Big]D(z)\,,$$

COEFFICIENTS

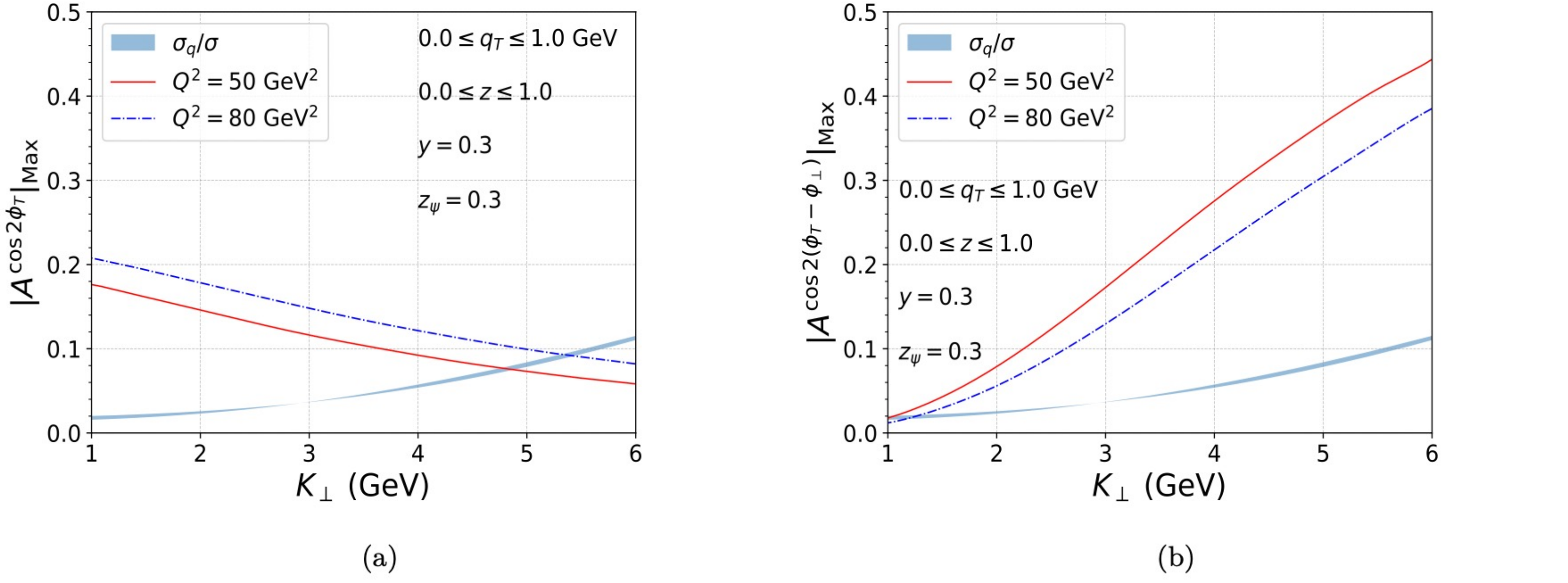
$$\mathcal{A}_0 = \langle 0|\mathcal{O}_{J/\psi}^{{}^3S_1[1]}|0\rangle\ \mathcal{A}_0^{{}^3S_1[1]} + \langle 0|\mathcal{O}_{J/\psi}^{{}^3S_1[8]}|0\rangle\ \mathcal{A}_0^{{}^3S_1[8]} + \langle 0|\mathcal{O}_{J/\psi}^{{}^1S_0[8]}|0\rangle\ \mathcal{A}_0^{{}^1S_0[8]} + \langle 0|\mathcal{O}_{J/\psi}^{{}^3P_0[8]}|0\rangle\ \mathcal{A}_0^{{}^3P_J[8]}$$

$$\mathcal{B}_{0,2} = \langle 0|\mathcal{O}_{J/\psi}^{{}^3S_1[1]}|0\rangle\ \mathcal{B}_{0,2}^{{}^3S_1[1]} + \langle 0|\mathcal{O}_{J/\psi}^{{}^3S_1[8]}|0\rangle\ \mathcal{B}_{0,2}^{{}^3S_1[8]} + \langle 0|\mathcal{O}_{J/\psi}^{{}^1S_0[8]}|0\rangle\ \mathcal{B}_{0,2}^{{}^1S_0[8]} + \langle 0|\mathcal{O}_{J/\psi}^{{}^3P_0[8]}|0\rangle\ \mathcal{B}_{0,2}^{{}^3P_J[8]}$$

Gluon channel : example of one of the contributions

$$\begin{aligned}
\mathcal{A}_0^{{}^3S_1[1]} = &\frac{1024Q^2}{y^2(Q^2+s)^2(Q^2+s+t)^2(2Q^2+s+u)^2\left(Q^2+t+u\right)^2}\Bigg\{2Q^2(y-1)\Big[u^2\left(Q^2+s\right)\left(t^2\left(Q^2+s\right)+\left(Q^2+s\right)^3\right.\\
&\left.+4t^3\right)+2u\left(t^2\left(Q^2+s\right)^2+2t^3\left(2Q^2+s\right)+Q^2\left(Q^2+s\right)^3\right)\left(Q^2+s+t\right)+(t^2\left(Q^2+s\right)^2+Q^4\left(Q^2+s\right)^2\\
&+4Q^2t^3)(Q^2+s+t)^2\Big]-((y-2)y+2)\Big[Q^{10}\left(2\left(5s^2+14st+6t^2\right)+14u(s+t)+3u^2\right)+Q^8(s^2(43t+26u)+\\
&10s^3+13s(t+u)(3t+u)+(t+u)\left(8t^2+7tu+u^2\right))+Q^6(u\left(73s^2t+24s^3+44st^2+7t^3\right)+47s^2t^2+31s^3t+\\
&5s^4+19st^3+u^3(4s+t)+u^2(s+t)(22s+5t)+4t^4)+Q^4\Bigg(s^3(26t^2+47tu+18u^2)+s^2(3t+2u)(5t^2+12tu\\
&+3u^2)+s^4(10t+11u)+s^5+st\left(13t^2u+4t^3+13tu^2+3u^3\right)+t^2(t+u)\left(2t^2+2tu+u^2\right)\Bigg)+Q^2s(s^3(7t^2+\\
&13tu+7u^2)+s^2(20t^2u+5t^3+17tu^2+4u^3)+s^4(t+2u)+stu\left(7t^2+11tu+3u^2\right)+2t^2u(t+u)^2)+Q^{12}(5s+\\
&7t+3u)+Q^{14}+s^2(s+t+u)(s^2(t^2+tu+u^2)+stu(t+u)+t^2u^2)\Big]\Bigg\}
\end{aligned}$$

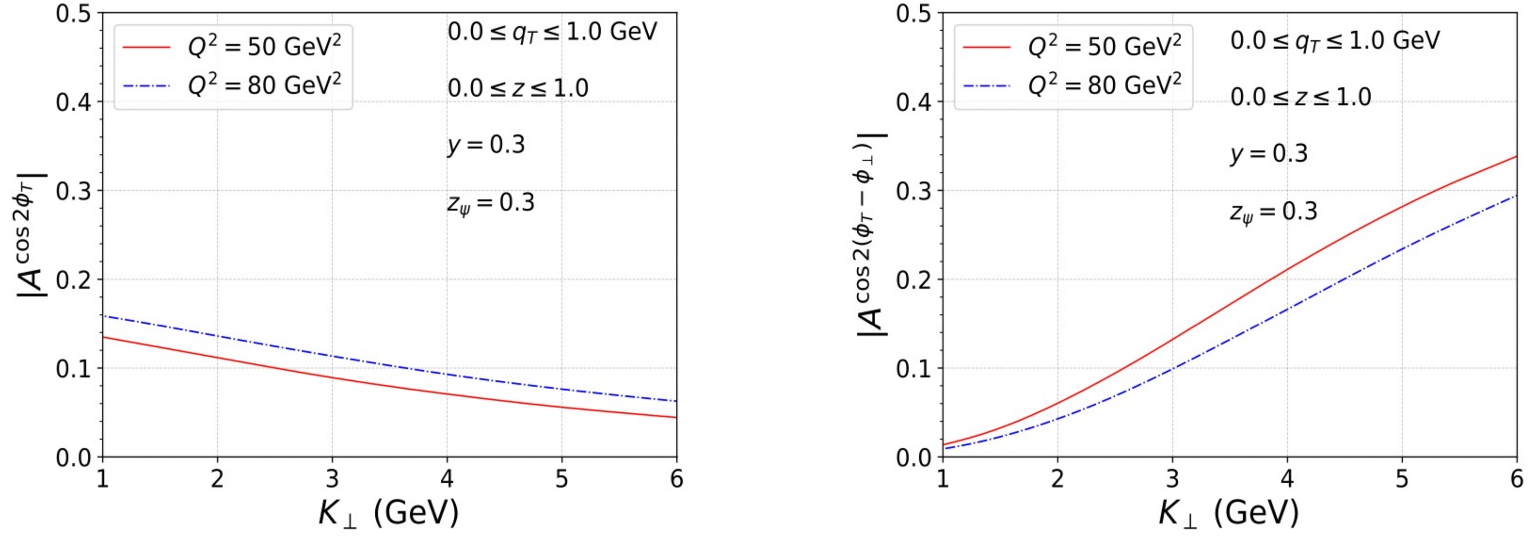
UPPER BOUND OF THE ASYMMETRIES



The upper bounds for the $A^{\cos 2\phi_T}$ (left panel) and $A^{\cos 2(\phi_T - \phi_\perp)}$ (right panel) azimuthal asymmetries are functions of $K_\perp$ in the process $ep \to e + J/\psi + \pi^\pm + X$ at $\sqrt{s} = 140$ GeV using CMSWZ [73] LDME set. The fixed parameters include $y = 0.3$, $z_\psi = 0.3$ and $Q^2 = 50$ and 80 GeV^2. Kinematic variables z and q_T are integrated over the interval $[0, 1]$. The ratio of quark contribution to the total scattering cross-section is shown as a band, obtained by varying Q^2 from 50 to 80 GeV^2.

Khatiza Sheikh, Amol Pawar, AM, Sangem Rajesh, 2406.00271[hep-ph]

ASYMMETRIES USING GAUSSIAN PARAMETRIZATION



(a) (b)

Gaussian parametrization for the $A^{\cos 2\phi_T}$ (left panel) and $A^{\cos 2(\phi_T-\phi_\perp)}$ (right panel) azimuthal asymmetries are shown as functions of $K_\perp$ at $\sqrt{s} = 140$ GeV using CMSWZ [73] LDME set. The fixed parameters include $y = 0.3$, $z_\psi = 0.3$ and $Q^2 = 50$ and 80 GeV^2. Kinematic variables z and q_T are integrated over the interval $[0, 1]$.

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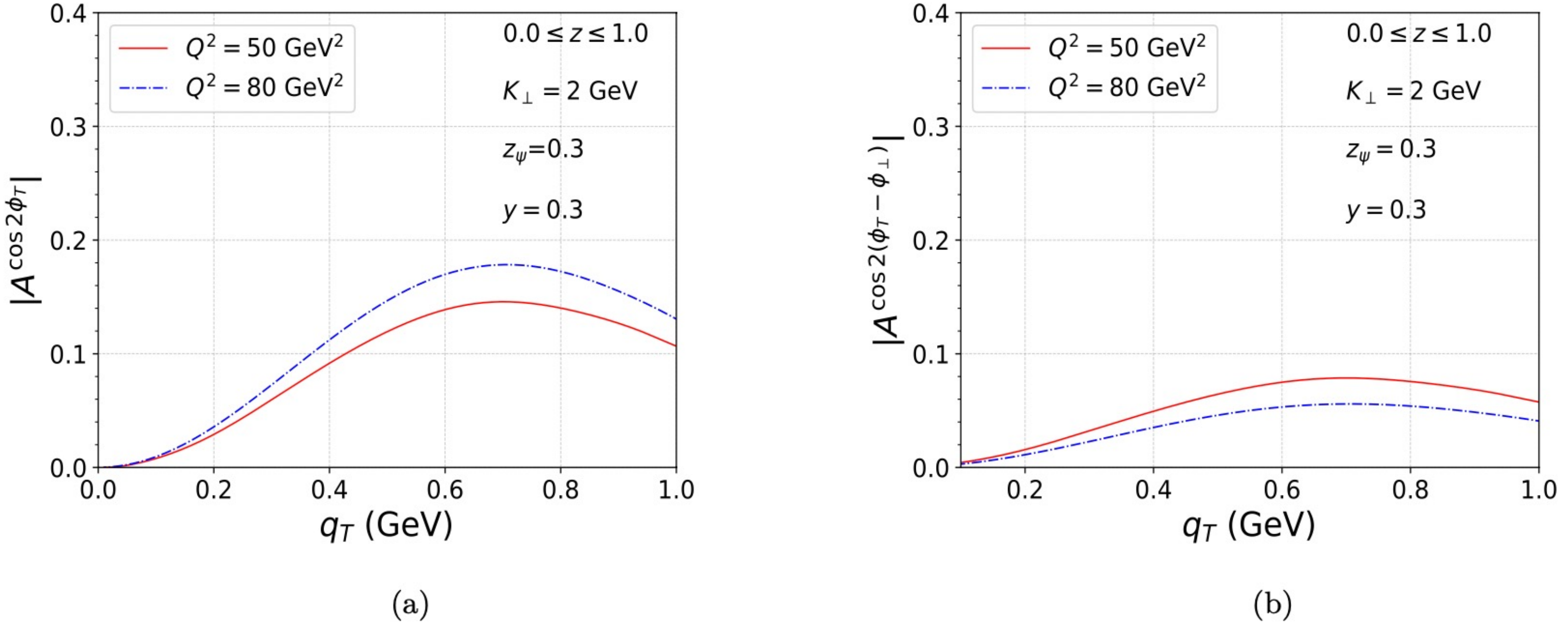

Gaussian parametrizations for the $A^{\cos 2\phi_T}$ (left panel) and $A^{\cos 2(\phi_T-\phi_\perp)}$ (right panel) azimuthal asymmetries are shown as functions of q_T at $\sqrt{s} = 140$ GeV using CMSWZ [73] LDME set. The fixed parameters include $K_\perp = 2.0$ GeV, $y = 0.3$, $z_\psi = 0.3$ and $Q^2 = 50$ and 80 GeV^2. The variable z is integrated over the interval $[0, 1]$.

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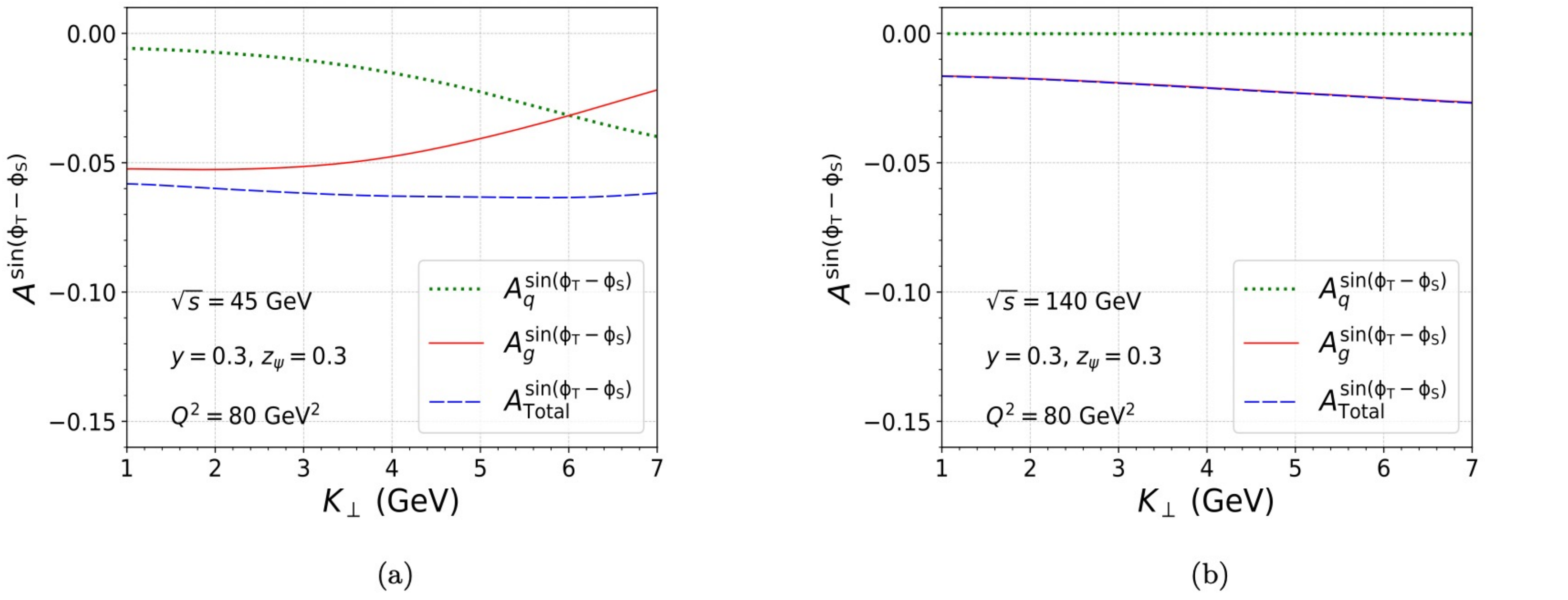
QUARK AND GLUON TMD CONTRIBUTIONS TO THE SIVERS ASYMMETRY



Siver asymmetry is shown as functions of $K_\perp$ in the process $ep \to e + J/\psi + \pi^\pm + X$ at the EIC with cm energy of $\sqrt{s} = 45, 140$ GeV using CMSWZ [73] LDME set. The fixed parameters include $y = 0.3$, $z_\psi = 0.3$ and $Q^2 = 80$ GeV^2. The variables z, q_T are integrated over the interval $[0, 1]$.

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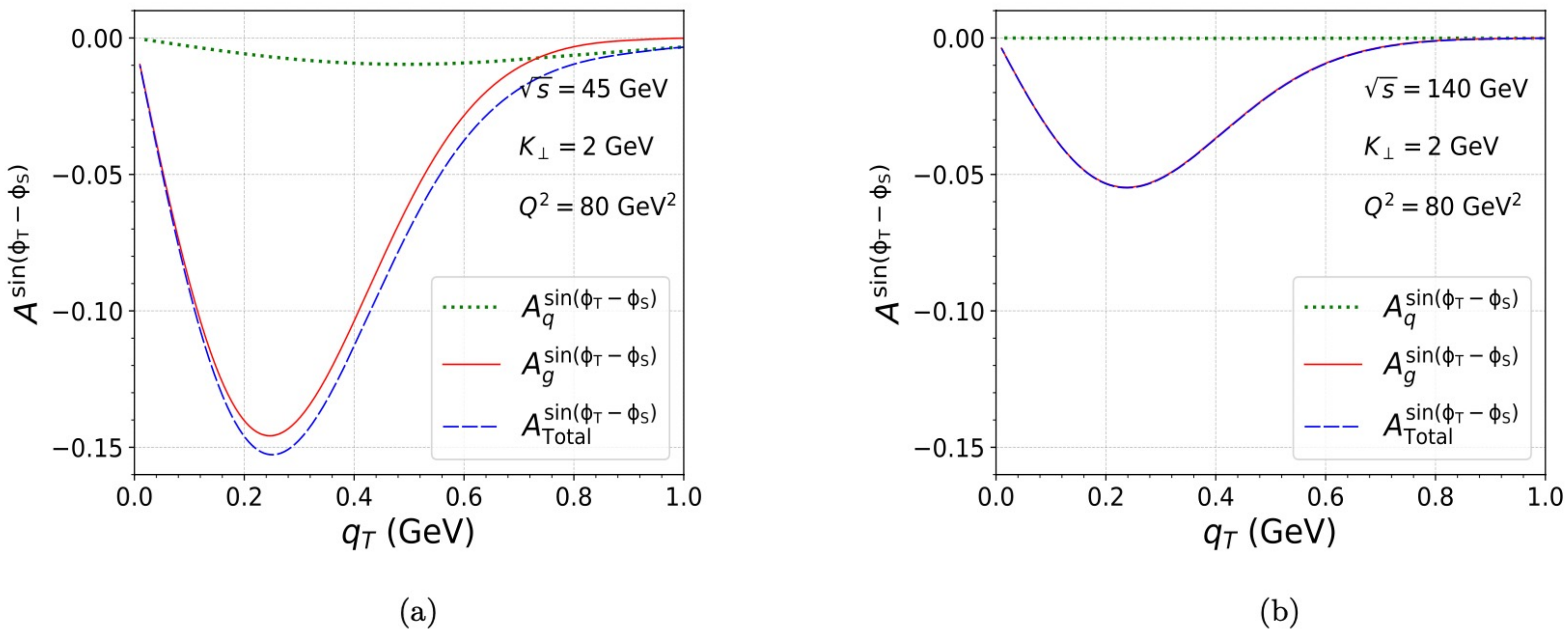
QUARK AND GLUON TMD CONTRIBUTIONS TO THE SIVERS ASYMMETRY



(a) (b)

Siver asymmetry is shown as functions of q_T in the process $ep \to e + J/\psi + \pi^{\pm} + X$ at the EIC with cm energy of $\sqrt{s} = 45, 140$ GeV using CMSWZ [73] LDME set. The fixed parameters include $K_\perp = 2.0$ GeV, $y = 0.3$, $z_\psi = 0.3$ and $Q^2 = 80$ GeV^2. The variable z is integrated over the interval $[0, 1]$.

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SUMMARY AND CONCLUSION

Discussed theoretical estimates of azimuthal asymmetries in back-to-back production of J/ψ –photon, J/ψ-jet and J/ψ-pion production in eP collision, in the kinematics of the upcoming EIC

Used NRQCD and CS mechanisms to calculate the J/ψ production rate

In J/ψ-photon production only one LDME contributes : asymmetry is independent of LDME choice. Robust probe of gluon TMDs . Cos 2ϕ asymmetry small but sizable Sivers asymmetry.

In J/ψ-jet production, significant contribution to cos 2ϕ asymmetry in NRQCD, smaller in CSM. Also considered effect of TMD evolution. The asymmetry is also sizable if one observes back-to-back J/ψ and pion.

Asymmetry depends on LDME sets chosen, as well as the parametrization of gluon TMDs.

For asymmetries in J/ψ-pion production, contribution from quark initiated channel small compared to gluon.

IIT Bombay at a Glance

Ranked as Number 1 Institute in India in 4 out of the past 5 years

Academic Units
16 Departments, 3 Schools,
6 Centres, 4 Interdisciplinary Programs

Centres of Excellence
34 Centres in total,
Several New Initiatives

Number 1 Preference
Faculty: 715, Post Doctoral Fellows: 280
Adjunct and Visiting 156, PoP: 5
Institute Staff: 800, Project Staff: 1500

First choice for UG and PG students
~ 13000
Preferred choice for top 47/50 JEE ranks

Research Outputs
Publications (approx) 5000 since 2021
240+ Sponsored Projects
350+ Patent Granted, 150 publications from industry collaborations

Alumni
Over 68,000

Institute of Eminence Since 2018

Academic Units at IITB

Engineering

- Aerospace Engineering
- Chemical Engineering
- Civil Engineering
- Computer Science & Engineering
- Electrical Engineering
- Energy Science and Engineering
- Environmental Science & Engineering
- Mechanical Engineering
- Metallurgical Engineering & Materials Science

Centres

- Technologies Alternatives for Rural Areas (CTARA)
- Machine Intelligence & Data Science (CMinDs)
- Ashank Desai Centre of Policy Studies (CPS)
- Urban Science & Engineering (CUSE)
- Koita Center of Digital Health(KCDH)
- Studies in Resources Engineering (CSRE)

Sciences

- Biosciences & Bioengineering
- Earth Sciences
- Chemistry
- Mathematics
- Physics

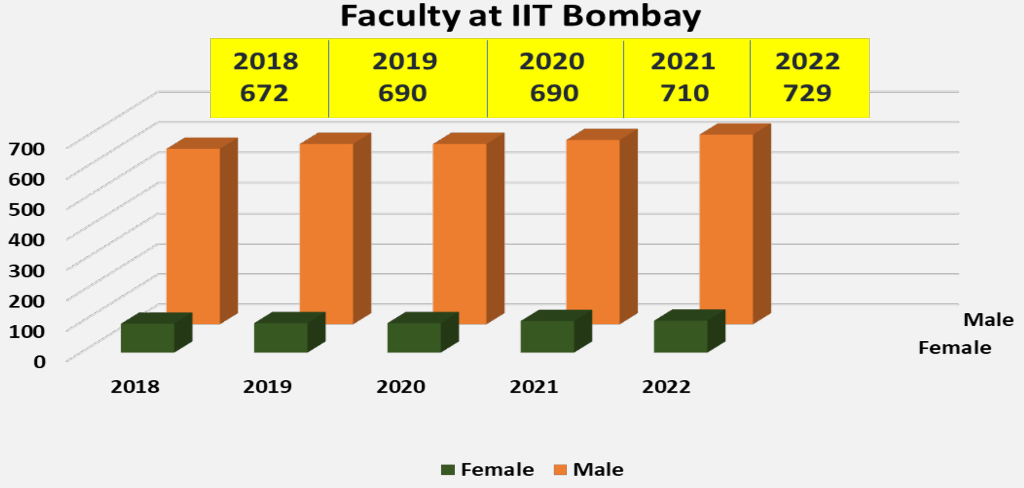
Humanities, Design, Management

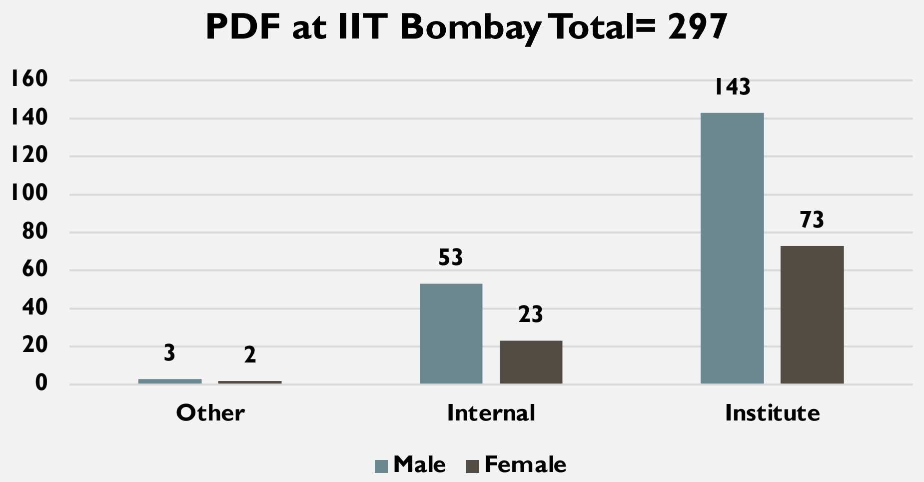
- Humanities & Social Science
- Economics
- Shailesh J. Mehta School of Management
- IDC School of Design
- Desai Sethi School of Entrepreneurship

Interdisciplinary Programs

- Climate Studies
- Educational Technology
- Industrial Engineering and Operations Research
- Systems and Control Engineering

Faculty and PDF at IIT Bombay





Foreign Faculty: 14
Professor of Practice: 5

INITIATIVE- RECRUITMENT OF FOREIGN FACULTY & PDF

Visiting faculty appointment : visit for a period of two months in one year

Salary + campus accommodation in the guest house

My group in Physics Department :

PhD students : Sudeep Saha, Amol Pawar, Ravi Singh Arghya Jana

Postdoc : Khatiza Banu (joint postdoc with CFNS), Poonam Chaudhary

UG students : Ram Prakash, Buddhadeb Dey

Former members : Ravi Manohar, Sreeraj Nair, Vikash K Ojha, Jai More, Mariyah Siddiqah, Rajesh Sangem, Raj Kishore


OF TECHNOLOGY BOMBAY