Gluon TMDs in quarkonium production at an EIC

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Transverse momentum dependent PDFs (TMDs)

Collinear factorization fails in the presence of two ordered scales

Solution: consistent 'TMD' framework which also takes the intrinsic transverse momentum of the partons into account Collins (2011)

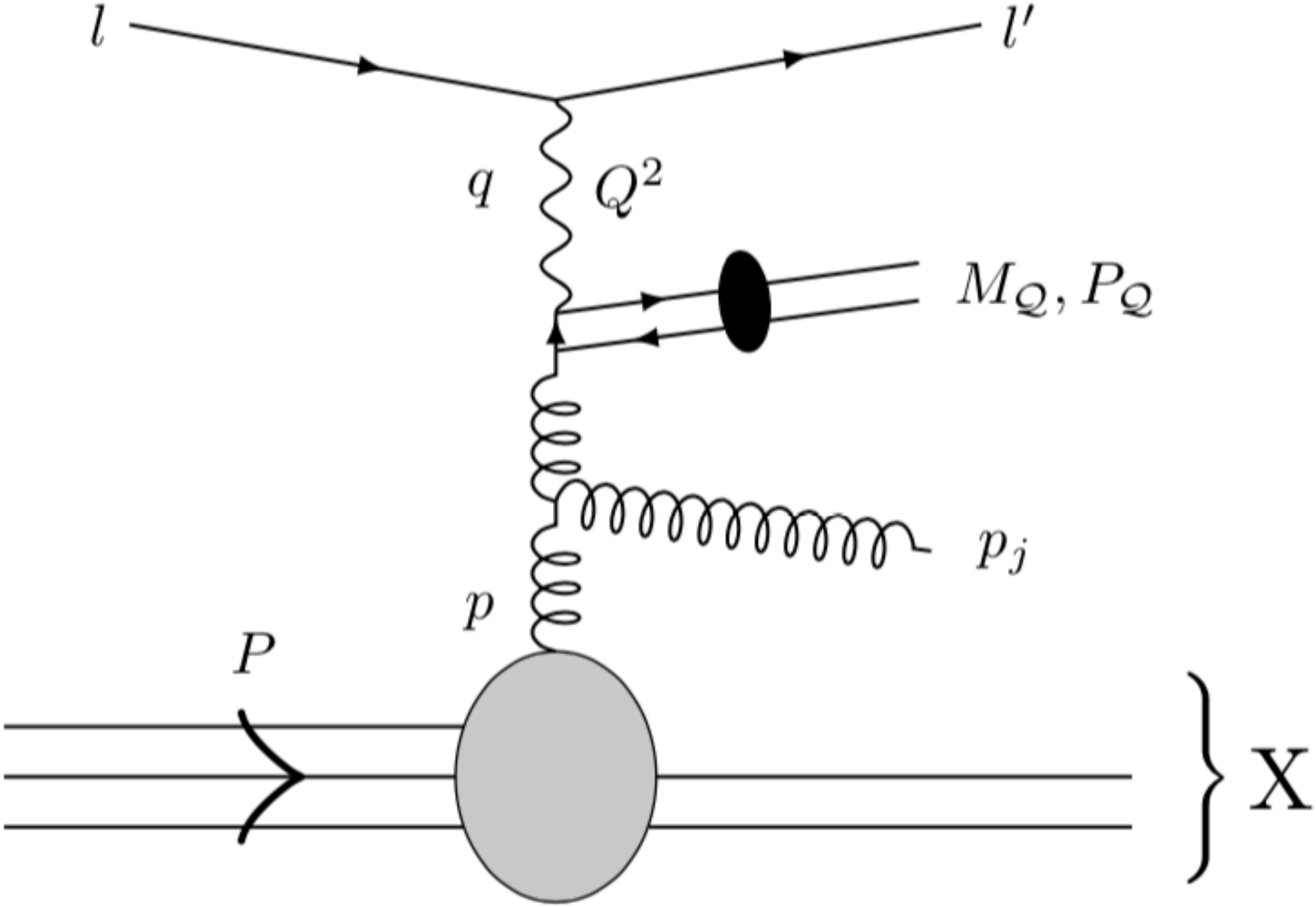
Many theoretical and experimental challenges: proves of factorization theorems, loss of universality, difficult extraction

TMD PDFs are fundamental objects: insight into 3D structure of the proton, spin physics

Used since many years to successfully describe single spin asymmetries by means of the Sivers function by the Torino and Cagliari groups

This talk: J/Psi+jet in DIS as a probe of *gluon* TMDs -> almost completely unknown (that is; beyond the many interesting efforts at low-x!)

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



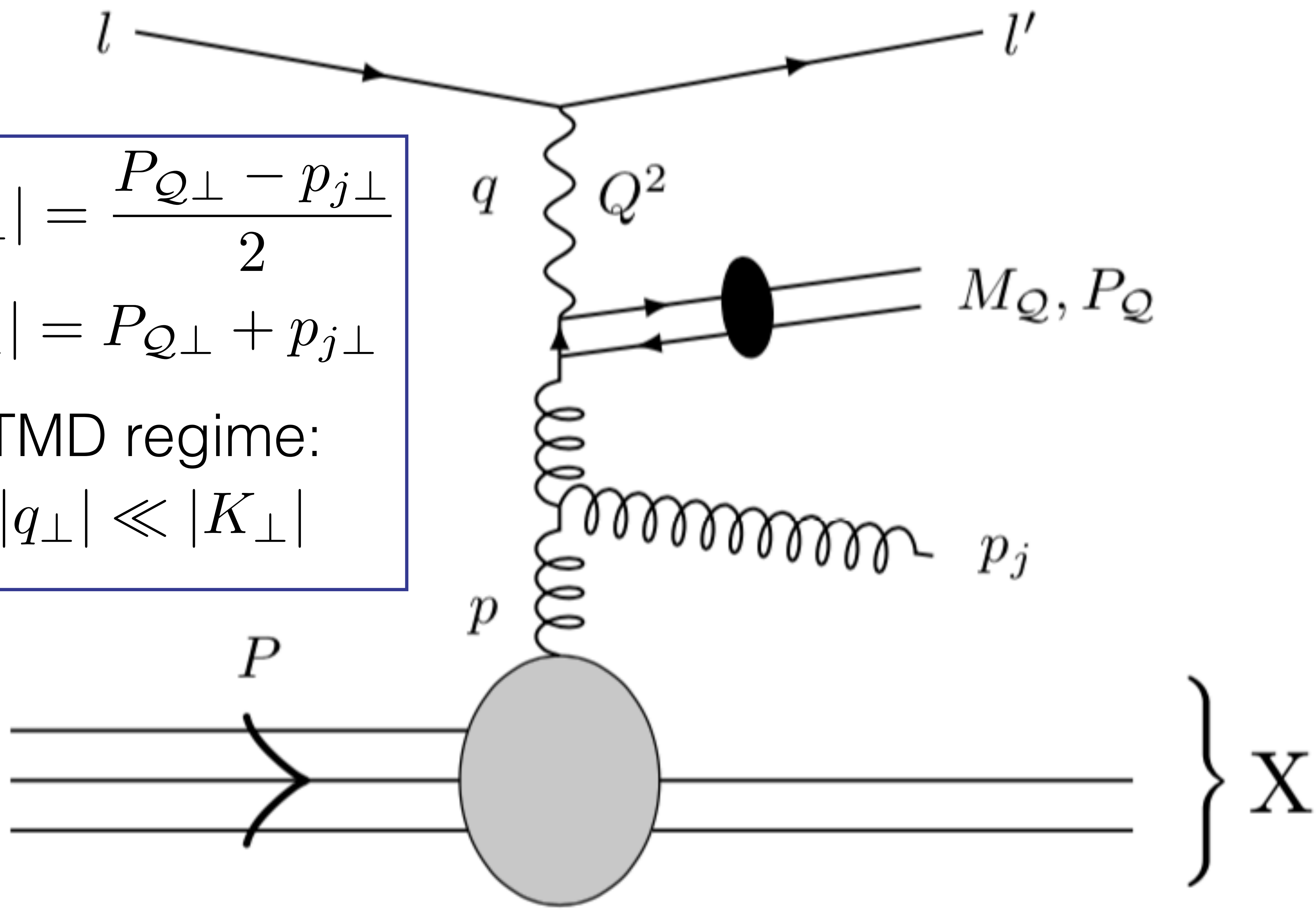
$$e + p \to e + J/\Psi + \text{jet}$$

$$|K_\perp| = \frac{P_{\mathcal{Q}\perp} - p_{j\perp}}{2}$$

$$|q_\perp| = P_{\mathcal{Q}\perp} + p_{j\perp}$$

TMD regime:

$$|q_\perp| \ll |K_\perp|$$



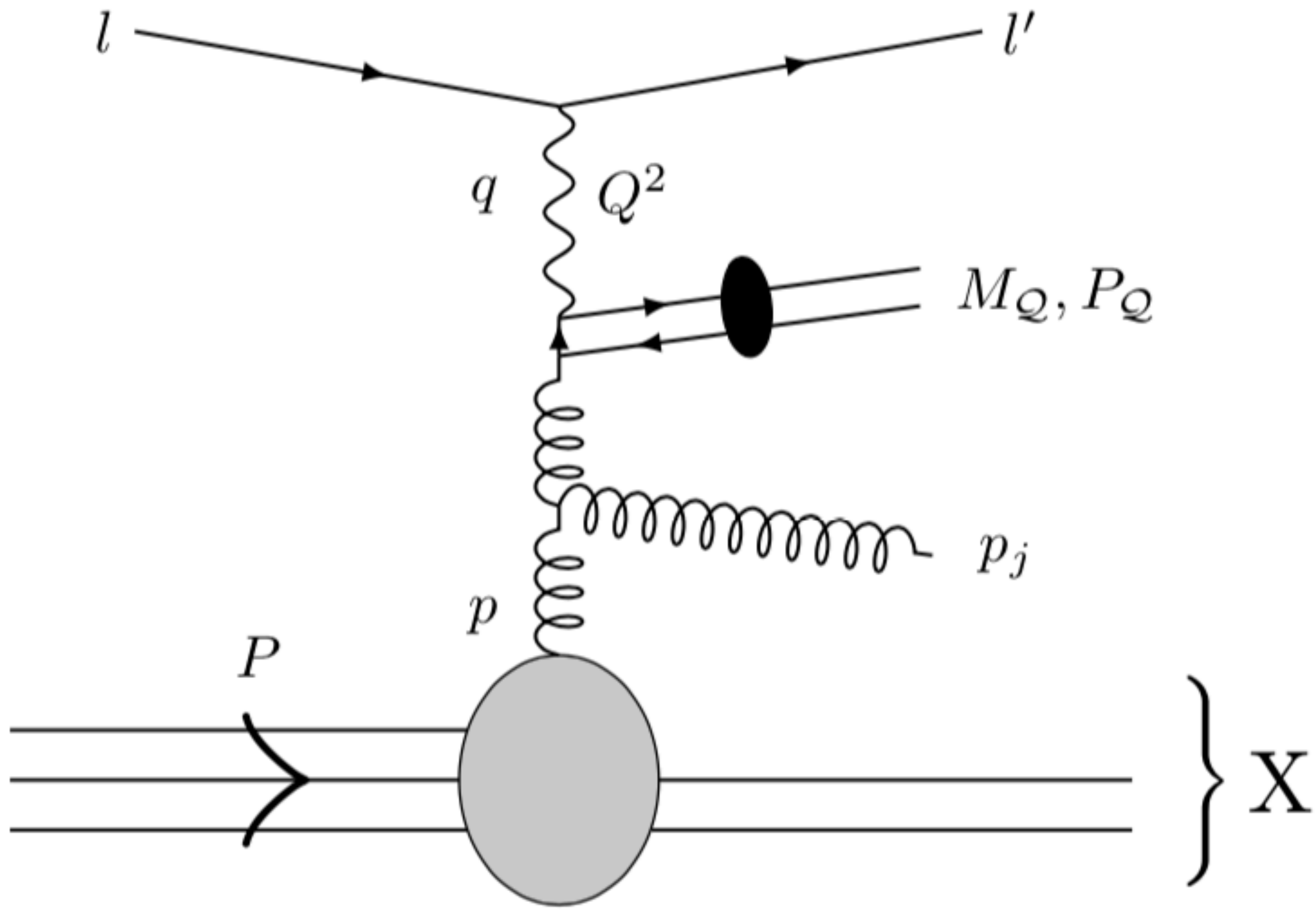
$$e + p \to e + J/\Psi + \text{jet}$$

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

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

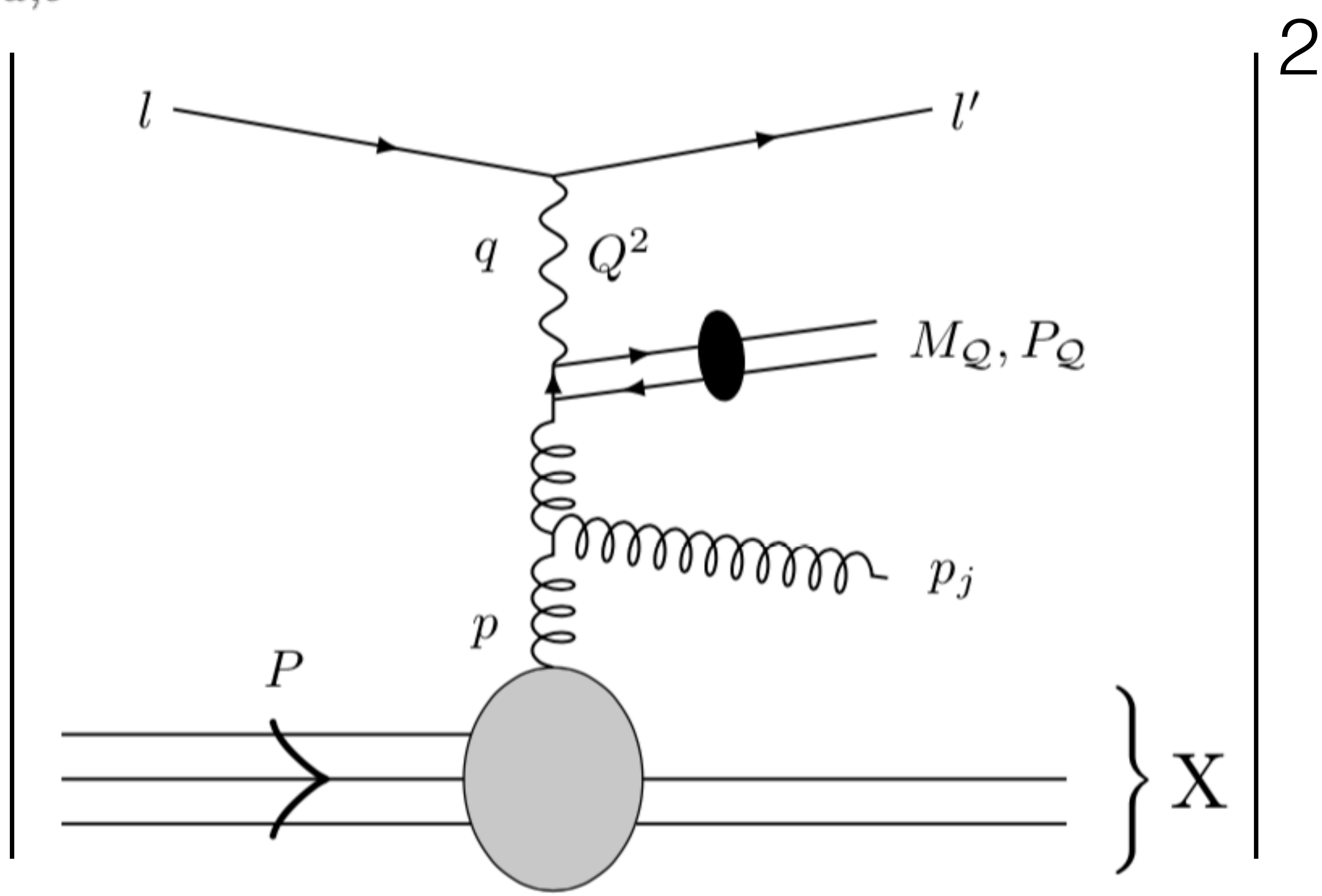
$$Q^2 = x_B y s$$

$$z = \frac{P_{\mathcal{Q}} \cdot P}{q \cdot P}$$



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

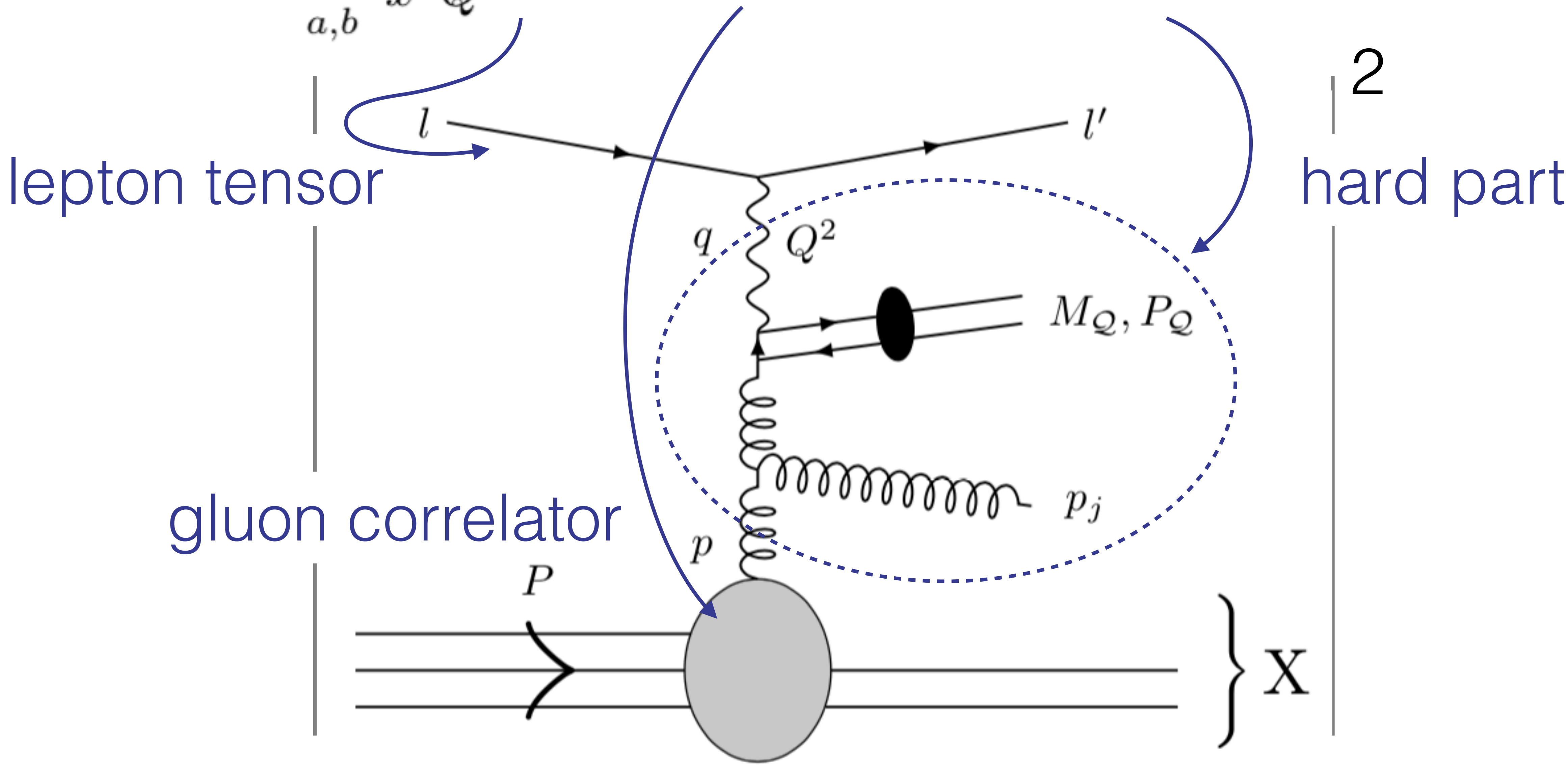
$$\mathrm{d}\sigma = \frac{1}{2s}\frac{\mathrm{d}^3 l'}{(2\pi)^3 2E'_e}\frac{\mathrm{d}^3 P_{\mathcal{Q}}}{(2\pi)^3 2E_{\mathcal{Q}}}\frac{\mathrm{d}^3 p_j}{(2\pi)^3 2E_j}\int \mathrm{d}x\mathrm{d}^2 p_\perp (2\pi)^4 \delta^{(4)}\left(q + p - p_j - P_{\mathcal{Q}}\right)$$
$$\times \sum_{a,b} \frac{1}{x^2 Q^4} L(l,q) \otimes \Phi_a(x, p_\perp) \otimes \left|H_{\gamma^* a \to J/\Psi + b}\right|^2$$



Ingredients of the cross section

$$\mathrm{d}\sigma = \frac{1}{2s}\frac{\mathrm{d}^3 l'}{(2\pi)^3 2E'_e}\frac{\mathrm{d}^3 P_{\mathcal{Q}}}{(2\pi)^3 2E_{\mathcal{Q}}}\frac{\mathrm{d}^3 p_j}{(2\pi)^3 2E_j}\int \mathrm{d}x \mathrm{d}^2 p_\perp (2\pi)^4 \delta^{(4)}(q+p-p_j-P_{\mathcal{Q}})$$

$$\times \sum_{a,b} \frac{1}{x^2 Q^4} L(l,q) \otimes \Phi_a(x,p_\perp) \otimes \left| H_{\gamma^* a \to J/\Psi + b} \right|^2$$



Gluon correlator

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

field strength

$$\Phi_g^{\mu\nu}(x,p_\perp) = \int \frac{d\xi^- d^2\xi_T}{(2\pi)^3} e^{ip\cdot\xi} \langle P,S| \mathrm{Tr}\, F^{\mu+}(0) U_{[0,\xi]} F^{\nu+}(\xi) U_{[\xi,0]} |P,S\rangle \Big|_{\xi^+=0}$$

proton state

gauge link / Wilson line

Unpolarized target:

$$\Phi_{gU}^{\mu\nu}(x,p_T) = \frac{x}{2}\left\{ -g_T^{\mu\nu} f_1^g(x,p_T) + \left(\frac{p_T^\mu p_T^\nu}{M_p^2} + g_T^{\mu\nu}\frac{p_T^2}{2M_p^2} \right) h_1^{\perp\, g}(x,p_T) \right\}$$

unpolarized TMD

linearly polarized TMD

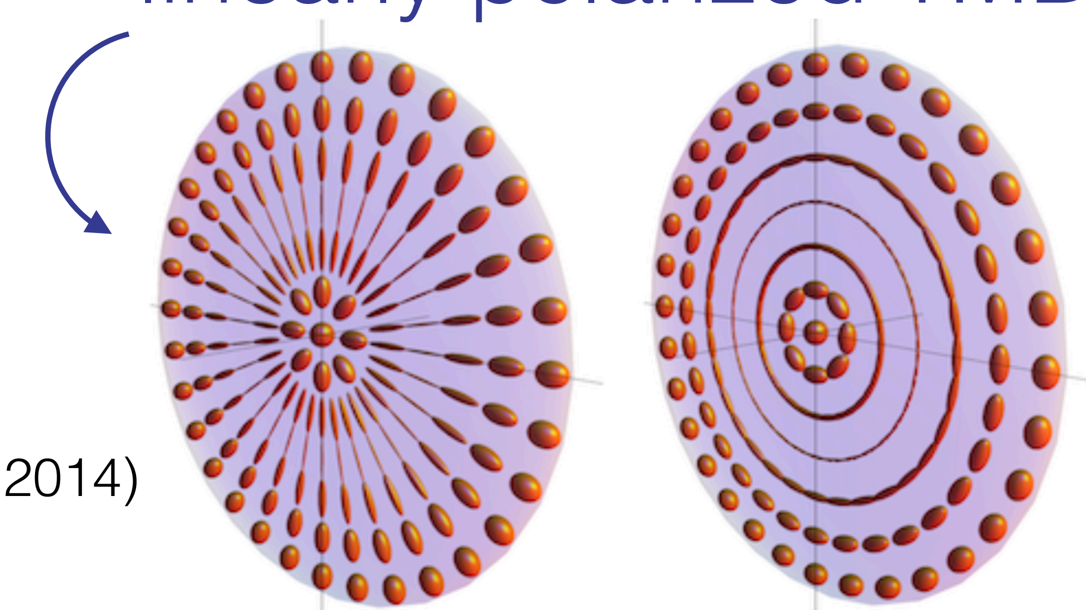


fig. from den Dunnen, Lansberg, Pisano, Schlegel (2014)

Gluon correlator

field strength

$$\Phi_g^{\mu\nu}(x, p_\perp) = \int \frac{d\xi^- d^2\xi_T}{(2\pi)^3} e^{ip\cdot\xi} \langle P, S | \mathrm{Tr}\, F^{\mu+}(0) U_{[0,\xi]} F^{\nu+}(\xi) U_{[\xi,0]} | P, S\rangle \Big|_{\xi^+=0}$$

proton state

gauge link / Wilson line

Transversely polarized target:

Sivers function

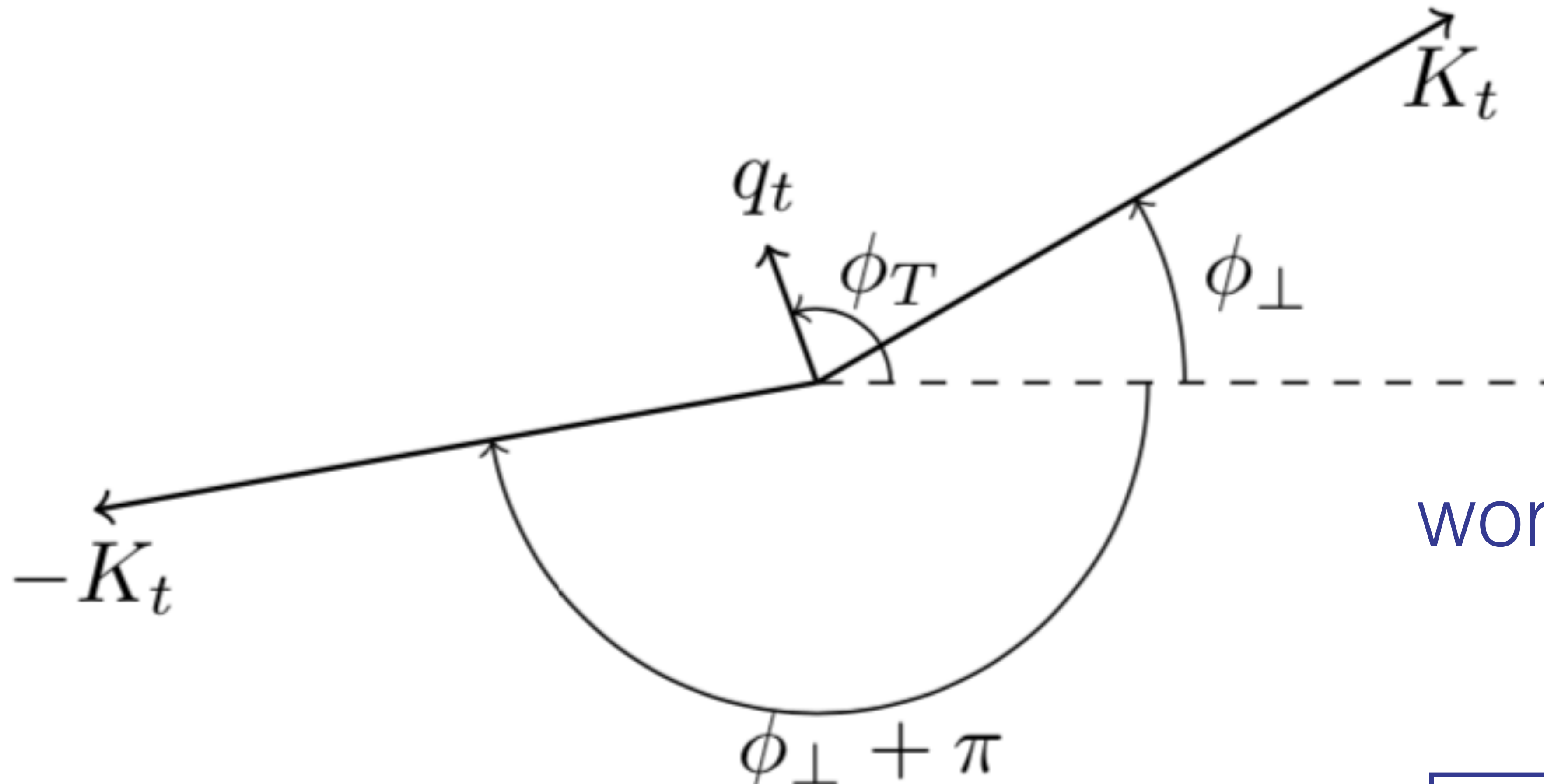
circularly polarized TMD

$$\Phi_{gT}^{\mu\nu}(x, p_T) = \frac{x}{2}\Big\{ g_T^{\mu\nu} \frac{\epsilon_T^{\rho\sigma} p_{T\rho} S_{T\sigma}}{M_p} f_{1T}^{\perp g}(x, p_T) + i\epsilon_T^{\mu\nu} \frac{p_T \cdot S_T}{M_h} g_{1T}^g(x, p_T)$$

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

linearly polarized TMDs

Definition of the angles



work in lepton plane

$$|K_\perp| = \frac{P_{\mathcal{Q}\perp} - p_{j\perp}}{2}$$

$$|q_\perp| = P_{\mathcal{Q}\perp} + p_{j\perp}$$

TMD regime:

$$|q_\perp| \ll |K_\perp|$$

Resulting cross section

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

$$\begin{aligned} \mathrm{d}\sigma^U = \mathcal{N}\bigg[& \Big(A_0^U + A_1^U \cos\phi_\perp + A_2^U \cos 2\phi_\perp\Big) \times f_1^g(x, p_T) \\ & + \Big(B_0^U \cos 2\phi_T + B_1^U \cos(2\phi_T - \phi_\perp) + B_2^U \cos 2(\phi_T - \phi_\perp) \\ & \quad + B_3^U \cos(2\phi_T - 3\phi_\perp) + B_4^U \cos(2\phi_T - 4\phi_\perp)\Big) \times h_1^{\perp\, g}(x, p_T)\bigg] \end{aligned}$$

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

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

Resulting cross section

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

$$\begin{aligned}
\mathrm{d}\sigma^T = \mathcal{N}\Big[& \sin(\phi_S-\phi_T)\Big(A_0^U + A_1^U\cos\phi_\perp + A_2^U\cos 2\phi_\perp\Big) \times f_{1T}^{\perp g}(x,p_T) \\
& + \cos(\phi_S-\phi_T)\Big(B_0^U\sin 2\phi_T + B_1^U\sin(2\phi_T-\phi_\perp) + B_2^U\sin 2(\phi_T-\phi_\perp) \\
& \quad + B_3^U\sin(2\phi_T-3\phi_\perp) + B_4^U\sin(2\phi_T-4\phi_\perp)\Big) \times \frac{p_T}{M_p} h_{1T}^{\perp g}(x,p_T) \\
& + \Big(B_0^U\sin(\phi_S+\phi_T) + B_1^U\sin(\phi_S+\phi_T-\phi_\perp) + B_2^U\sin(\phi_S+\phi_T-2\phi_\perp) \\
& \quad + B_3^U\sin(\phi_S+\phi_T-3\phi_\perp) + B_4^U\sin(\phi_S+\phi_T-4\phi_\perp)\Big) \times h_{1T}^{g}(x,p_T)\Big]
\end{aligned}$$

Azimuthal asymmetries

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

are sensitive to ratios of TMDs

e.g.:

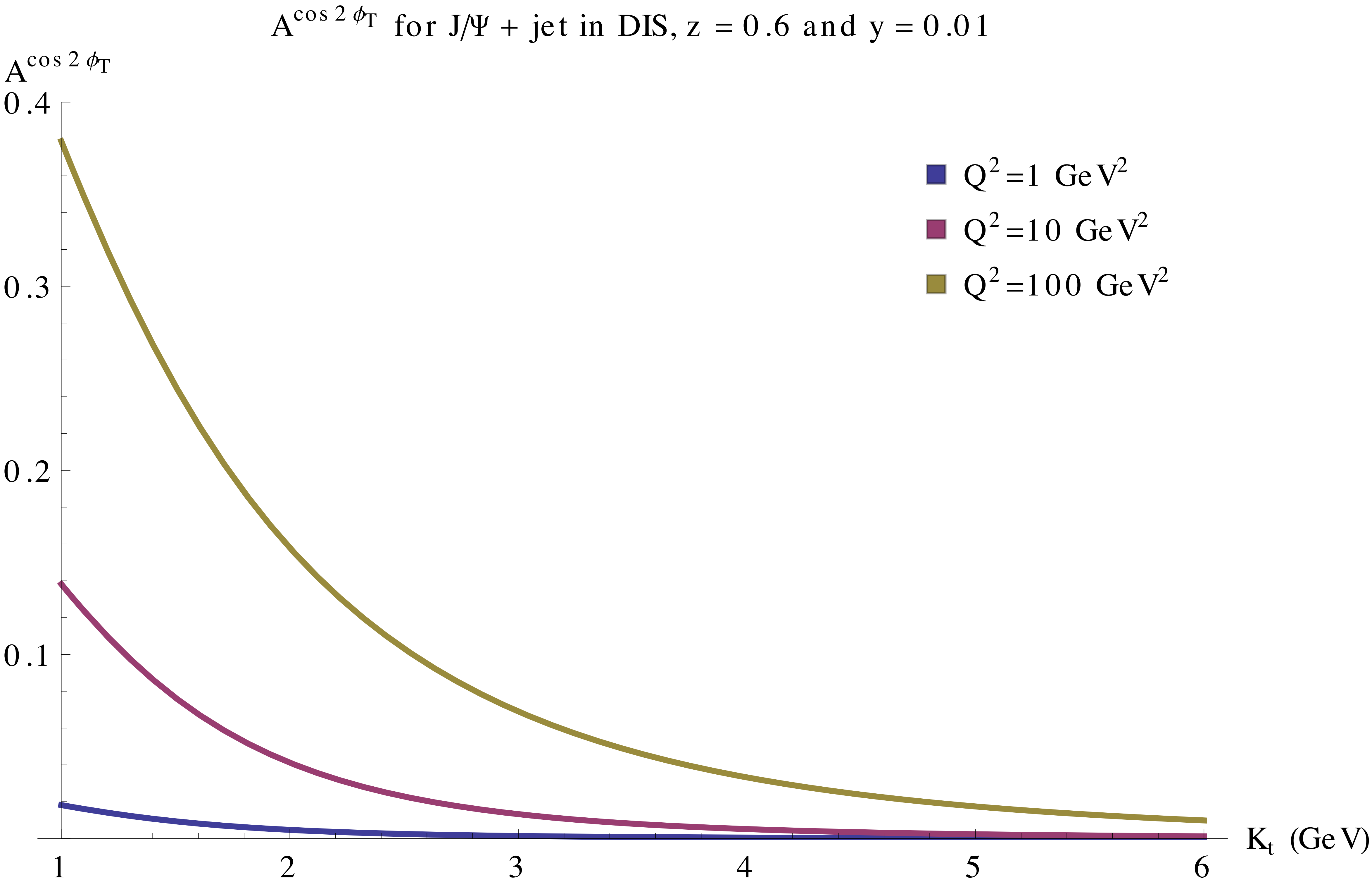
$$A^{\cos(2\phi_T)} = 2\,\frac{\int \mathrm{d}\phi_T \mathrm{d}\phi_\perp \cos(2\phi_T)\mathrm{d}\sigma^U(\phi_T,\phi_\perp)}{\int \mathrm{d}\phi_T \mathrm{d}\phi_\perp \mathrm{d}\sigma^U(\phi_T,\phi_\perp)} = \frac{B_0^U}{A_0^U}\,\frac{h_1^{\perp\,g}(x,p_T)}{f_1^g(x,p_T)}$$

polarized gluon TMDs satisfy the following positivity bounds:

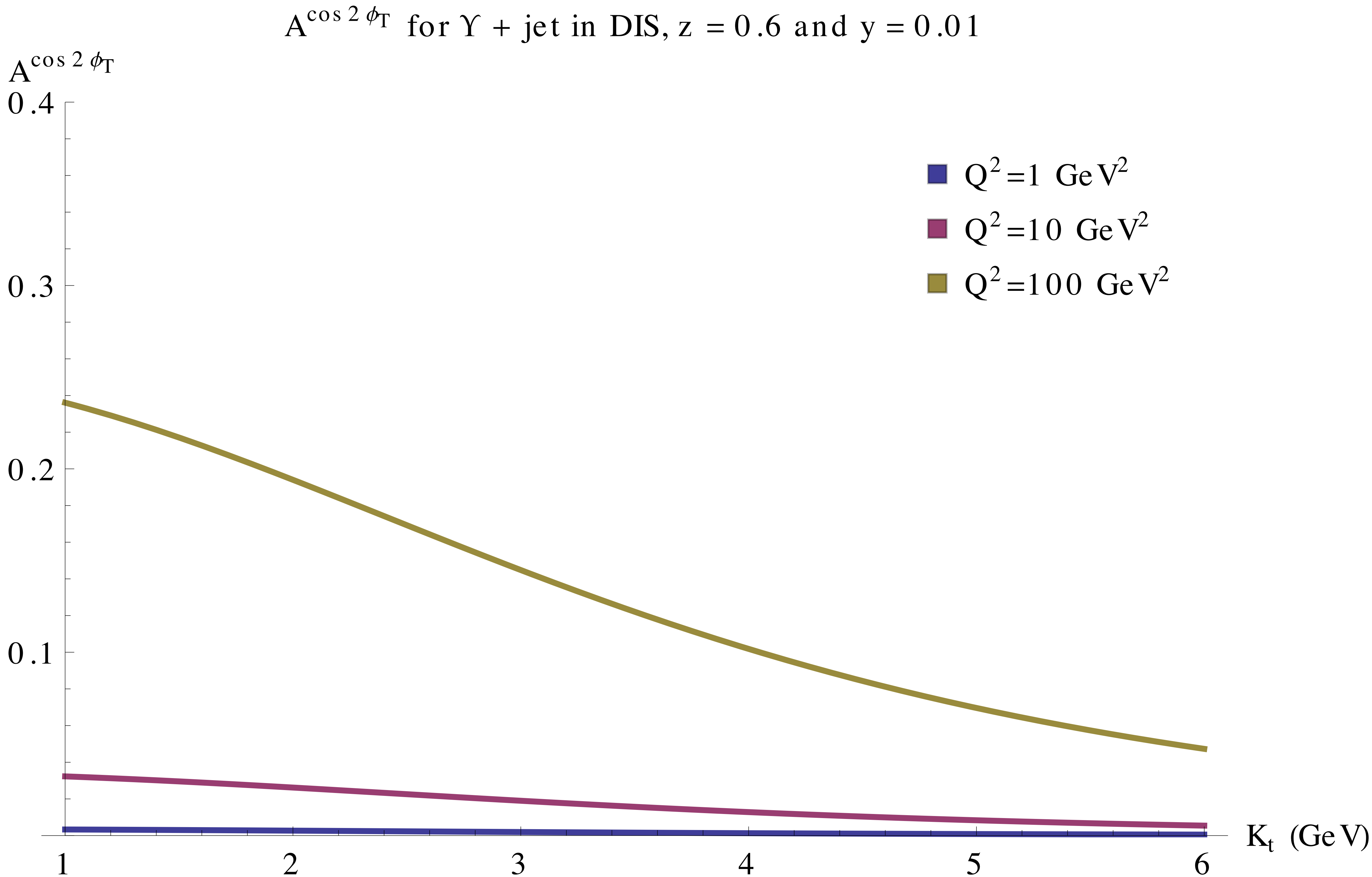
$$\frac{|\boldsymbol{p}_T|}{M_p}\,|f_{1T}^{\perp\,g}(x,\boldsymbol{p}_T^2)| \le f_1^g(x,\boldsymbol{p}_T^2) \qquad \frac{|\boldsymbol{p}_T|}{M_p}\,|h_1^g(x,\boldsymbol{p}_T^2)| \le f_1^g(x,\boldsymbol{p}_T^2)$$

$$\frac{\boldsymbol{p}_T^2}{2M_p^2}\,|h_1^{\perp\,g}(x,\boldsymbol{p}_T^2)| \le f_1^g(x,\boldsymbol{p}_T^2) \qquad \frac{|\boldsymbol{p}_T|^3}{2M_p^3}\,|h_{1T}^{\perp\,g}(x,\boldsymbol{p}_T^2)| \le f_1^g(x,\boldsymbol{p}_T^2)$$

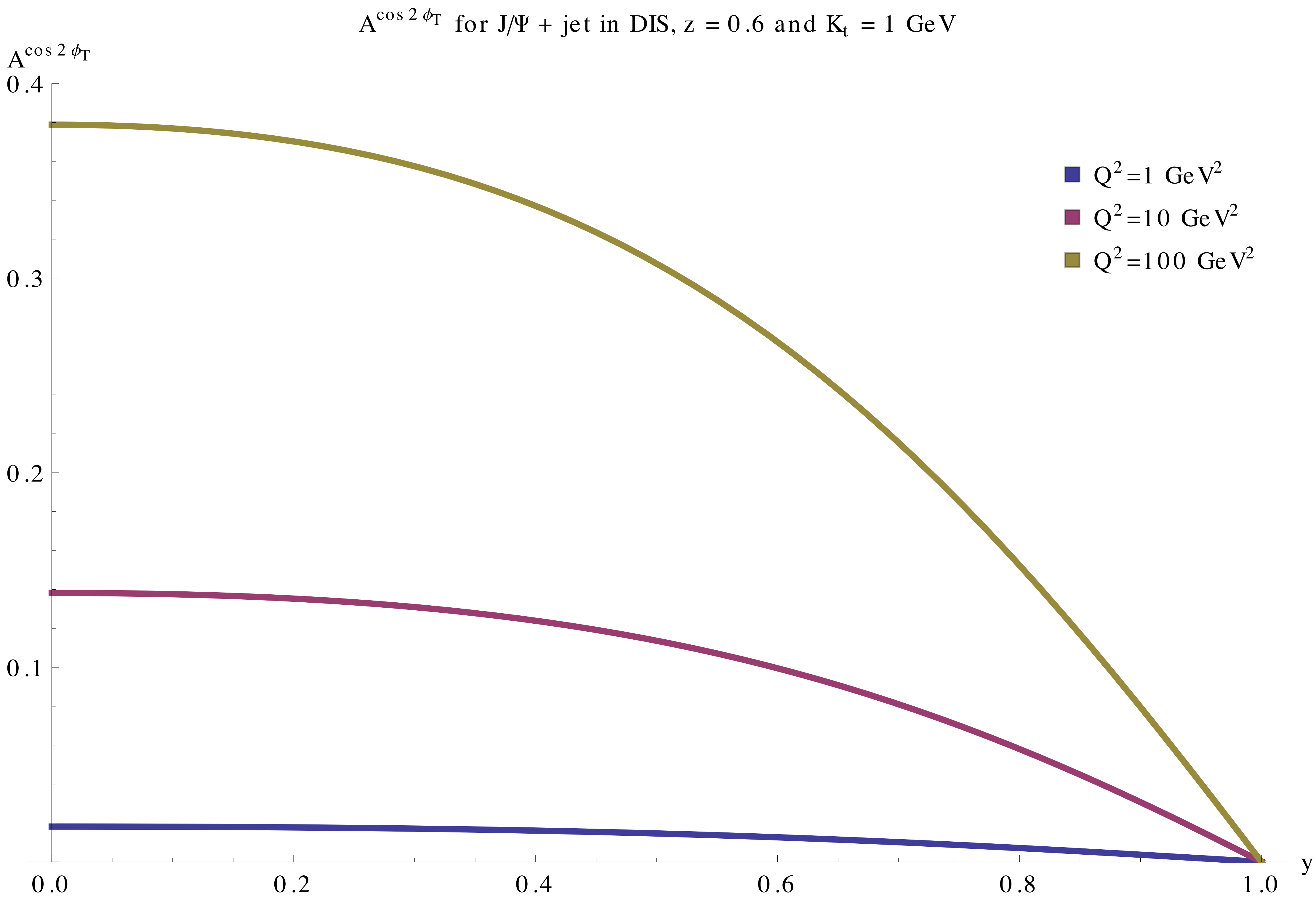
Azimuthal asymmetries: maxima



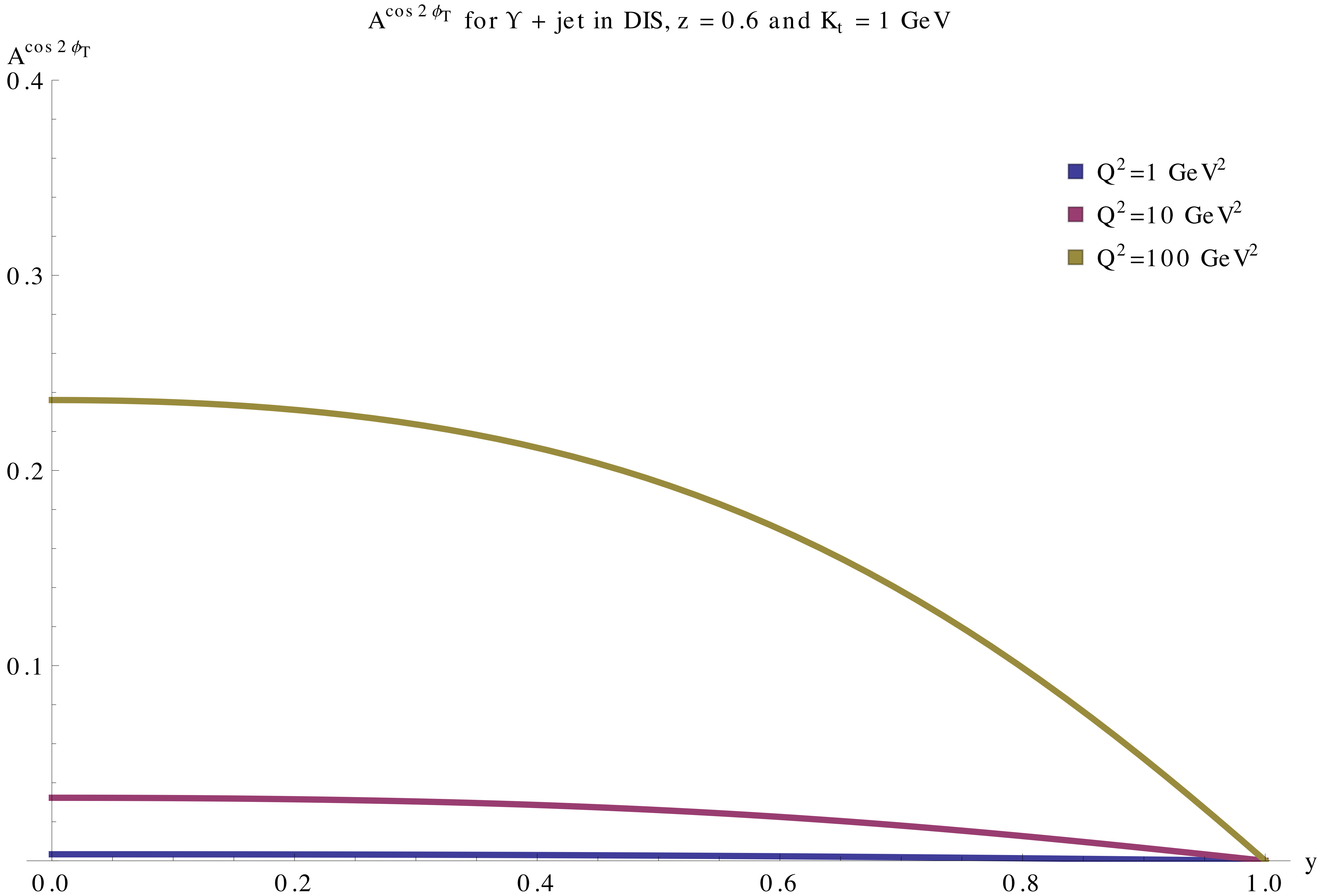
Azimuthal asymmetries: maxima



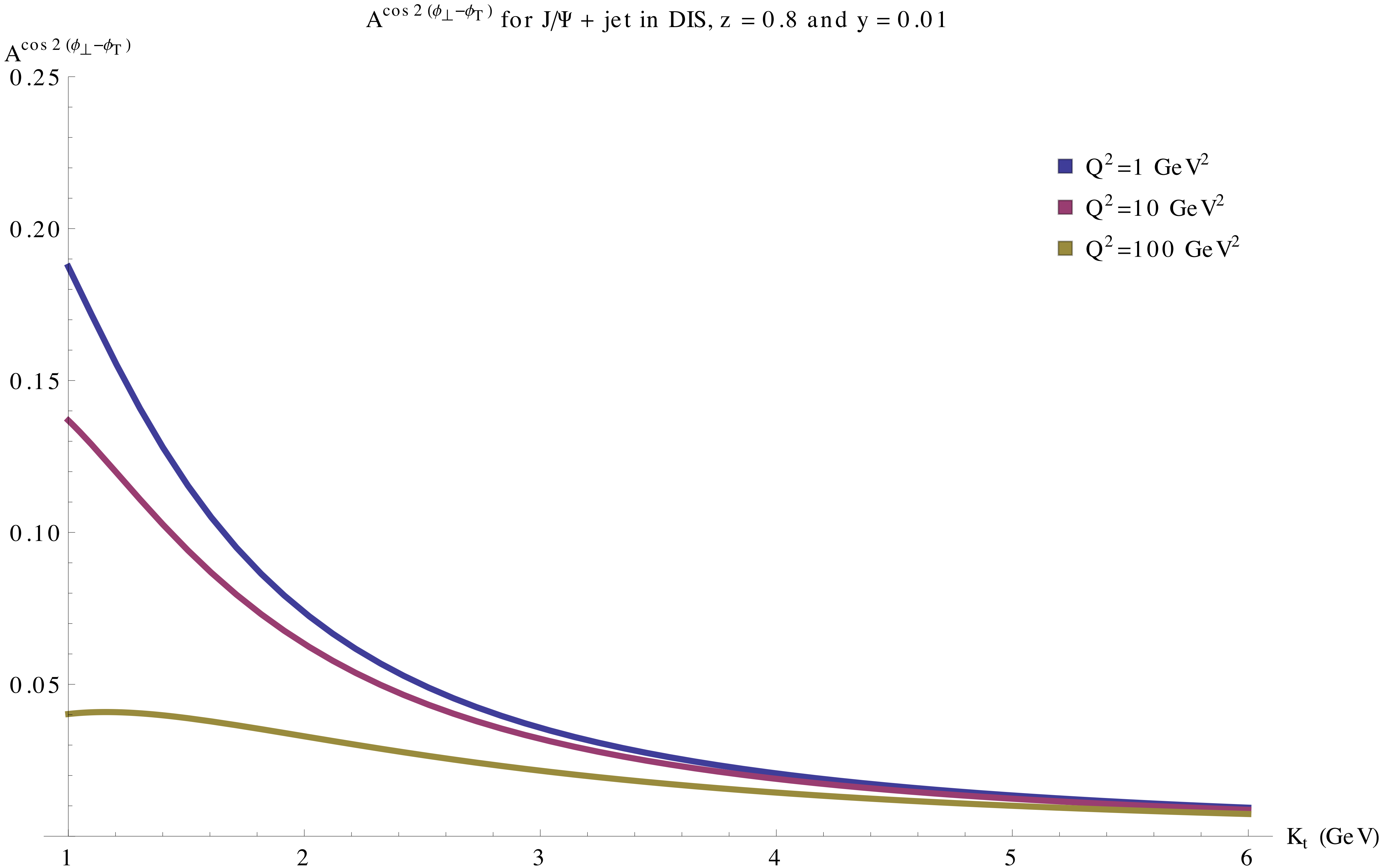
Azimuthal asymmetries: maxima



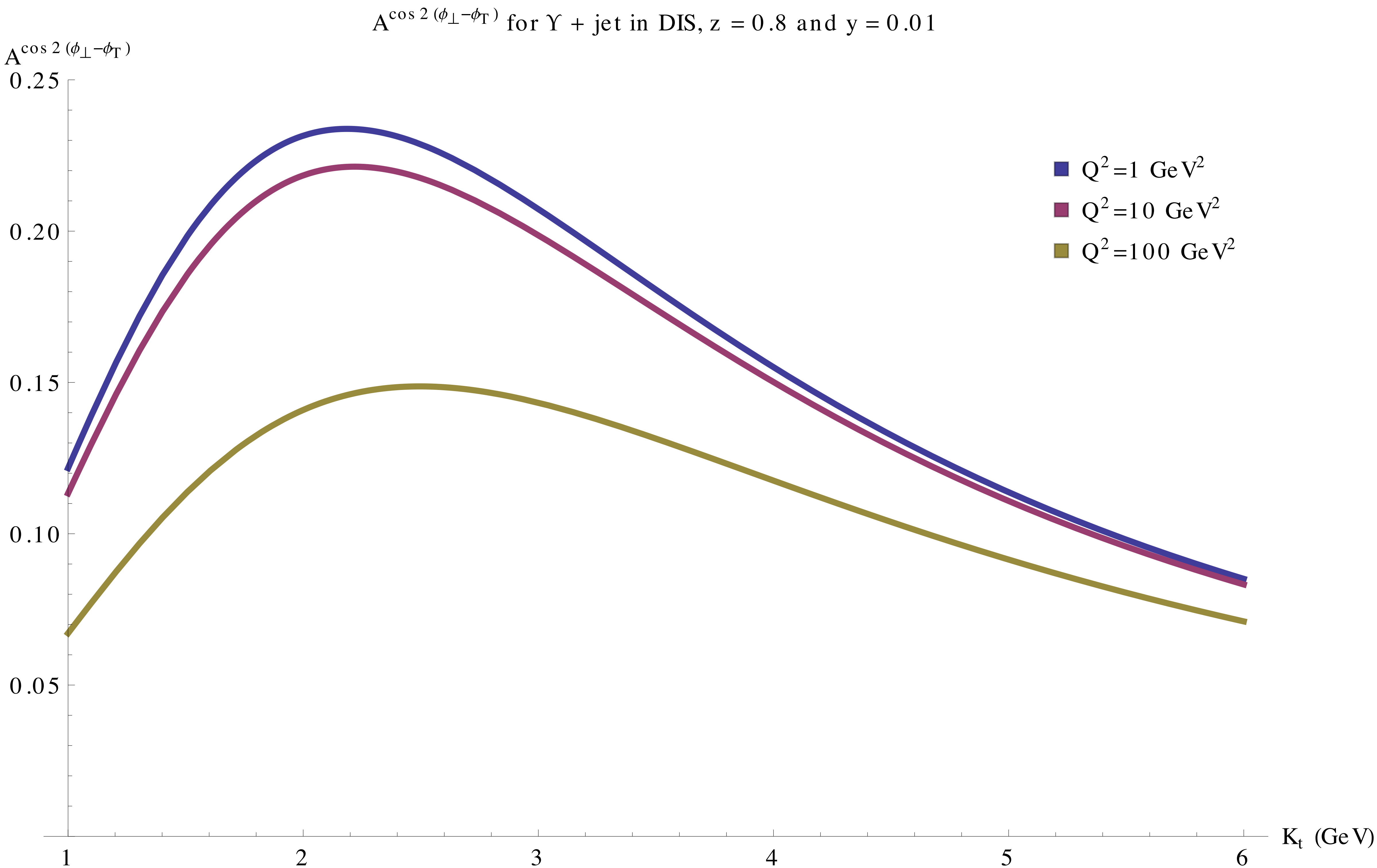
Azimuthal asymmetries: maxima



Azimuthal asymmetries: maxima



Azimuthal asymmetries: maxima



Conclusions

Asymmetries are sitting in a corner of phase space, but are potentially sizeable

Work in progress: taking color octet contributions to the NRQCD description of the quarkonium into account

Predictions at low-x based on Color Glass Condensate calculations of dijet or heavy-quark production

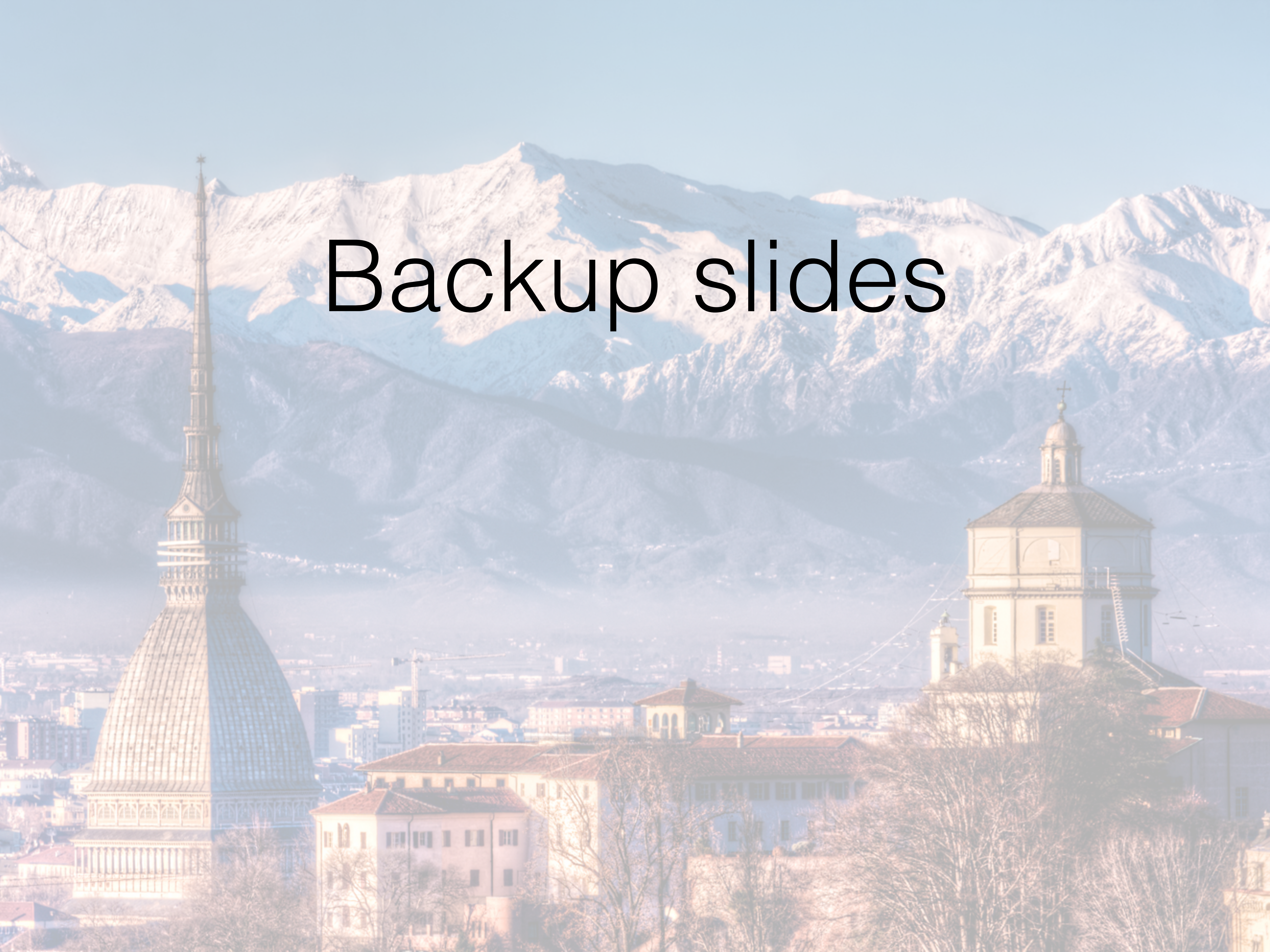
Marquet, Petreska, Roiesnel (2016)
Marquet, Roiesnel, PT (2018)

Extension of similar study of single inclusive quarkonium production

Bacchetta, Boer, Pisano, PT (2018)

Thanks to the organizers,
thanks for your attention!

Backup slides



Non-Relativistic QCD (NRQCD)

Problem of bound states involves multiple scales

For a quarkonium with mass M and relative velocity v of quarks in rest frame:

Mv^2	$<$	Mv	$<$	M
energy		momentum		mass
nonperturbative		?		perturbative

From $Mv^2 \sim \Lambda_{\mathrm{QCD}}$, we have $v^2 \simeq 0.3$ for charmonium and $v^2 \simeq 0.1$ for bottomium. v provides small expansion parameter

NRQCD provides factorization between perturbative small distance physics $\sim 1/M$, and long distance effects at $\mathrm{length}_{J/\psi} \sim 1/Mv$

Hadronization is encoded in Long-Distance Matrix Elements (LDMEs) which follow scaling rules in v

Bodwin, Braaten and Lepage (1995)