Perturbatively stable observables in heavy flavor production

as probes of the nucleon spin and flavor content

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Novel proposals for heavy quark physics at *ep*-, *pp*- and *AA*- colliders

(COMPASS, EIC, LHeC, LHC and NICA)

Dubna, April 2, 2018

Outline:

- Perturbatively (and parameterically) stable observables:
  - Azimuthal asymmetry in photoproduction;
  - Calan-Gross ratio $R = F_L / F_T$, $\cos\phi$ and $\cos 2\phi$ asymmetries in electroproduction

- Proposed applications:
  - Test of pQCD;
  - Determination of the charm content of the proton;
  - Search for the linearly polarized gluons in unpolarized proton

- Outlook for NICA: Azimuthal correlations in *pp* and *AA*

References

1. Perturbative stability :

- N.Ya.Ivanov, A.Capella, A.B.Kaidalov, Nucl. Phys. **B** 586 (2000), 382
- N.Ya.Ivanov, Nucl. Phys. **B** 615 (2001), 266
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- L.N.Ananikyan and N.Ya.Ivanov, Phys. Rev. **D** 75 (2007), 014010
- N.Ya.Ivanov and B.A. Kniehl, Eur. Phys. J. **C** 59 (2009), 647

2. Heavy-quark densities in the proton:

- L.N.Ananikyan and N.Ya.Ivanov, Nucl. Phys. **B** 762 (2007), 256
- N.Ya.Ivanov, Nucl. Phys. **B** 814 (2009), 142

3. Test of pQCD grounds:

- N.Ya.Ivanov, P.E.Bosted, K.Griffioen, Nucl. Phys. **B** 650 (2003), 271
- A.V.Efremov, N.Ya.Ivanov, O.V.Teryaev, Phys.Lett. **B** 772 (2017), 283

4. Linearly polarized gluons in unpolarized proton:

- A.V.Efremov, N.Ya.Ivanov, O.V.Teryaev, Phys.Lett. **B** 777 (2018), 435
- A.V.Efremov, N.Ya.Ivanov, O.V.Teryaev, Phys.Lett. **B** 780 (2018), 303

Perturbative stability in charm photoproduction

We propose to test the pQCD applicability to heavy flavor production with the help of azimuthal $\cos 2\varphi$ asymmetry in charm photoproduction

$$\gamma^{\uparrow} + N \to Q + X[\overline{Q}]$$

Corresponding cross section is:

$$\frac{\mathrm{d}\sigma_{\gamma h}}{\mathrm{d}\varphi}(S,\varphi) = \frac{\sigma_{\gamma h}^{\mathrm{unp}}(S)}{2\pi}\left(1 + A(S)\mathcal{P}_{\gamma}\cos 2\varphi\right)$$

where $\mathcal{P}_{\gamma}$ is the degree of linear polarization of the photon,

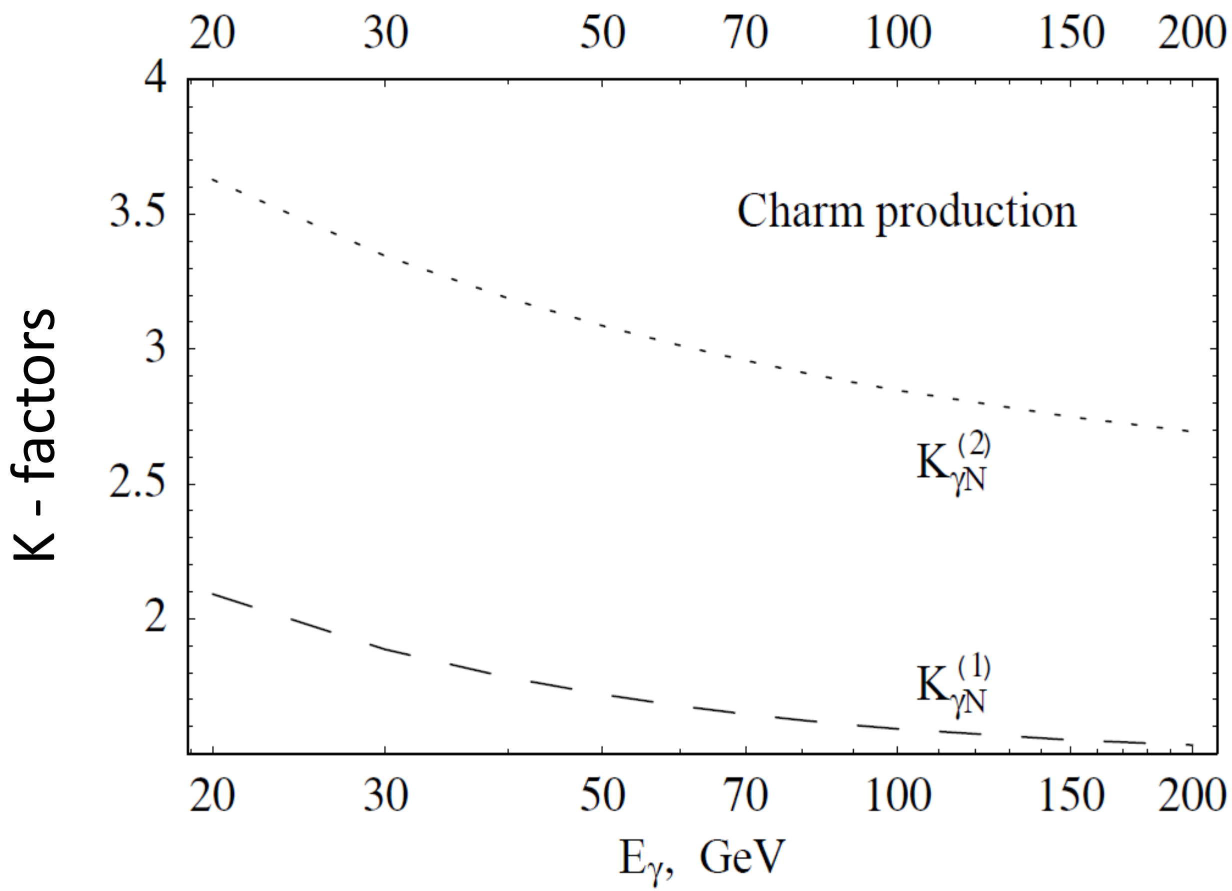
$\sqrt{S}$ is the centre of mass energy of the reaction,

and φ is the angle between the photon polarization and quark $\perp$ momentum

We observe the following remarkable properties:

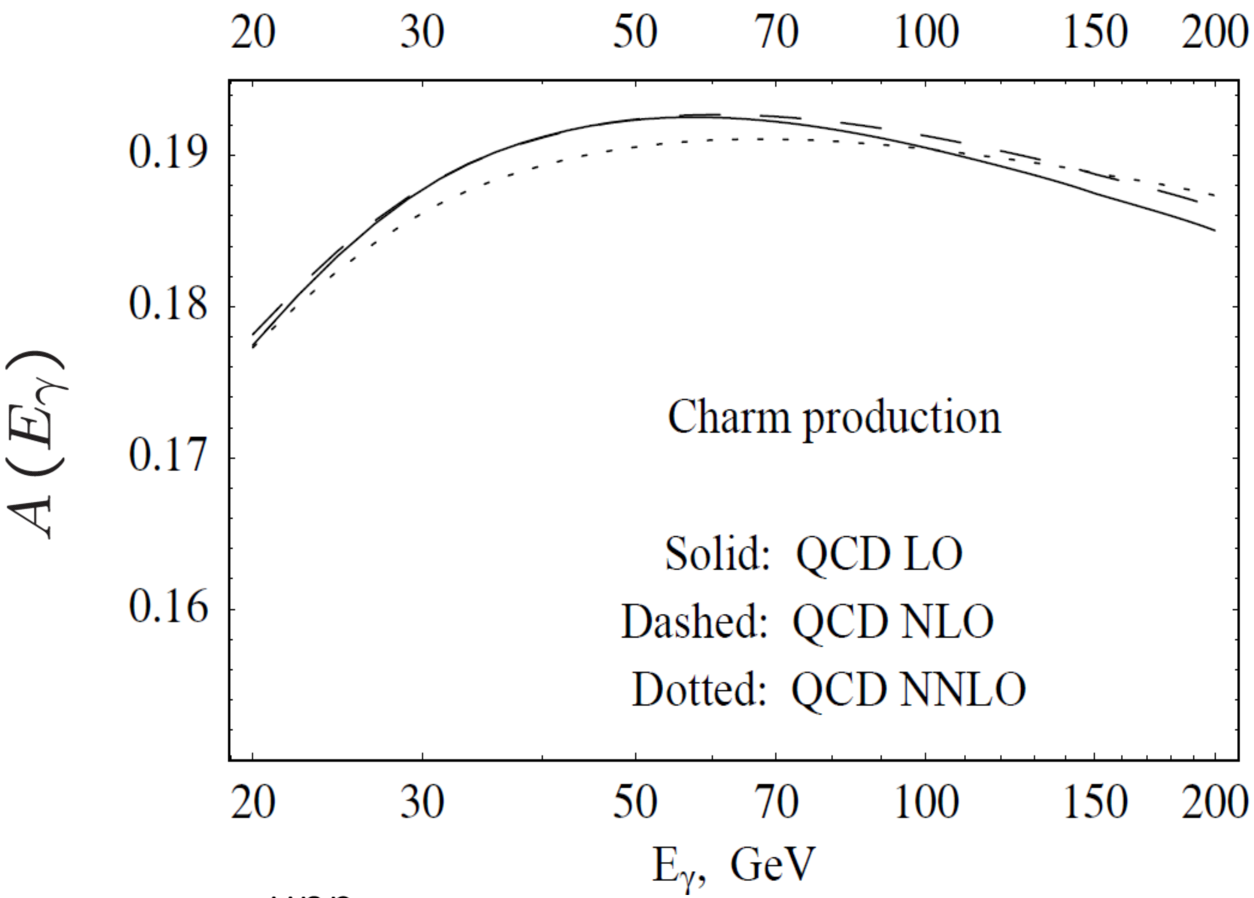
- The azimuthal asymmetry is large: it is predicted to be about 20% for both charm and bottom;
- Contrary to the production cross sections, the $\cos 2\varphi$ asymmerty in azimuthal distributions of heavy quark is practically insensitive to soft-gluon radiation;
- pQCD predictions for A(S) are insensitive (to within few percent) to uncertainties in the QCD input parameters: $m, \mu_R, \mu_F, \Lambda_{QCD}$ and PDFs;
- The nonperturbative contributions are also small. The following mechanisms was considered:
  - Gluon transverse motion in the target;
  - Heavy quark fragmentation;
  - The bound state effects due to Fermi motion of the c-quark inside the D-meson.

Perturbative instability of the cross section



$$K_{\gamma h}^{(1)}(S) \;=\; \sigma_{\gamma h}^{\mathrm{NLO}}(S) \,/\, \sigma_{\gamma h}^{\mathrm{LO}}(S)$$
$$K_{\gamma h}^{(2)}(S) \;=\; \sigma_{\gamma h}^{\mathrm{NNLO}}(S) \,/\, \sigma_{\gamma h}^{\mathrm{NLO}}(S)$$

Perturbative stability of the asymmetry



$$\frac{d\sigma_{\gamma h}}{d\varphi}(S,\varphi) = \frac{\sigma_{\gamma h}^{\text{unp}}(S)}{2\pi}(1 + A(S)\mathcal{P}_\gamma \cos 2\varphi)$$

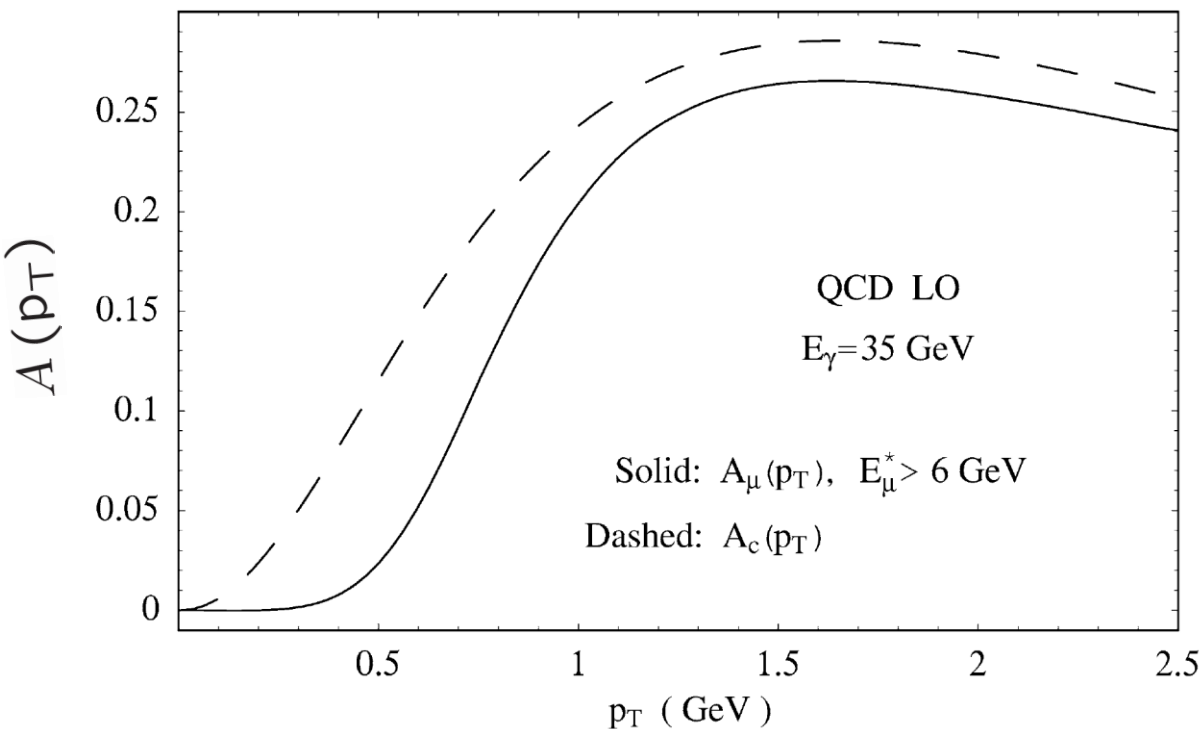
$$A(S) = \frac{1}{\mathcal{P}_\gamma}\frac{d\sigma_{\gamma h}(S,\varphi=0) - d\sigma_{\gamma h}(S,\varphi=\pi/2)}{d\sigma_{\gamma h}(S,\varphi=0) + d\sigma_{\gamma h}(S,\varphi=\pi/2)}$$

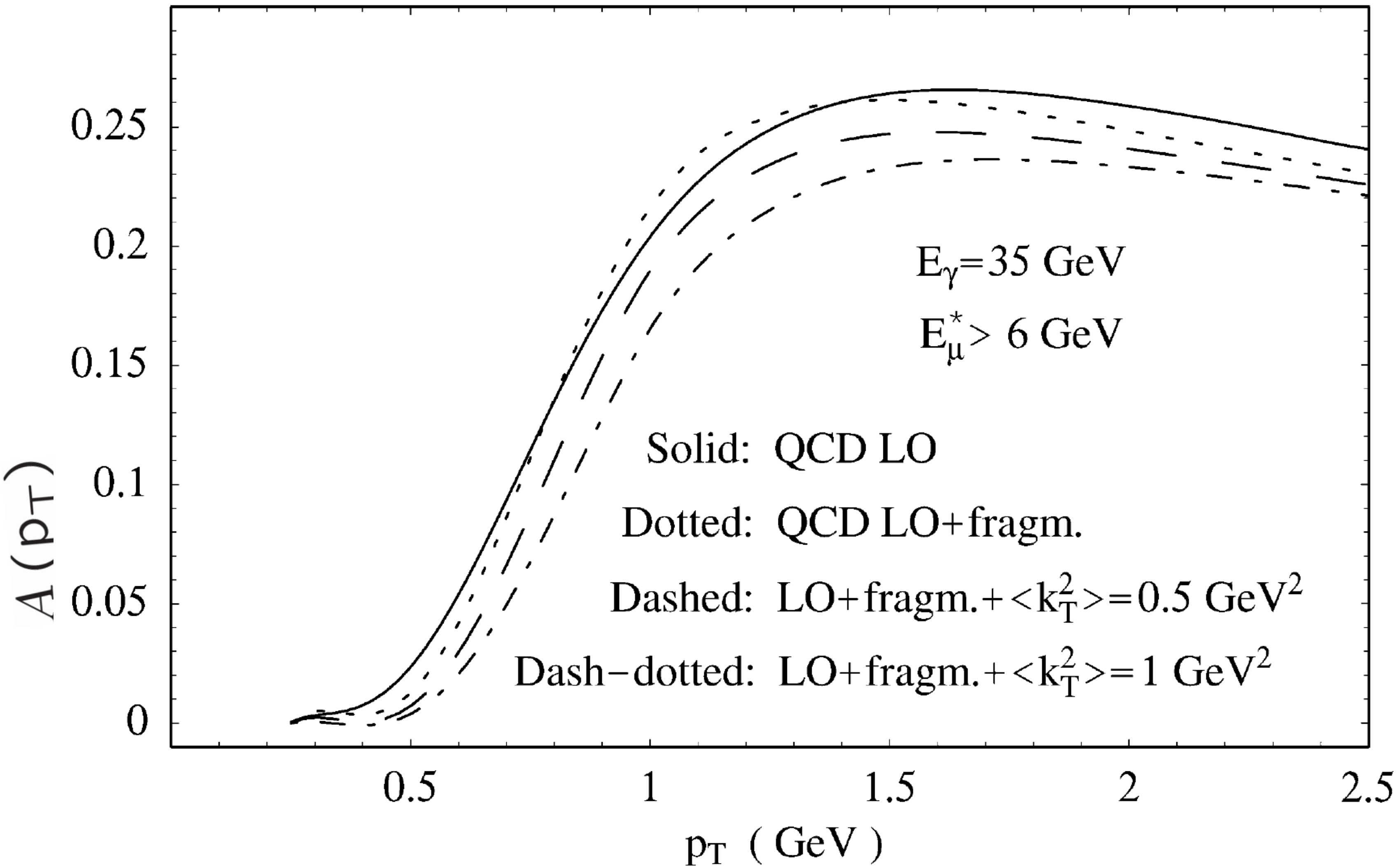
Azimuthal asymmetry in charm photoproduction at SLAC

Azimuthal asymmetry in charm photoproduction could be measured at SLAC in E160/E161 experiments using the inclusive spectra of secondary (decay) leptons: **[Ivanov, Bosted, Griffioen, Rock, NP B 650 (2003) 271]**

$$\gamma^{\uparrow} + N \;\to\; c \;+ X[\bar{c}] \;\to\; \mu^{+} + X$$

$$c \;\to\; \mu^{+}\nu_{\mu}\, q \qquad (q = d, s)$$





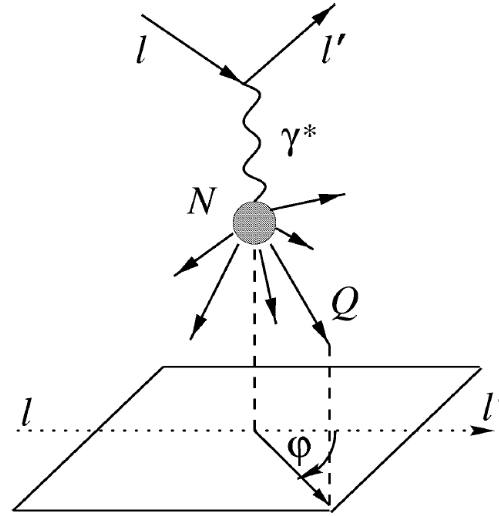
0.25
0.2
0.15
0.1
0.05
0
0.5
1
1.5
2
2.5
p_T (GeV)
$A(p_T)$
E_γ=35 GeV
E_μ^*> 6 GeV
Solid: QCD LO
Dotted: QCD LO+fragm.
Dashed: LO+fragm.+<k_T^2>=0.5 GeV^2
Dash−dotted: LO+fragm.+<k_T^2>=1 GeV^2

Perturbative stability in charm electroproduction

Definitions and Cross Sections

We consider the Callan-Gross ratio $R = F_L / F_T$ and azimuthal $\cos 2\varphi$ asymmetry, $A = 2xF_A / F_2$, in heavy-quark leptoproduction:

$$l(\ell) + N(p) \to l(\ell - q) + Q(p_Q) + X[\overline{Q}](p_X)$$

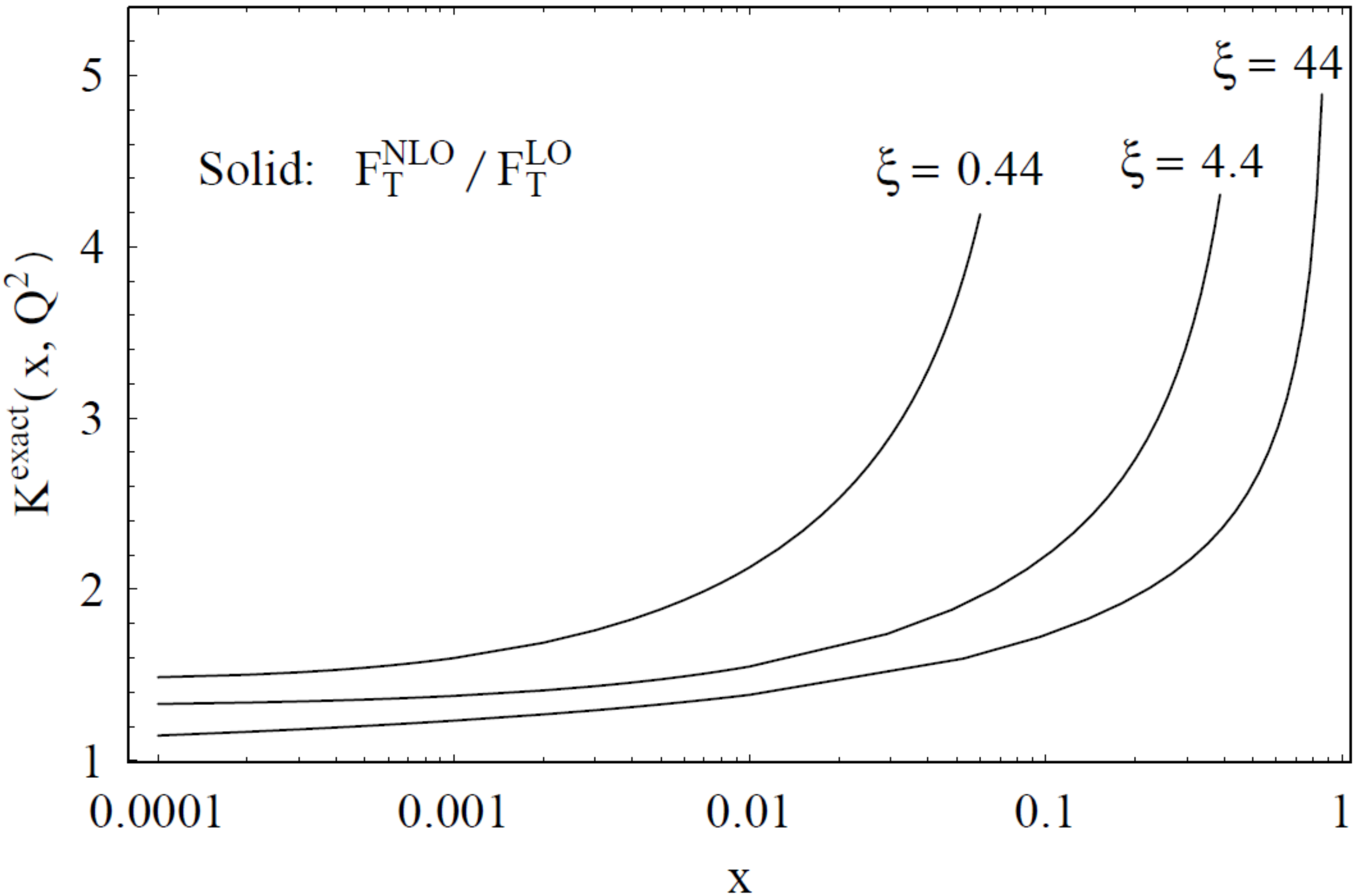


Corresponding cross section is:

$$\frac{\mathrm{d}^3\sigma_{lN}}{\mathrm{d}x\mathrm{d}Q^2\mathrm{d}\varphi} = \frac{\alpha_{em}^2}{xQ^4}\Big\{ \left[1 + (1-y)^2\right] F_2(x,Q^2) - 2xy^2 F_L(x,Q^2) + 4x(1-y)\, F_A(x,Q^2)\cos 2\varphi + 4x(2-y)\sqrt{2(1-y)}F_I(x,Q^2)\cos\varphi \Big\}$$

where $F_2(x,Q^2) = 2x(F_T + F_L)$ and x, y, Q^2 are usual DIS observables

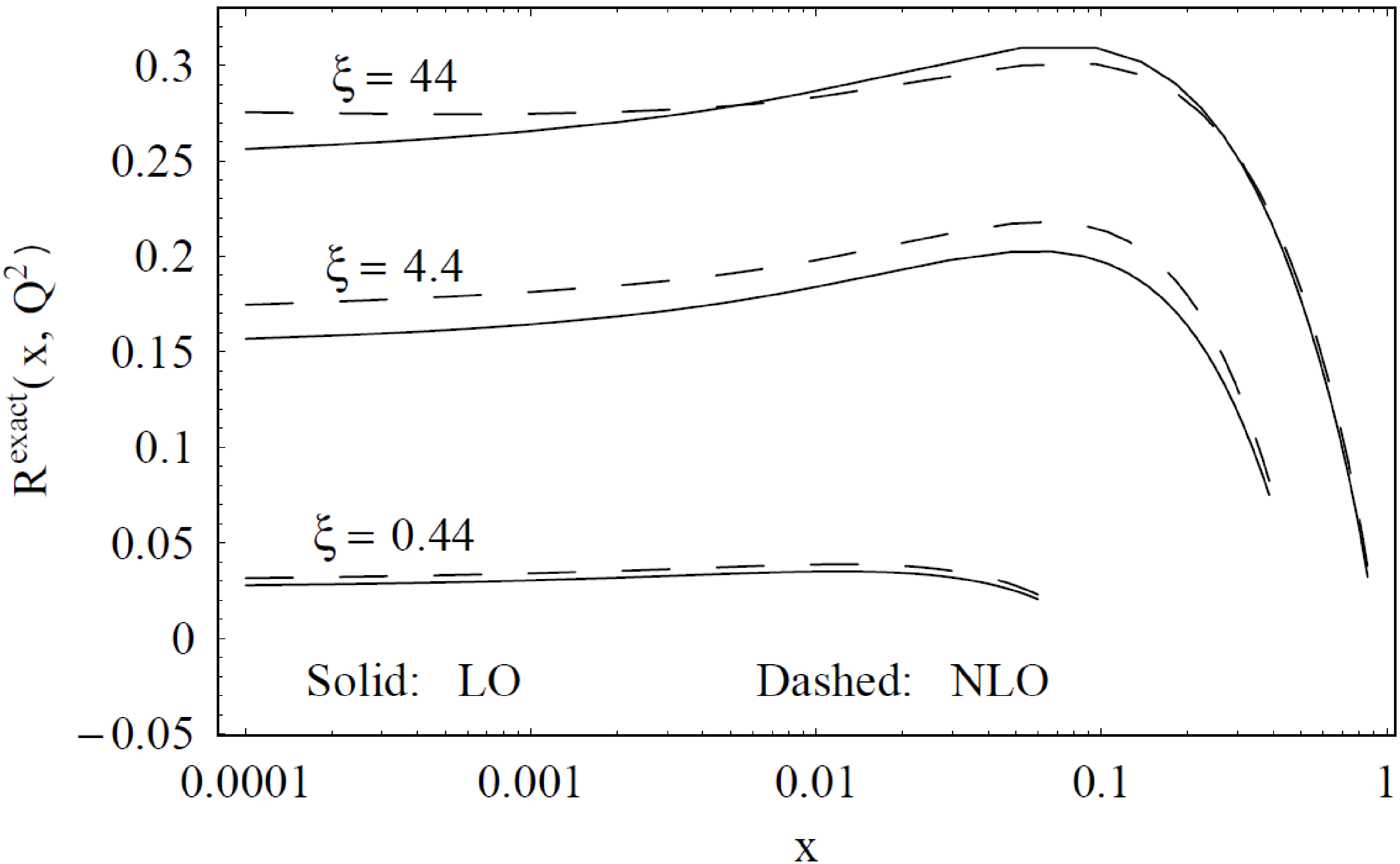
Perturbative intability of the cross section



$$\xi = \frac{Q^2}{m^2}$$

$$K(x, Q^2) = \frac{F_T^{\mathrm{NLO}}}{F_T^{\mathrm{LO}}}$$

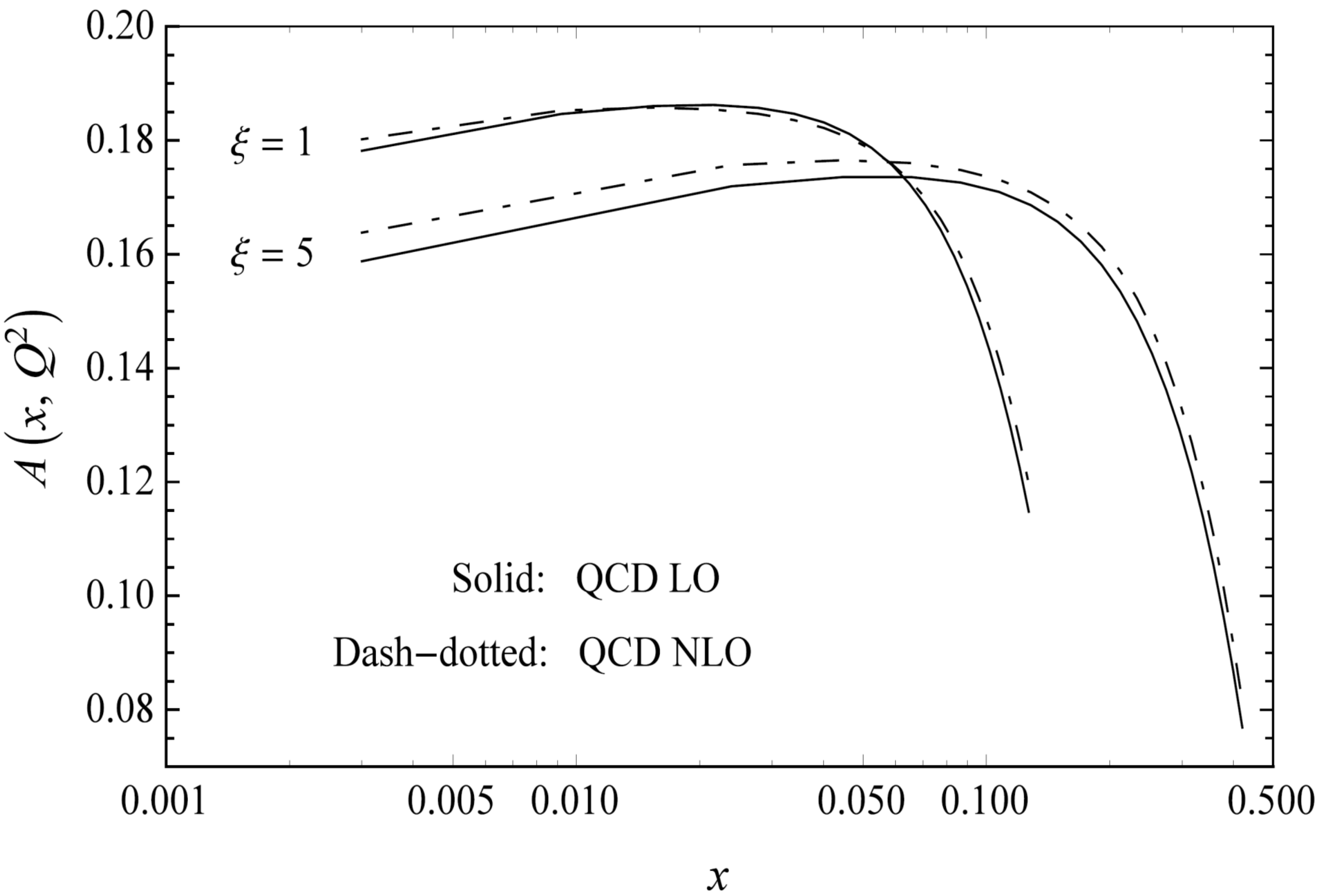
Perturbative stability of R = F_L / F_T



$$\xi = \frac{Q^2}{m^2}$$

$$R(x, Q^2) = \frac{F_L}{F_T}$$

Perturbative stability of $A = 2xF_A / F_2$



Laenen ,Moch, PR D 59 (1999) 034027

Ivanov, Kniehl, Eur. Phys. J. C 59 (2009) 647

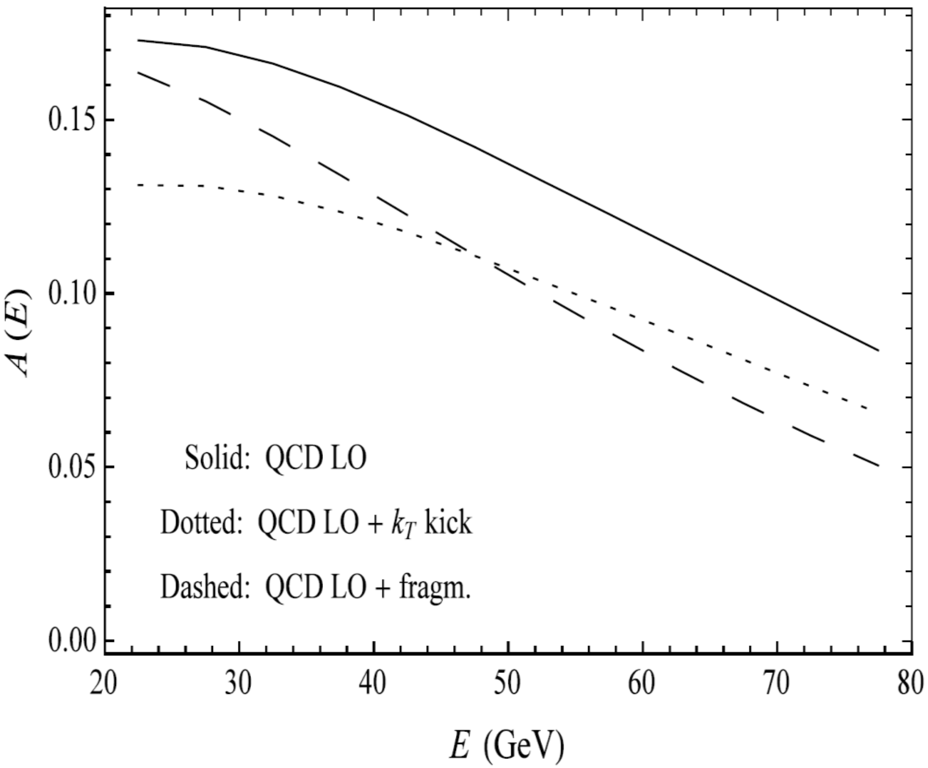
$$\xi = \frac{Q^2}{m^2}$$

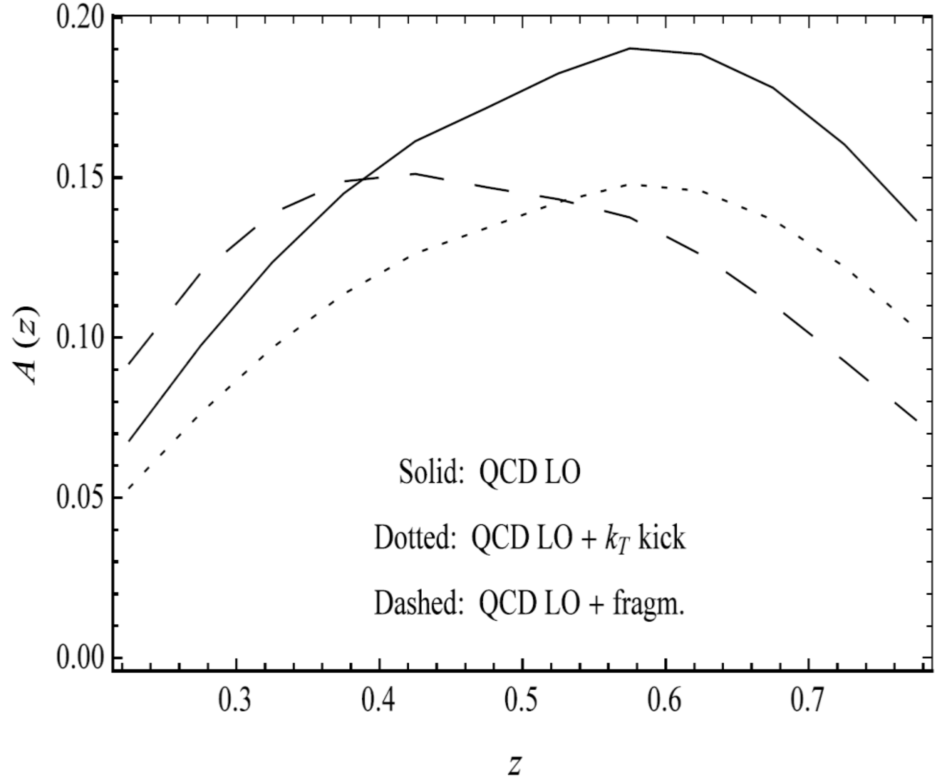
$$A(x, Q^2) = 2x\frac{F_A}{F_2}$$

- The soft-gluon NLO NLL corrections are given

cos2ϕ asymmetry in charm electroproduction at COMPASS

cos2ϕ asymmetry in charm electroproduction can be measured at COMPASS : **Efremov, Ivanov, Teryaev, Phys.Lett. B 772 (2017), 283**





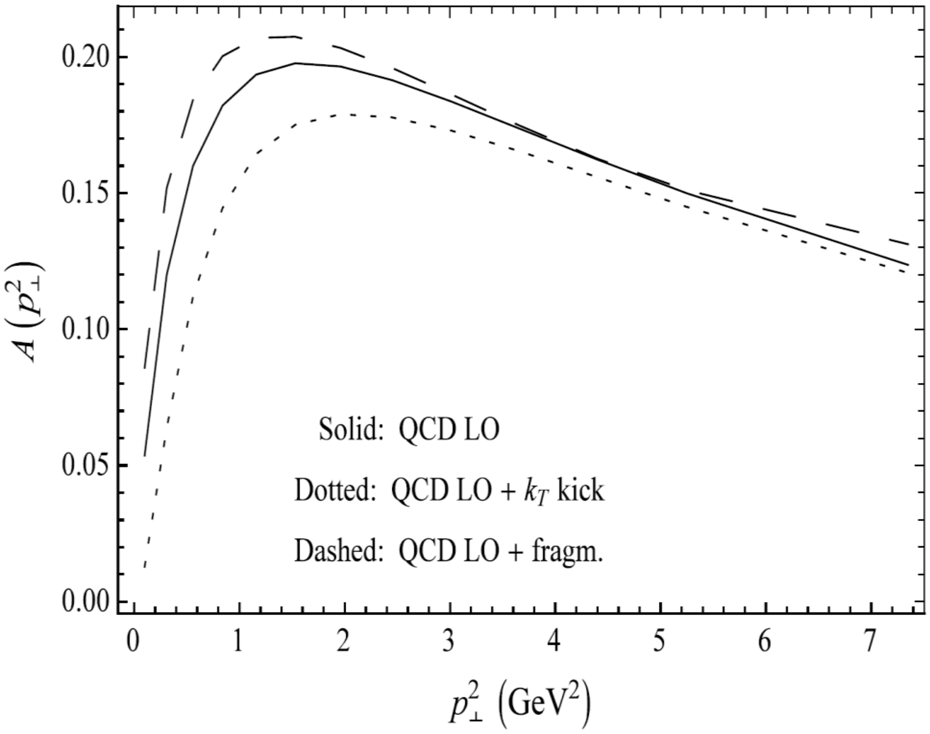
$$\nu = E_l - E_l'$$

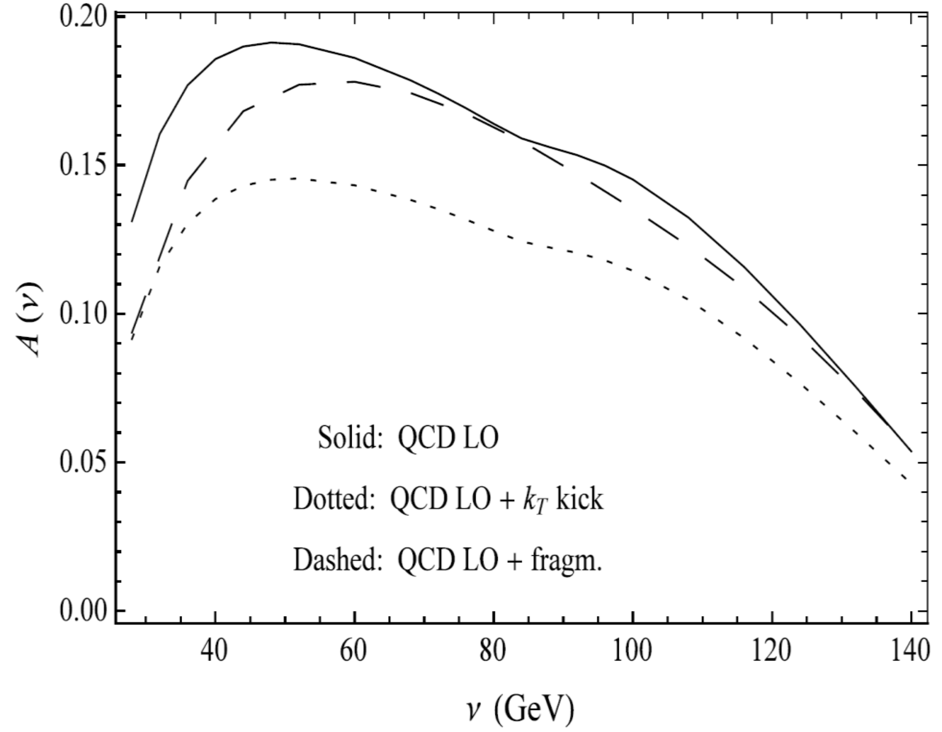
$$z = \frac{E}{\nu}$$

$\cos 2\phi$ asymmetry in charm electroproduction at COMPASS

COMPASS kinematics:

$$0.003 < Q^2 < 10 \text{ GeV}^2, \quad 3 \cdot 10^{-5} < x < 0.1, \quad 20 < E < 80 \text{ GeV}$$





$$\nu = E_l - E_l'$$

Application I: Charm density in the proton

The ***perturbative charm*** was introduced about 20 years ago in

- J.C.Collins, Phys. Rev. **D** 58 (1998) , 094002
- M.A.G.Aivazis, J.C.Collins, F.I.Olness, and W.-K.Tung, Phys. Rev. **D** 50 (1994) , 3102

The perturbative charm contribution

- ❑ is defined in the VFNS :
  - ➢ FFNS : *p* → *(u, d, s, g)*
  - ➢ VFNS : *p* → *(u, d, s, g) + (c, b, t)*
- ❑ originates from $g \to c\bar{c}$ process,
- ❑ has perturbative nature and $c(x, Q^2)$ obeys usual DGLAP evolution

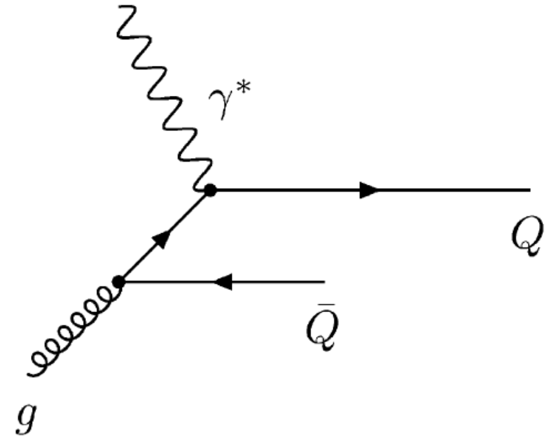
Our approach is based on following observations:

- The ratios $R = F_L / F_T$ and $A = 2xF_A / F_2$ in heavy-quark leptoproduction are perturbatively stable within the FFNS.
- The quantities F_L / F_T and $2xF_A / F_2$ are sensitive to resummation of the mass logarithms of the type $\alpha_s \ln(Q^2 / m^2)$ within the VFNS.

These facts together imply that (future) high-Q^2 data on the ratios $R = F_L / F_T$ and $A = 2xF_A / F_2$ will make it possible to probe the heavy-quark densities in the nucleon, and thus to compare the convergence of perturbative series within the FFNS and VFNS.

Remember that, within the VFNS, the heavy-quark content of the proton is due to resummation of the mass logarithms of the type $\alpha_s \ln(Q^2 / m^2)$ and, for this reason, closely related to behavior of asymptotic perturbative series for high Q^2.

The leading mechanism is the photon-gluon fusion



$$\gamma^*(q) + g(k_g) \to Q(p_Q) + \overline{Q}(p_{\bar{Q}})$$

Leveille, Weiler, PRD 24 (1981) 1789
Watson, Z. Phys. C 12 (1982) 123

$$\hat{\sigma}^{(0)}_{2,g}(z,\lambda) = \frac{\alpha_s}{2\pi}\hat{\sigma}_B(z)\{\left[(1-z)^2+z^2+4\lambda z(1-3z)-8\lambda^2 z^2\right]\ln\frac{1+\beta_z}{1-\beta_z} - [1+4z(1-z)(\lambda-2)]\,\beta_z\},$$

$$\hat{\sigma}^{(0)}_{L,g}(z,\lambda) = \frac{2\alpha_s}{\pi}\hat{\sigma}_B(z)z\{-2\lambda z\ln\frac{1+\beta_z}{1-\beta_z} + (1-z)\,\beta_z\},$$

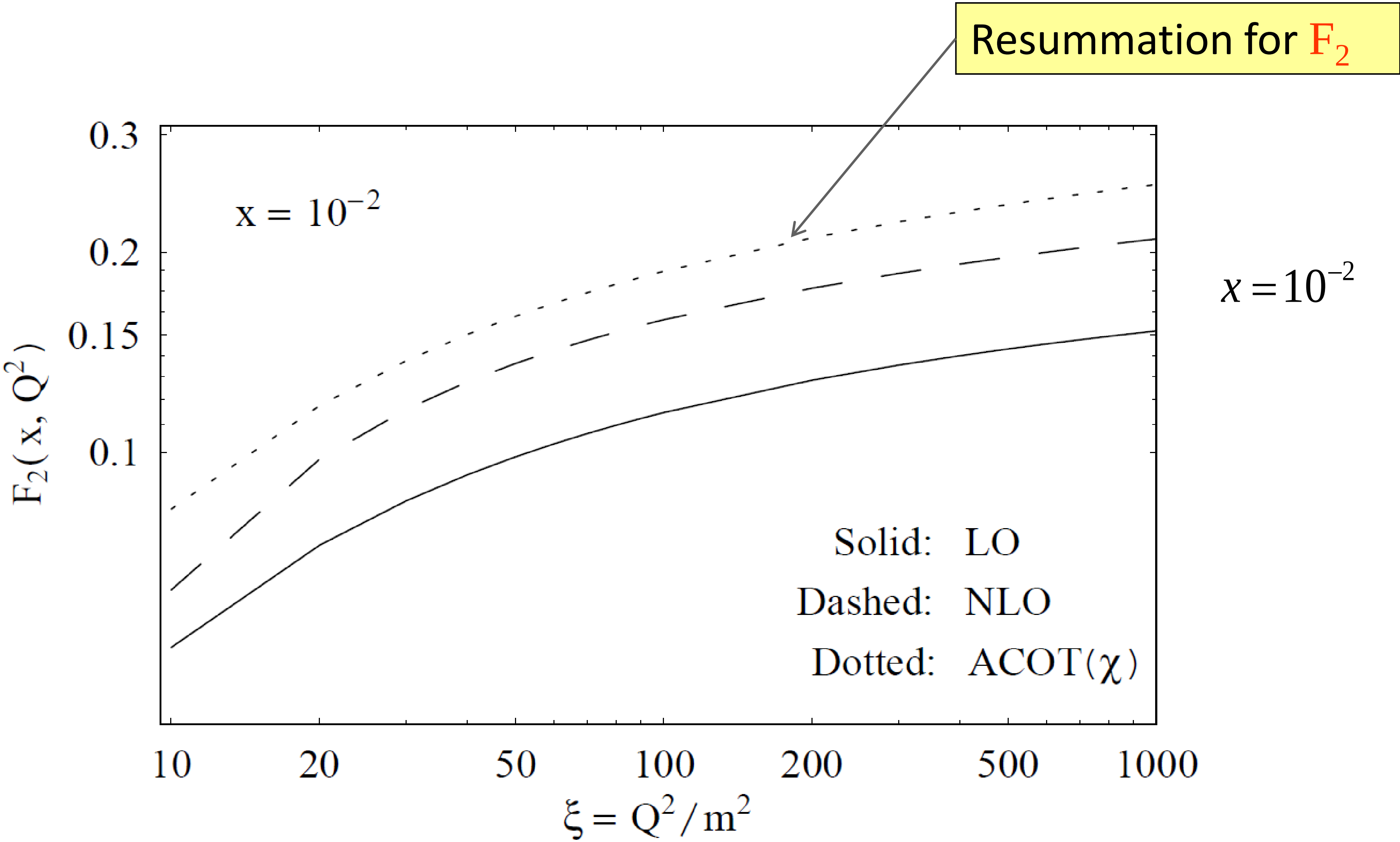
$$\hat{\sigma}^{(0)}_{A,g}(z,\lambda) = \frac{\alpha_s}{\pi}\hat{\sigma}_B(z)z\{2\lambda[1-2z(1+\lambda)]\ln\frac{1+\beta_z}{1-\beta_z} + (1-2\lambda)(1-z)\beta_z\},$$

$$\hat{\sigma}^{(0)}_{I,g}(z,\lambda) = 0$$

$$z = \frac{Q^2}{2q\cdot k_g}, \qquad \lambda = \frac{m^2}{Q^2}, \qquad \beta_z = \sqrt{1-\frac{4\lambda z}{1-z}}$$

$$\hat{\sigma}_B(z) = \frac{(2\pi)^2 e_Q^2 \alpha_{em}}{Q^2}\, z$$

pQCD predictions for F_2

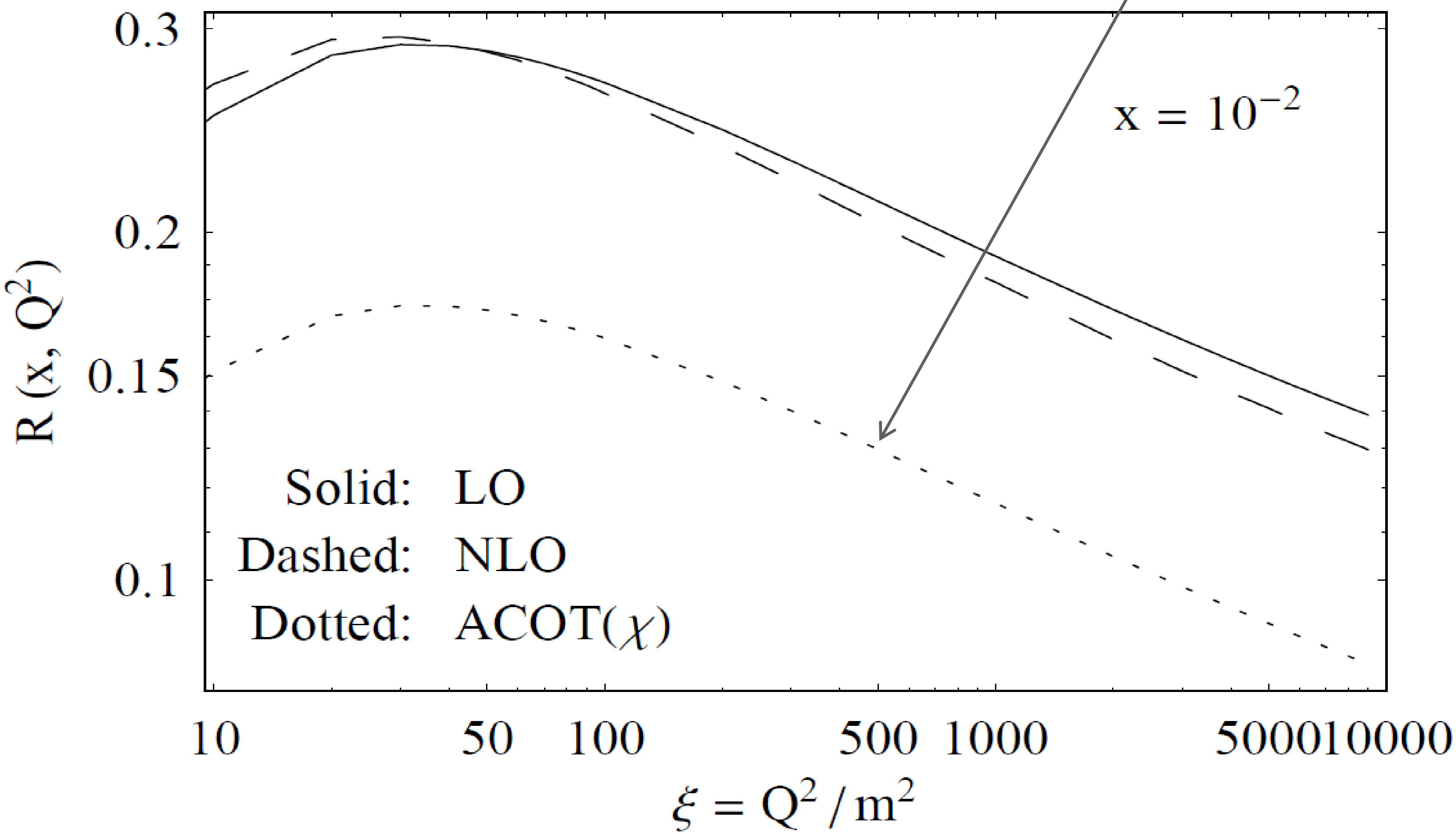


$x = 10^{-2}$

For F_2 the NLO and resummation contributions are very close

pQCD predictions for R

Resummation for R

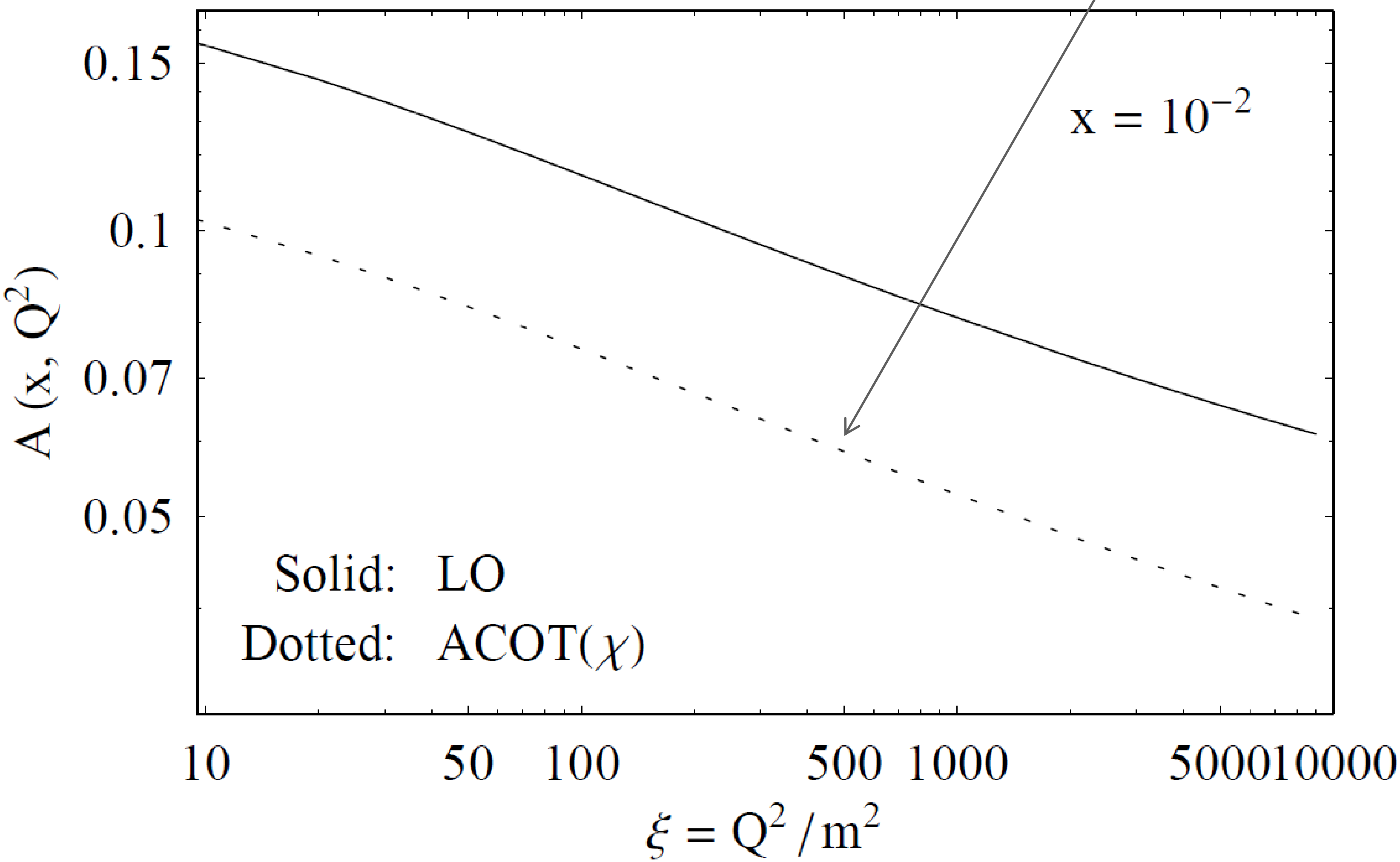


$x = 10^{-2}$

CTEQ6M PDFs are used for estimates

pQCD predictions for A

Resumming for A



$x = 10^{-2}$

CTEQ6M PDFs are used for estimates

Application II: Linearly polarized gluons in unpolarized proton

To probe the TMD distribution, the momenta of both heavy quark and anti-quark should be measured (reconstructed) in the reaction:

$$l(\ell) + N(p) \to l'(\ell - q) + Q(p_Q) + \bar{Q}(p_{\bar{Q}}) + X(p_X)$$

Corresponding cross section is:

$$d\sigma \propto L(\ell, q) \otimes \Phi_g(\zeta, k_T) \otimes \left| H_{\gamma^* g \to Q\bar{Q}X}(q, k_g, p_Q, p_{\bar{Q}}) \right|^2$$

$$\Phi_g^{\mu\nu}(\zeta, k_T) \propto -g_T^{\mu\nu} f_1^g(\zeta, \vec{k}_T^2) + \left(g_T^{\mu\nu} - 2\frac{k_T^\mu k_T^\nu}{k_T^2} \right) \frac{\vec{k}_T^2}{2m_N^2} h_1^{\perp g}(\zeta, \vec{k}_T^2)$$

$$k_g^\mu \simeq \zeta P^\mu + k_T^\mu, \qquad \vec{q}_T = \vec{k}_T$$

The resulting cross section is:

$$\frac{d^6\sigma^{(\pi)}}{dy\,dx\,dz\,d\vec{K}_\perp^2 d\vec{q}_T^2 d\varphi} = \frac{e_Q^2\alpha_{em}^2\alpha_s}{8\,\bar{S}^2}\frac{f_1^g(\zeta,\vec{q}_T^2)\hat{B}_2}{y^3 x\,\zeta z\,(1-z)}\Big\{\left[1+(1-y)^2\right]\left(1-2r\frac{\hat{B}_2^h}{\hat{B}_2}\right) - y^2\frac{\hat{B}_L}{\hat{B}_2}\left(1-2r\frac{\hat{B}_L^h}{\hat{B}_L}\right)$$

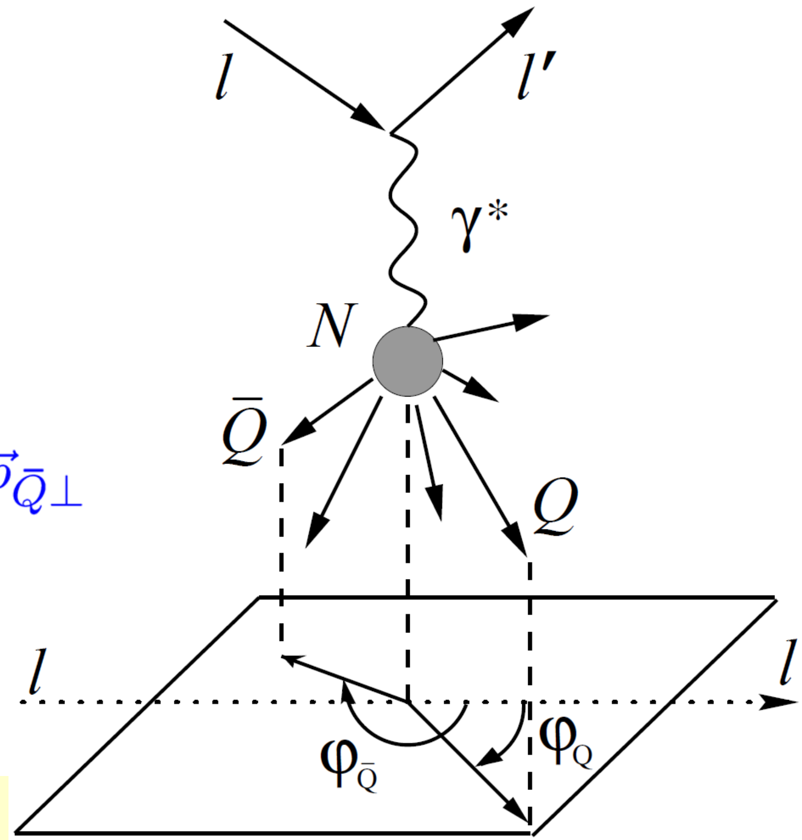
$$+2(1-y)\frac{\hat{B}_A}{\hat{B}_2}\left(1-2r\frac{\hat{B}_A^h}{\hat{B}_A}\right)\cos 2\varphi + (2-y)\sqrt{1-y}\frac{\hat{B}_I}{\hat{B}_2}\left(1-2r\frac{\hat{B}_I^h}{\hat{B}_I}\right)\cos\varphi\Big\}$$

$$r \equiv r(\zeta,\vec{q}_T^2) = \frac{\vec{q}_T^2}{2m_N^2}\frac{h_1^{\perp g}(\zeta,\vec{q}_T^2)}{f_1(\zeta,\vec{q}_T^2)}$$

$$\zeta = \frac{-U_1}{y\bar{S}+T_1} = x + \frac{m^2+\vec{K}_\perp^2}{z\,(1-z)y\,\bar{S}}$$

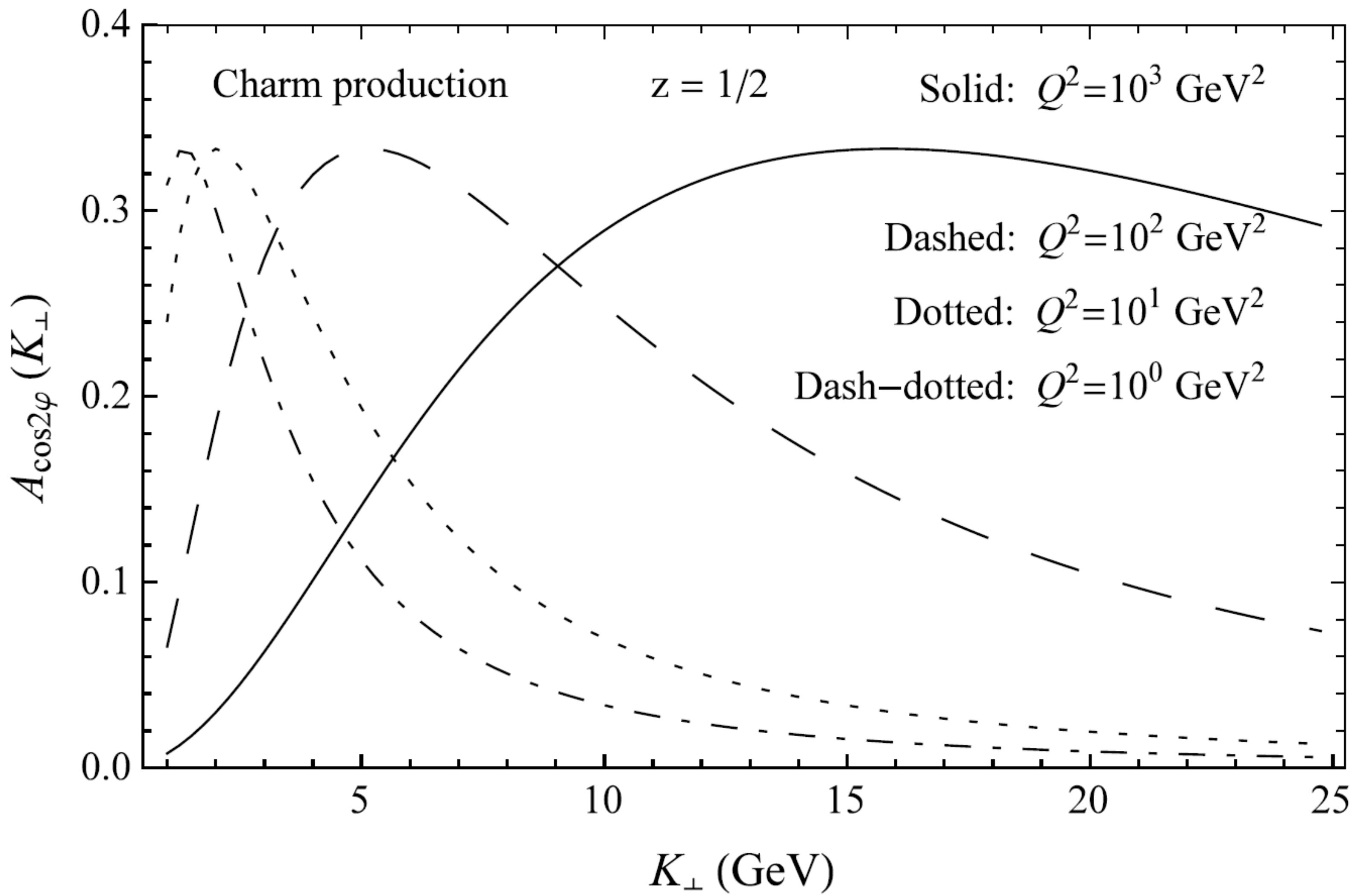
$$\vec{K}_\perp = \frac{1}{2}\left(\vec{p}_{Q\perp} - \vec{p}_{\bar{Q}\perp}\right), \qquad \vec{q}_T = \vec{p}_{Q\perp} + \vec{p}_{\bar{Q}\perp}$$

$$\varphi = \varphi_Q$$



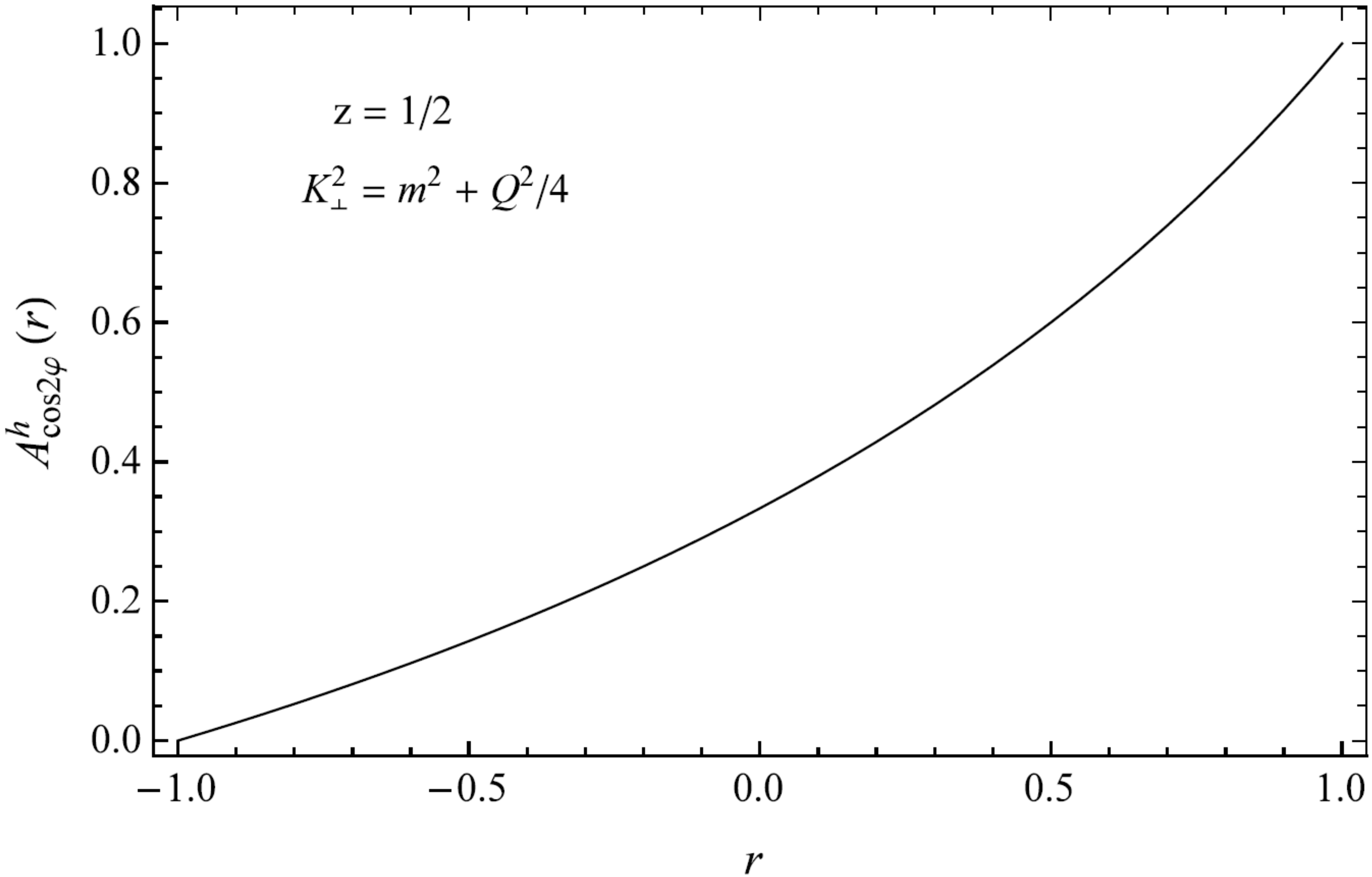
Efremov, Ivanov, Teryaev, Phys.Lett. B 777 (2018), 435

pQCD predictions for cos 2φ asymmetry (r = 0)



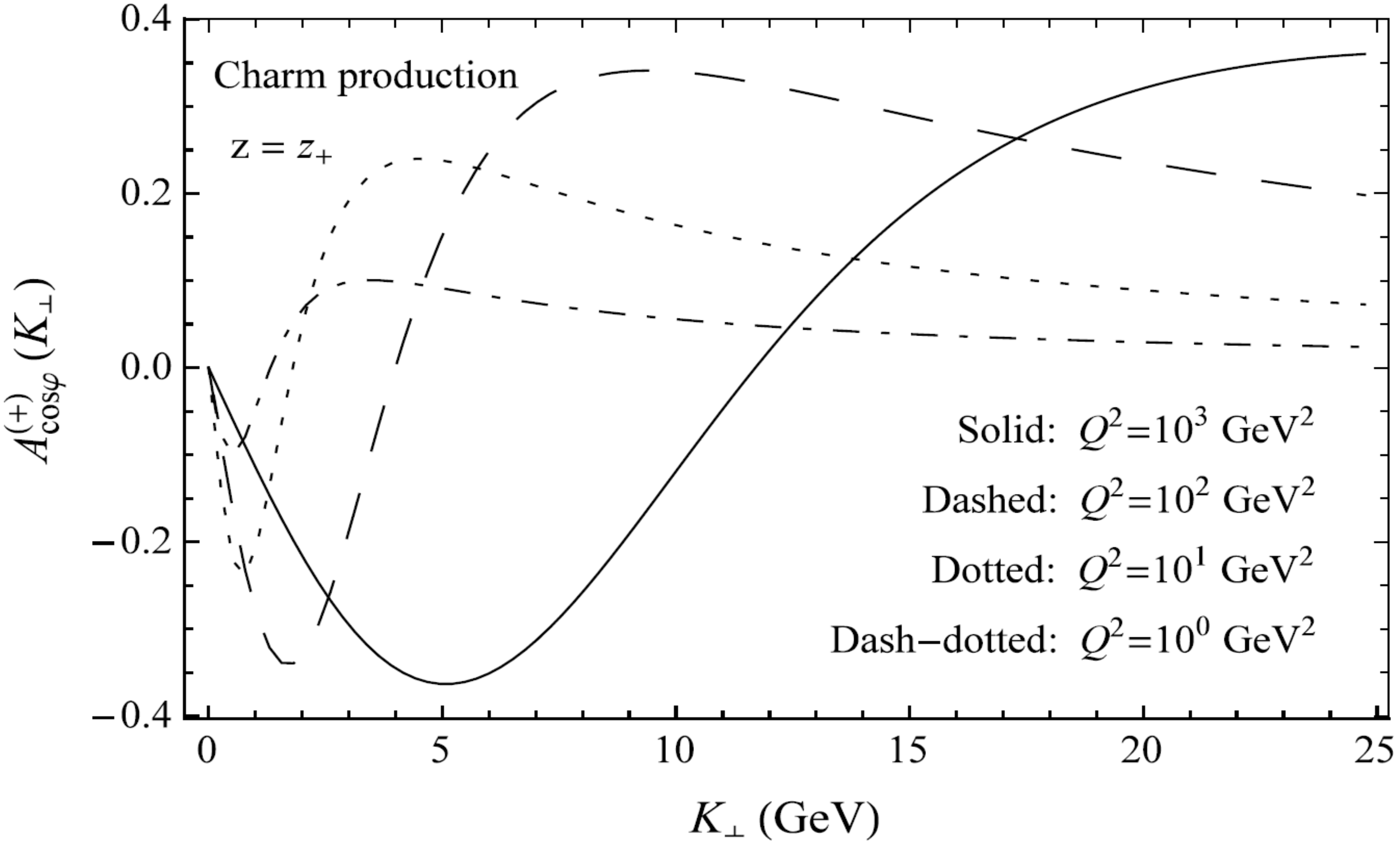
$$A_{\cos 2\varphi}\left(z=1/2, \vec{K}_\perp^2 = m^2 + Q^2/4\right) = \frac{1}{3}$$

pQCD predictions for cos 2φ asymmetry (r ≠ 0)



$$A^h_{\cos 2\varphi}(r) \equiv A^h_{\cos 2\varphi}\left(z = 1/2, \vec{K}_\perp^2 = m^2 + Q^2/4, r\right) = \frac{1+r}{3-r}$$

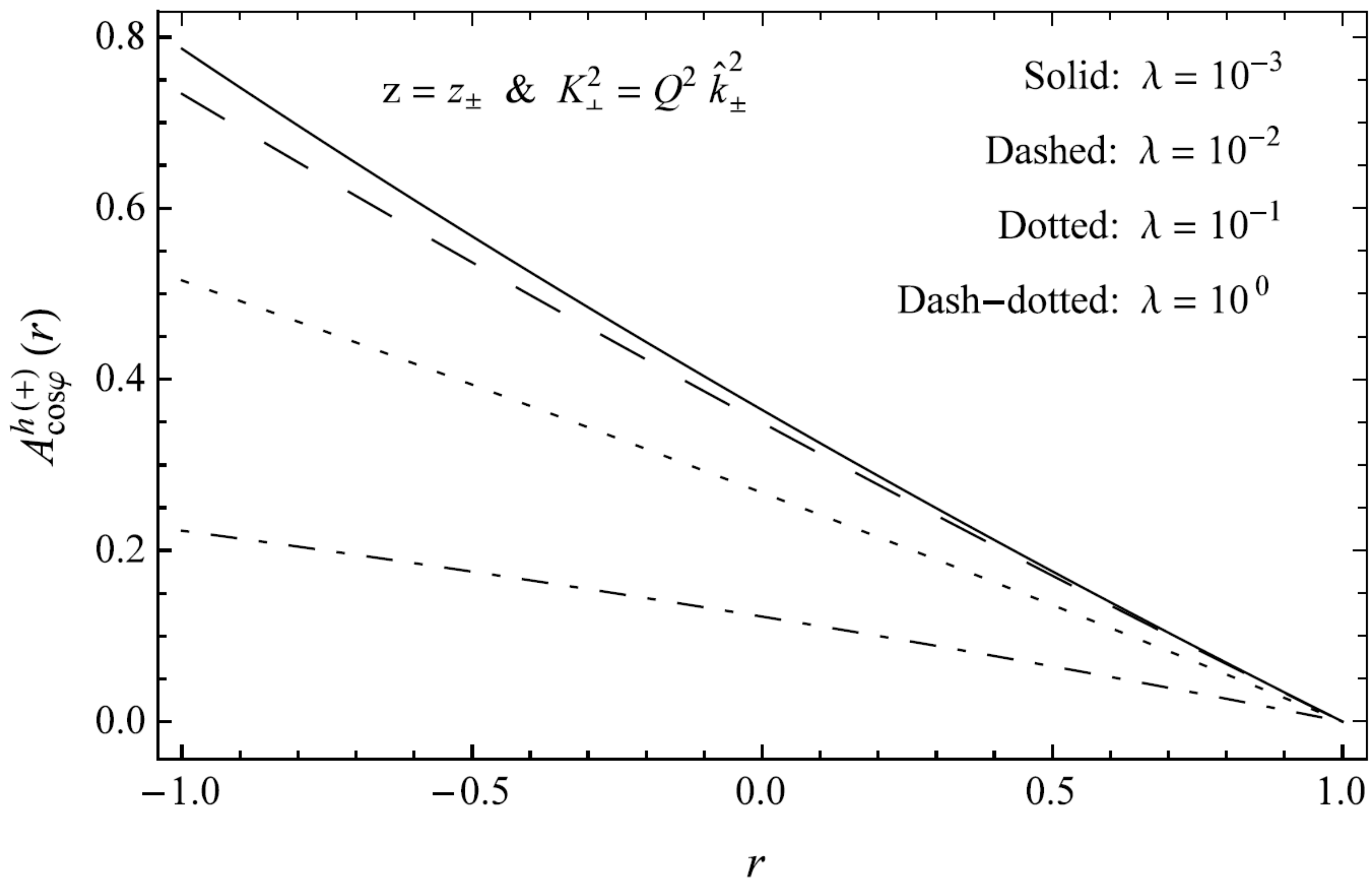
pQCD predictions for cos φ asymmetry (r = 0)



$$A^{(\pm)}_{\cos\varphi}(K_\perp) \equiv A_{\cos\varphi}(z = z_\pm, K_\perp), \quad A^{(-)}_{\cos\varphi} = -A^{(+)}_{\cos\varphi}, \quad z_\pm(\lambda \to 0) \simeq \begin{cases} 0.841 \\ 0.159 \end{cases}$$

$$\left|A^{(\pm)}_{\cos\varphi}\right|_{\max} \simeq 0.366 \qquad \lambda = \frac{m^2}{Q^2}$$

pQCD predictions for cos φ asymmetry (r ≠ 0)



$$A^{h(\pm)}_{\cos\varphi}(r) \overset{\lambda\to 0}{=} \pm\frac{(\sqrt{3}-1)\,(1-r)}{2-r\,(1-2/\sqrt{3})}$$

$$\left|A^{h(\pm)}_{\cos\varphi}\right|_{\max} \simeq 0.793$$

Azimuthal correlations in charm hadroproduction

To probe the TMD distributions in ***pp***- and ***AA***- collisions, the momenta of both heavy quark and anti-quark should be measured,

$$p_1(P_1) + p_2(P_2) \to Q(p_Q) + \bar{Q}(p_{\bar{Q}}) + X(p_X)$$

Corresponding cross section is:

$$\mathrm{d}\sigma \propto \sum_{a,b} \Phi_a(\zeta_a, k_{aT}) \otimes \Phi_b(\zeta_b, k_{bT}) \otimes \left| H_{ab\to Q\bar{Q}X}(k_a, k_b, p_Q, p_{\bar{Q}}) \right|^2$$

$$k_a^\mu \simeq \zeta_a P_1^\mu + k_{aT}^\mu, \qquad k_b^\mu \simeq \zeta_b P_2^\mu + k_{bT}^\mu$$

In this case, both quark and gluon densities do contribute at LO:

$$\Phi_g^{\mu\nu}(\zeta, k_T) \propto -g_T^{\mu\nu} f_1^g(\zeta, \vec{k}_T^2) + \left(g_T^{\mu\nu} - 2\frac{k_T^\mu k_T^\nu}{k_T^2} \right) \frac{\vec{k}_T^2}{2m_N^2} h_1^{\perp g}(\zeta, \vec{k}_T^2)$$

$$\Phi_q(\zeta, k_T) \propto f_1^q(\zeta, \vec{k}_T^2)\hat{P} + i h_1^{\perp q}(\zeta, \vec{k}_T^2) \frac{[\hat{k}_T, \hat{P}]}{2m_N}$$

The resulting cross section is:

$$\frac{d^6\sigma}{dy_1\, dy_2\, d^2\vec{K}_\perp d^2\vec{q}_T} = \mathcal{N}\left\{A + B\,\vec{q}_T^{\,2}\cos 2(\phi_\perp - \phi_T) + C\,\vec{q}_T^{\,4}\cos 4(\phi_\perp - \phi_T)\right\}$$

$$\vec{K}_\perp = \frac{1}{2}\left(\vec{p}_{Q\perp} - \vec{p}_{\bar{Q}\perp}\right), \qquad \vec{q}_T = \vec{p}_{Q\perp} + \vec{p}_{\bar{Q}\perp}$$

Schematically, the functions ***A***, ***B*** and ***C*** have the following structure:

$$A \;:\; f_1^q \otimes f_1^{\bar{q}}, \qquad f_1^g \otimes f_1^g, \qquad h_1^{\perp g} \otimes h_1^{\perp g}$$
$$B \;:\; h_1^{\perp q} \otimes h_1^{\perp \bar{q}}, f_1^g \otimes h_1^{\perp g}$$
$$C \;:\; h_1^{\perp g} \otimes h_1^{\perp g}$$

Pisano, Boer, Brodsky, Buffing, Mulders, JHEP 1310 (2013) 024


Thank You!