J/ψ and J/ψ+jet leptoproduction: what to expect from the EIC

Quarkonia as Tools 2020, Aussois

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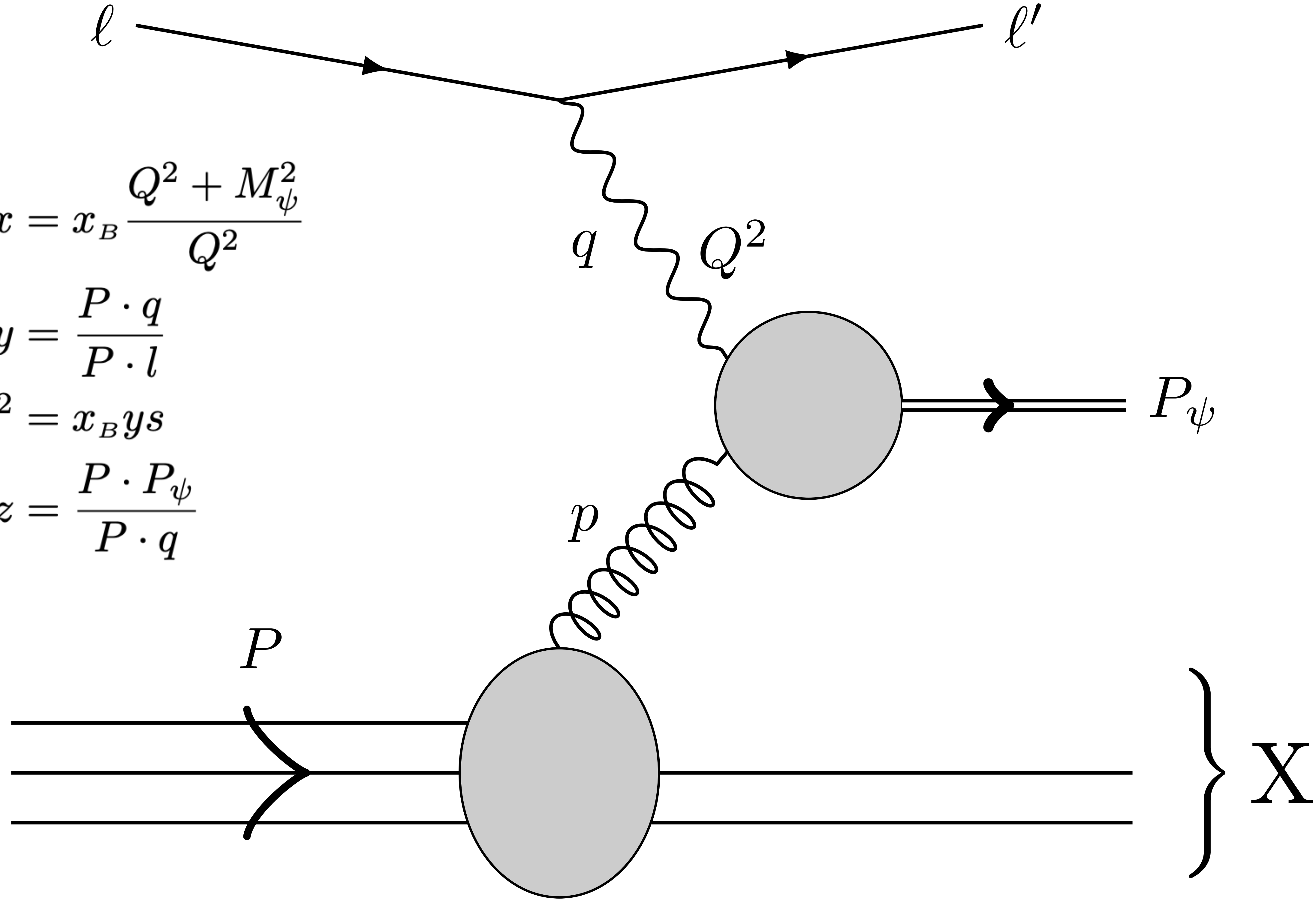
IP PARIS

$$\ell + p \to \ell + J/\psi + X$$

as a probe of gluon TMDs

$$\ell + p \to \ell + J/\psi + X$$



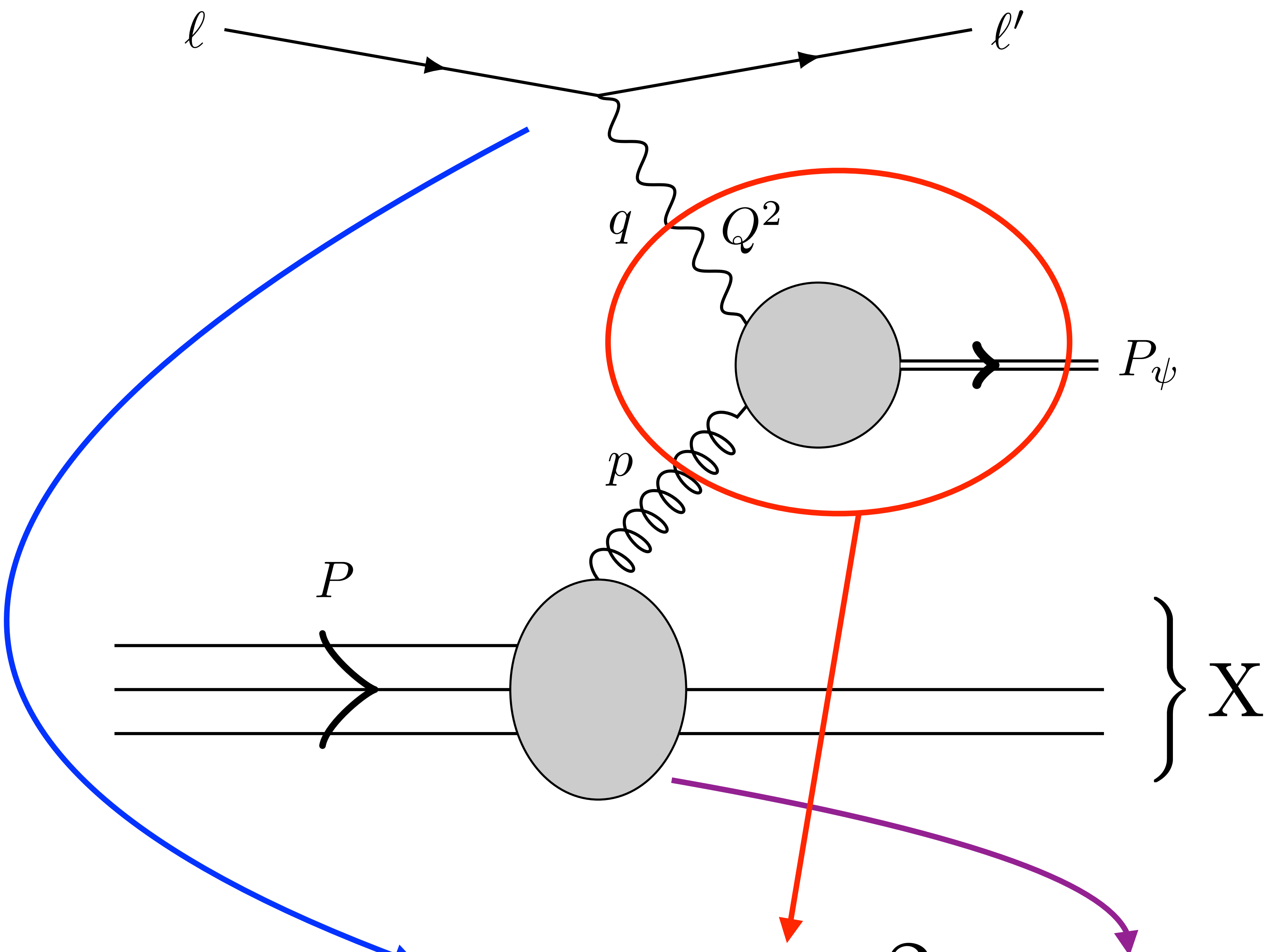
$$x = x_{_B}\,\frac{Q^2 + M_\psi^2}{Q^2}$$

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

$$Q^2 = x_{_B}\,y s$$

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

$$\ell + p \to \ell + J/\psi + X$$



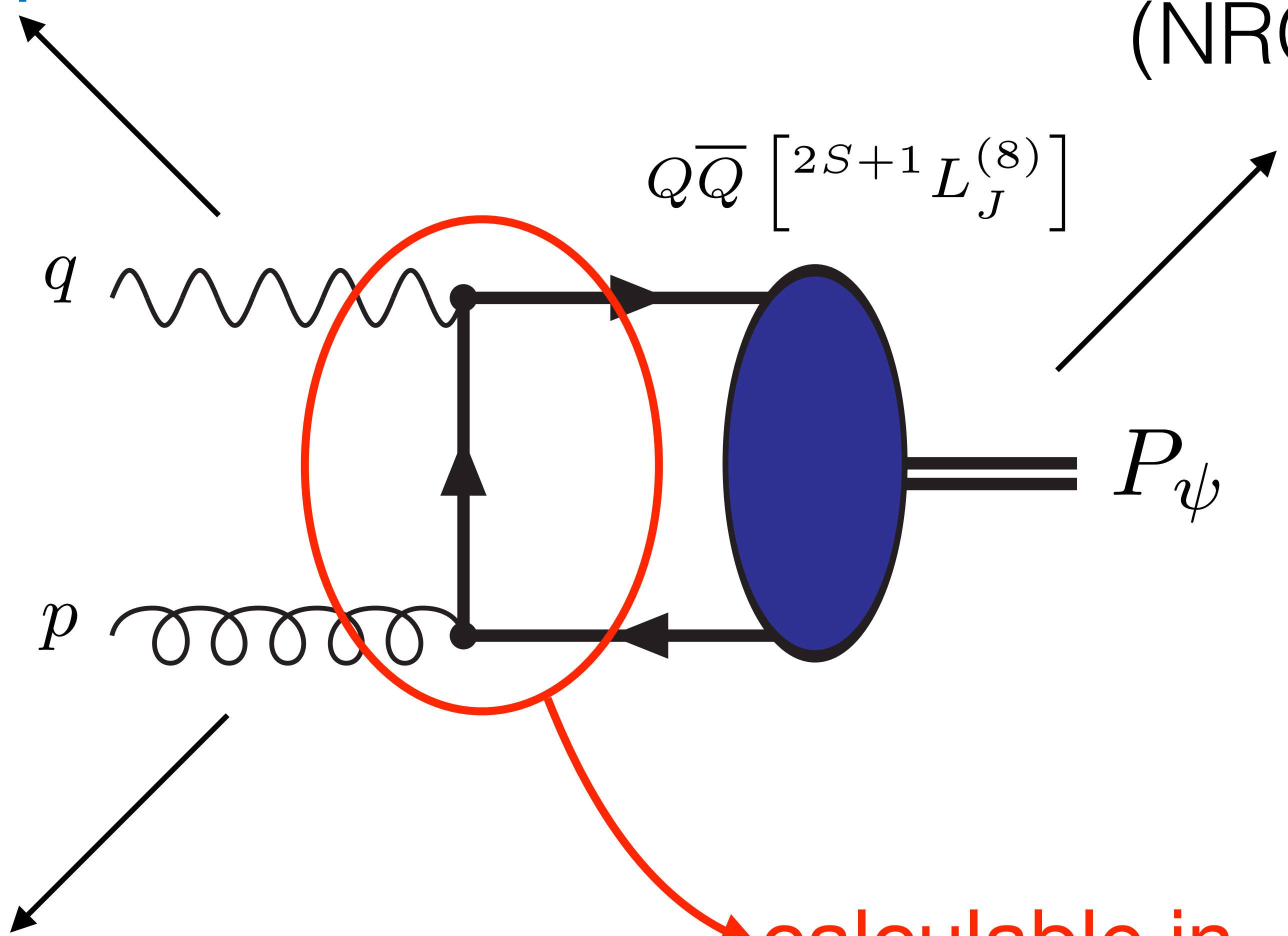
$$\mathrm{d}\sigma = \Gamma \otimes |M|^2 \otimes \Phi$$

Lepton tensor ‘Hard’ part Hadron tensor

‘Hard’ part

couples to lepton tensor Γ

non-relativistic QCD (NRQCD)



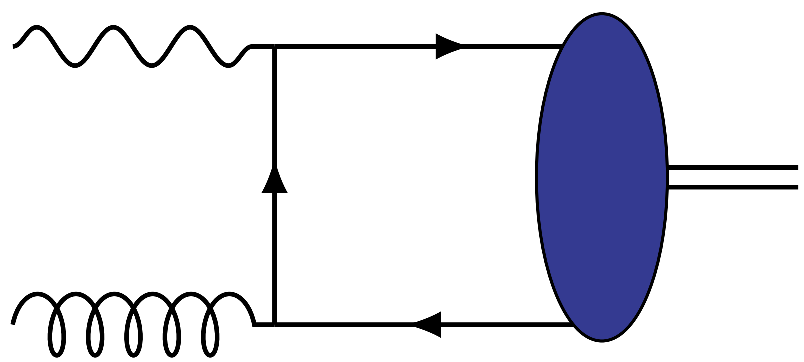
couples to hadron tensor Φ

calculable in perturbation theory

Non-relativistic QCD (NRQCD)

Color octet (CO) mechanism: heavy-quark pair is produced with *all allowed quantum numbers* and then hadronizes as encoded in the non-perturbative long-distance matrix elements (LDMEs)

$$\langle|\mathcal{O}_8^{J/\psi}(^3P_J)|0\rangle \qquad \langle|\mathcal{O}_8^{J/\psi}(^1S_0)|0\rangle$$



$$Q\bar{Q}[^{2S+1}L_J^{(8)}] \quad \mathcal{O}(\alpha_{\mathrm{em}}\alpha_{\mathrm{s}})$$

NRQCD also encompasses color singlet (CS) mechanism where J/ψ is directly produced with correct quantum numbers

At least for leptoproduction, CO mechanism is the dominant one in the low-$P_{\psi\perp}$ regime Fleming and Mehen (1998)

Hadron tensor

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

f_1^g ↓ unpolarized gluons; $h_1^{\perp\, g}$ ↓ linearly polarized gluons

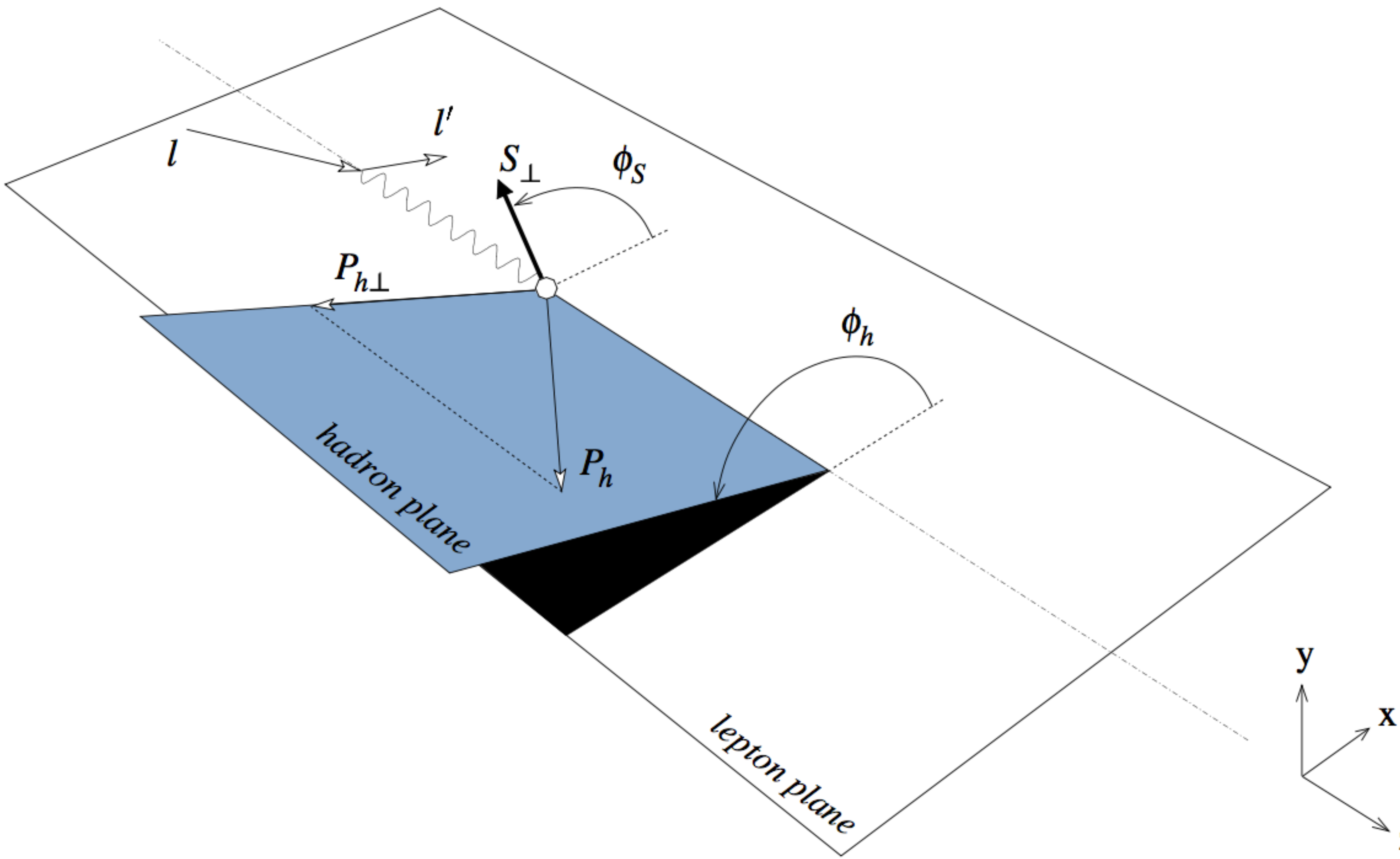
Sivers function ↑ ($f_{1T}^{\perp g}$); circularly polarized gluons ↑ (g_{1T}^g)

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

$h_{1T}^{\perp g}$, h_{1T}^g → linearly polarized gluons

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

Reference frame



Bacchetta, D'Alesio, Diehl & Miller (2004)

Cross section

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y\,\mathrm{d}x_B\,\mathrm{d}^2\mathbf{q}_T} \equiv \mathrm{d}\sigma^U(\phi_T) + \mathrm{d}\sigma^T(\phi_T, \phi_S)$$

$$\mathrm{d}\sigma^U = \mathcal{N}\left[A^U f_1^g(x, \boldsymbol{q}_T^2) + \frac{\boldsymbol{q}_T^2}{M_p^2} B^U h_1^{\perp\, g}(x, \boldsymbol{q}_T^2) \cos 2\phi_T\right]$$

unpolarized (f_1^g) — linearly polarized ($h_1^{\perp\, g}$) — T even

Sivers function ($f_{1T}^{\perp g}$)

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

T odd -> only CO!

linearly polarized (h_1^g, $h_{1T}^{\perp g}$)

Azimuthal asymmetries

probe *ratios* of gluon TMDs

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

…we have:

$$\int \mathrm{d}\phi_S\, \mathrm{d}\phi_T\, \mathrm{d}\sigma(\phi_S,\phi_T) = (2\pi)^2\, \mathcal{N}\, A^U\, f_1^g(x,\boldsymbol{q}_T^2)$$

$$A^{\cos 2\phi_T} = H(y,M_\psi,Q)\, \frac{\boldsymbol{q}_T^2}{M_p^2}\, \frac{h_1^{\perp\, g}(x,\boldsymbol{q}_T^2)}{f_1^g(x,\boldsymbol{q}_T^2)}$$

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

$$A^{\sin(\phi_S+\phi_T)} = H(y,M_\psi,Q)\, \frac{|\boldsymbol{q}_T|}{M_p}\, \frac{h_1^g(x,\boldsymbol{q}_T^2)}{f_1^g(x,\boldsymbol{q}_T^2)}$$

$$A^{\sin(\phi_S-3\phi_T)} = -H(y,M_\psi,Q)\, \frac{|\boldsymbol{q}_T|^3}{2M_p^3}\, \frac{h_{1T}^{\perp\, g}(x,\boldsymbol{q}_T^2)}{f_1^g(x,\boldsymbol{q}_T^2)}$$

Bachetta, Boer, Pisano, PT (2018)

Upper bounds

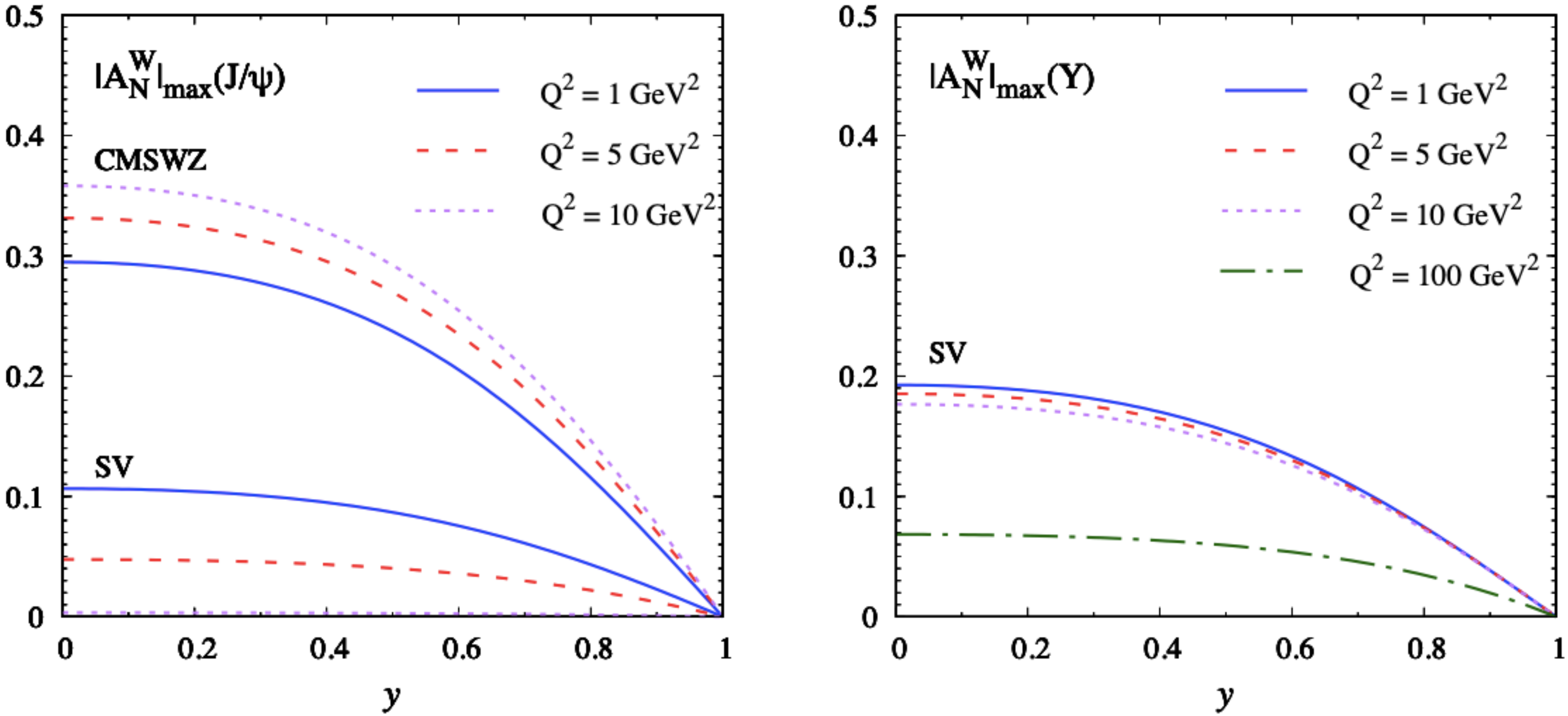
Polarized gluon TMDs satisfy the following positivity bounds:

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

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

We can use the maximum allowed values of the gluon TMDs to illustrate the sensitivity of our inclusive charmonium electroproduction to the gluon content of the proton:

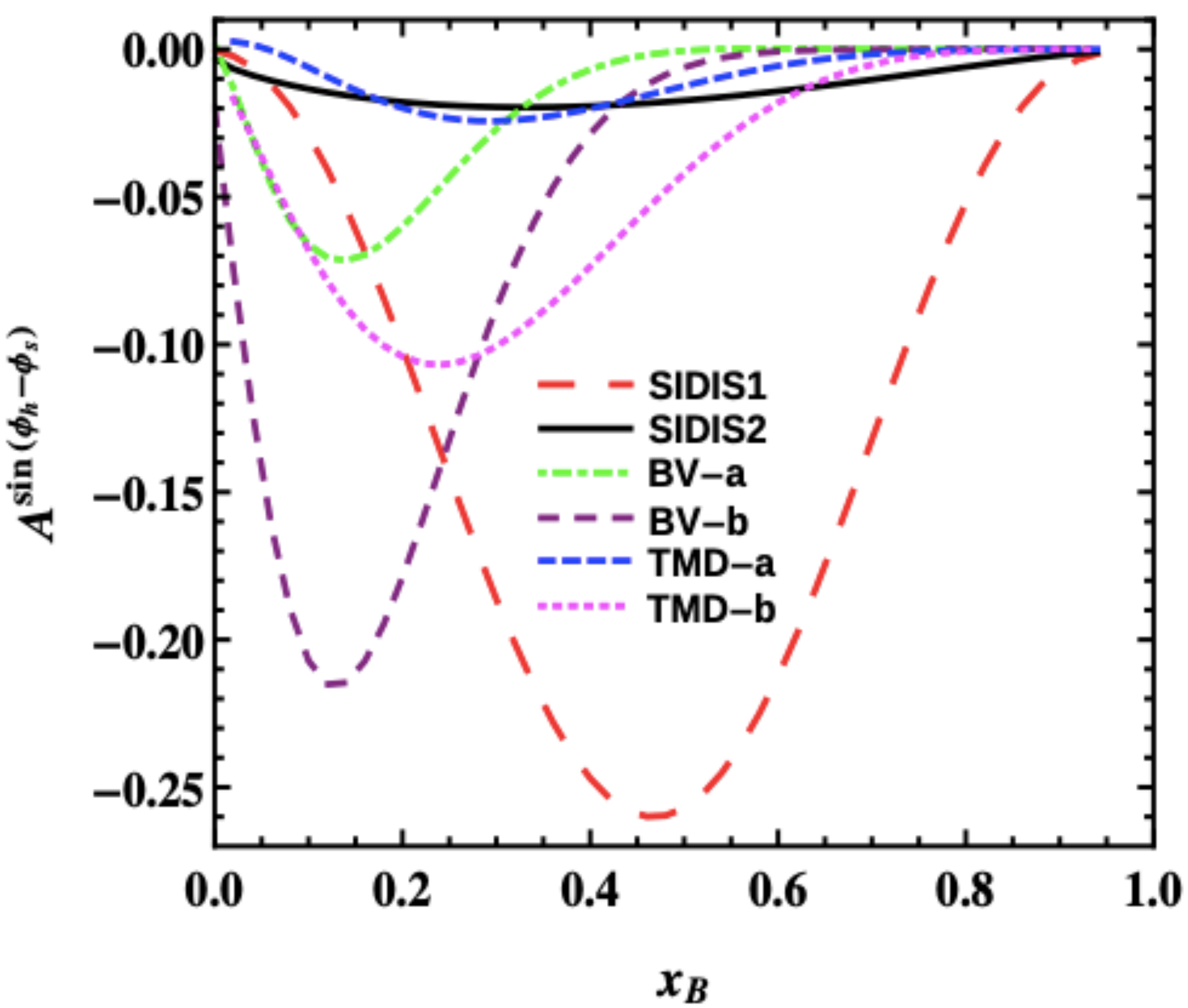
Upper bounds

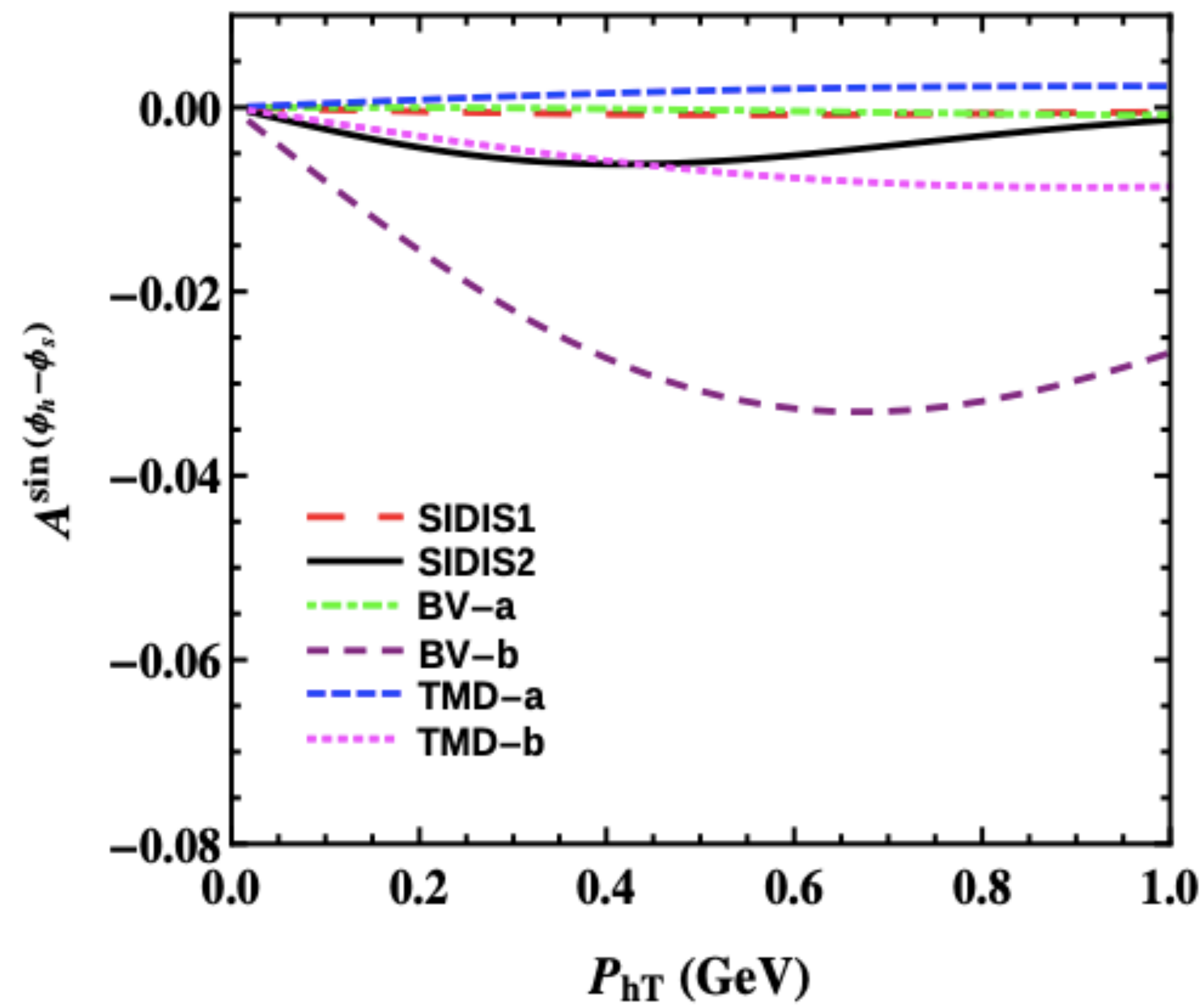


Bachetta, Boer, Pisano, PT (2018)

Single-spin asymmetries

$$\ell + p \to \ell + J/\psi + X$$



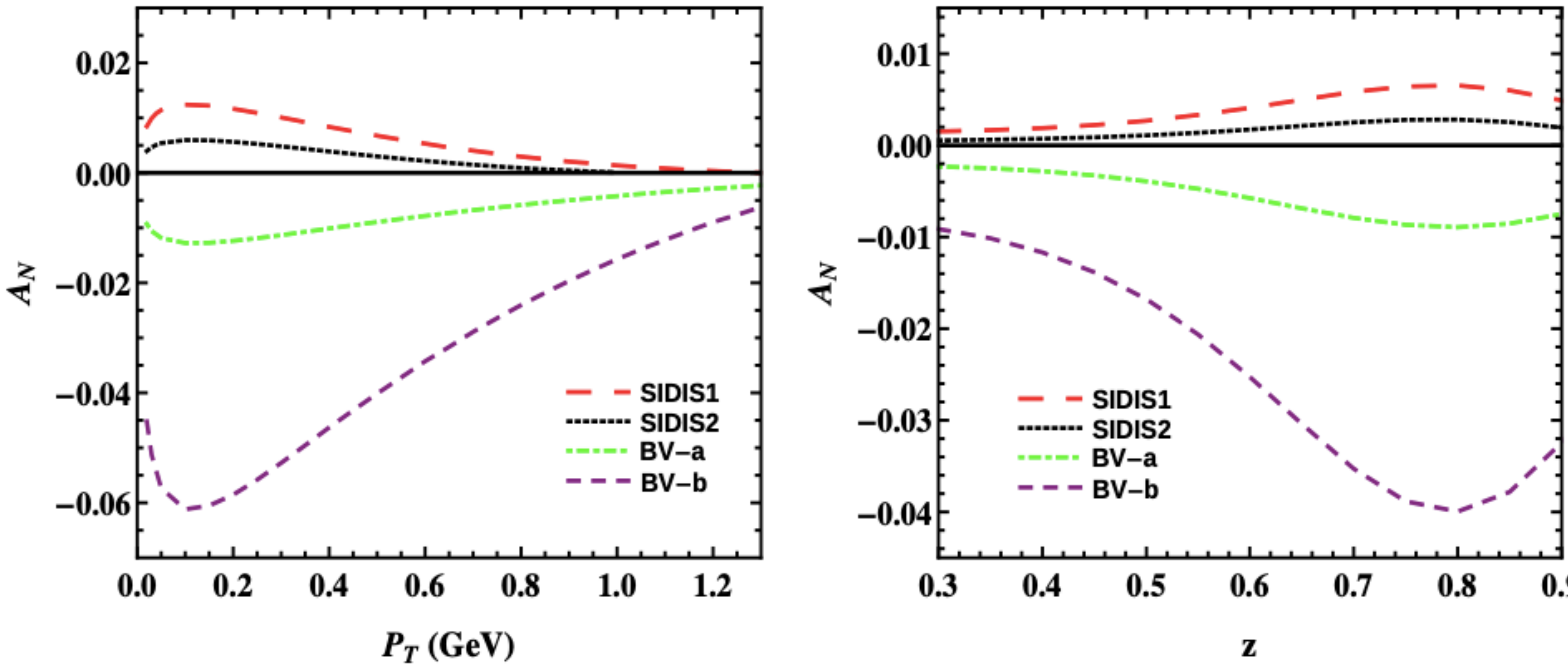


for $\sqrt{s} = 45\,\mathrm{GeV}$

Rajesh & Mukherjee (2018)

Single-spin asymmetries

$$\ell + p \to \ell + J/\psi + X$$

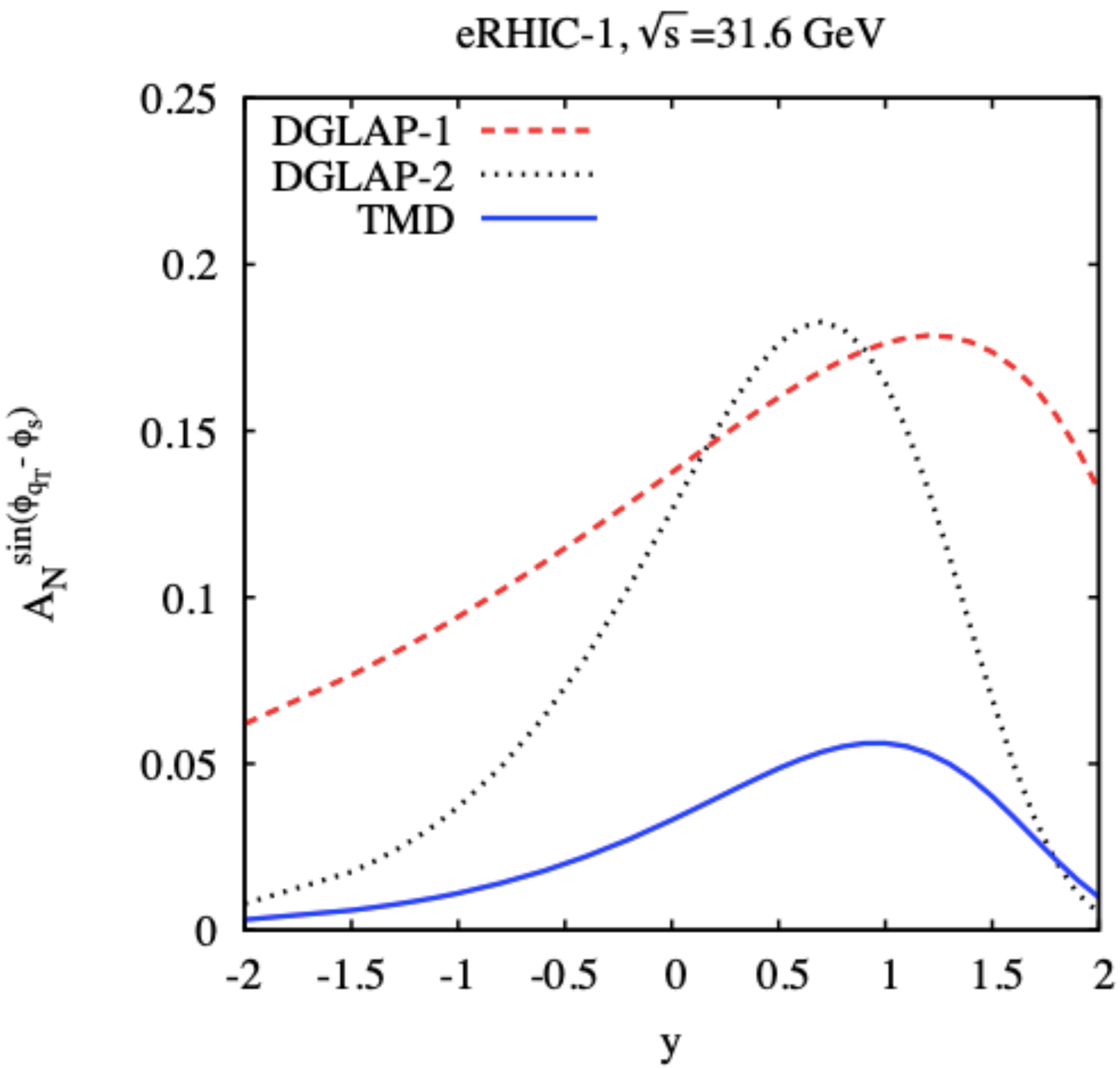


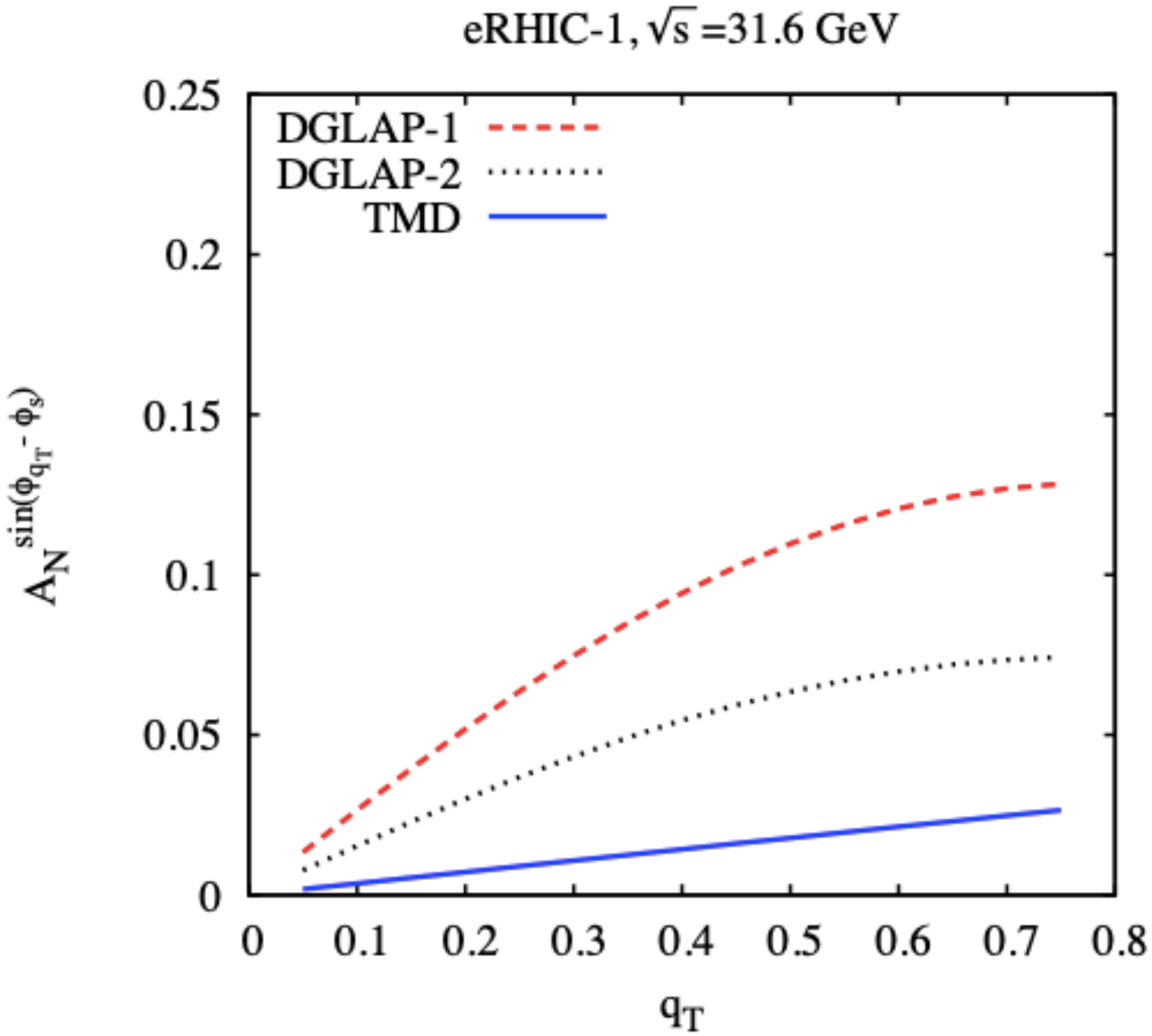
for $\sqrt{s} = 45\,\mathrm{GeV}$, calculated at NLO*

Rajesh, Kishore & Mukherjee (2018)

Single-spin asymmetries

$$\gamma + p \rightarrow \gamma + J/\psi + X$$





In Color Evaporation Model

Godbole, Misra, Mukherjee & Rawoot (2018)

$$\ell + p \to \ell + J/\psi + \textbf{jet} + X$$

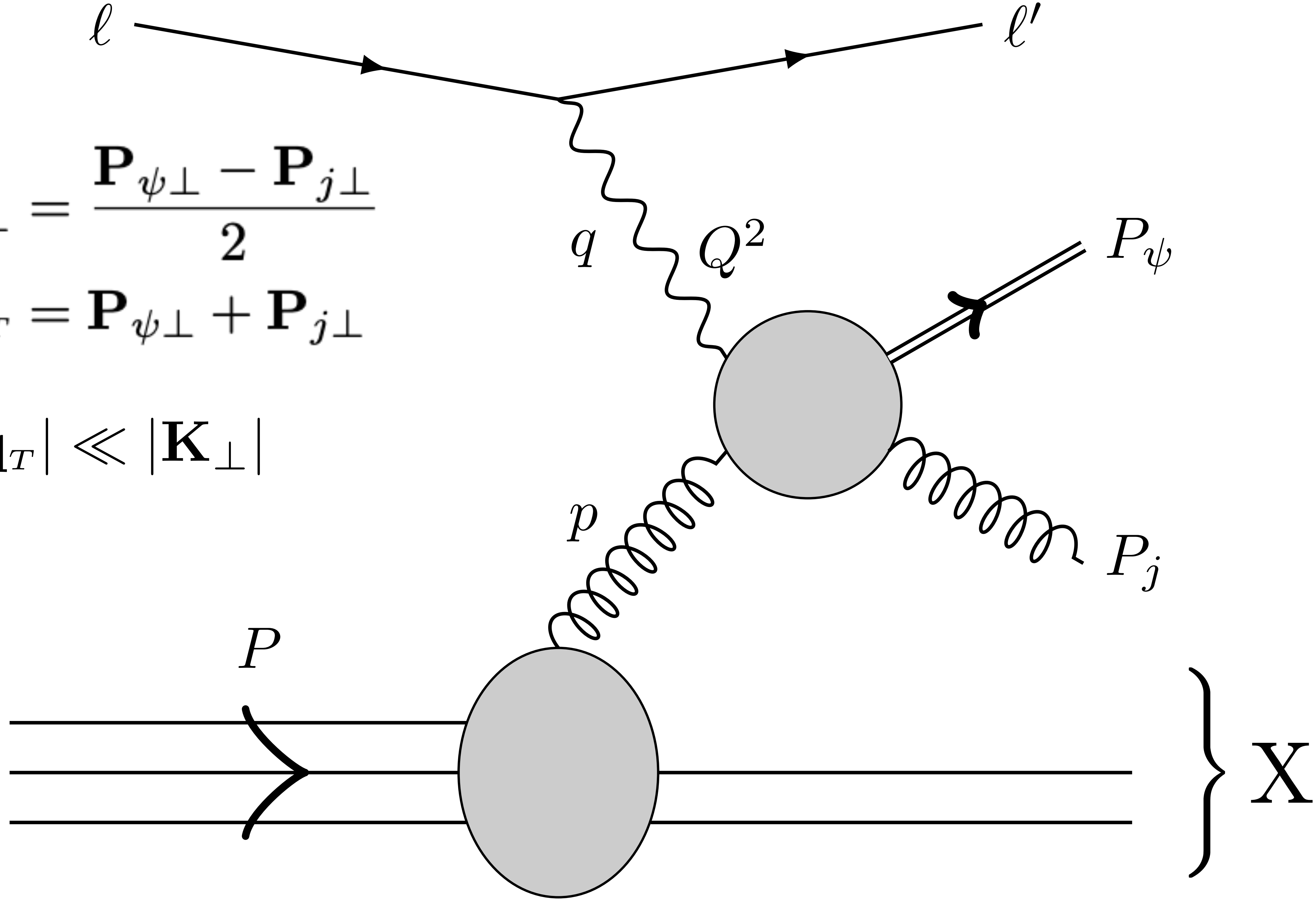
as a probe of gluon TMDs

$$\ell + p \to \ell + J/\psi + g + X$$

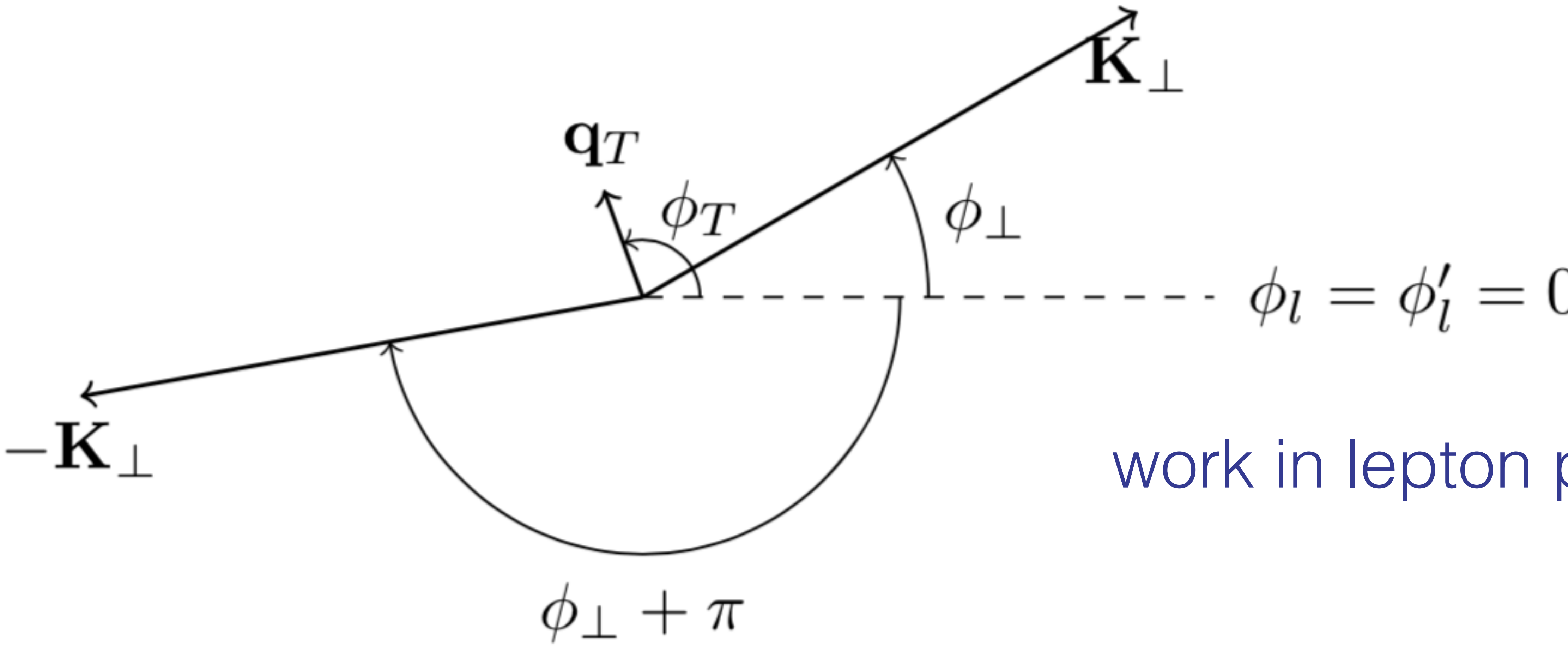
$$\mathbf{K}_\perp = \frac{\mathbf{P}_{\psi\perp} - \mathbf{P}_{j\perp}}{2}$$

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

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



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

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

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

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

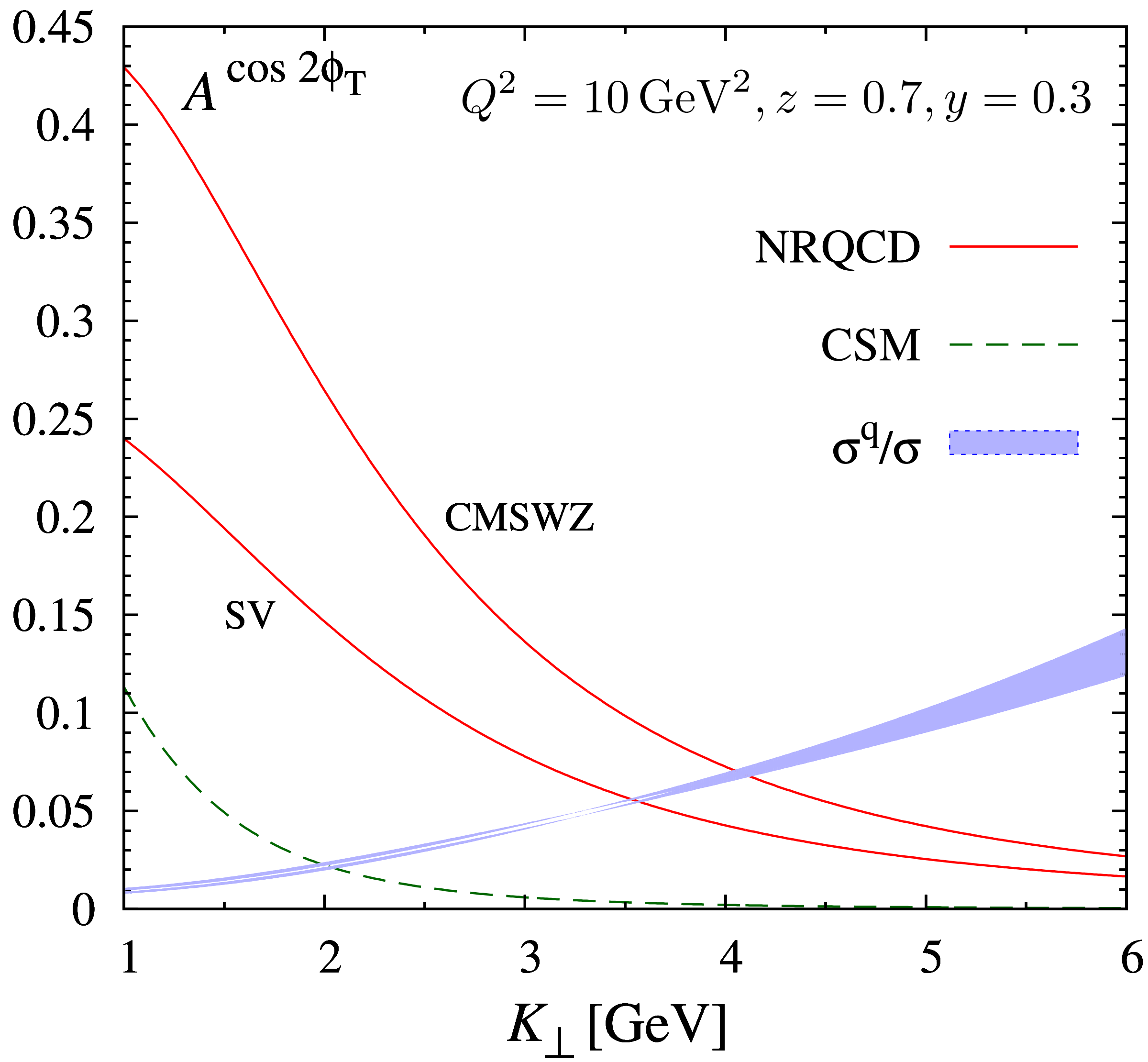
Pisano, Boer, Brodsky, Buffing & Mulders (2013);
Boer, Mulders, Pisano, Zhou (2016)

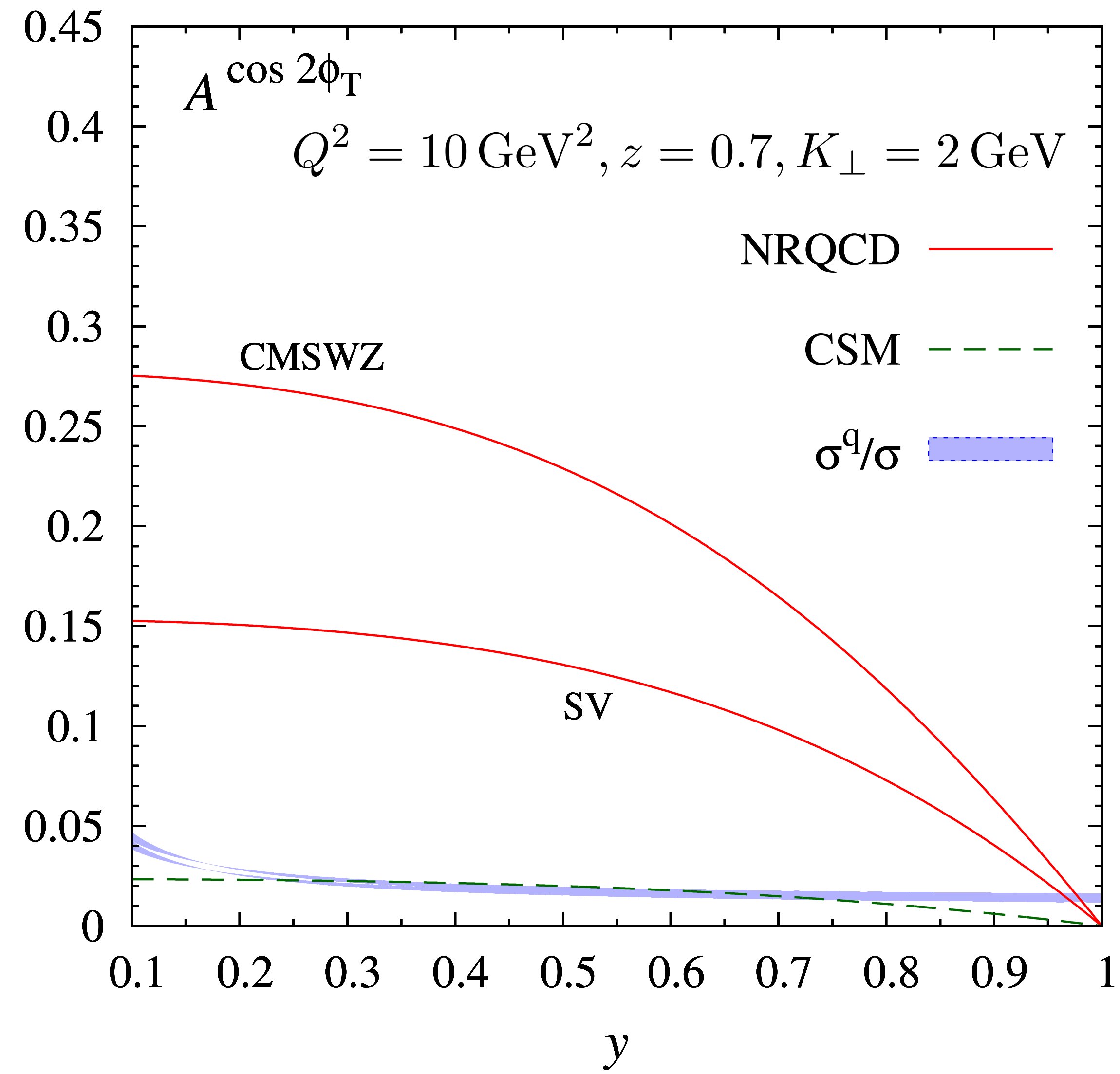
Cross section

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

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

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





D'Alesio, Murgia, Pisano, PT (2019)

See the talk by Rajesh for SSA's in $\gamma + p \to \gamma + J/\psi + \text{jet} + X$

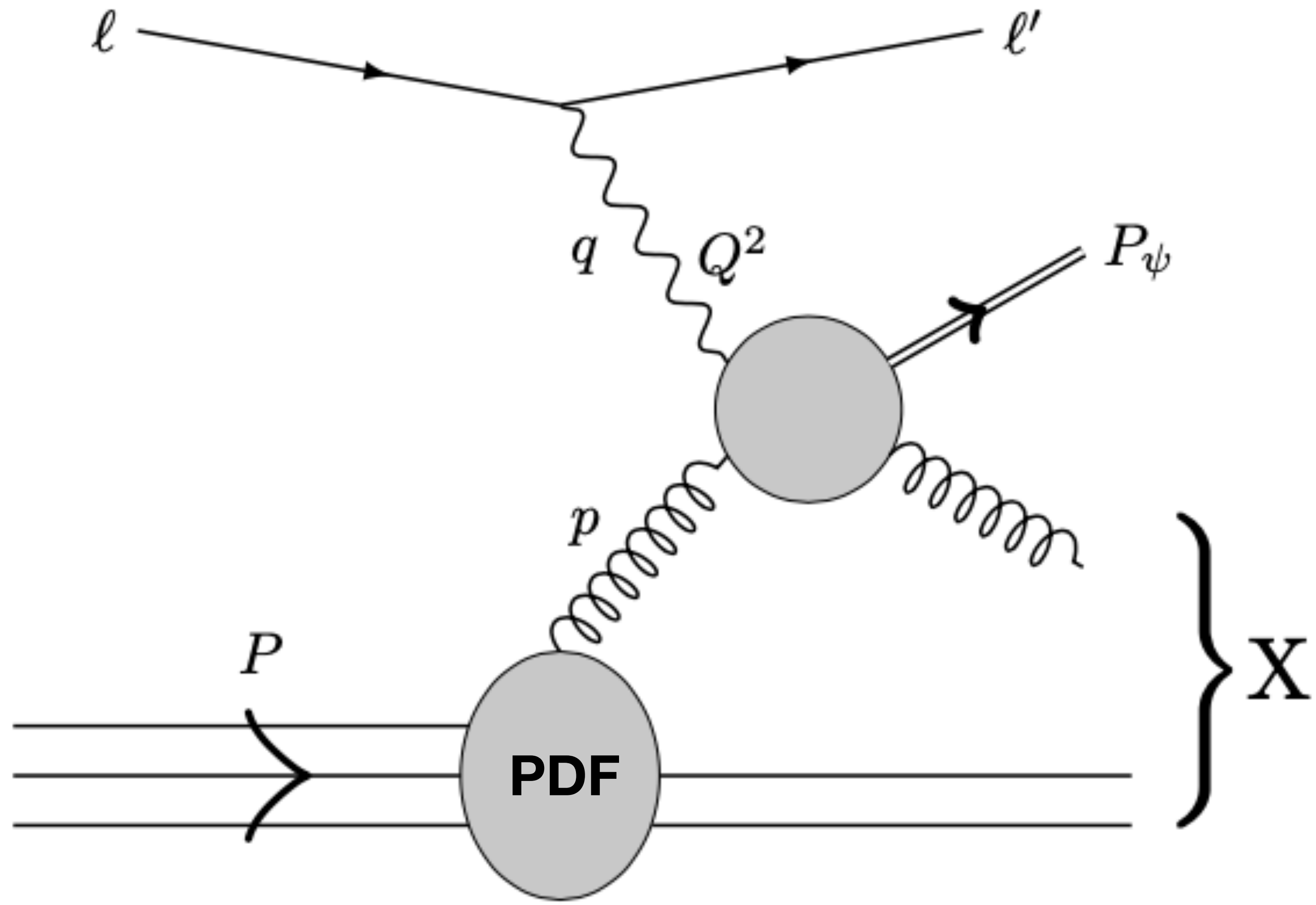
$\ell + p \to \ell + J/\psi + X$:
matching of collinear and TMD calculation

In collaboration with Daniel Boer,
Umberto D'Alesio, Francesco Murgia
& Cristian Pisano

$\ell + p \to \ell + J/\psi + X$: matching of collinear and TMD calculation

In the collinear regime: $\mu \sim P_{\psi T} \gg M_p$ with $\mu = \sqrt{Q^2 + M_\psi^2}$

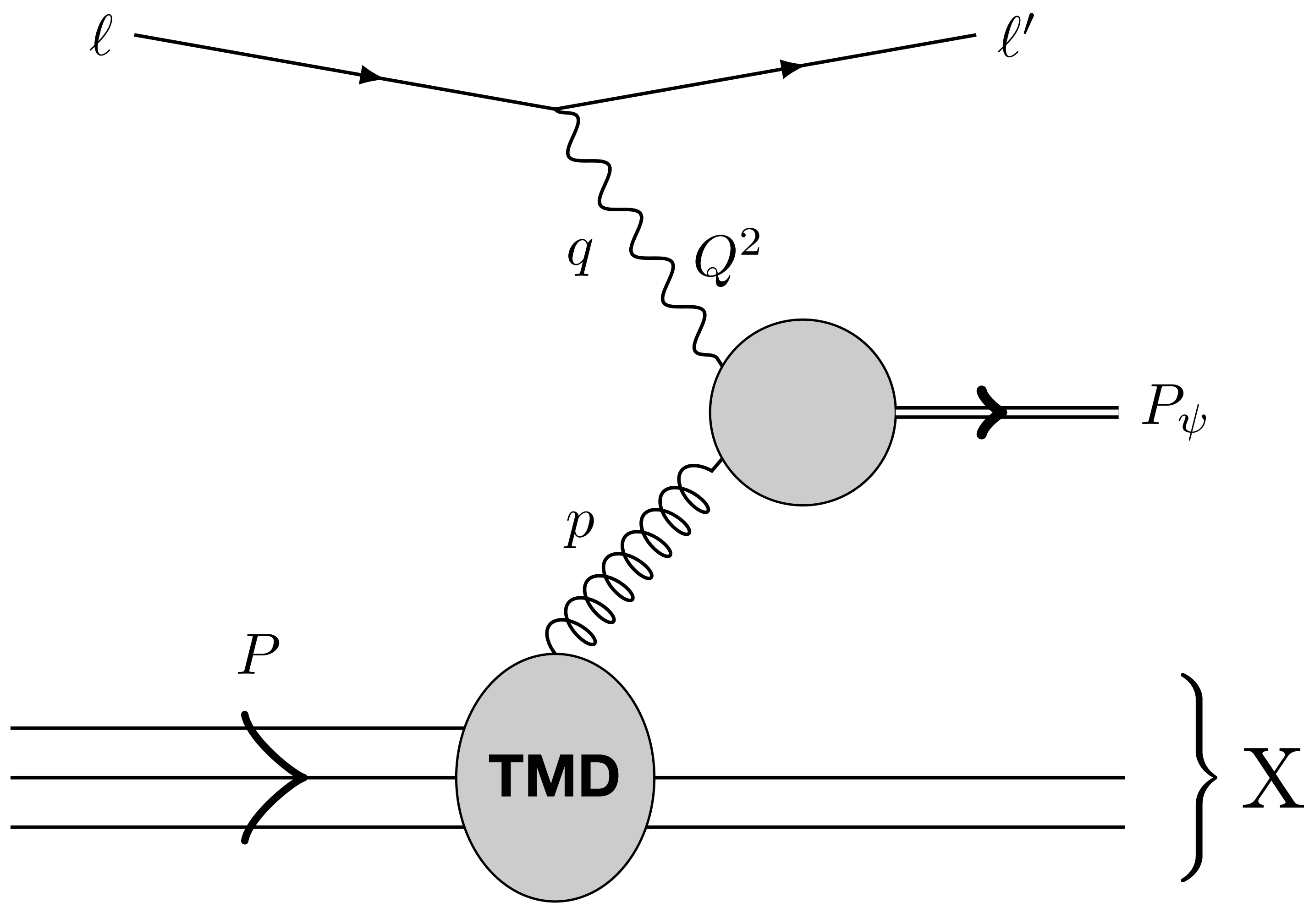
$P_{\psi T}$ is generated by recoil off hard parton



$\ell + p \to \ell + J/\psi + X$: matching of collinear and TMD calculation

In the TMD regime: $\mu \gg P_{\psi T} \gtrsim M_p$

$P_{\psi T}$ stems from intrinsic transverse momentum in target, or from soft emissions



$\ell + p \to \ell + J/\psi + X$: matching of collinear and TMD calculation

If TMD factorization holds, both the collinear and the TMD calculation should match in overlapping kinematic region $\mu \gg P_{\psi T} \gg M_p$

From collinear calculation: hard emission is absorbed into DGLAP

From TMD calculation: high-$p_\perp$ tail also matches to DGLAP

Bacchetta, Boer, Diehl & Mulders (2008)
Bacchetta, Bozzi, Echevarria, Pisano, Prokudin & Radici (2019)

$\ell + p \to \ell + J/\psi + X$: matching of collinear and TMD calculation

Collinear calculation at small q_T:

$$\frac{d\sigma}{dy\, dx_B\, dz\, dq_T^2\, d\phi_\psi} = \frac{\alpha^2}{y}\left[\frac{1+(1-y)^2}{Q^2} F_{UU,T} + 4(1-y)\, F_{UU,L} + (1-y)\cos 2\phi_\psi\, F_{UU}^{\cos 2\phi_\psi}\right]$$

transverse γ^* **longitudinal γ^*** **lin. pol. γ^***

TMD calculation at high q_T:

$$\frac{d\sigma}{dy\, dx_B\, dz\, d\boldsymbol{q}_T^2\, d\phi_\psi} = \frac{\alpha^2}{y}\left[\frac{1+(1-y)^2}{Q^2} \mathcal{F}_{UU,T} + 4(1-y)\, \mathcal{F}_{UU,L} + (1-y)\cos 2\phi_\psi\, \mathcal{F}_{UU}^{\cos 2\phi_\psi}\right]\delta(1-z)$$

In kinematic region of overlap:

$$\mathcal{F}_{UU,T} = F_{UU,T} - \sigma_{UU,T}\, C_A \ln\left(\frac{Q^2 + M_\psi^2}{q_T^2}\right)$$

$$\mathcal{F}_{UU,L} = F_{UU,L} - \sigma_{UU,L}\, C_A \ln\left(\frac{Q^2 + M_\psi^2}{q_T^2}\right)$$

$$\mathcal{F}_{UU}^{\cos 2\phi_\psi} = F_{UU}^{\cos 2\phi_\psi}$$

$\ell + p \to \ell + J/\psi + X$: matching of collinear and TMD calculation

Therefore, assuming both TMD factorization and enforcing the matching:

$$\mathcal{F}_{UU,T} = \sum_n \mathcal{H}^{[n]}_{UU,T} \mathcal{C}\big[f_1^g \Delta^{[n]}\big](x, \mathbf{q}_T^2)$$

$$\mathcal{F}_{UU,L} = \sum_n \mathcal{H}^{[n]}_{UU,L} \mathcal{C}\big[f_1^g \Delta^{[n]}\big](x, \mathbf{q}_T^2)$$

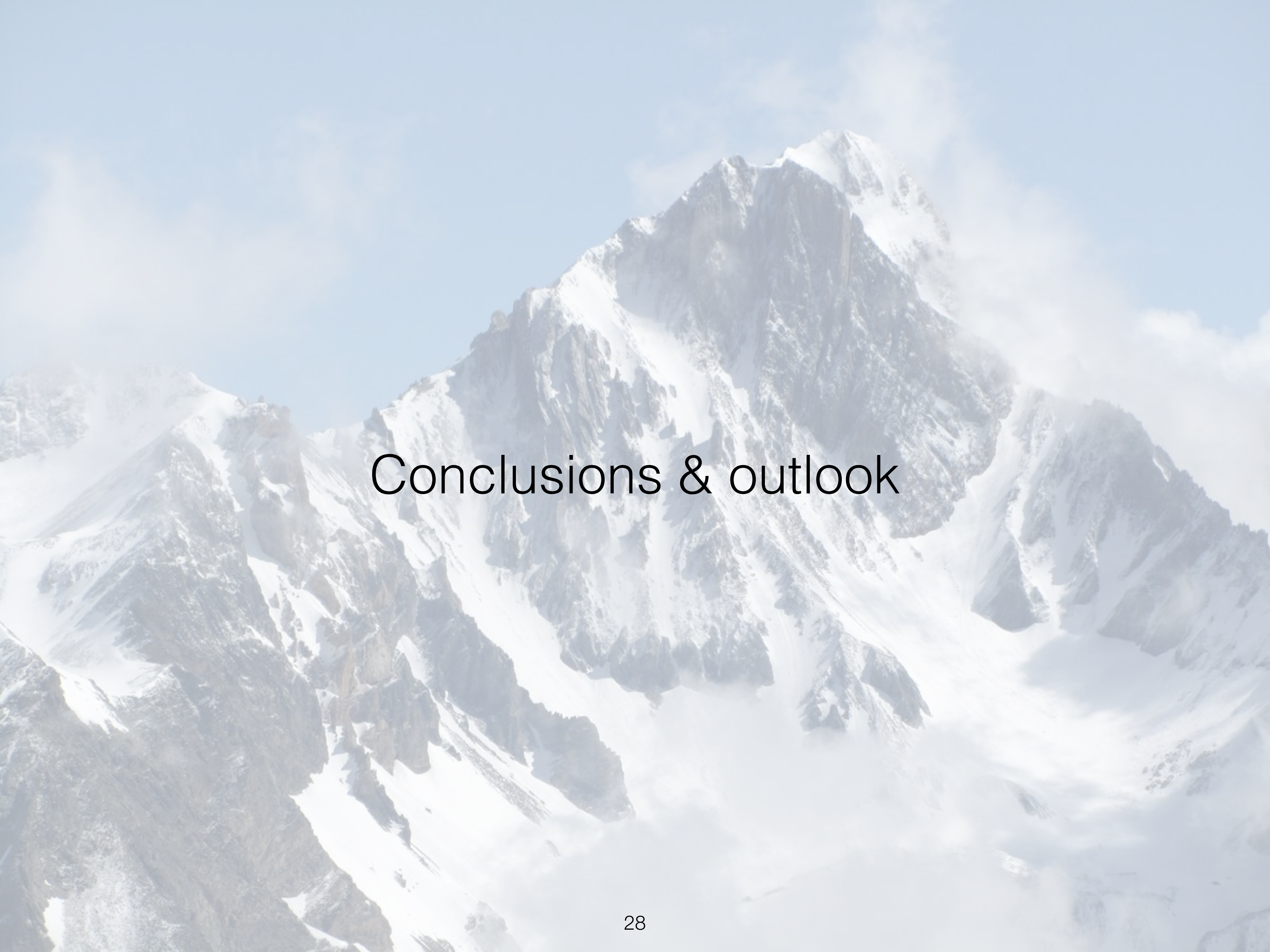
$$\mathcal{F}^{\cos 2\phi_\psi}_{UU} = \sum_n \mathcal{H}^{[n],\cos 2\phi_\psi}_{UU,} \mathcal{C}\big[w h_1^{\perp g} \Delta^{[n]}\big](x, \mathbf{q}_T^2)$$

we have to introduce the following 'smearing' function:

$$\Delta^{[n]}(\boldsymbol{k}_T^2, \mu^2) = \frac{\alpha_s}{2\pi^2 \boldsymbol{k}_T^2}\, C_A \,\langle 0|\mathcal{O}_c(n)|0\rangle\, \ln \frac{\mu^2}{\boldsymbol{k}_T^2}$$

Are these the perturbative tails of the 'shape' functions introduced by Miguel, Tom & Yannis?

Echevarria (2019); Fleming, Makris, Mehen (2019)



Conclusions & outlook

Conclusions & outlook

Leptoproduction of J/ψ (+jet) at the Electron-Ion Collider seems a very promising process to probe gluon TMDs

Largest source of theoretical uncertainty are the nonperturbative LDMEs

For a real accurate extraction, we need a dedicated fit at low $q_\perp$ of the LDMEs + shape function (and an NLO calculation, probably)

Thanks to the organizers,
thanks for your attention!