# Gluon TMDs in J/psi + jet production at an EIC

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CAGLIARI

# Gluon TMDs

Relatively new field: first paper Mulders, Rodrigues (2001)

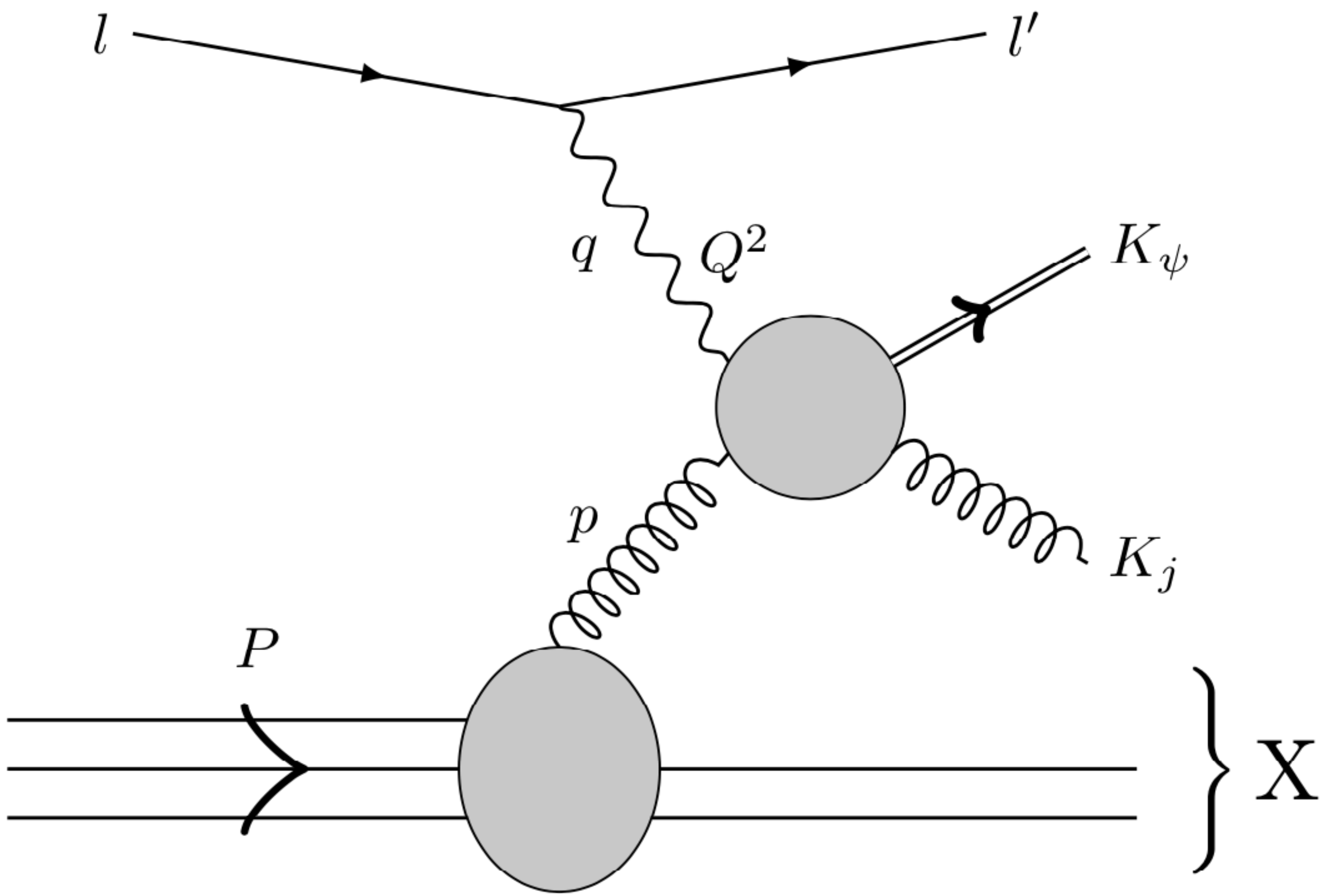
Phenomenology ten years later:
Sun, Xiao, Yuan (2011)
Boer, Brodsky, Mulders, Pisano (2011)
Boer, den Dunnen, Pisano, Schlegel, Vogelsang (2012)

Even more elusive than their quark counterparts…

Used since a long time in the low-x community under the name unintegrated PDF

Connection first established in Dominguez, Marquet, Xiao, Yuan (2011)

$$e + p \to J/\psi + \text{jet} + X$$

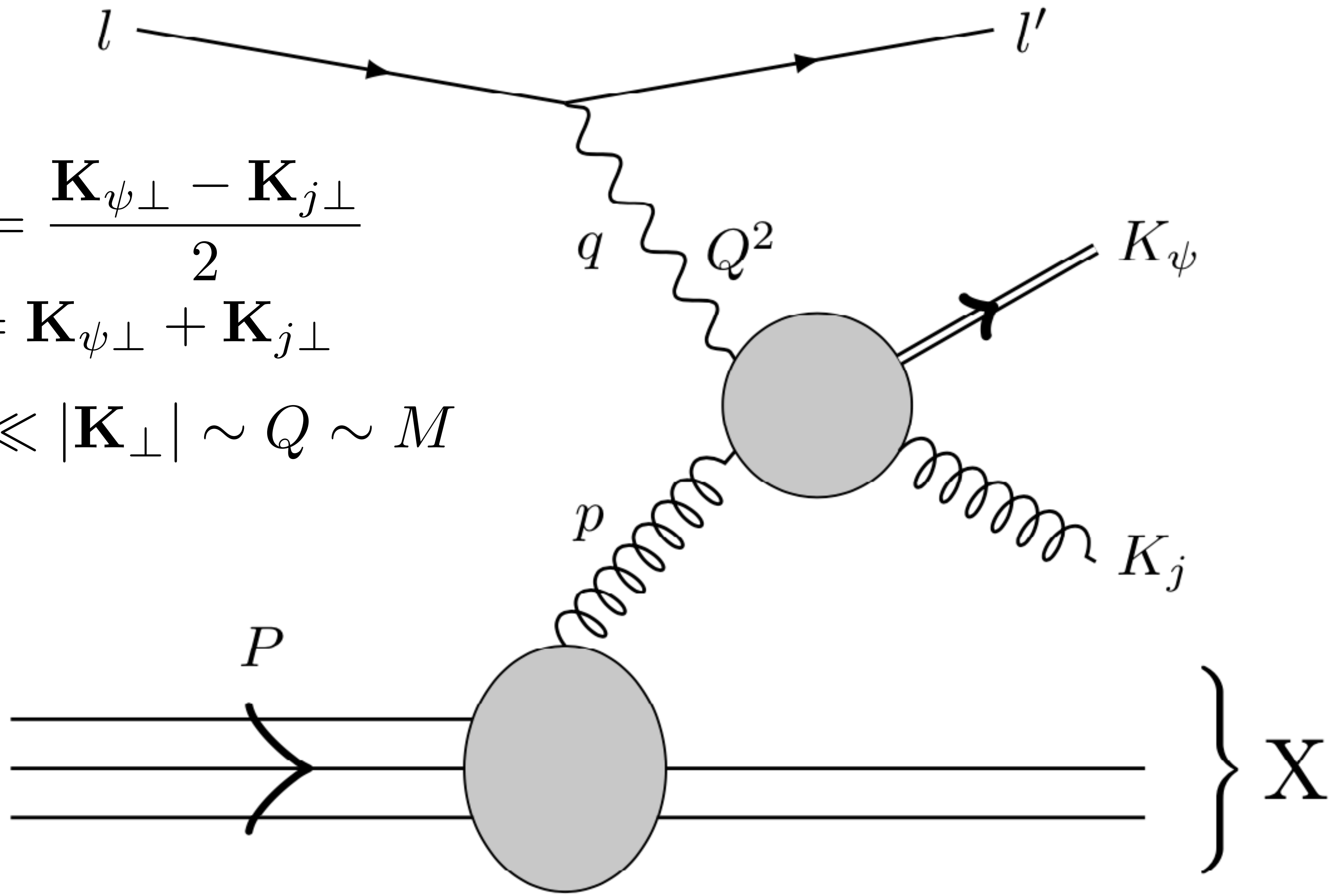


$$e + p \to J/\psi + \text{jet} + X$$

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

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

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



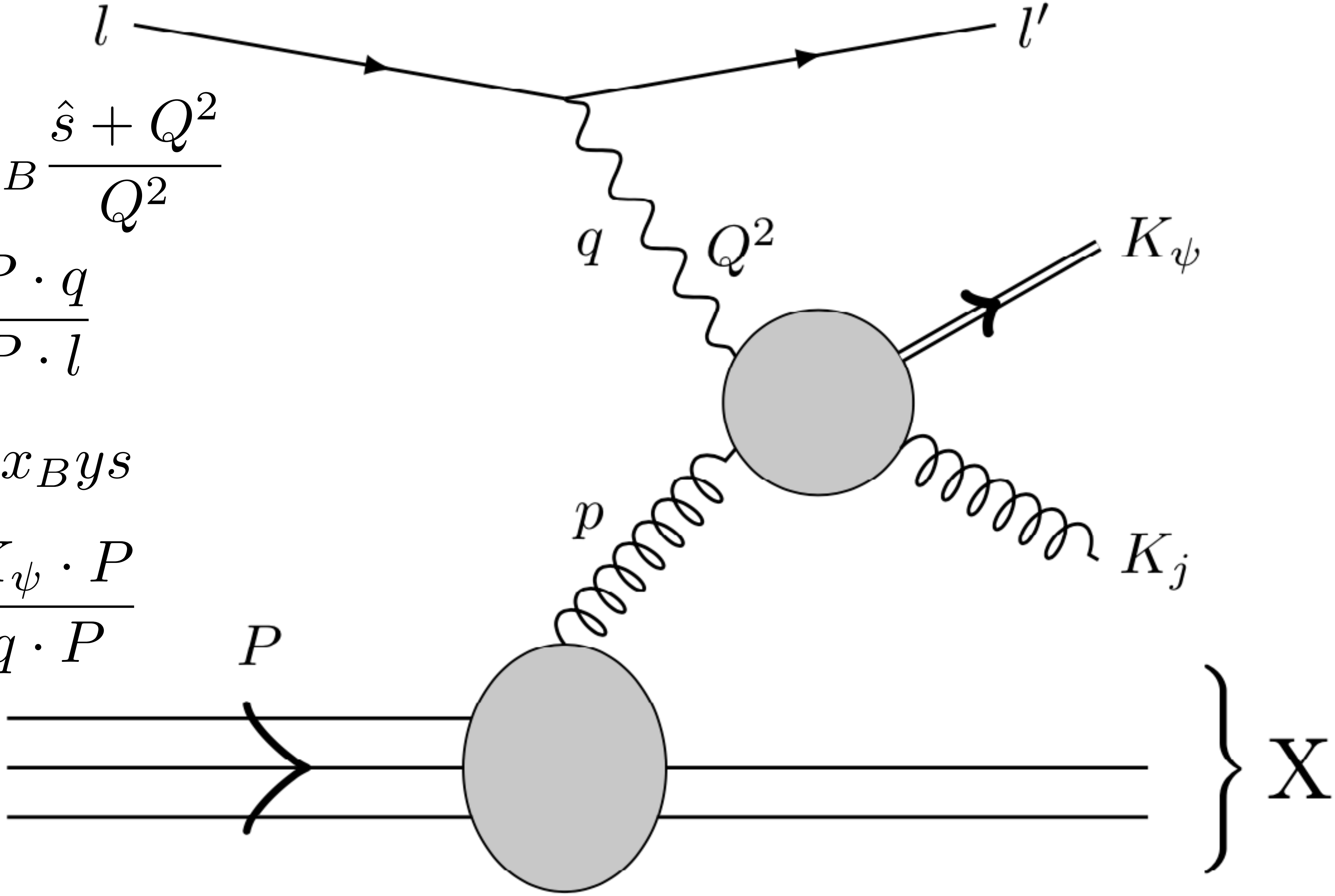
# $e + p \to J/\psi + \text{jet} + X$

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

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

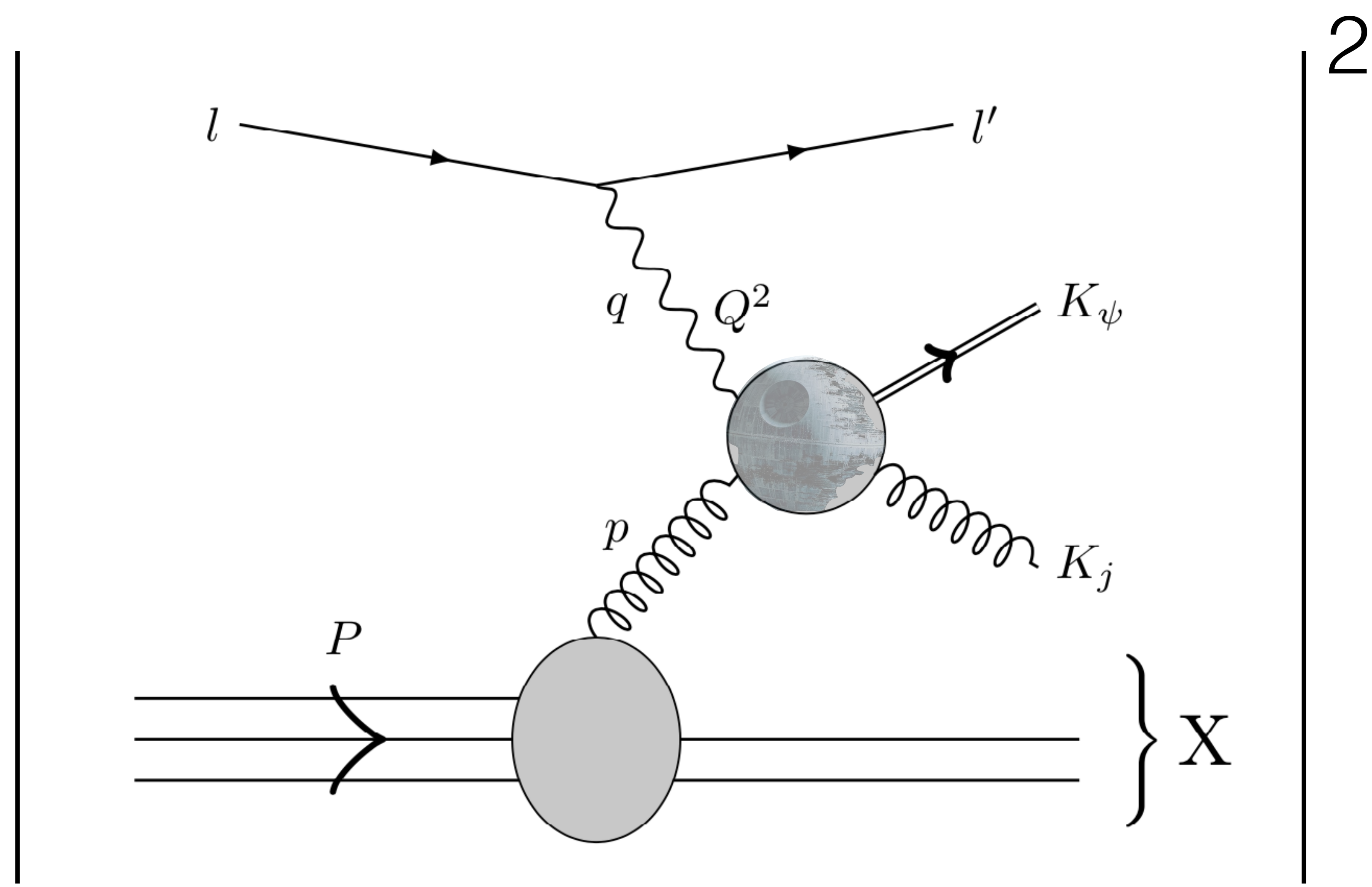
$$Q^2 = x_B y s$$

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



# Ingredients of the cross section

$$\mathrm{d}\sigma = \frac{1}{2s}\frac{\mathrm{d}^3 l'}{(2\pi)^3 2E_{l'}}\frac{\mathrm{d}^3 K_\psi}{(2\pi)^3 2E_\psi}\frac{\mathrm{d}^3 K_j}{(2\pi)^3 2E_j}\int \mathrm{d}x\,\mathrm{d}^2\boldsymbol{p}_T\,(2\pi)^4\delta^{(4)}\big(q+p-K_j-K_\psi\big)$$
$$\times \frac{1}{Q^4} L(l,q)\otimes\Gamma_g(x,\boldsymbol{p}_T)\otimes|H|^2$$



# Ingredients of the cross section

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

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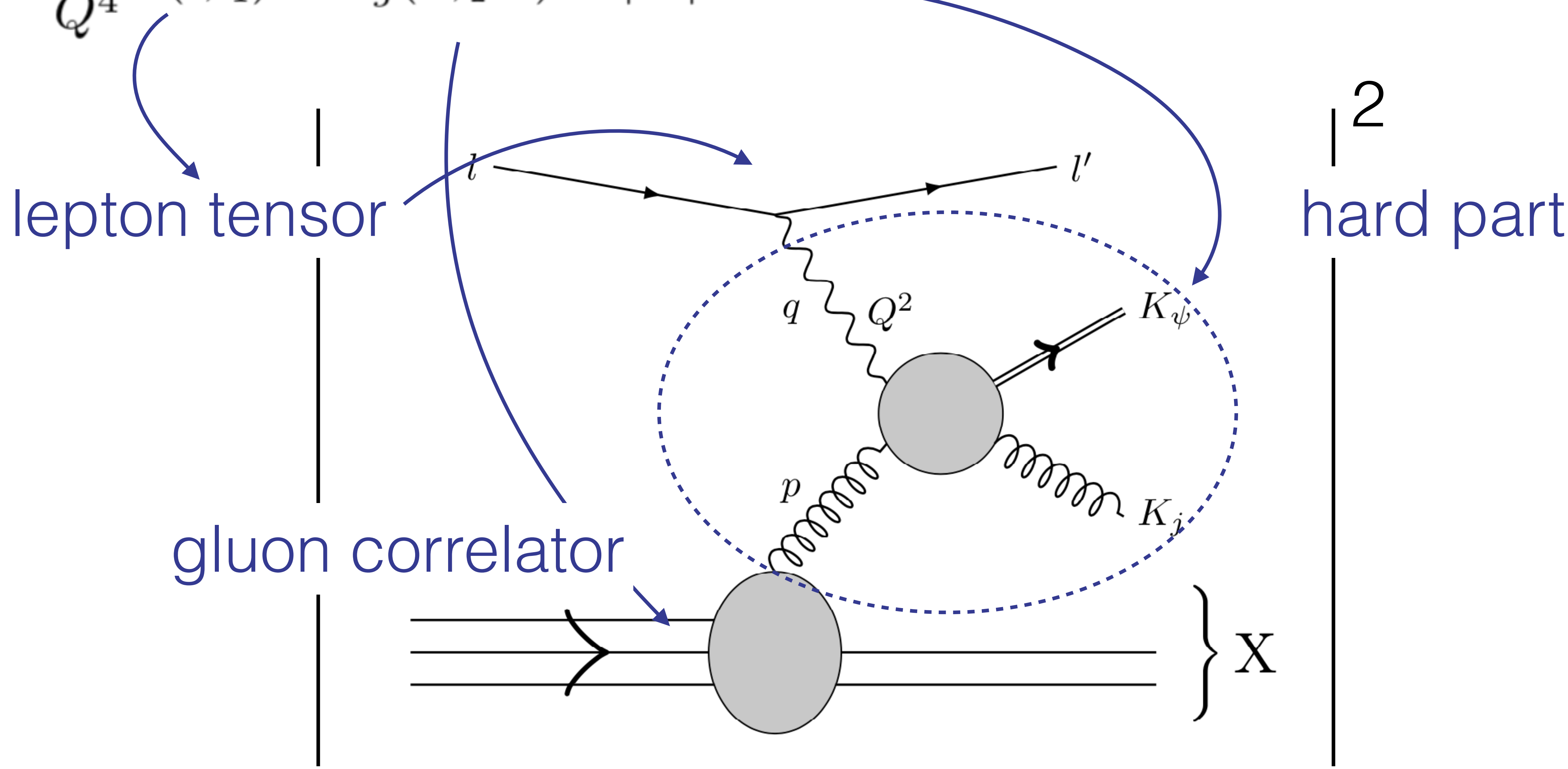


# Gluon correlator

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

field strength

$$\Gamma_g^{\mu\nu}(x, \mathbf{q}_T) = \int \frac{\mathrm{d}\xi^- \mathrm{d}^2\xi_T}{(2\pi)^3} e^{iq\cdot\xi} \langle P, S | \mathrm{Tr}\, F^{\mu+}(0) U_{[0,\xi]} F^{\nu+}(\xi) U_{[\xi,0]} | P, S \rangle |_{\xi^+=0}$$

proton state

gauge link / Wilson line

## Unpolarized target:

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

unpolarized TMD

linearly polarized TMD

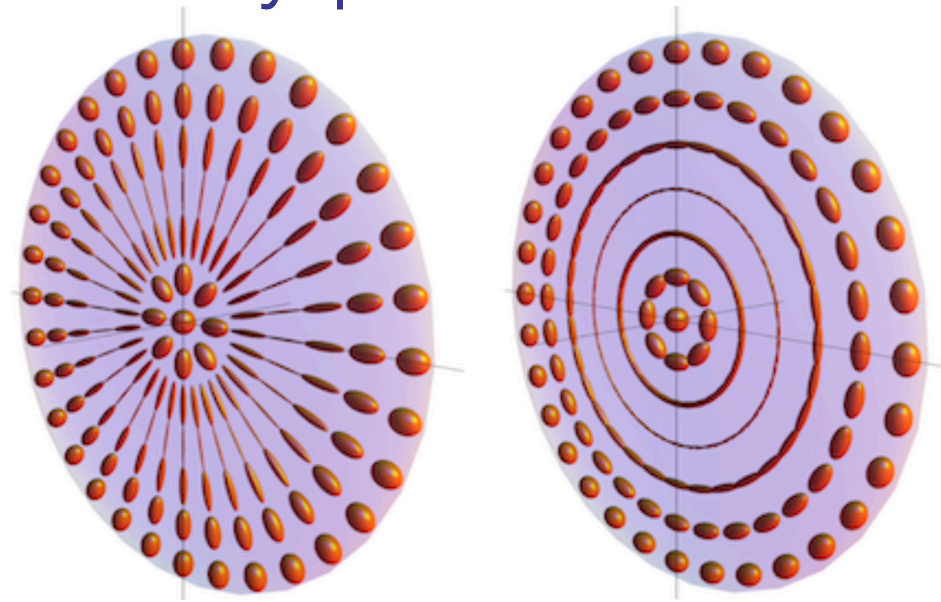


fig. from den Dunnen, Lansberg, Pisano, Schlegel (2014)

# Gluon correlator

field strength

$$\Gamma_g^{\mu\nu}(x, \mathbf{q}_T) = \int \frac{\mathrm{d}\xi^- \mathrm{d}^2\xi_T}{(2\pi)^3} e^{iq\cdot\xi} \langle P, S| \mathrm{Tr}\, F^{\mu+}(0) U_{[0,\xi]} F^{\nu+}(\xi) U_{[\xi,0]} |P, S\rangle|_{\xi^+=0}$$

proton state

gauge link / Wilson line

Transversely polarized target:

Sivers function

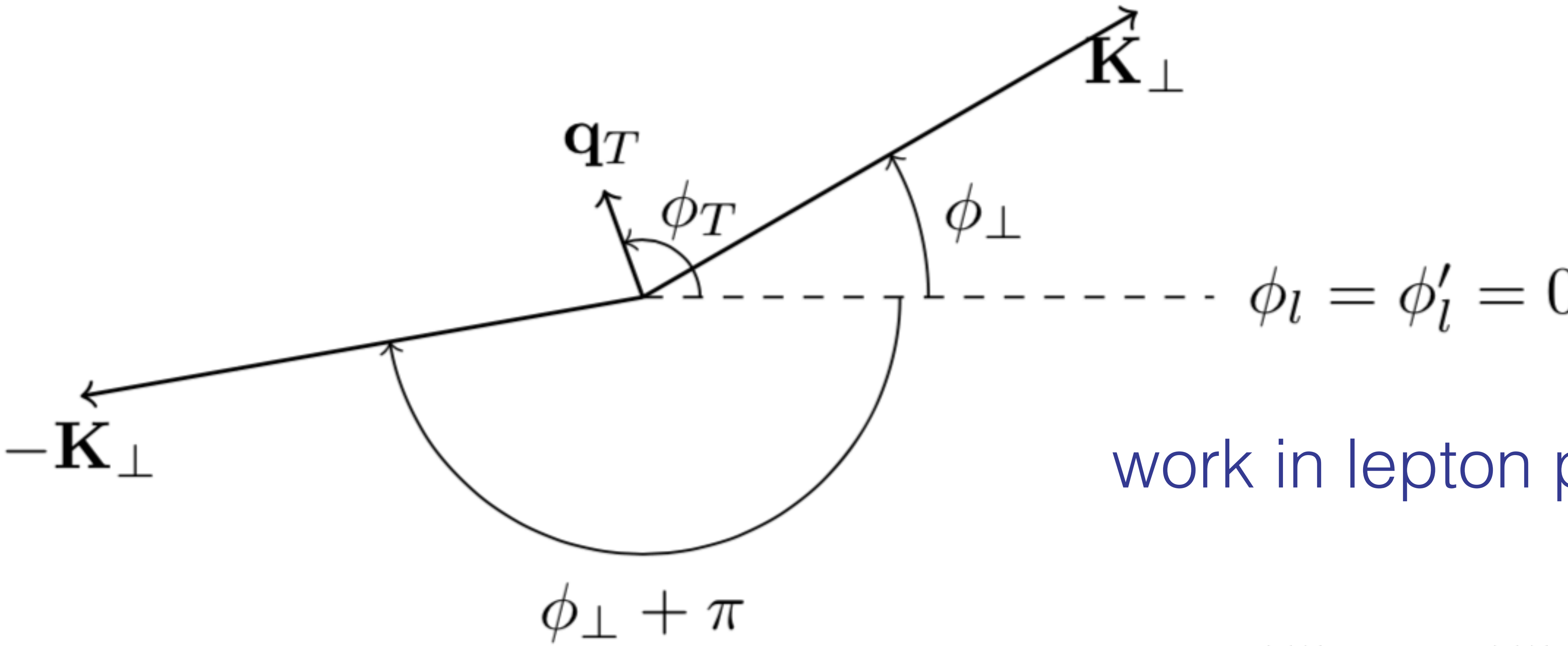
circularly polarized TMD

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

$$+ \frac{p_{T\rho}\, \epsilon_T^{\rho\{\mu} p_T^{\nu\}}}{2M_p^2} \frac{p_T \cdot S_T}{M_p} h_{1T}^{\perp g}(x, \boldsymbol{p}_T^2) - \frac{p_{T\rho}\epsilon_T^{\rho\{\mu} S_T^{\nu\}} + S_{T\rho}\epsilon_T^{\rho\{\mu} p_T^{\nu\}}}{4M_p} h_{1T}^g(x, \boldsymbol{p}_T^2) \Bigg\}$$

linearly polarized TMDs

# Definition of the angles




work in lepton plane

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

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

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

# Cross section

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

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

Similar structure as in the case of heavy-quark pair production

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

# Cross section

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

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

# 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

# Azimuthal asymmetries

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

are sensitive to ratios of TMDs

e.g.:

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

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

# Positivity bound

polarized gluon TMDs satisfy the following positivity bounds:

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

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

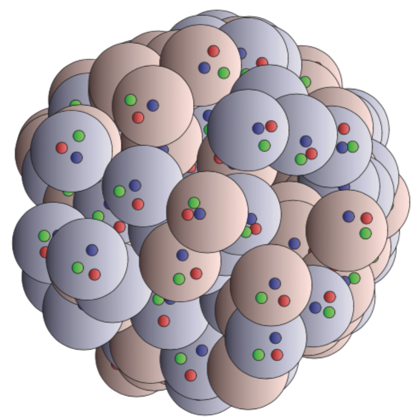
$$\frac{|\boldsymbol{p}_T|}{M_p}\,|h_1^g(x,\boldsymbol{p}_T^2)| \le f_1^g(x,\boldsymbol{p}_T^2)$$

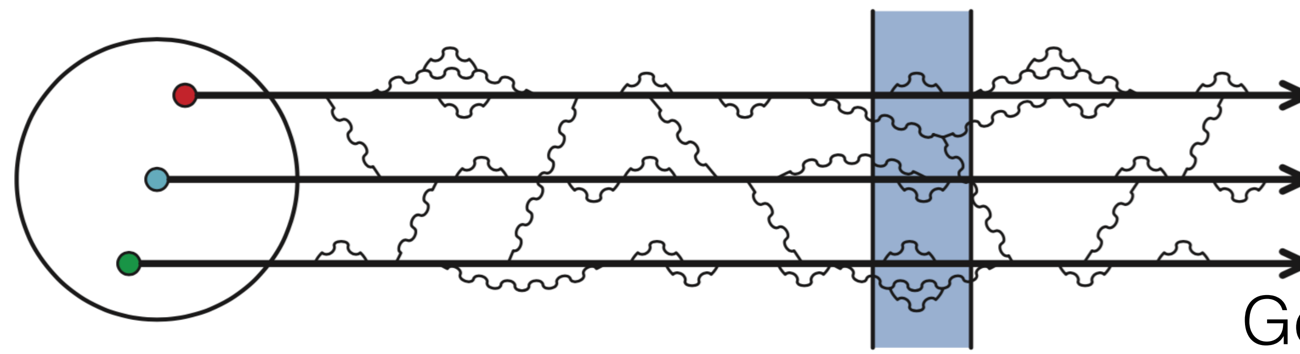
$$\frac{|\boldsymbol{p}_T|^3}{2M_p^3}\,|h_{1T}^{\perp\,g}(x,\boldsymbol{p}_T^2)| \le f_1^g(x,\boldsymbol{p}_T^2)$$

Mulders, Rodrigues (2001)

# Model calculation

McLerran-Venugopalan (MV) model for a large nucleus:





Gelis (2013)

Valence quarks are static sources of color for the classical gluon fields, generated by Yang-Mills equation:

$$\left(\partial_\nu F_a^{\nu\mu} + g_s f^{abc} A_\nu^b F_c^{\nu\mu}\right)(\vec{x}) = \delta^{\mu+} \rho_a(\vec{x})$$

Sources follow Gaussian distribution:

$$\Phi_A[\rho] = \mathcal{N} \exp\left(-\frac{1}{2}\int \mathrm{d}^3x \frac{\rho_a(x)\,\rho_a(x)}{\lambda_A(x^-)}\right)$$

Correlators:

$$\langle \mathcal{O} \rangle_A = \frac{\int \mathcal{D}[\rho]\,\Phi_A[\rho]\,\mathcal{O}}{\int \mathcal{D}[\rho]\,\Phi_A[\rho]}$$

McLerran-Venugopalan (1994)

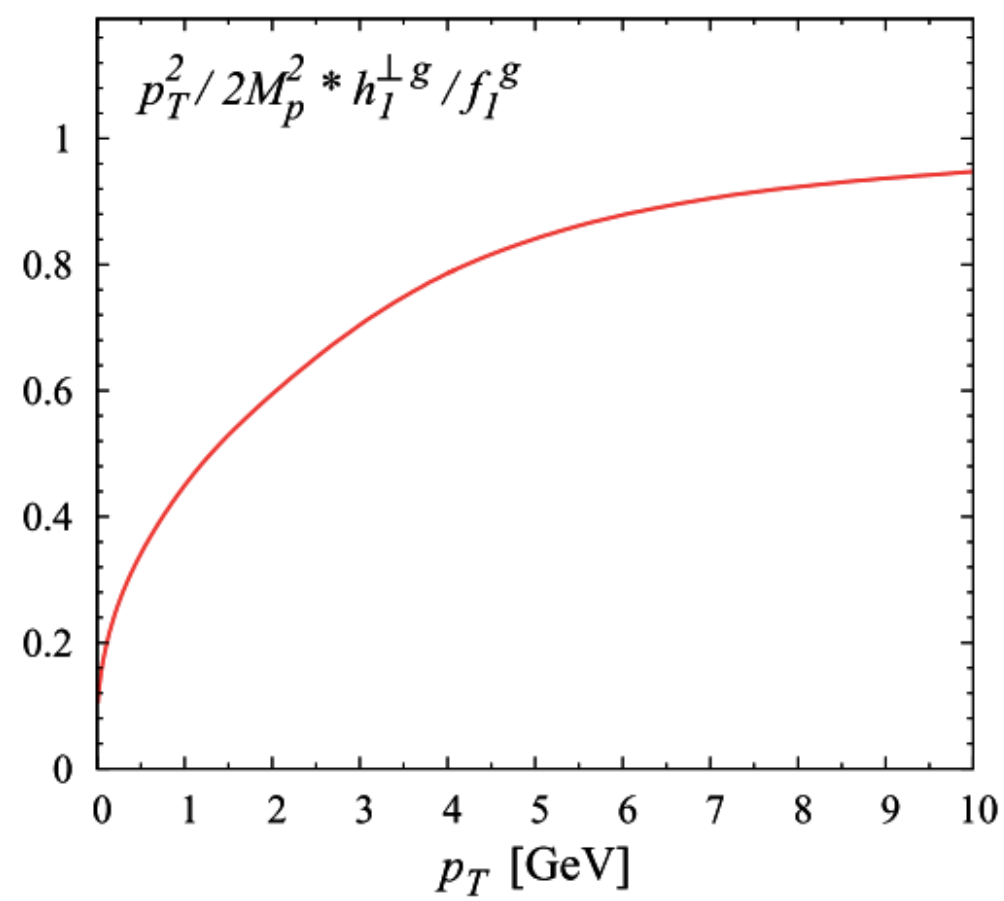
# Model calculation

Possible to calculate the gluon TMDs in an unpolarized nucleus / proton within this model. In our case, the relevant ones are the Weizsäcker-Williams:

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

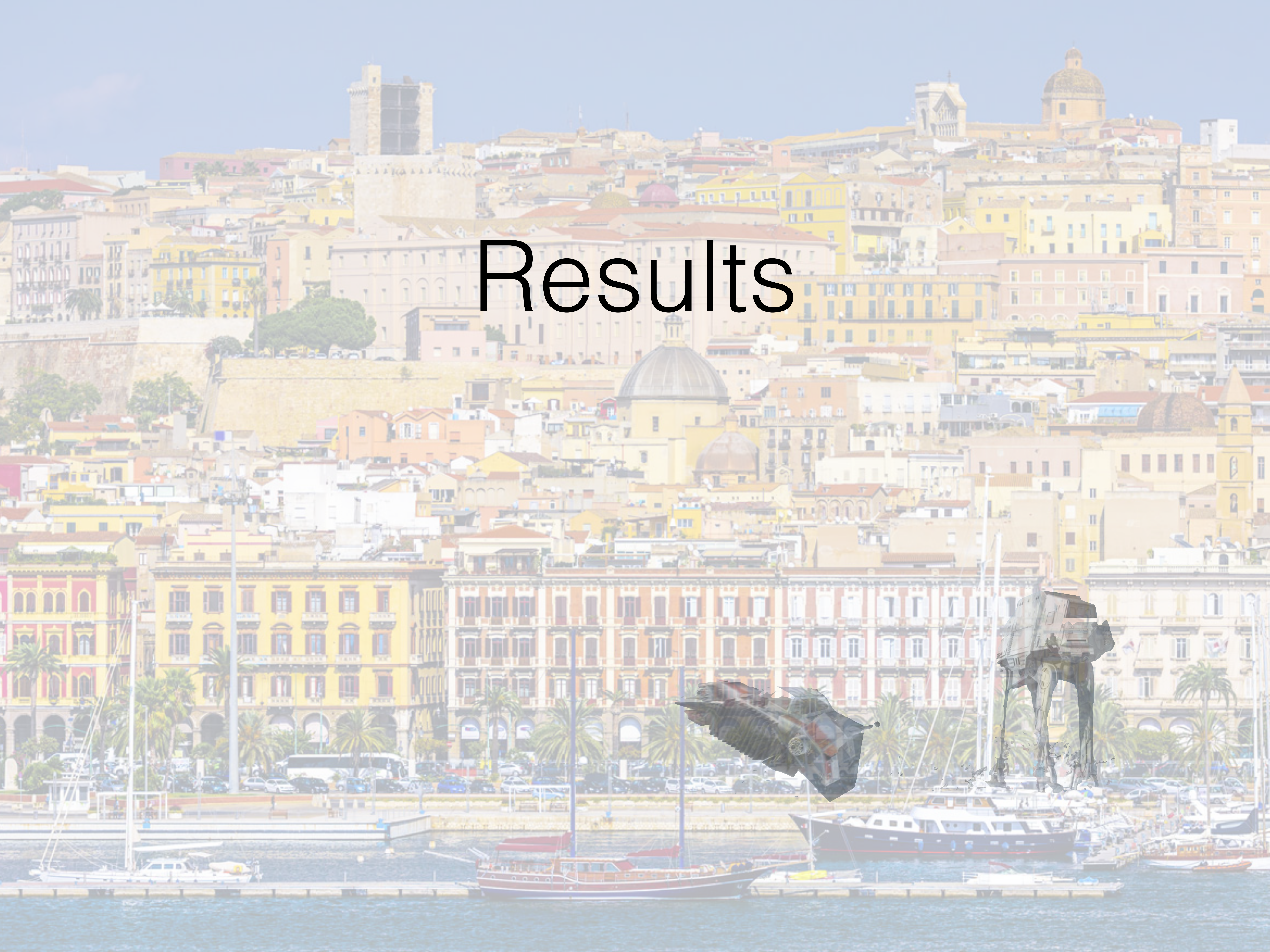
$$f_1^g(x, \boldsymbol{q}_T^2) = \frac{S_\perp C_F}{\alpha_s \pi^3} \int \mathrm{d}r \, \frac{J_0(q_T r)}{r} \left(1 - e^{-\frac{r^2}{4} Q_{sg}^2(r)}\right)$$

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

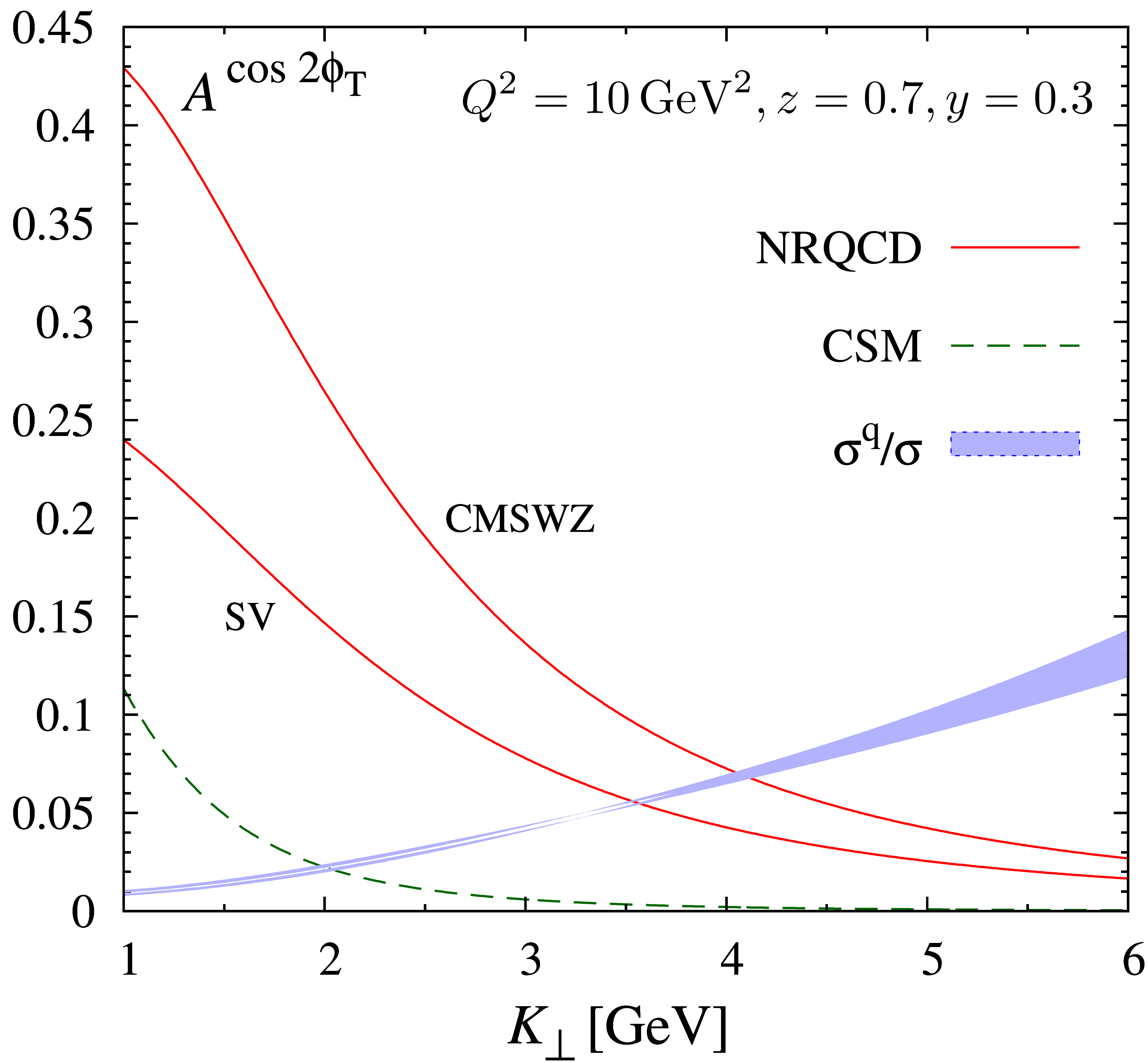



Boer, Mulders, Pisano, Zhou (2016)

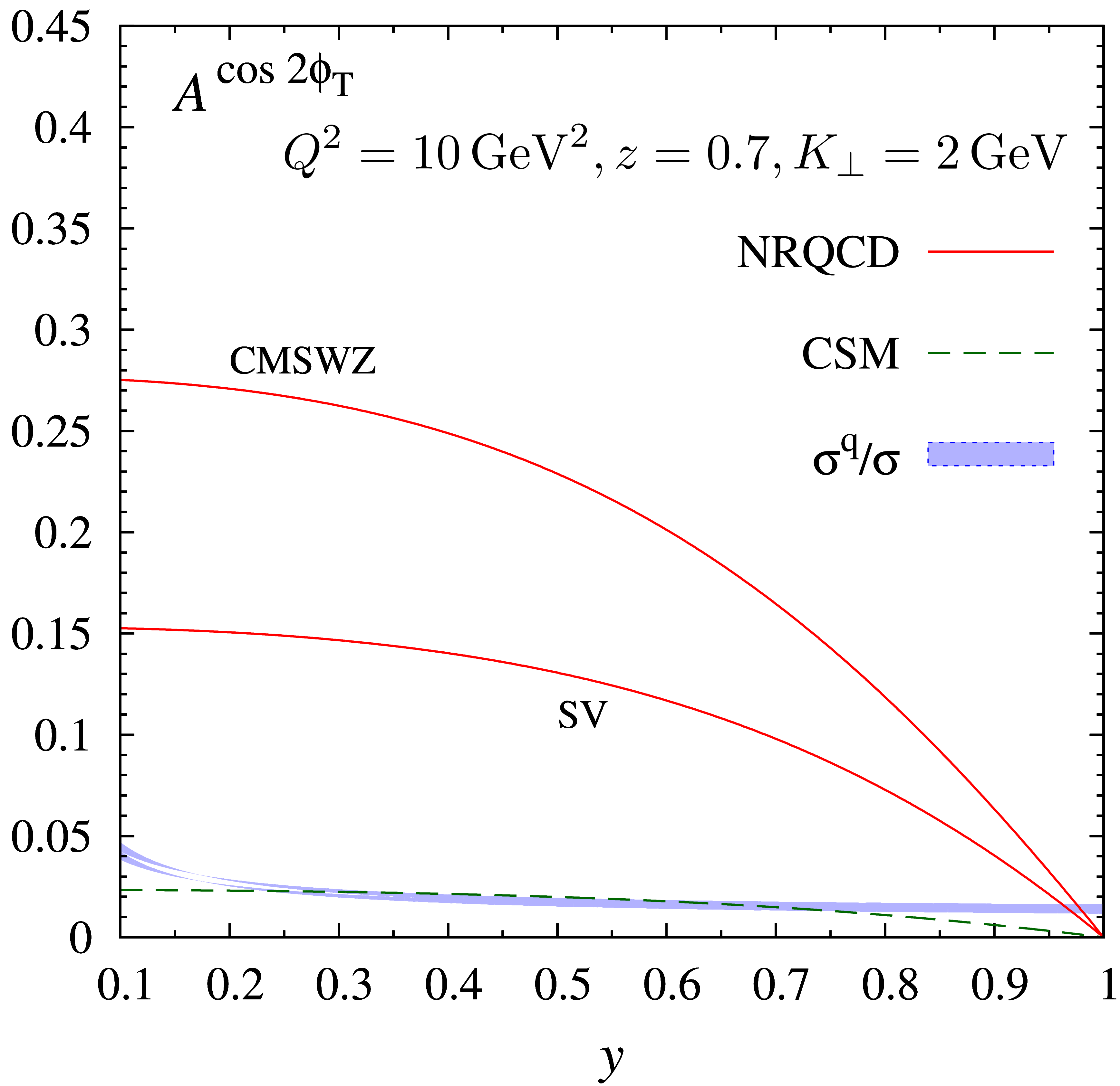
# Results



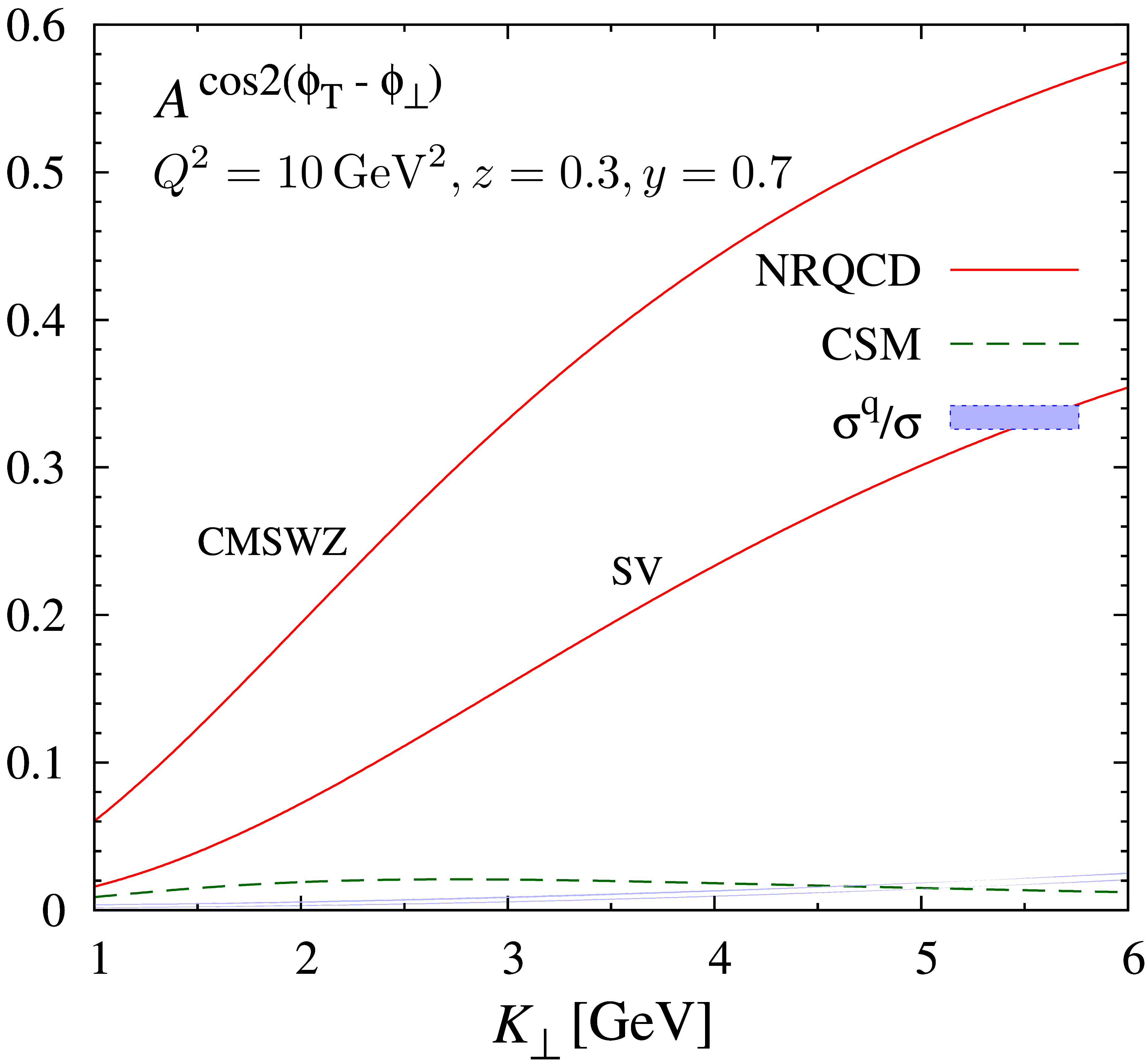
## $A^{\cos 2\phi_T}_{\max}$ in $e + p \to J/\psi + \text{jet} + X$



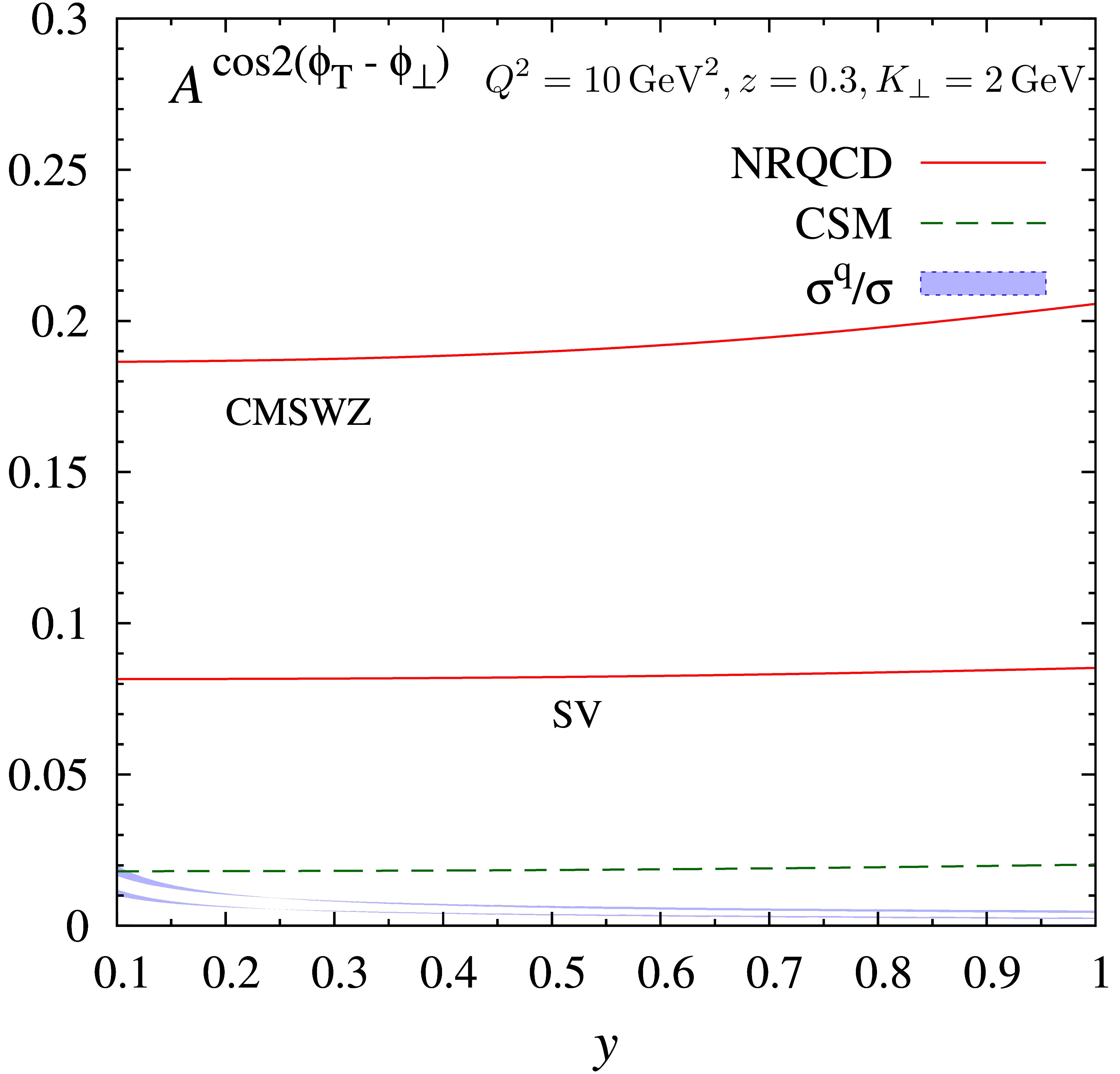
$A^{\cos 2\phi_T}_{\max}$ in $e + p \to J/\psi + \text{jet} + X$



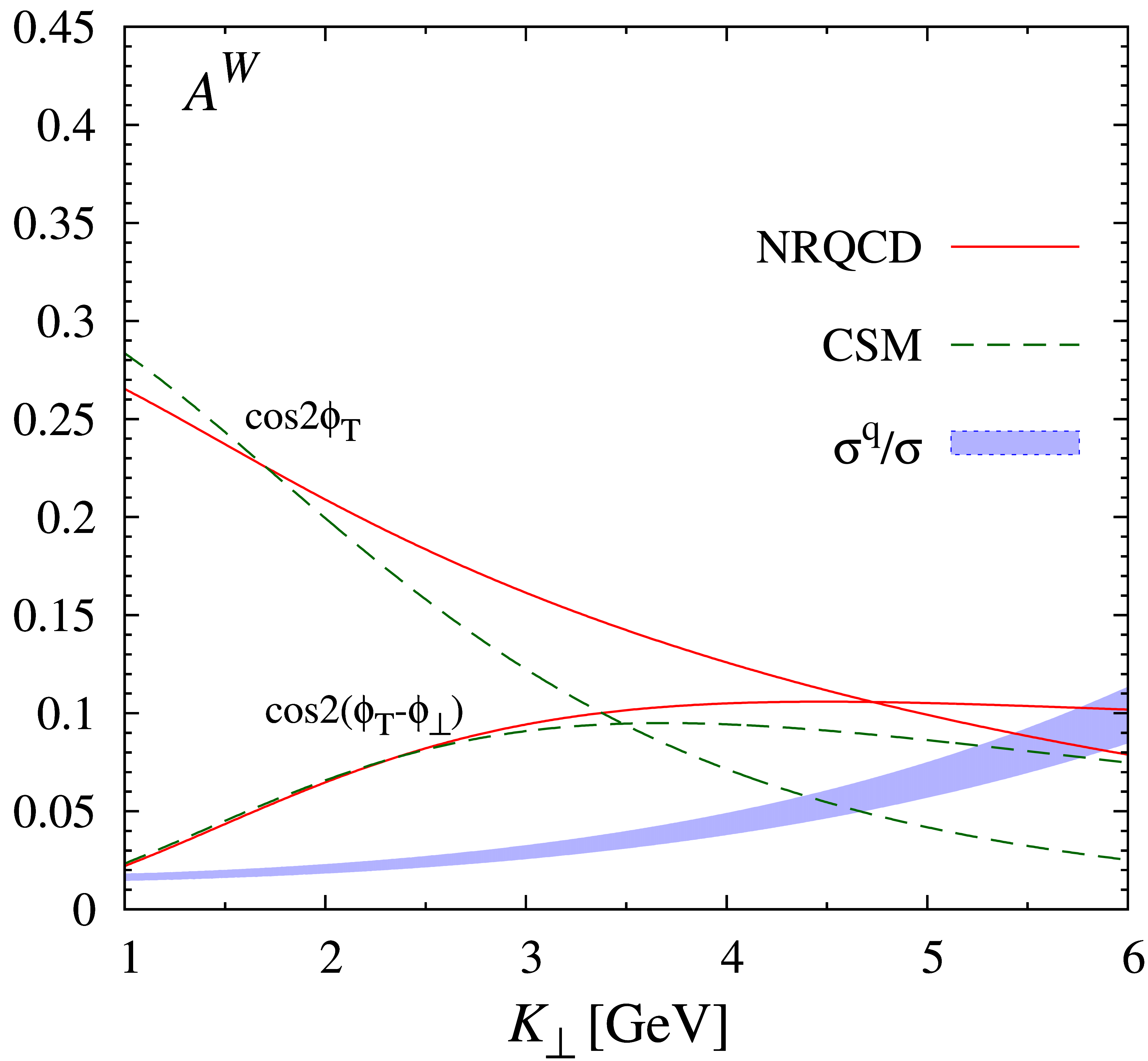
## $A_{\rm max}^{\cos 2(\phi_T - \phi_\perp)}$ in $e + p \to J/\psi + \text{jet} + X$



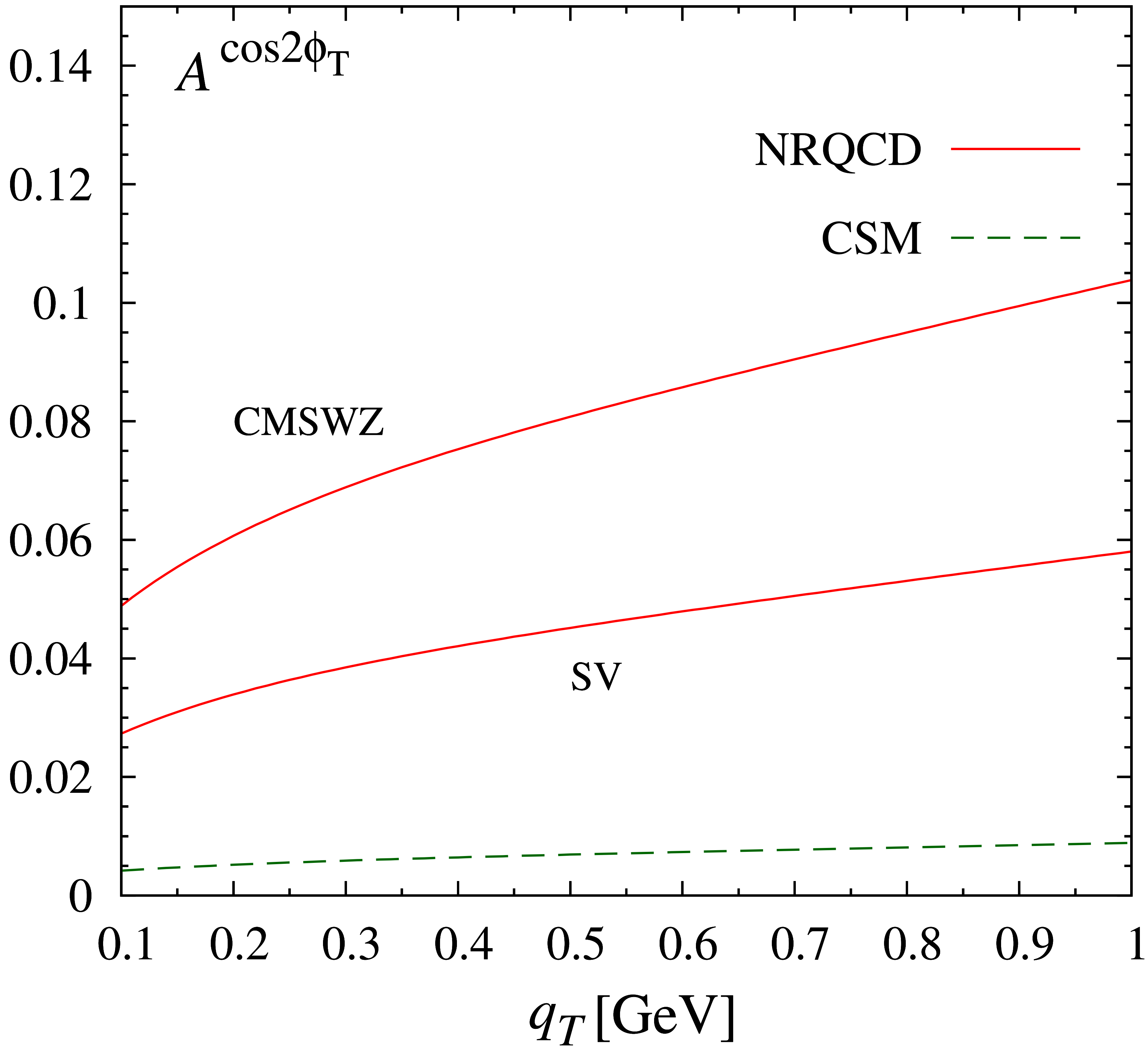
## $A^{\cos 2(\phi_T - \phi_\perp)}_{\max}$ in $e + p \to J/\psi + \text{jet} + X$



## $A_{\max}^{\cos 2\phi_T}$, $A_{\max}^{\cos 2(\phi_T - \phi_\perp)}$ in $e + p \to \Upsilon + \text{jet} + X$

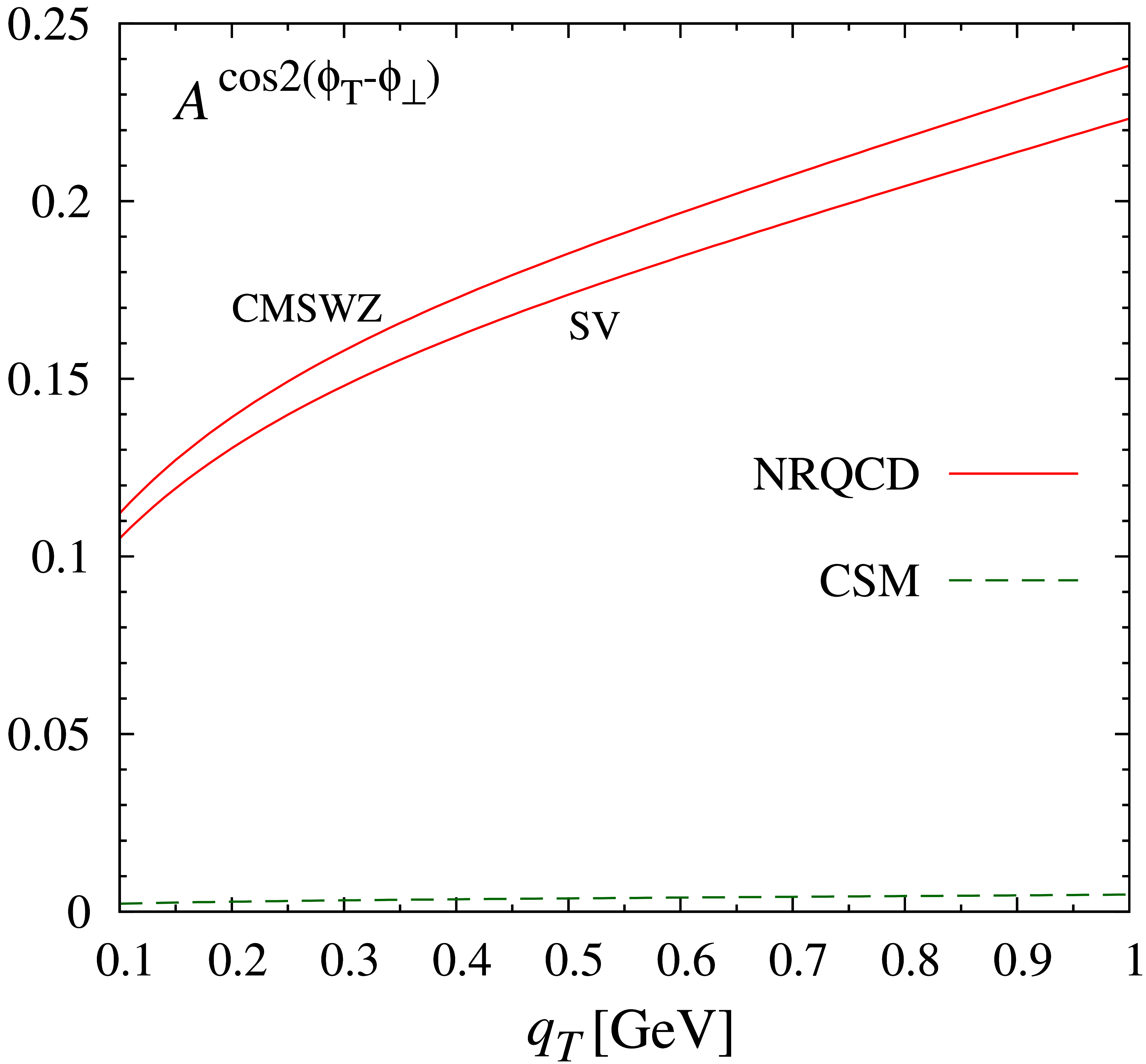


# MV model



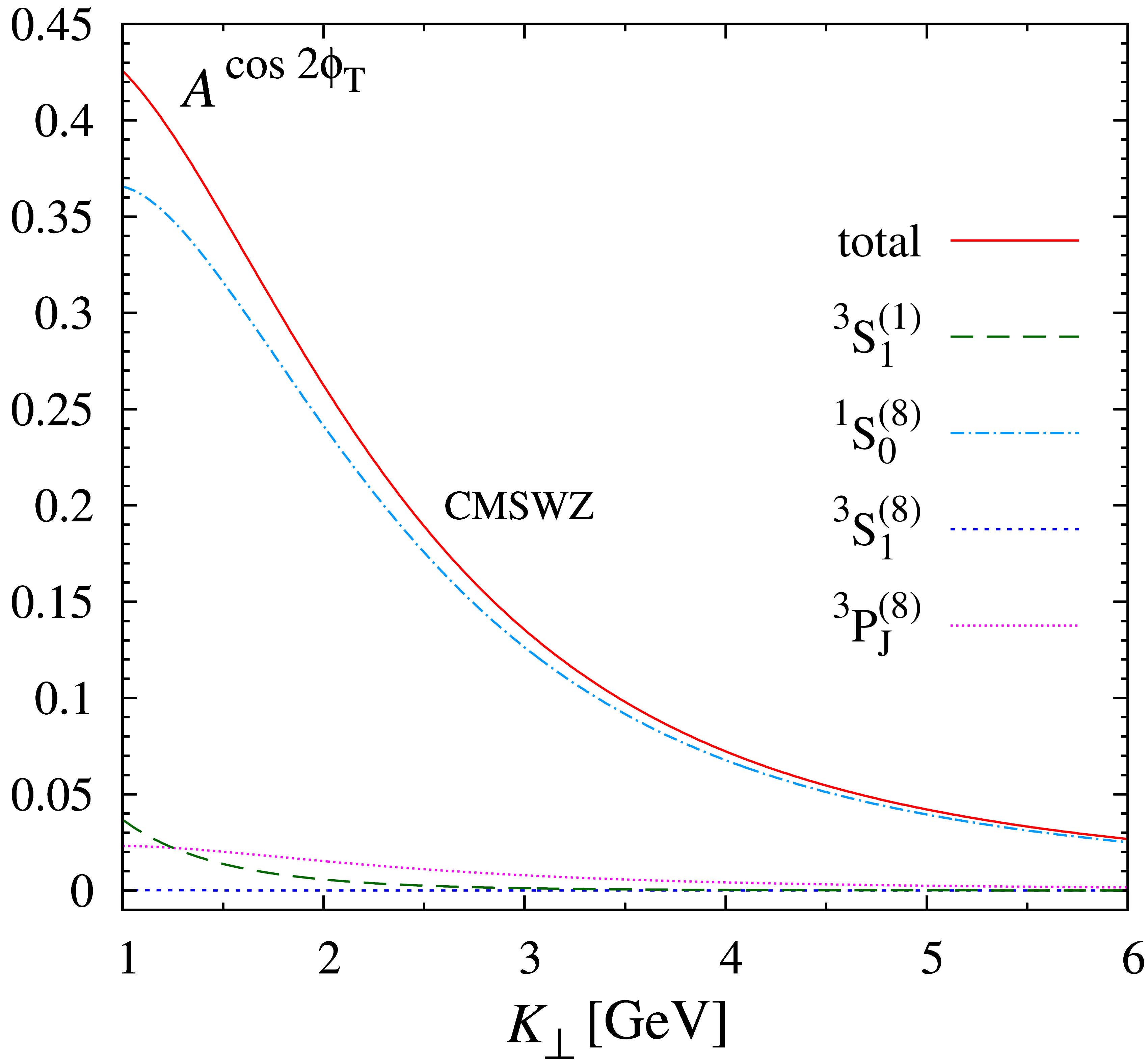
$A^{\cos 2\phi_T}$
NRQCD
CSM
CMSWZ
SV
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
$q_T$ [GeV]

# MV model



0.25
0.2
0.15
0.1
0.05
0
$A^{\cos 2(\phi_T - \phi_\perp)}$
CMSWZ
SV
NRQCD
CSM
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
$q_T$ [GeV]

# NRQCD decomposition



# Conclusions

Asymmetries are potentially sizeable over a rather large part of phase space

Even at the low COM energies of an EIC, the quark contribution would be sufficiently suppressed

As expected, there is a strong dependence on the choice of LDMEs

Extension of similar study of single inclusive quarkonium production

Bacchetta, Boer, Pisano, PT (2018)

Asmita will tell us soon about the situation in photoproduction, within the GPM model

Thanks to the organizers,
thanks for your attention!