Single-Spin Asymmetry in $pp^{\uparrow} \rightarrow J/\Psi + X$

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Phy.Rev. D 102 (2020) 9, 094011 & Eur.Phys.J.C 79 (2019) 12

TMDs

Mulders and Rodrigues PRD 63 094021(2001)

Quark correlator

Quark field

$$\Phi_{ij}(x,k) = \int \frac{d^4\xi}{(2\pi)^4} e^{ik.\xi}\langle P \mid \overline{\Psi}_j(0)W[0,\xi]\Psi_i(\xi) \mid P\rangle$$

Gluon correlator

Gluon field

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

Wilson line

quark pol.

nucleon pol.

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

gluon pol.

nucleon pol.

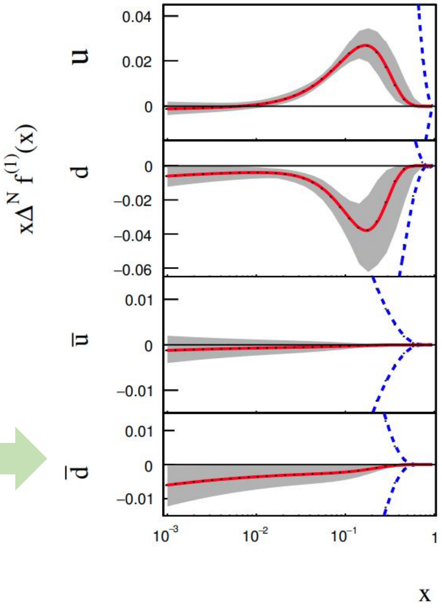
	U	Circularly	Linearly
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	$h_1^g,\ h_{1T}^{\perp g}$

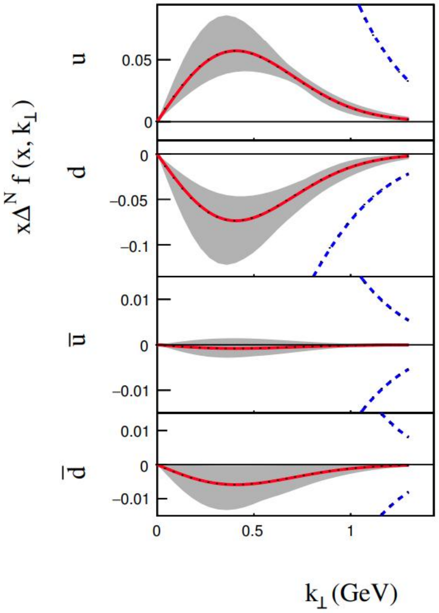
U: Unpolarized, **L**: Longitudinally, **T**: Transverse

Quark Sivers TMDs

- Global fit for quark Sivers functions (QSF) within the generalized parton model (GPM)
- Data from HERMES, COMPASS and JLab experiments in pion and kaon production

M. Anselmino, M. Boglione, U. D'Alesio, F. Murgia and A. Prokudin, JHEP 2017





Sea QSF is poorly constrained

$Q^2 = 2.4\ GeV^2$

$x = 0.1$

Quark Sivers TMDs

- Another study (in GPM): QFS extracted using latest SIDIS data from HERMES, COMPASS and JLab experiments in pion and kaon production

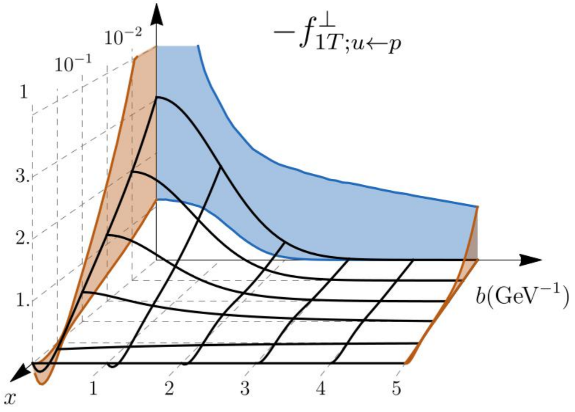
M. Boglione, U. D'Alesio, C. Flore and G. Hernandez, JHEP 2018

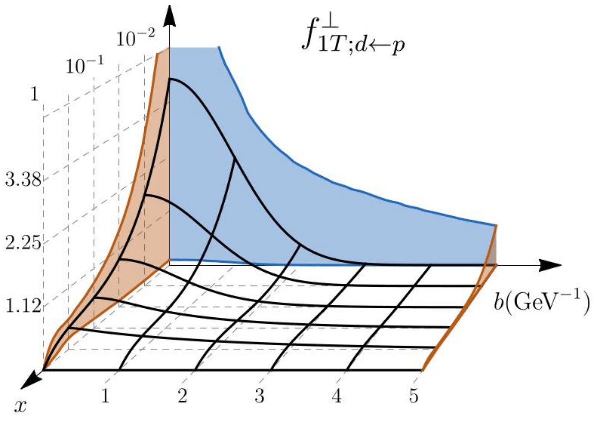
M. Boglione, U. D'Alesio, C. Flore, G. Hernandez, F. Murgia and A. Prokudin, PLB 815(2021)

- QSF has been extracted by using SIDIS, DY and $W^{\pm}$ /Z-boson data within the TMD evolution framework

Global fit @ NNLL: M.G. Echevarria, Z.B. Kang and J.Terry JHEP01(2021)126

Global fit @ NNNLO: M. Bury, A. Prokudin, A. Vladimirov JHEP 05 (2021) 151, PRL 126, 112002 (2021)





3D landscape of transversely polarized proton in terms of unp. quarks

Quark Sivers TMDs

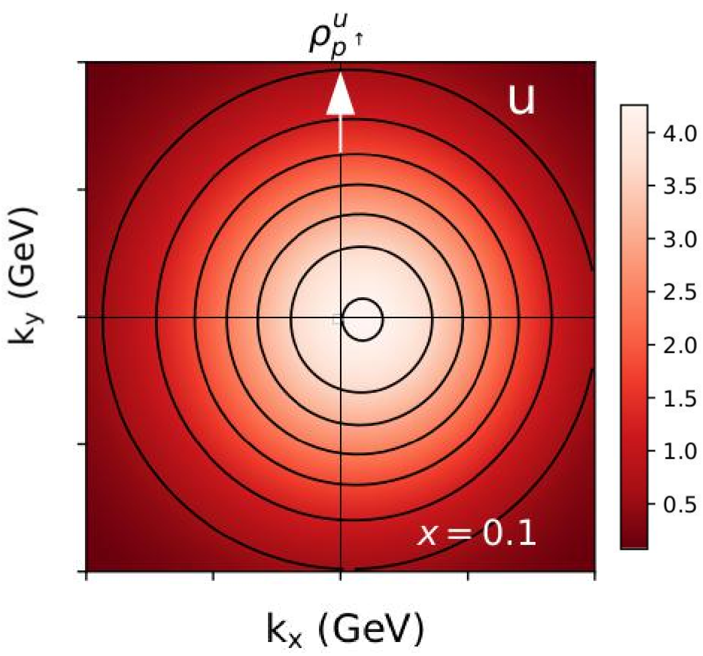
- Density of Unp. quarks inside a transversely polarized proton:

Global fit @ NLL for QSF using SIDIS data from COMPASS, HERMES and JLab

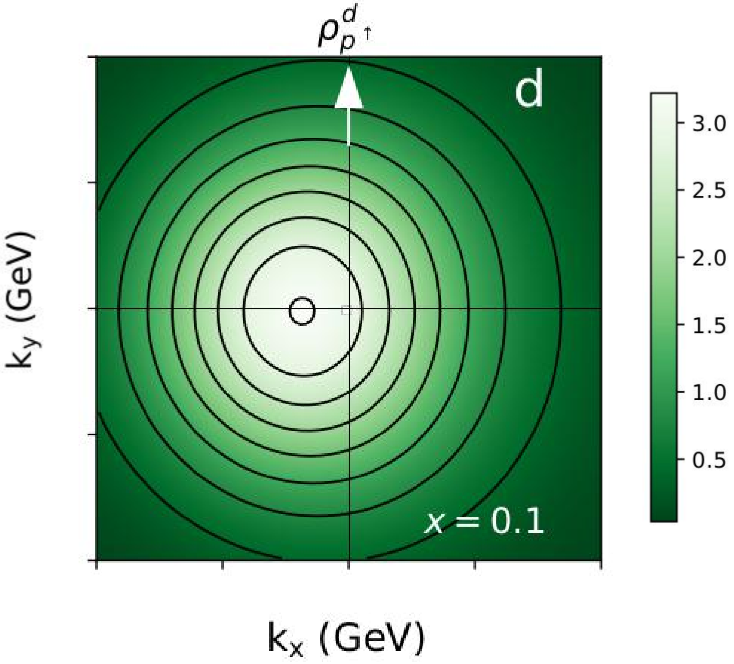
A. Bacchetta, F.Delcarro, C.Pisano, M.Radici and A. Signori JHEP06(2017) 081

A.Bacchetta, F.Delcarro, C.Pisano and M.Radici arXiv:2004.14278

$$\rho^a_{N\uparrow}(x, k_x, k_y; Q^2) = f_1^a(x, k_T^2; Q^2) - \frac{k_x}{M} f_{1T}^{\perp a}(x, k_T^2; Q^2)$$



$Q^2 = 4\ GeV^2$



What about Gluon Sivers TMD?

- Gluon Sivers function (GSF) is not known fully

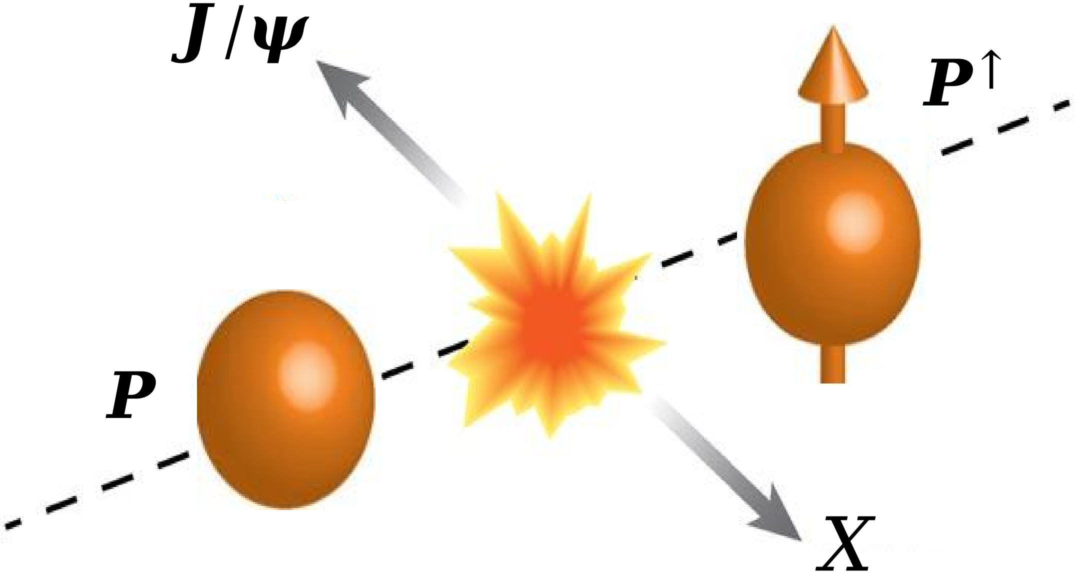
U. D’Alesio, F. Murgia, and C. Pisano, JHEP 09 (2015) 119

- GSF has been extracted from mid rapidity $pp^{\uparrow} \rightarrow \pi^0 + X$
- Upper values of first moment of the GSF has been extracted from mid rapidity $pp^{\uparrow} \rightarrow \pi^0 + X$ and $pp^{\uparrow} \rightarrow D^0 + X$ data at RHIC

U. D’Alesio, C. Flore, F. Murgia, C. Pisano and P. Taels, PRD 99 (2019) 036013

- Due to the limited data, GSF could not be constrained over the wide range in x and $K_\perp$
- Moreover, the light sea QSF has large uncertainties in the global fit
- The $pp^{\uparrow} \rightarrow J/\Psi + X$ process plays significant role in shaping the GSF

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



$@\alpha_s^2$

Partonic Channels

$@\alpha_s^3$

$gg \rightarrow J/\Psi$ (3)

$\overline{q}q \rightarrow J/\Psi$ (1) [small]

$q\overline{q} \rightarrow J/\Psi$ (1) [large]

@SpinQuest

$gg \rightarrow J/\Psi + g$ (16)

$g + q(\overline{q}) \rightarrow J/\Psi + q(\overline{q})$ (5)

$q(\overline{q}) + g \rightarrow J/\Psi + q(\overline{q})$ (5)

$q + \overline{q} \rightarrow J/\Psi + g$ (5)

$\overline{q} + q \rightarrow J/\Psi + g$ (5)

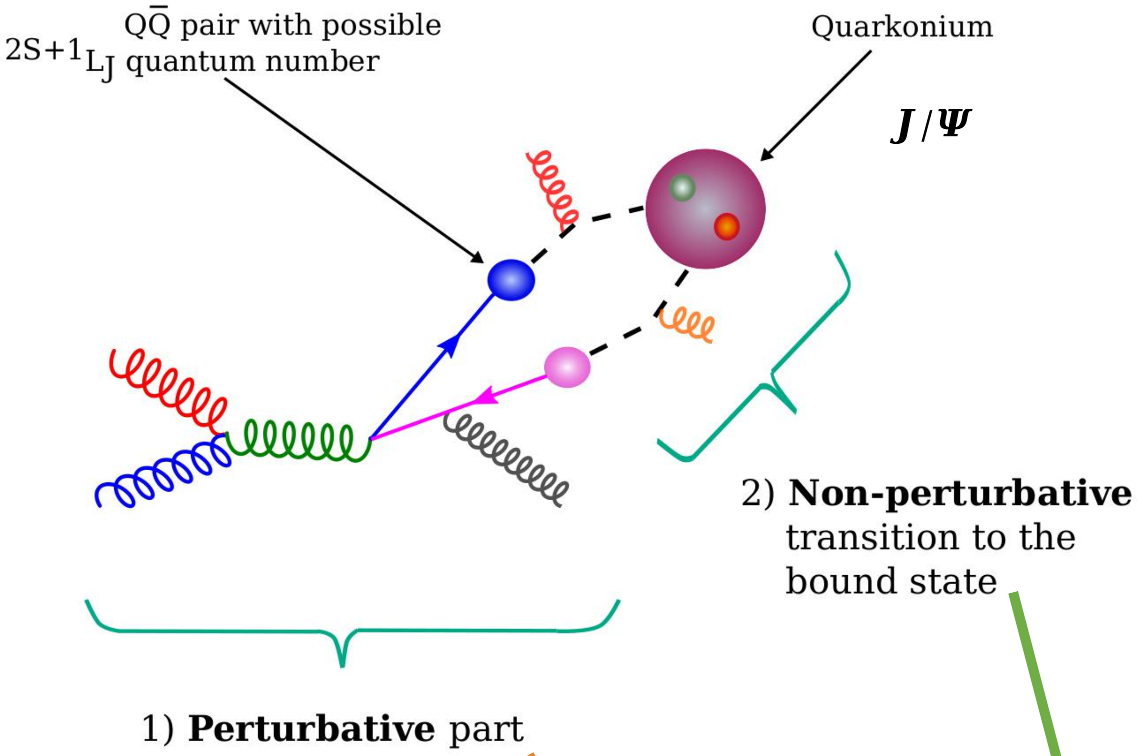
J/ψ as a probe for Gluon TMDs

- Color Singlet Model (CSM)

  Baier and R. Ruckl, Z.Phys.C 19 (1983) 251

- Color Evaporation Model (CEM)

  H. Fritzsch, PL 67B (1977) 217-221

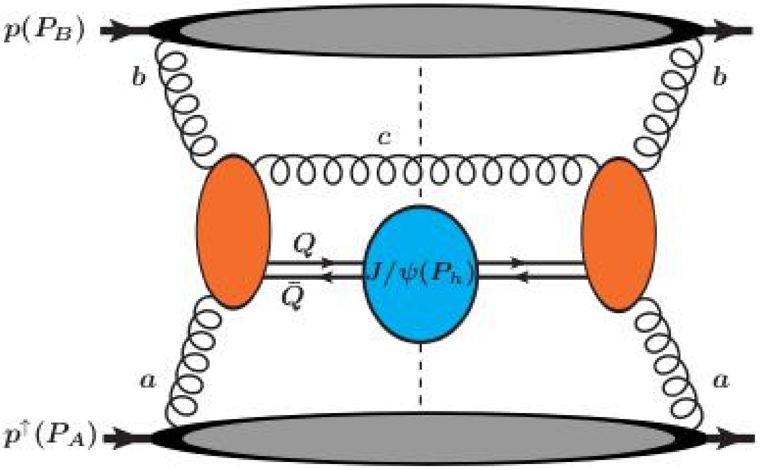


- Non-Relativistic QCD (NRQCD)

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

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

Generalized Parton Model(GPM)



- Inclusion of intrinsic transverse momentum and spin effects in a natural way
- Assumed TMD factorization
- Infrared divergences regulated by intrinsic transverse momentum of the partons
- Gaussian ansatz for TMD parametrization

Unpolarized cross section: $pp \to J/\Psi + X$ in GPM

$$E_h \frac{d^3\sigma^{2\to1}}{d^3\boldsymbol{P}_h} = \sum_{a,b} \frac{\pi}{x_a x_b s^2} \int d^2\boldsymbol{k}_{\perp a} d^2\boldsymbol{k}_{\perp b} f_{a/p}(x_a, k_{\perp a}) f_{b/p}(x_b, k_{\perp b})\, \delta^2(\boldsymbol{k}_{\perp a} + \boldsymbol{k}_{\perp b} - \boldsymbol{P}_T) |\mathcal{M}_{ab\to J/\psi}|^2$$

$$E_h \frac{d^3\sigma^{2\to2}}{d^3\boldsymbol{P}_h} = \frac{1}{2(2\pi)^2} \frac{1}{2s} \sum_{a,b,c} \int \frac{dx_a}{x_a} \frac{dx_b}{x_b}\, d^2\boldsymbol{k}_{\perp a} d^2\boldsymbol{k}_{\perp b} f_{a/p}(x_a, k_{\perp a}) f_{b/p}(x_b, k_{\perp b}) \delta(\hat{s} + \hat{t} + \hat{u} - M^2) |\mathcal{M}_{ab\to J/\psi + c}|^2$$

NRQCD ← Hard part

Unpol. cross section

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

For Quarks: $< k_\perp^2 >= 0.25\ GeV^2$ Gluons: $< k_\perp^2 >= 1\ GeV^2$

M. Anselmino, M. Boglione, U. D'Alesio, A. Kotzinian, F. Murgia and A. Prokudin PRD 71 (2005) 074006

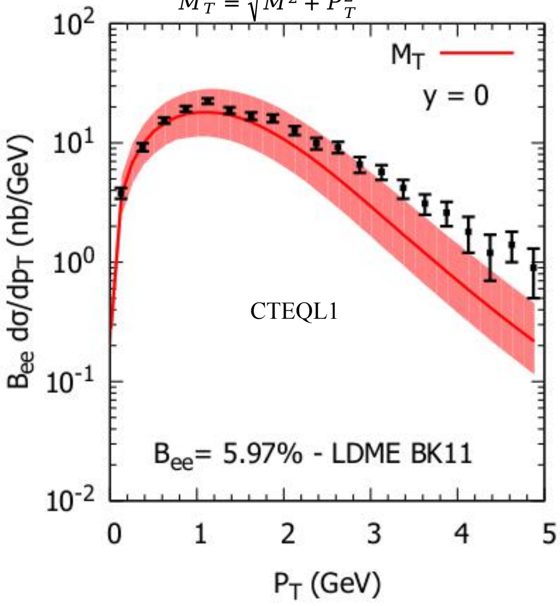
- Two sets of LDMEs are considered

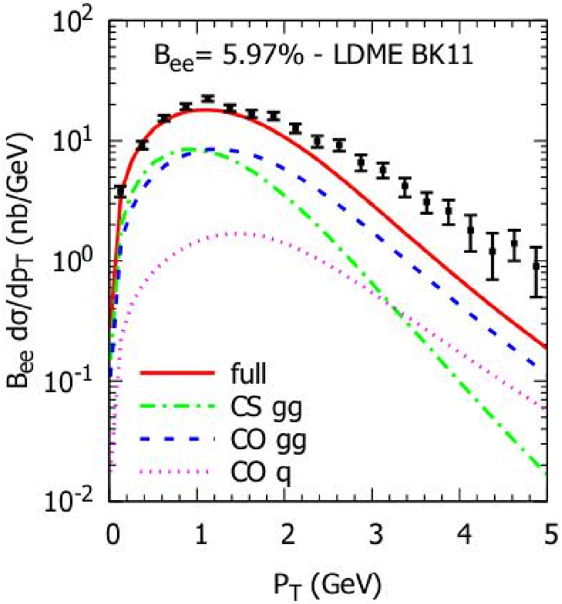
M. Butenschoen and B. Kniehl, PRD84 (2008) 051501 (BK11)
P. Sun, C. Yuan and F. Yuan PRD88 (2013) 054008 (SYY13)

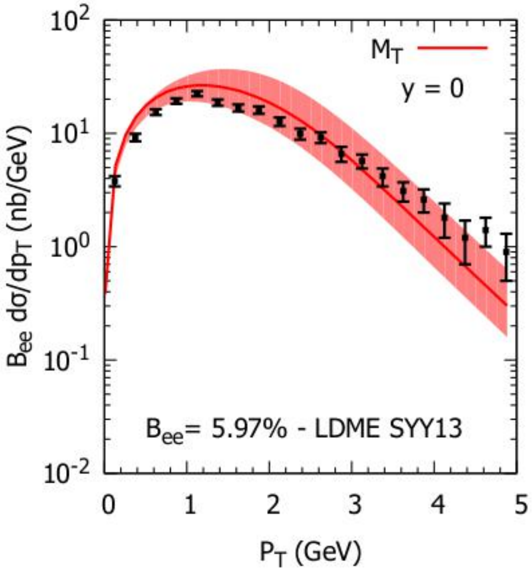
$\sqrt{s} = 200$ GeV RHIC

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

$M_T = \sqrt{M^2 + P_T^2}$







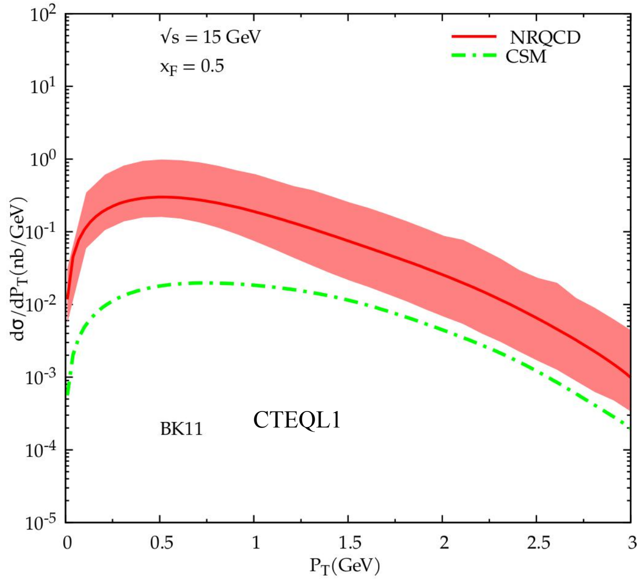
Main contribution from $gg \to J/\Psi + g$ and $gg \to J/\Psi$ @RHIC

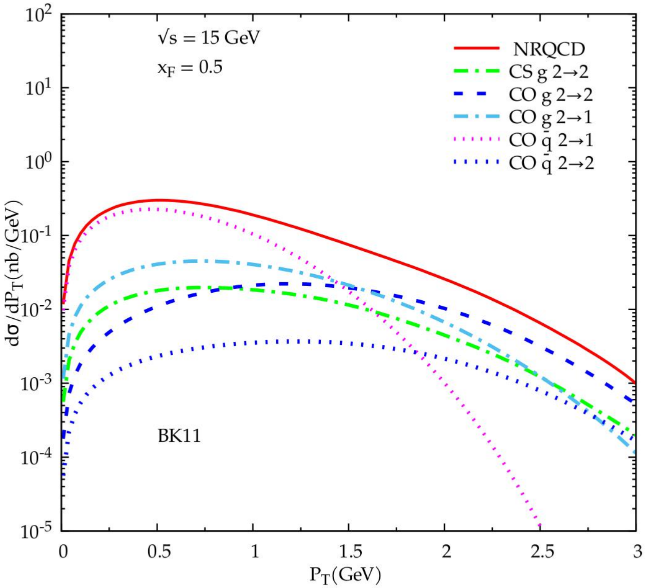
U. D'Alesio, F. Murgia, C.Pisano and SR, EPJC 79 (2019) 12

Unpol. cross section

$\sqrt{s}$ = 15 GeV @ SpinQuest

$M_T = \sqrt{M^2 + P_T^2}$





- In $2 \rightarrow 1$ channel, kinematics is fixed $x_{a,b} = \frac{M_T}{\sqrt{s}} e^{\pm y}$

  $x_a(beam) = [0.57, 0.63]$, $x_b(target) = [0.07, 0.13]$ at $x_F = 0.5$

- @SpinQuest kinematics, the $2 \rightarrow 1$ channel, particularly $q\bar{q} \rightarrow J/\Psi$, is contributing significantly in the low P_T region upto 1.5 GeV

- The high P_T region is dominated by the $2 \rightarrow 2$ channel, mainly $gg \rightarrow J/\Psi + g$

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

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

- The denominator is twise the unpolarized differential cross section
- The numerator of the asymmetry is sensitive to the Sivers function

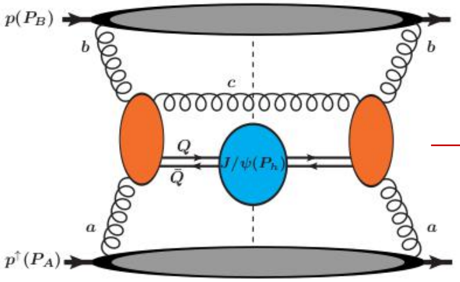
$$\mathrm{d}\Delta\sigma_{2\to 2}^{\mathrm{GPM}} = \frac{1}{(2\pi)^2}\frac{1}{2s}\sum_{a,b,c}\int \frac{dx_a}{x_a}\frac{dx_b}{x_b} d^2\boldsymbol{k}_{\perp a} d^2\boldsymbol{k}_{\perp b}\, \delta(\hat{s}+\hat{t}+\hat{u}-M^2)\left(-\frac{k_{\perp b}}{M_p}\right)\cos\phi_b\, f_{a/p}(x_a, k_{\perp a}) f_{1T}^{\perp b}(x_b, \boldsymbol{k}_{\perp b})|\mathcal{M}_{2\to 2}|^2$$

- In GPM: 1 QSF and 1 GSF (Universal, process independent)
- In CGI-GPM: 1 QSF and 2 GSFs (Universal but process dependent)

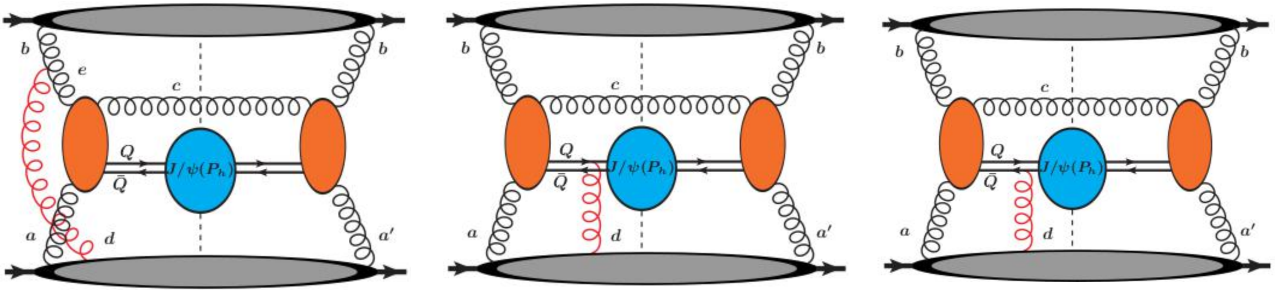
$$\begin{aligned} \mathrm{d}\Delta\sigma_{2\to 2}^{\mathrm{CGI-GPM}} = {} & \frac{1}{(2\pi)^2}\frac{1}{2s}\int \frac{dx_a}{x_a}\frac{dx_b}{x_b}\, d^2\boldsymbol{k}_{\perp a}\, d^2\boldsymbol{k}_{\perp b}\, \delta(\hat{s}+\hat{t}+\hat{u}-M^2)\Big(-\frac{k_{\perp b}}{M_p}\Big)\cos\phi_b \\ & \times \Big\{ \sum_q \Big[f_{1T}^{\perp q}(x_b, k_{\perp b}) \Big(f_{\bar{q}/p}(x_a, k_{\perp a})\, |\mathcal{M}^{\mathrm{Inc}}_{\bar{q}q\to J/\psi+g}|^2 + f_{g/p}(x_a, k_{\perp a})\, |\mathcal{M}^{\mathrm{Inc}}_{gq\to J/\psi+q}|^2 \Big) \Big] \\ & + \sum_{m=f,d} f_{1T}^{\perp g(m)}(x_b, k_{\perp b}) \Big(\sum_q f_{q/p}(x_a, k_{\perp a})\, |\mathcal{M}^{\mathrm{Inc}(m)}_{qg\to J/\psi+q}|^2 + f_{g/p}(x_a, k_{\perp a})\, |\mathcal{M}^{\mathrm{Inc}(m)}_{gg\to J/\psi+g}|^2 \Big) \Big\} \end{aligned}$$

CGI-GPM

GPM



CGI-GPM



C_U $C_I^{(f/d)}$ $C_F^{(f/d)}$ [color factors]

- The new color factors are shifted to hard part

$$|M^{Inc(f/d)}|^2 \equiv \frac{C_I^{(f/d)} + C_F^{(f/d)}}{C_U} |M^U|^2$$

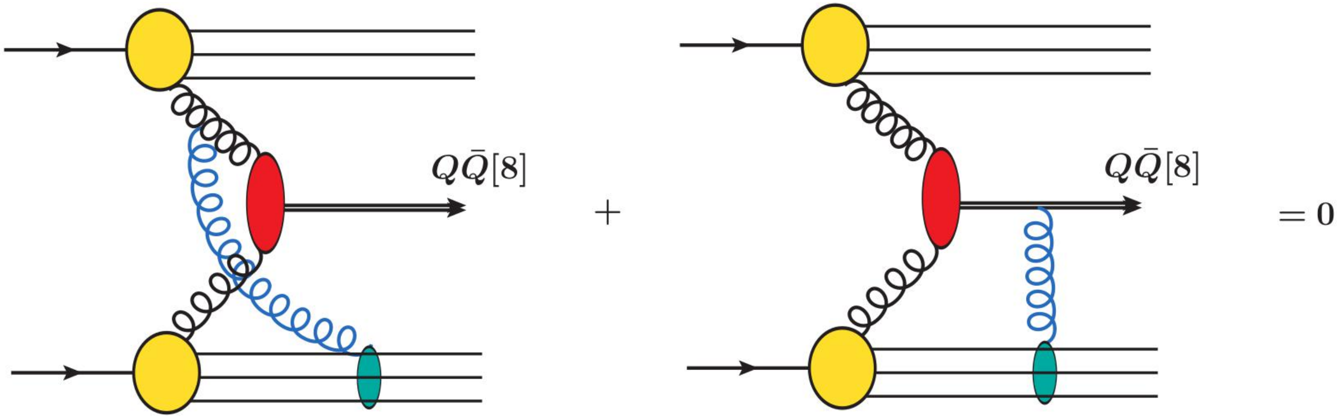
Gamberg and Kang, PLB 696 (2011)

- Two independent $f_{1T}^{\perp(f/d)}$ which are process dependent

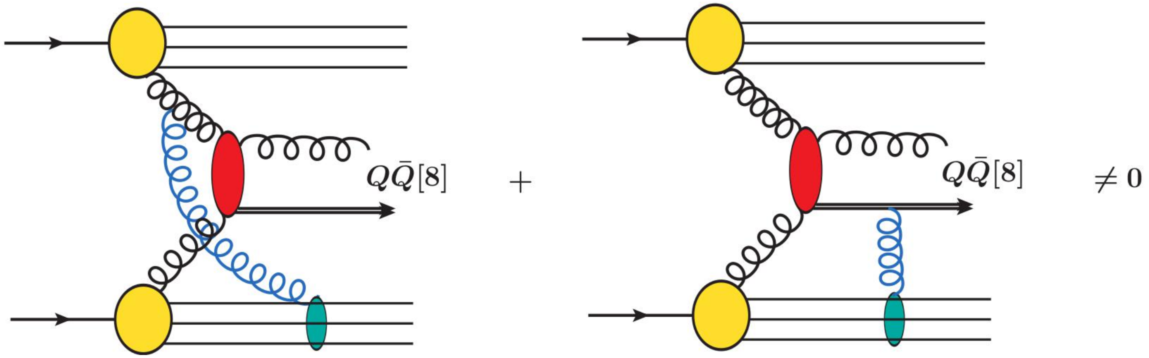
$$\text{[GPM] } f_{1T}^{\perp g}|M^U|^2 \longrightarrow f_{1T}^{\perp f}|M^{Inc(f)}|^2 + f_{1T}^{\perp d}|M^{Inc(d)}|^2 \text{ [CGI-GPM]}$$

CGI-GPM

$2 \rightarrow 1$



$2 \rightarrow 2$



$pp^{\uparrow} \rightarrow J/\psi + X$ [CSM] $|M^{Inc(f)}|^2 \equiv -\frac{1}{2}|M^U|^2$ $|M^{Inc(d)}|^2 \equiv 0$

U. D'Alesio, F. Murgia, C. Pisano and P. Taels, PRD 96 (2017)

$pp^{\uparrow} \rightarrow J/\psi + X$ [NRQCD] $|M^{Inc(f/d)}|^2 \neq 0$

U. D'Alesio, L. Maxia, F. Murgia, C.Pisano and SR, PRD 102 (2020)

TMDs Parametrization

- Parametrization of TMDs within GPM: Gaussian ansatz

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

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

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

U. D'Alesio, C. Flore, F. Murgia, C. Pisano and P. Taels, PRD 99 (2019) 036013

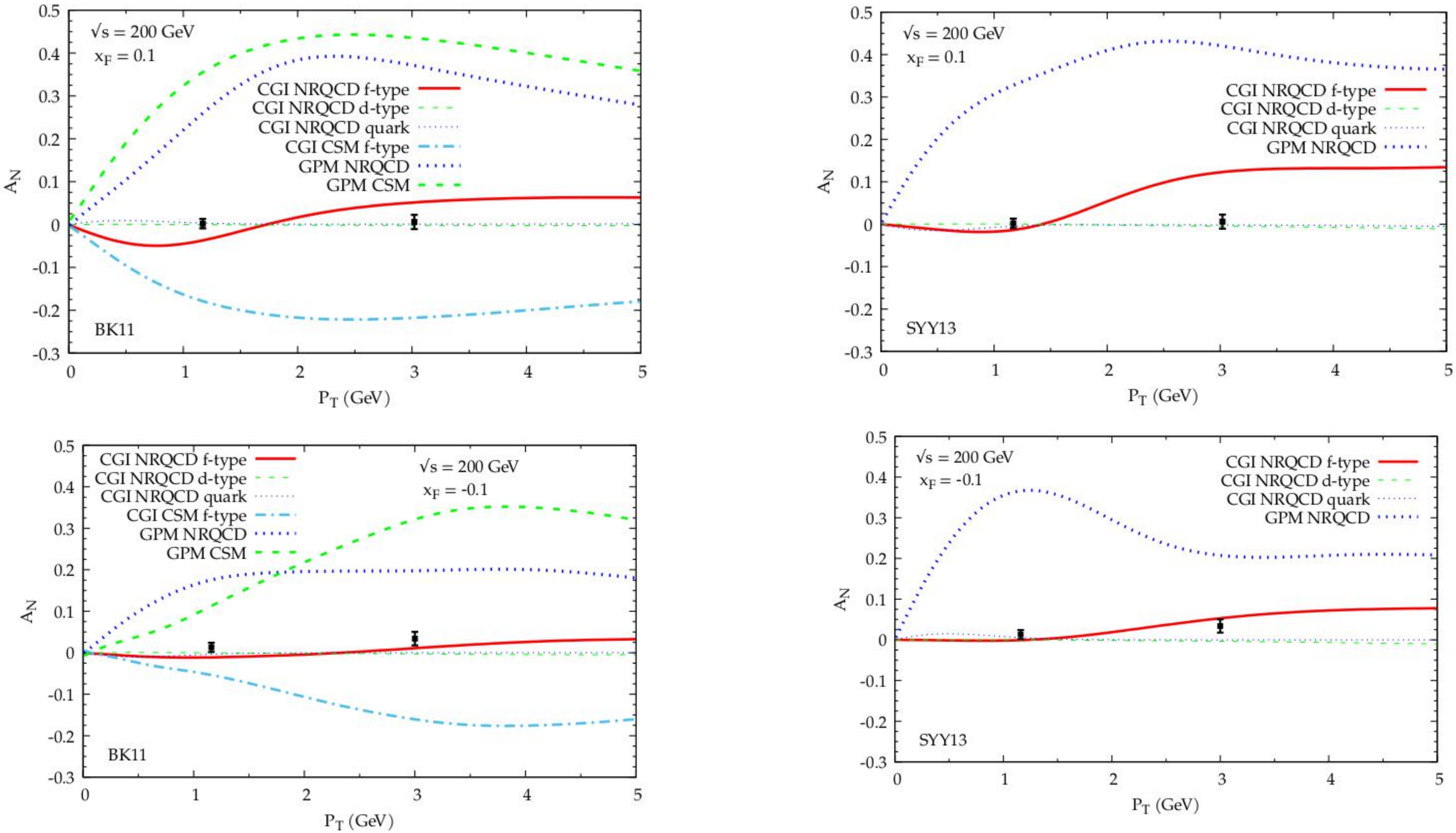
- For maximized asymmetry: Saturate the Sivers function

$$\rho = 2/3,\ \mathcal{N}_a(x_a) = +1\ \&\ \mathcal{N}_g^{(f,d)}(x_g) = +1$$

SSA Results @ RHIC

$\sqrt{s} = 200$ GeV RHIC

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

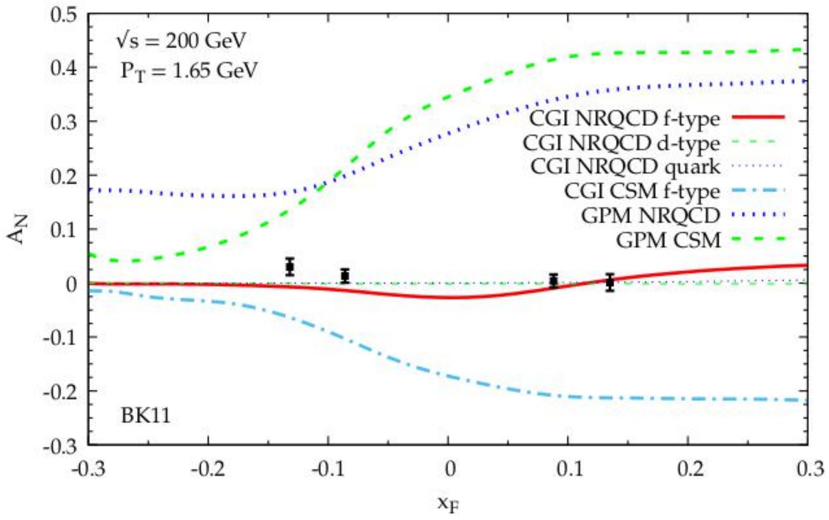


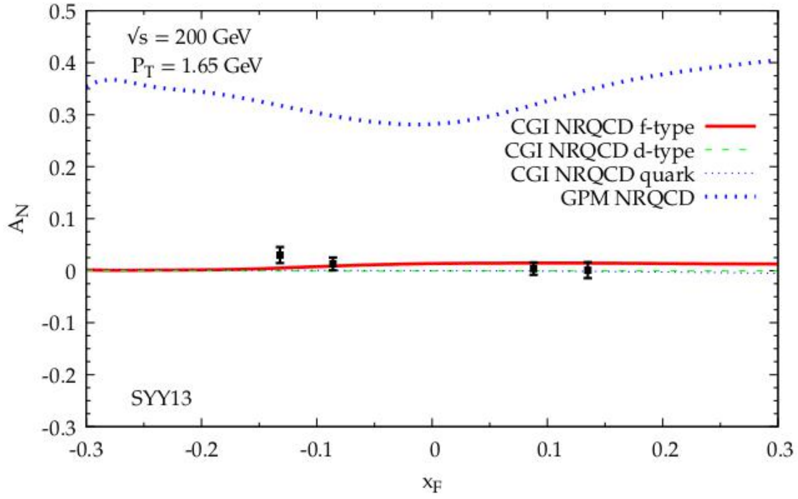
U. D'Alesio, L. Maxia, F. Murgia, C.Pisano and SR, PRD 102 (2020)

SSA Results @ RHIC

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

$\sqrt{s} = 200$ GeV RHIC

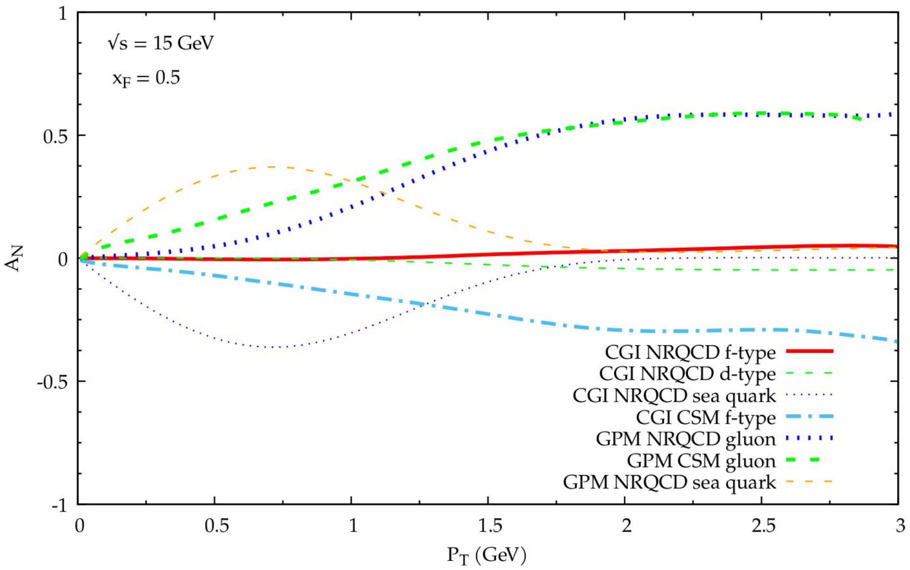


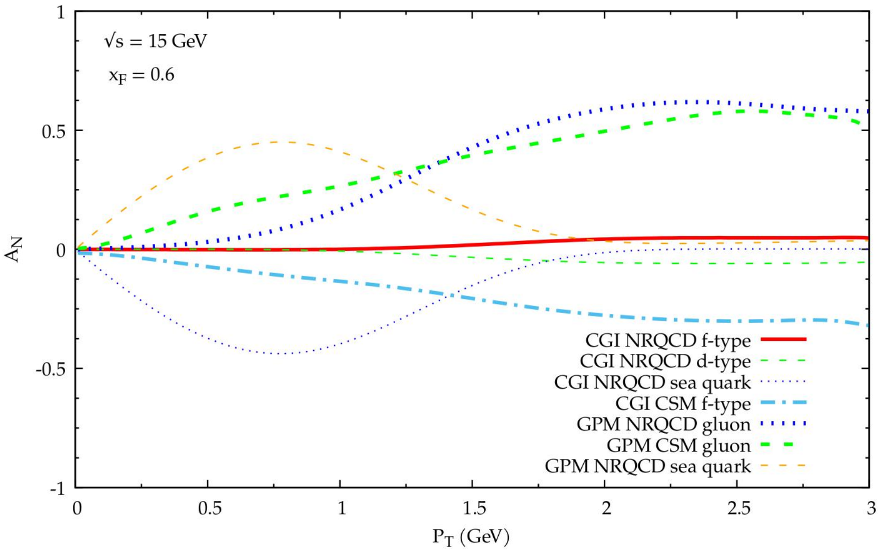


U. D’Alesio, L. Maxia, F. Murgia, C.Pisano and SR, PRD 102 (2020)

SSA Results @ SpinQuest

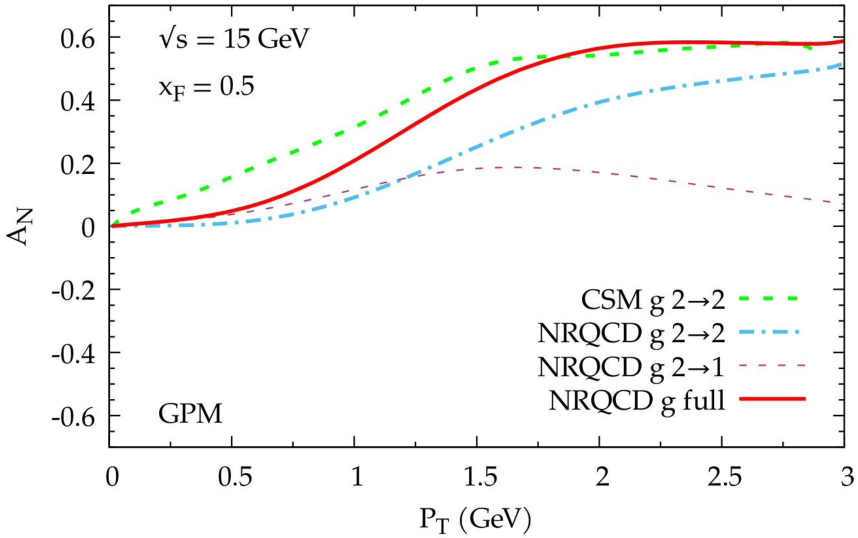
$\sqrt{s} = 15$ GeV @ SpinQuest

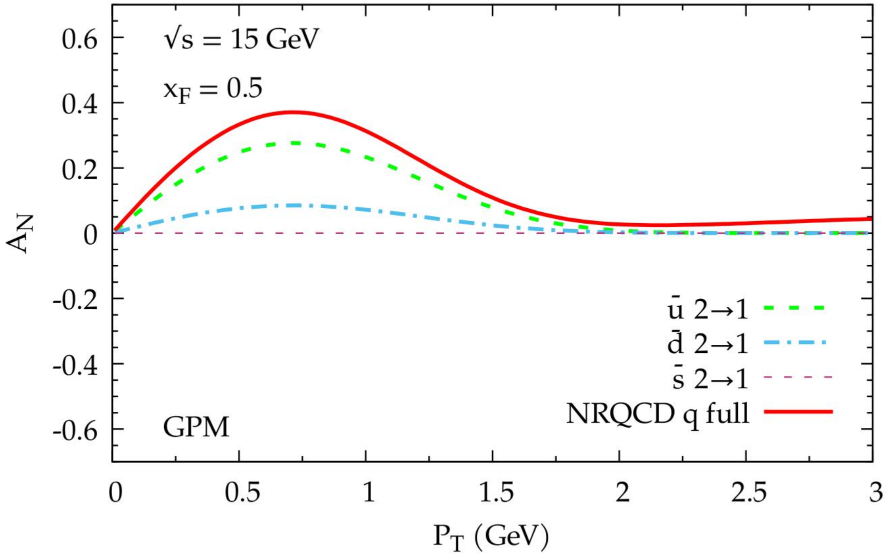




SSA Results @ SpinQuest

$\sqrt{s}$ = 15 GeV @ SpinQuest





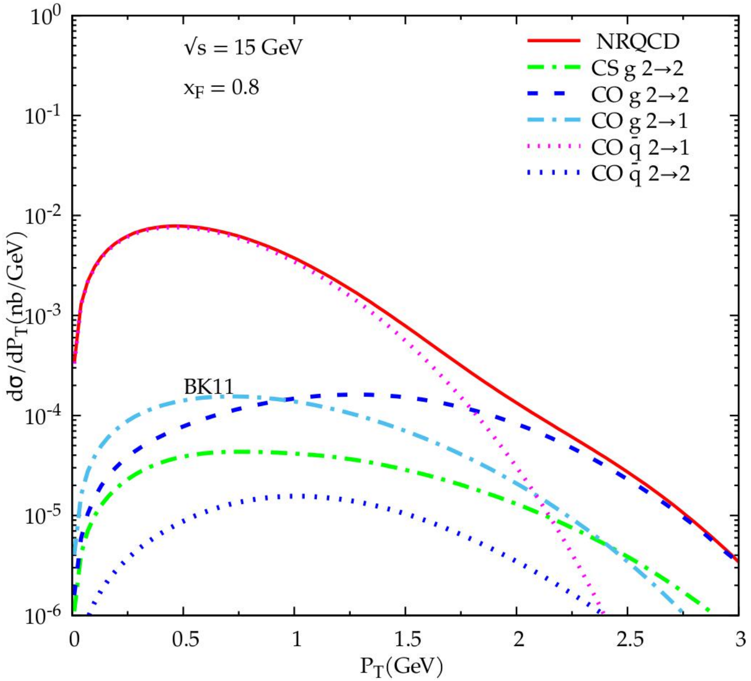
Summary

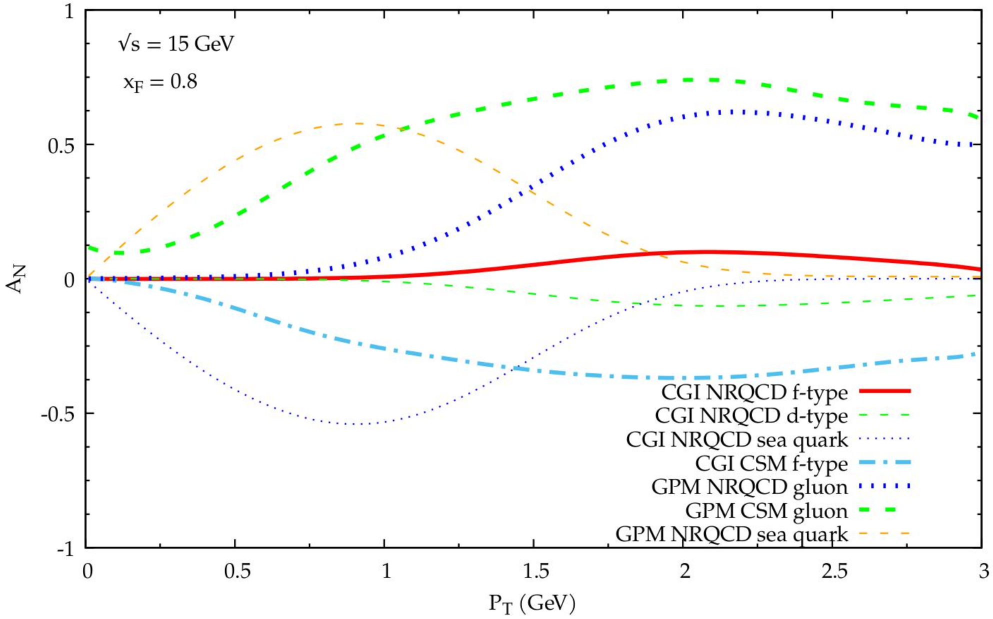
- Single-Spin asymmetry in $pp^{\uparrow} \to J/\psi + X$ collision has been studied
- For the formation of quarkonium production NRQCD model is used
- Unpolarized cross section is in good agreement with the PHENIX data within the GPM framework
- The asymmetry is strongly suppressed in CGI-GPM compared to the GPM due to the suppression of color factors
- More data are needed to constrain the GSF
- The J/ψ production is a ideal process to probe the GSF @ RHIC, while the GSF and light sea QSF could be probed @ SpinQuest kinematics

Thank you for the attention

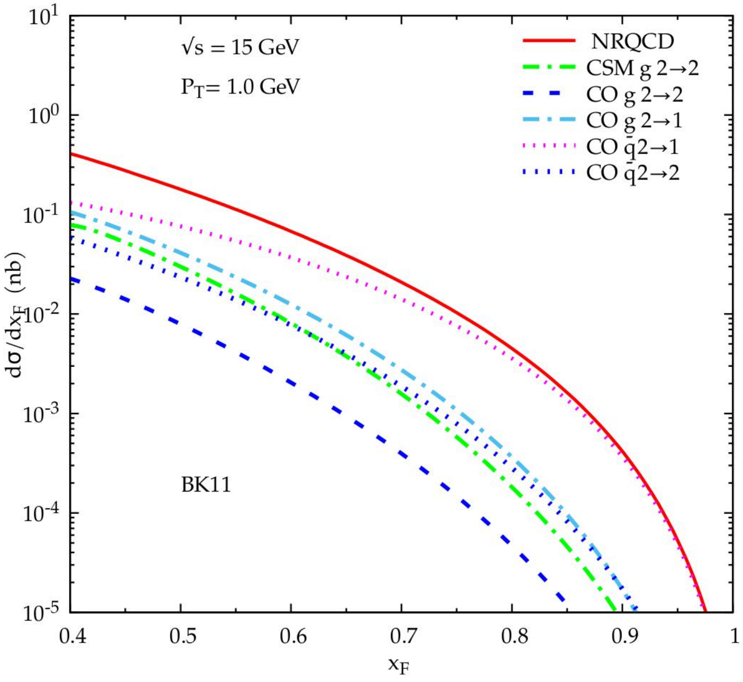
Backup Slides

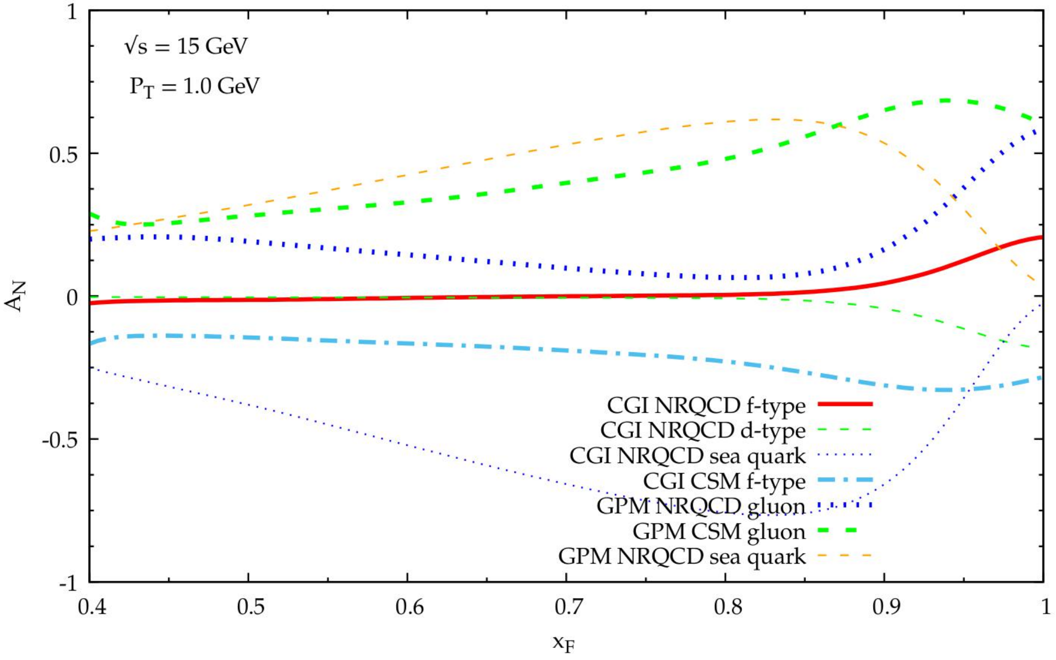
SSA Results @ SpinQuest



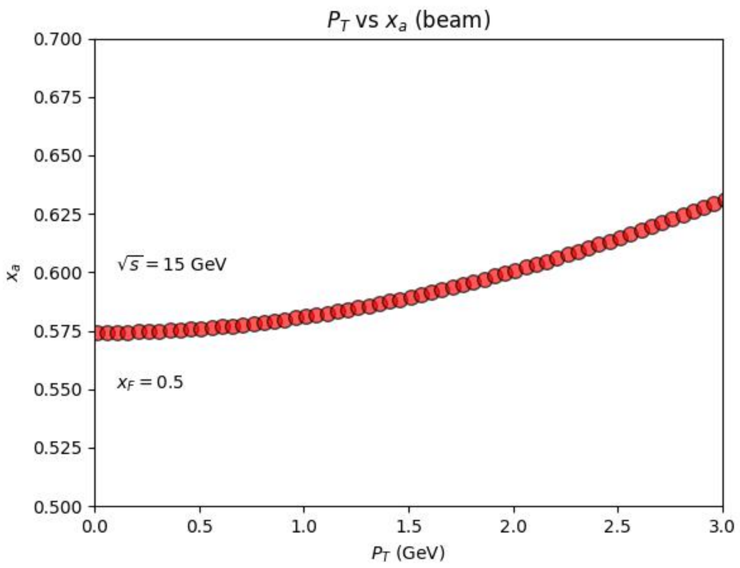


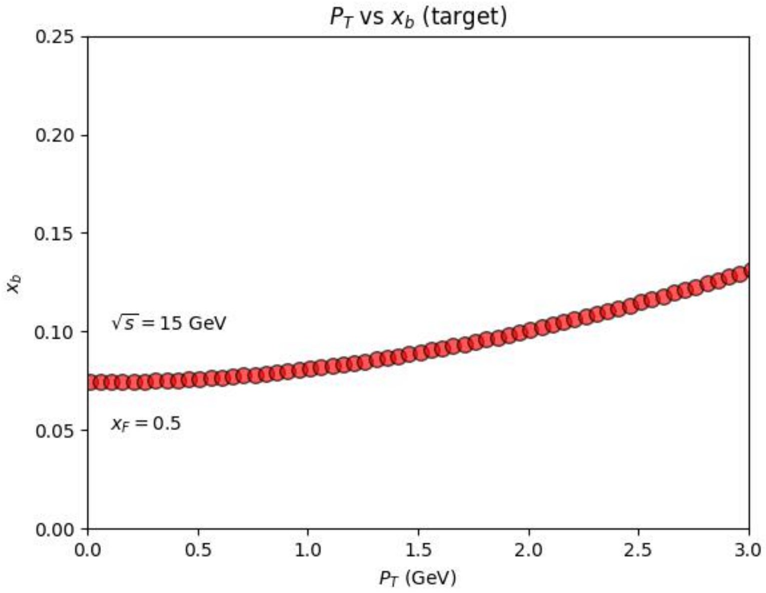
SSA Results @ SpinQuest

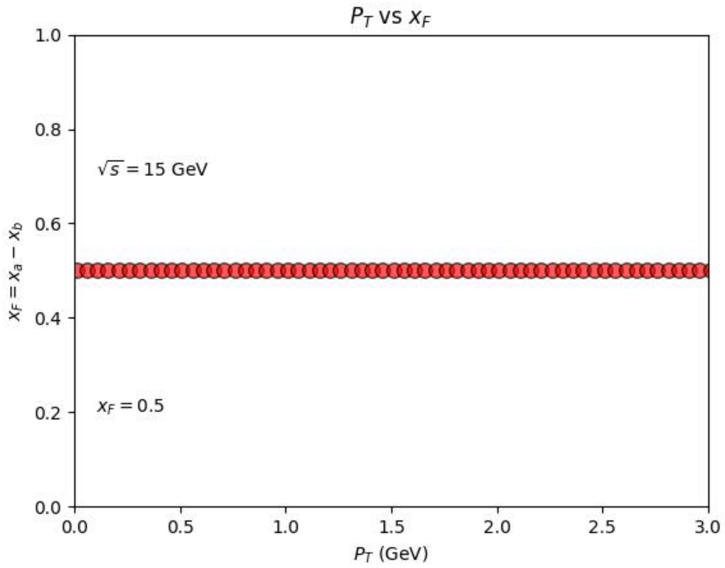




Kinematics of 2→ 1 @SpinQuest


P_T vs x_a (beam)


P_T vs x_b (target)


P_T vs x_F

Kinematics of $2\rightarrow 2$ @SpinQuest