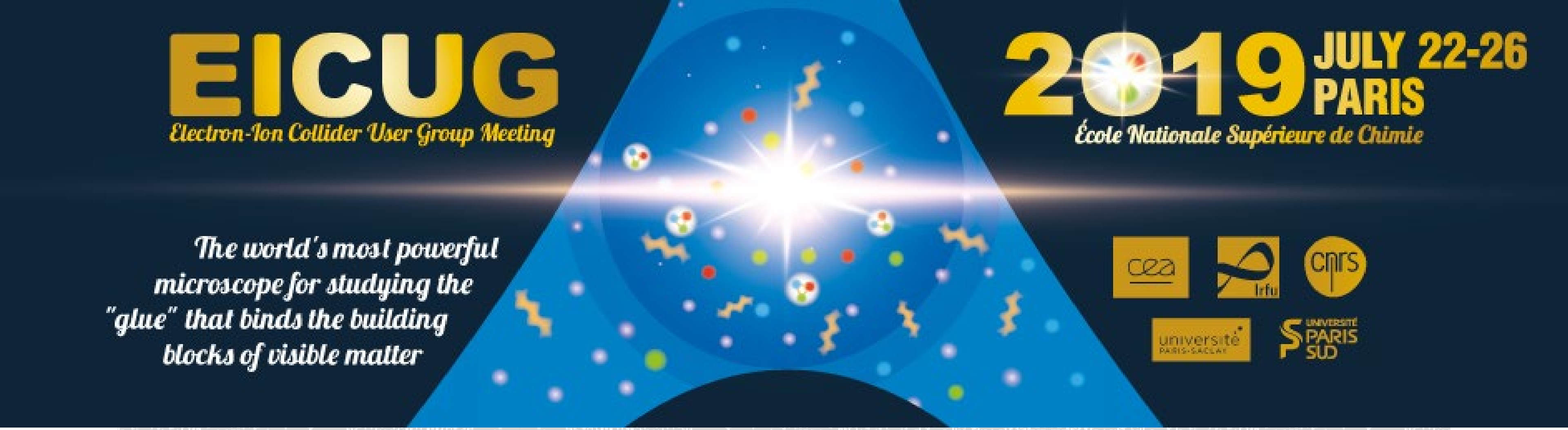

QUARKONIUM PRODUCTION IN EP AND PP COLLISIONS WITHIN A TMD APPROACH

U. D'Alesio in collaboration with

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Sangem Rajesh and Pieter Taels

INFN CAGLIARI

OUTLINE

- J/ψ production within a TMD scheme
- $e\,p \;\rightarrow e\;\; J/\psi + jet\; + X$ at an EIC
  - ◊ direct access to TMDs for linearly polarized gluons
- $pp \;\rightarrow J/\psi + X$
  - ◊ cross sections and SSAs (access to the Sivers function):
- Role of the production mechanisms [CS vs. NRQCD]
- Concluding remarks

3D Nucleon Structure
(a more complete description)

- Quark TMDs : information and direct evidence from several experiments, rich phenomenology (about 20 years)
- Gluon TMDs: poorly known

Golden channels to access gluon TMDs:

- $pp \to \pi\, X$ at mid-rapidity
- $pp \to \gamma\, X \;\; pp \to D\, X$, dijet production….and many more
- quarkonium production (this talk)

First phenomenological studies

Sun, Xiao, Yuan (2011)
Boer, Brodsky, Mulders, Pisano (2011)
Boer, den Dunnen, Pisano, Schlegel, Vogelsang (2012)

Disclaimer

- A challenging (open) issue: production mechanisms/polarization states

…a lot of work and many papers [see Lansberg 2019 for a review]

- Here: A phenomenological TMD approach within NRQCD **focused** on azimuthal and spin asymmetries as a tool to access gluon TMDs

$$e(\ell) + p(P,S) \to e(\ell') + J/\psi(K_\psi) + \mathrm{jet}(K_\mathrm{j}) + X$$

[UD, Murgia, Pisano, Taels, in progress]

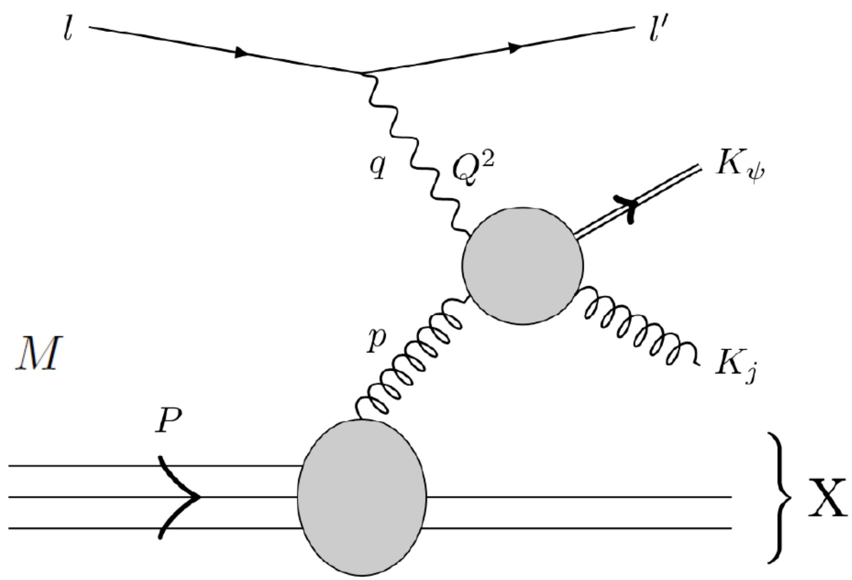
Transverse variables

$$\mathbf{K}_\perp = \frac{\mathbf{K}_{\psi\perp} - \mathbf{K}_{j\perp}}{2}$$

$$\mathbf{q}_T = \mathbf{K}_{\psi\perp} + \mathbf{K}_{j\perp}$$

$$|\mathbf{q}_T| \ll |\mathbf{K}_\perp| \sim Q \sim M$$

Two ordered scales



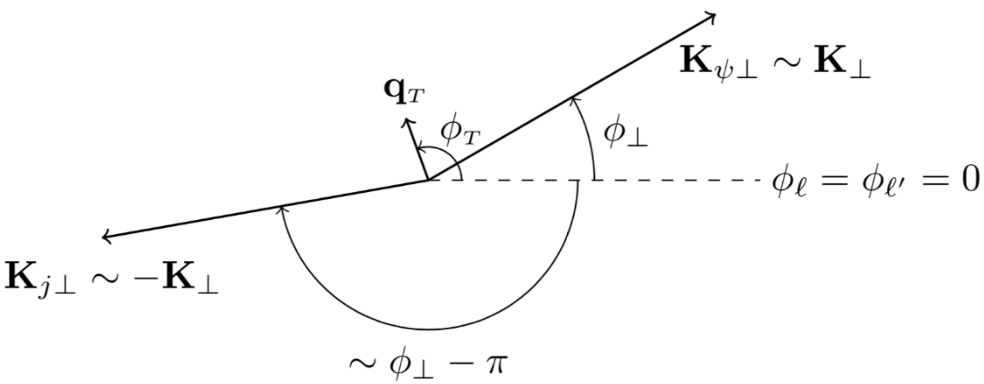
Collinear variables

$$x = x_B \frac{\hat{s} + Q^2}{Q^2}$$

$$y = \frac{P \cdot q}{P \cdot l}$$

$$Q^2 = x_B y s$$

$$z = \frac{K_\psi \cdot P}{q \cdot P}$$



$$e\,p \to e\,J/\psi\,X$$

Bacchetta, Boer, Pisano, Taels 2018

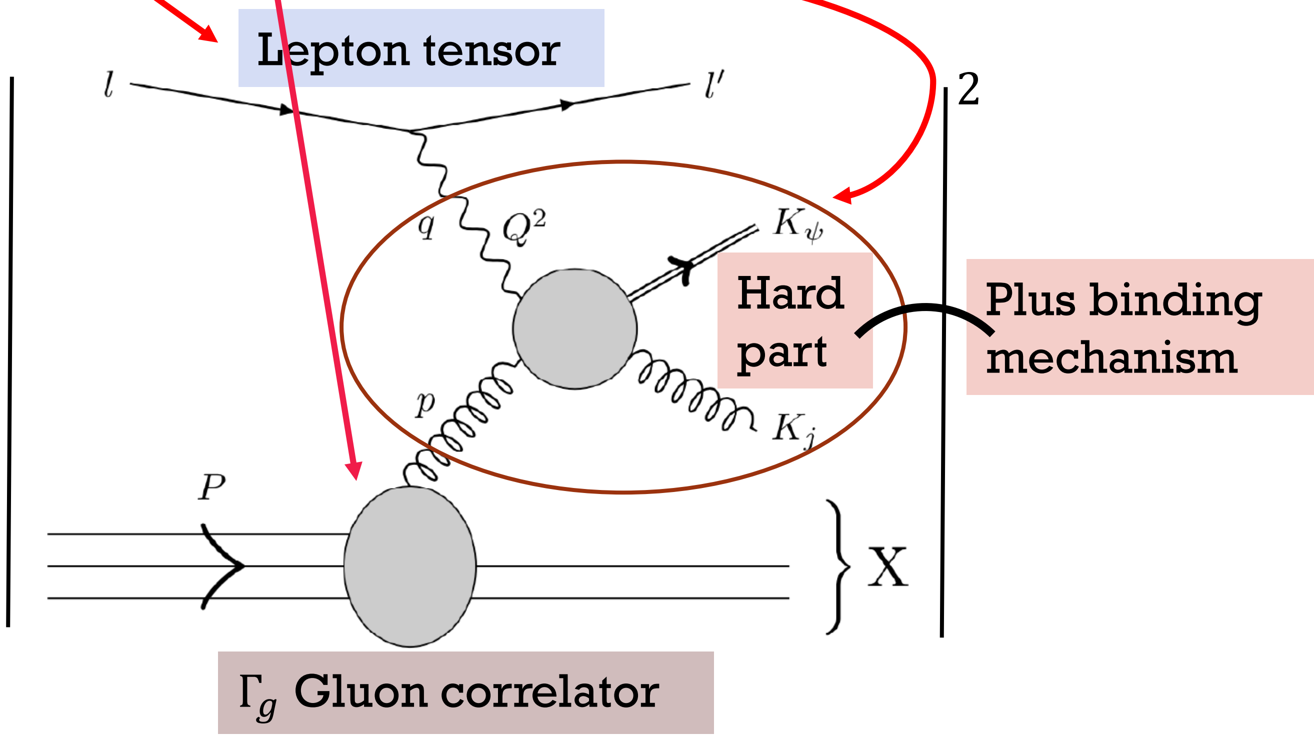
$$e(\ell) + p(P,S) \to e(\ell') + J/\psi(K_\psi) + \mathrm{jet}(K_\mathrm{j}) + X$$

cross section

intrinsic p_T

$$\mathrm{d}\sigma = \frac{1}{2s}\frac{\mathrm{d}^3\ell'}{(2\pi)^3 2E_{\ell'}}\frac{\mathrm{d}^3K_\psi}{(2\pi)^3 2E_\psi}\frac{\mathrm{d}^3K_j}{(2\pi)^3 2E_j}\int \mathrm{d}x \int \mathrm{d}^2\boldsymbol{p}_T (2\pi)^4\delta^{(4)}(q+p-K_j-K_\psi)$$

$$\times \frac{1}{Q^4} L^{\mu\nu}(\ell,q)\,\Gamma_g^{\rho\sigma}(x,\boldsymbol{p}_T)\,H_{\mu\rho}\,H^*_{\nu\sigma}\,.$$



Gluon correlator

Mulders, Rodrigues (2001)
Meissner, Metz & Goeke (2007)

Unpolarized target

Unpol. TMD

Linearly polarized gluon TMD

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

Transversely polarized target

Gluon Sivers TMD

Circularly polarized gluon TMD

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

Linearly polarized gluon TMDs

Gluon TMDs at leading twist

Target \ Gluons	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

collinear

Cross section

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

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

T-even TMDs: no need of initial/final state interactions

Similar to heavy-quark pair production

Pisano, Boer, Brodsky, Buffing & Mulders (2013); Boer, Mulders, Pisano, Zhou (2016)

$$\int \mathrm{d}\phi_\perp \mathrm{d}\sigma^T = 2\pi\mathcal{N}\,|\boldsymbol{S}_T|\,\frac{|\boldsymbol{q}_T|}{M_p}\Big[\mathcal{A}_0^{eg}\sin(\phi_S-\phi_T)f_{1T}^{\perp\,g}(x,\boldsymbol{q}_T^2)$$
$$-\frac{1}{2}\mathcal{B}_0^{eg}\sin(\phi_S-3\phi_T)\frac{|\boldsymbol{q}_T|^2}{M_p^2}\,h_{1T}^{\perp\,g}(x,\boldsymbol{q}_T^2)$$
$$+\mathcal{B}_0^{eg}\sin(\phi_S+\phi_T)h_1^g(x,\boldsymbol{q}_T^2)\Big]$$

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

T-odd TMDs

Quarkonium production mechanism

In Color Singlet Model (CSM), heavy-quark pair is produced directly with the quantum numbers of the quarkonium:

Chang (1980); Baier and Rückl (1983)

$$\mathcal{A}_i^{\gamma^* g} = \mathcal{C}_{CS}\, \mathcal{A}_i^{CS}\, \langle 0|\mathcal{O}_1(^3S_1)|0\rangle \quad \text{and} \quad \mathcal{B}_i^{\gamma^* g} = \mathcal{C}_{CS}\, \mathcal{B}_i^{CS}\, \langle 0|\mathcal{O}_1(^3S_1)|0\rangle$$

nonperturbative Long Distance Matrix Element (LDME)

In nonrelativistic QCD (NRQCD), the pair is produced in *every allowed quantum number*, and hadronizes only later

Bodwin, Braaten, and Lepage (1995)

$$\mathcal{A}_i^{\gamma^* g} = \mathcal{C}^{^1S_0}\, \langle 0|\mathcal{O}_8(^1S_0)|0\rangle\, \mathcal{A}_i^{^1S_0} + \mathcal{C}^{^3S_1}\, \langle 0|\mathcal{O}_8(^3S_1)|0\rangle\, \mathcal{A}_i^{^3S_1} + \mathcal{C}^{^3P_0}\, \langle 0|\mathcal{O}_8(^3P_0)|0\rangle\, \mathcal{A}_i^{^3P_0}$$
$$+ \mathcal{C}^{^3P_1}\, \langle 0|\mathcal{O}_8(^3P_1)|0\rangle\, \mathcal{A}_i^{^3P_1} + \mathcal{C}^{^3P_2}\, \langle 0|\mathcal{O}_8(^3P_2)|0\rangle\, \mathcal{A}_i^{^3P_2}\,,$$

LDMEs for Color Octet states

Spectroscopic notation: $^{2S+1}L_J$

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

As in SIDIS

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

Unpolarized target

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

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

Transversely polarized target

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

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

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

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

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

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

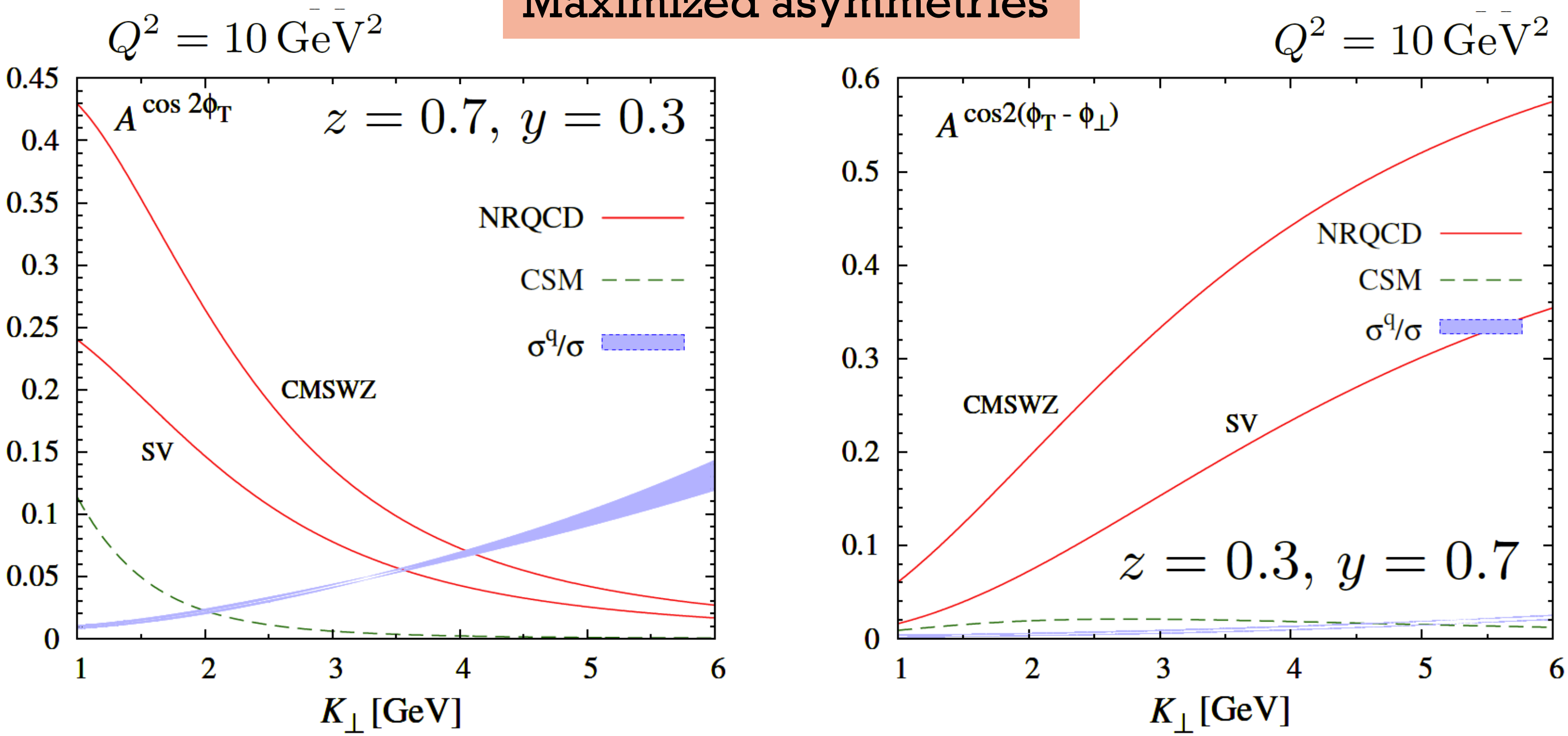
Positivity bounds for TMDs

$$A^{\cos\phi_T} \le \frac{2\mathcal{B}_0^{eg}}{\mathcal{A}_0^{eg}} \qquad A^{\cos 2(\phi_T-\phi_\perp)} \le \frac{2\mathcal{B}_2^{eg}}{\mathcal{A}_0^{eg}}$$

$$A^{\sin(\phi_S+\phi_T)} \le \frac{\mathcal{B}_0^{eg}}{\mathcal{A}_0^{eg}} \qquad A^{\sin(\phi_S-3\phi_T)} \le \frac{\mathcal{B}_0^{eg}}{\mathcal{A}_0^{eg}}$$

Model independent

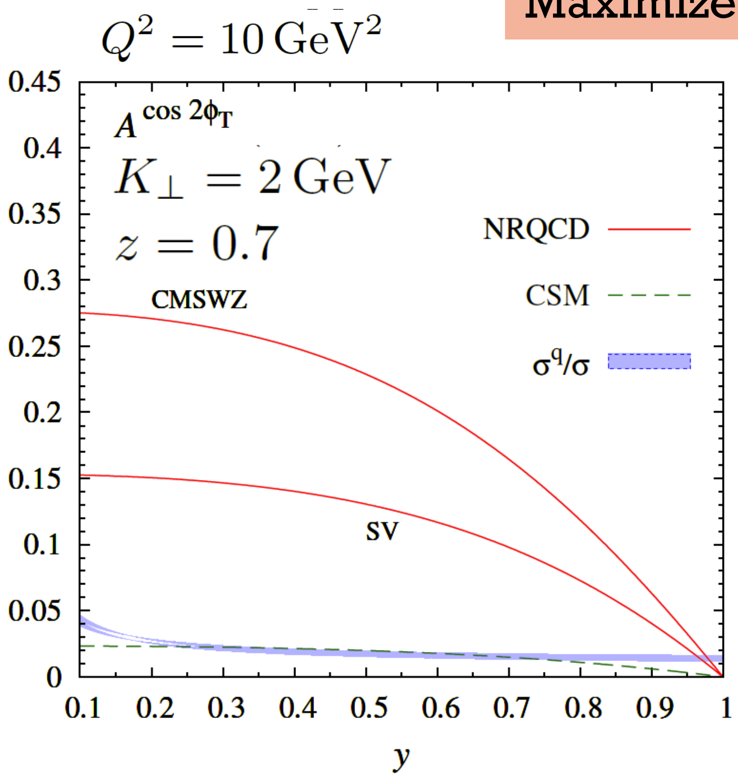
Maximized asymmetries

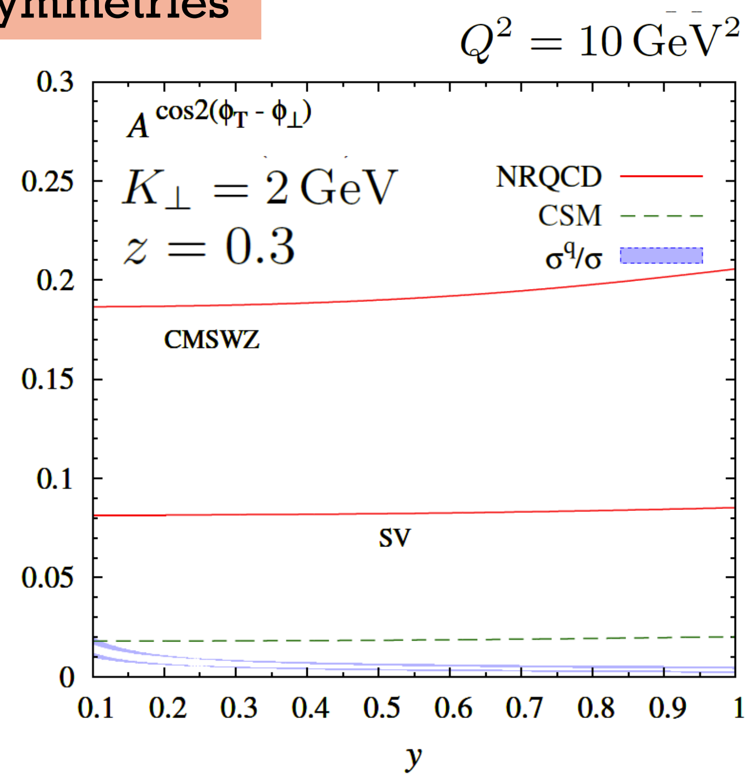


- ❑ No direct energy dependence in the maximized values
- ❑ Gluon dominance: quark/full **negligible** (band: scale uncertainty) [$\sqrt{s}$=65 GeV]

Two LDME sets: SV : Sharma & Vitev PRC 87, 2013
CMSWZ: Chao et al, PRL 108, 2012

Maximized asymmetries





- ❑ CSM: almost negligible
- ❑ Sizeable effects for Color Octet Mechanism
- ❑ Quark contribution under control (negligible)
- ❑ Strong dependence on LDMEs

$pp \to J/\Psi\, X$

[UD, Murgia, Pisano, Rajesh, in progress]

TMD scheme

- Effects: no separable (like for pion production)
- Integration over intrinsic azimuthal phases implies
  - ❑ Unpolarized cross section: only unpol. TMDs
  - ❑ Single spin asymmetry: only Sivers effect survives

$$A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} = \frac{d\Delta\sigma}{2d\sigma}$$

[UD, Murgia, Pisano, Taels (2017); Godbole et al. (2017)]

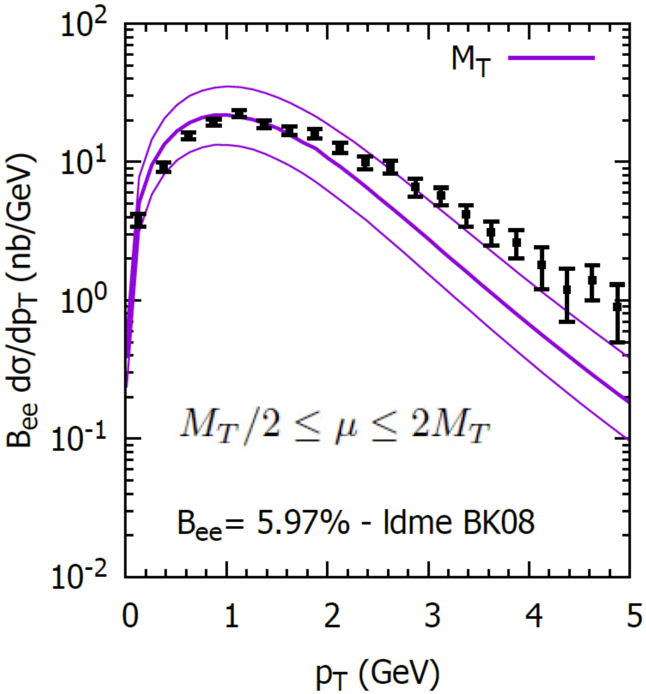
again use of NRQCD: 30 Feynman diagrams

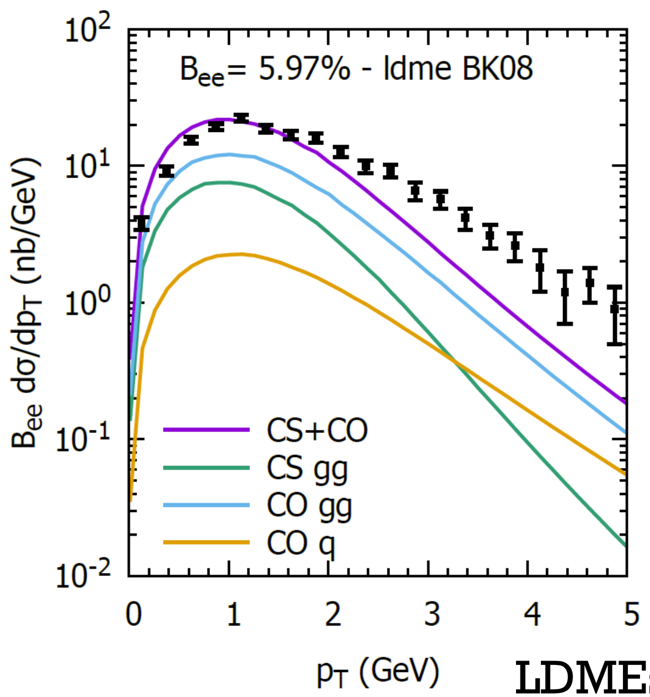
P. L Cho et al, Phys. Rev. **D53**, 6203 (1996)

- NRQCD at low p_T: infrared divergences (LDMEs at p_T>2-5 GeV)
- Resummation, k_T-factorization, Color Glass Condensate…
- In a TMD scheme, intrinsic k_T (Gaussian k_T dep.) can "help"…

$$f_{g/p}(x, k_\perp) = f_{g/p}(x)\, \frac{1}{\pi\langle k_\perp^2\rangle}\, e^{-k_\perp^2/\langle k_\perp^2\rangle} \qquad \langle k_\perp^2\rangle = 1\mathrm{GeV}^2$$

& IR regular.

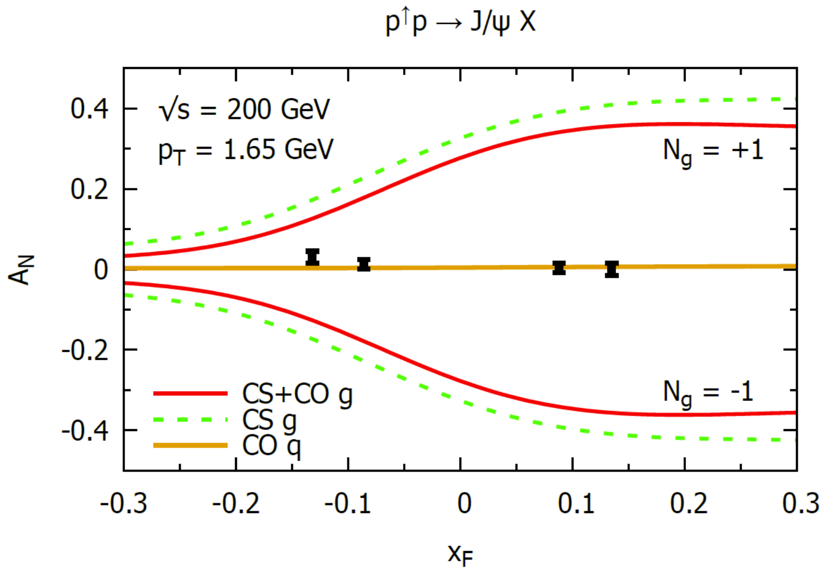




Data from PHENIX [Adare et al. 10]

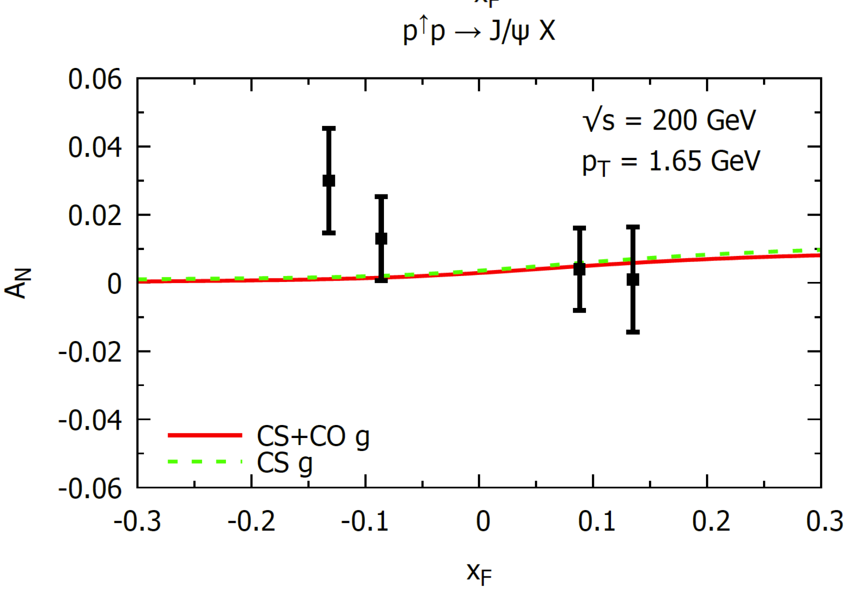
LDMEs from Butenschoen, Kniehl 2008

No feed-down: its inclusion could improve the description



Sivers effect

Maximized contributions:
Quark contributions almost zero
Small differences between CS and CS+CO



Predictions adopting the GSF from
UD, Flore, Murgia, Pisano, Taels 19
Data from PHENIX [Aidala et al. 18]

CONCLUDING REMARKS

- ❑ Quarkonium production in a TMD scheme & NRQCD
- ❑ $e\,p \to e\,J/\psi\,\mathrm{jet}\,X$

✓ sizeable asymmetries over a large kinematic range (@EIC)

✓ quark contribution negligible (even at "low" EIC energy)

✓ strong dependence on LDMEs

✓ direct access to TMDs for linearly polarized gluons

- ❑ $pp \to J/\psi\,X$

✓ intrinsic k_T: helpful for the low-p_T spectrum

✓ SSAs: gluon (Sivers) dominated; no strong dependence on the production mechanism

✓ process dependence via initial/final state interact.s: (2 GSFs)

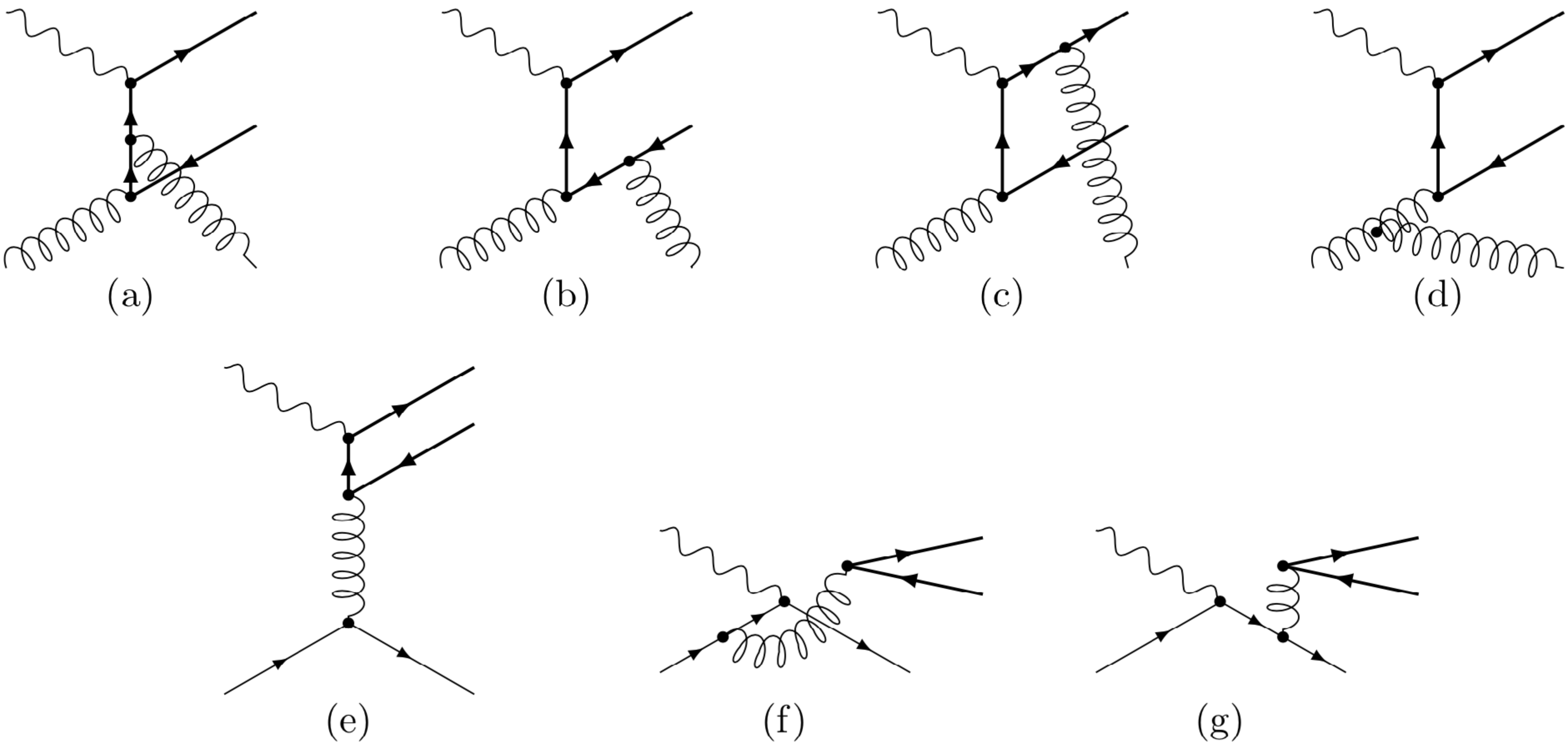
CSM done, in progress for NRQCD

BACK-UP SLIDES

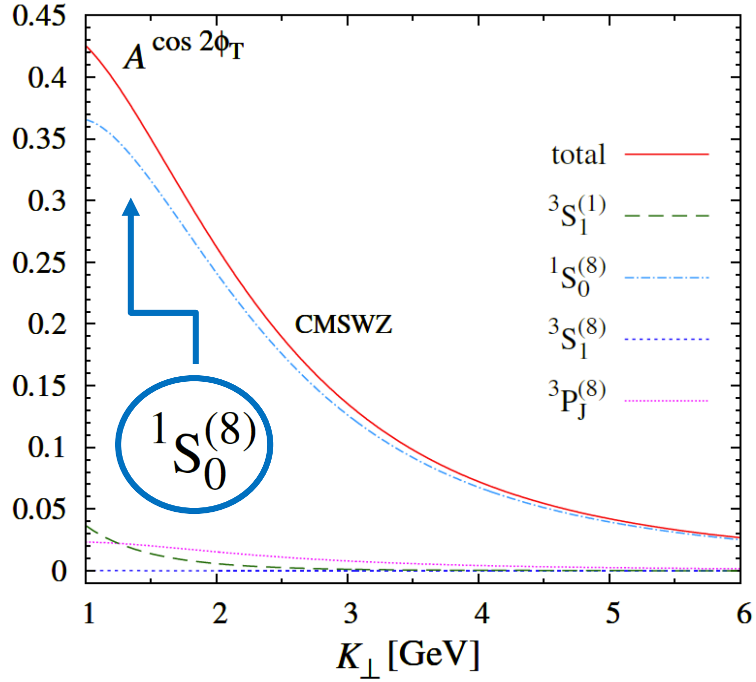
Full transversely polarized cross section

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

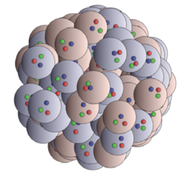
Feynman Diagrams at LO

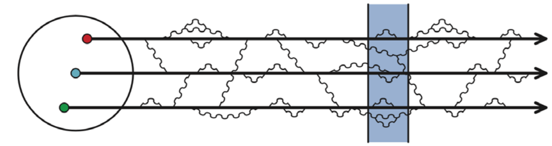


NRQCD decomposition



Model calculation





McLerran-Venugolapan Low-x Model

Valence quarks: static sources of color for the classical gluon fields

McLerran-Venugopalan (1994)

Gluon TMDs within this model as Weizsäcker-Williams

Dominguez, Marquet, Xiao, Yuan (2011)
Metz, Zhou (2011)

$$f_1^g(x, \boldsymbol{q}_T^2) = \frac{S_\perp C_F}{\alpha_s \pi^3} \int \mathrm{d}r \frac{J_0(q_T r)}{r} \left(1 - e^{-\frac{r^2}{4} Q_{sg}^2(r)}\right)$$

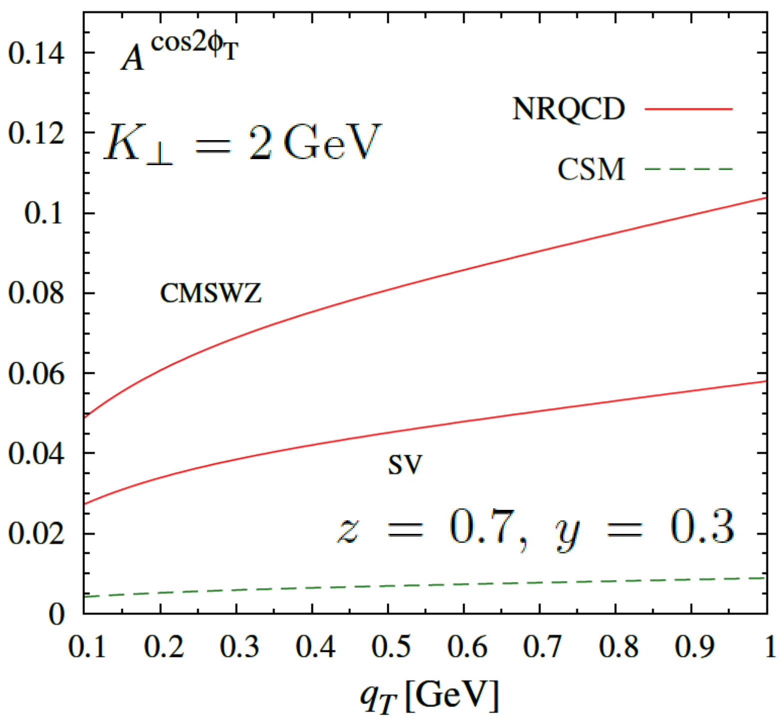
$$h_1^{\perp g}(x, \boldsymbol{q}_T^2) = \frac{S_\perp C_F}{\alpha_s \pi^3} \frac{2M_p^2}{\boldsymbol{q}_T^2} \int \mathrm{d}r \frac{J_2(q_T r)}{r \ln \frac{1}{r^2 \Lambda^2}} \left(1 - e^{-\frac{r^2}{4} Q_{sg}^2(r)}\right)$$

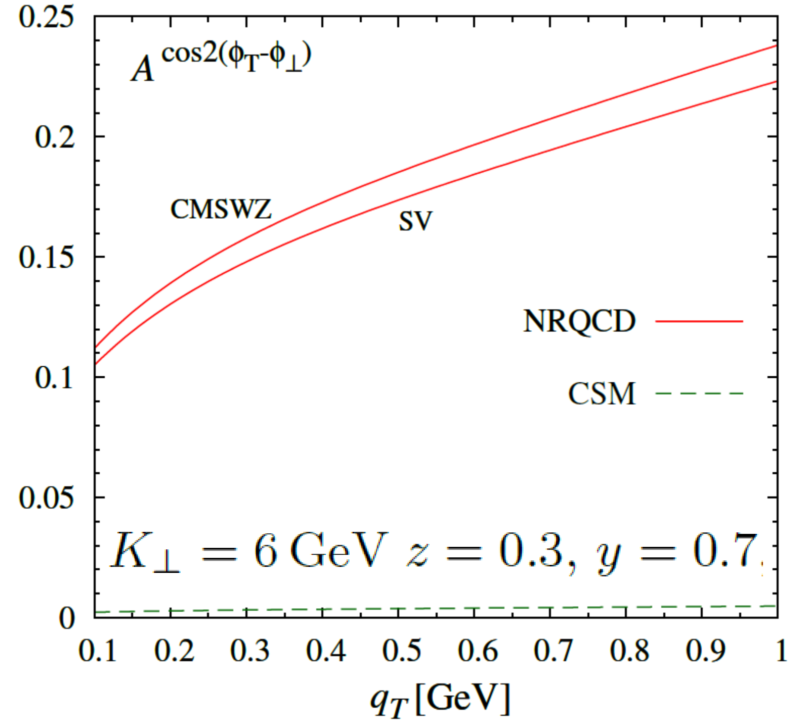
$S_\perp$ is the transverse size of the proton

$Q_{sg}(r)$ is the gluon saturation scale

Model calculation

EIC@100 GeV $x \sim 0.01$





A^W for Υ production

$Q^2 = 100\,\mathrm{GeV}^2$, $z = 0.7$, and $y = 0.3$