Back-to-back dijet photoproduction at NLO in the CGC

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Color Glass Condensate at the Electron-Ion Collider

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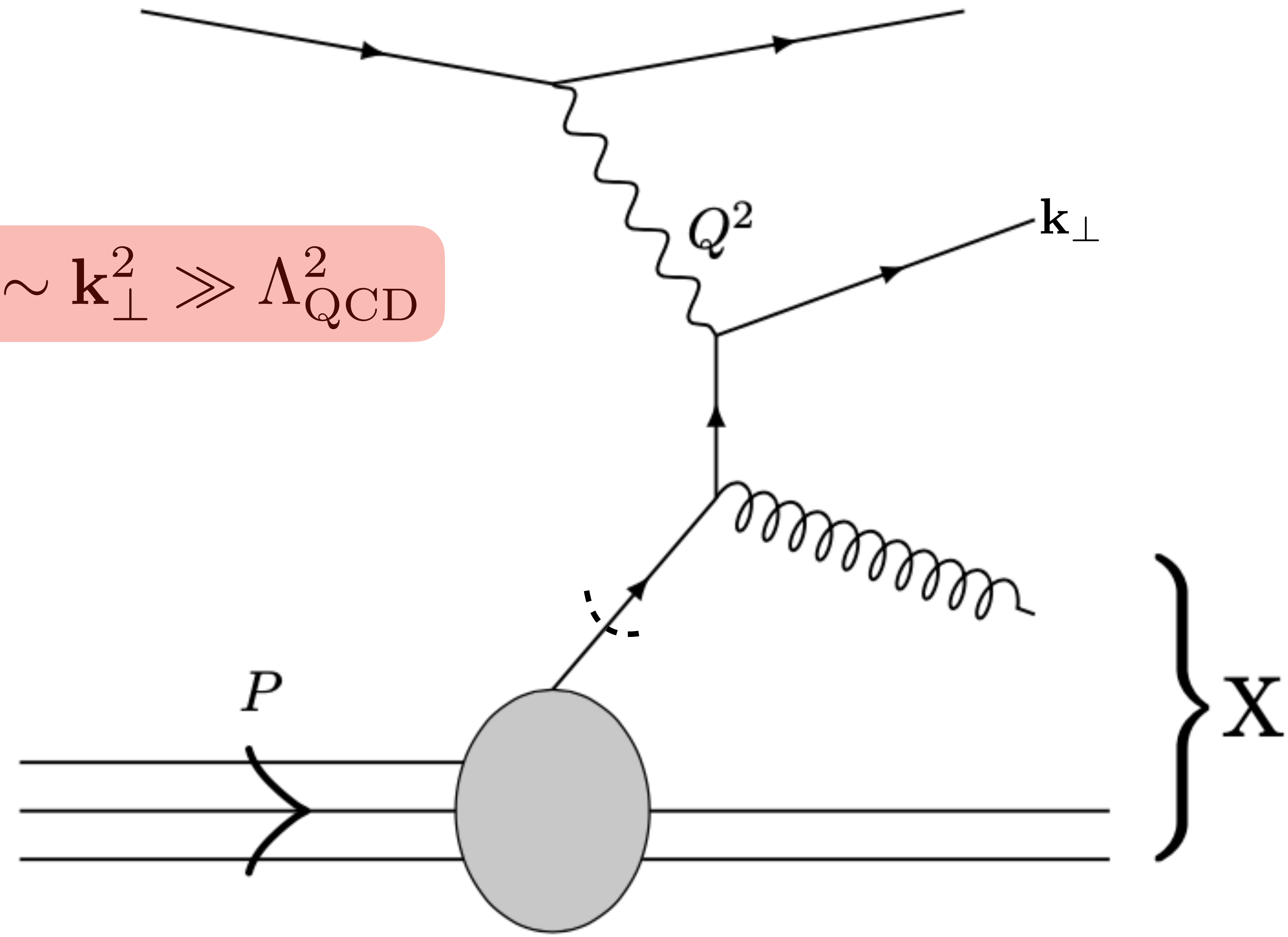
Particle Physics Group

Talk outline

- Motivation
  - Resummation
  - 3D structure of the nucleus
- NLO calculation
- Sudakov double logs and kinematically-improved low-x resummation

Collinear factorisation

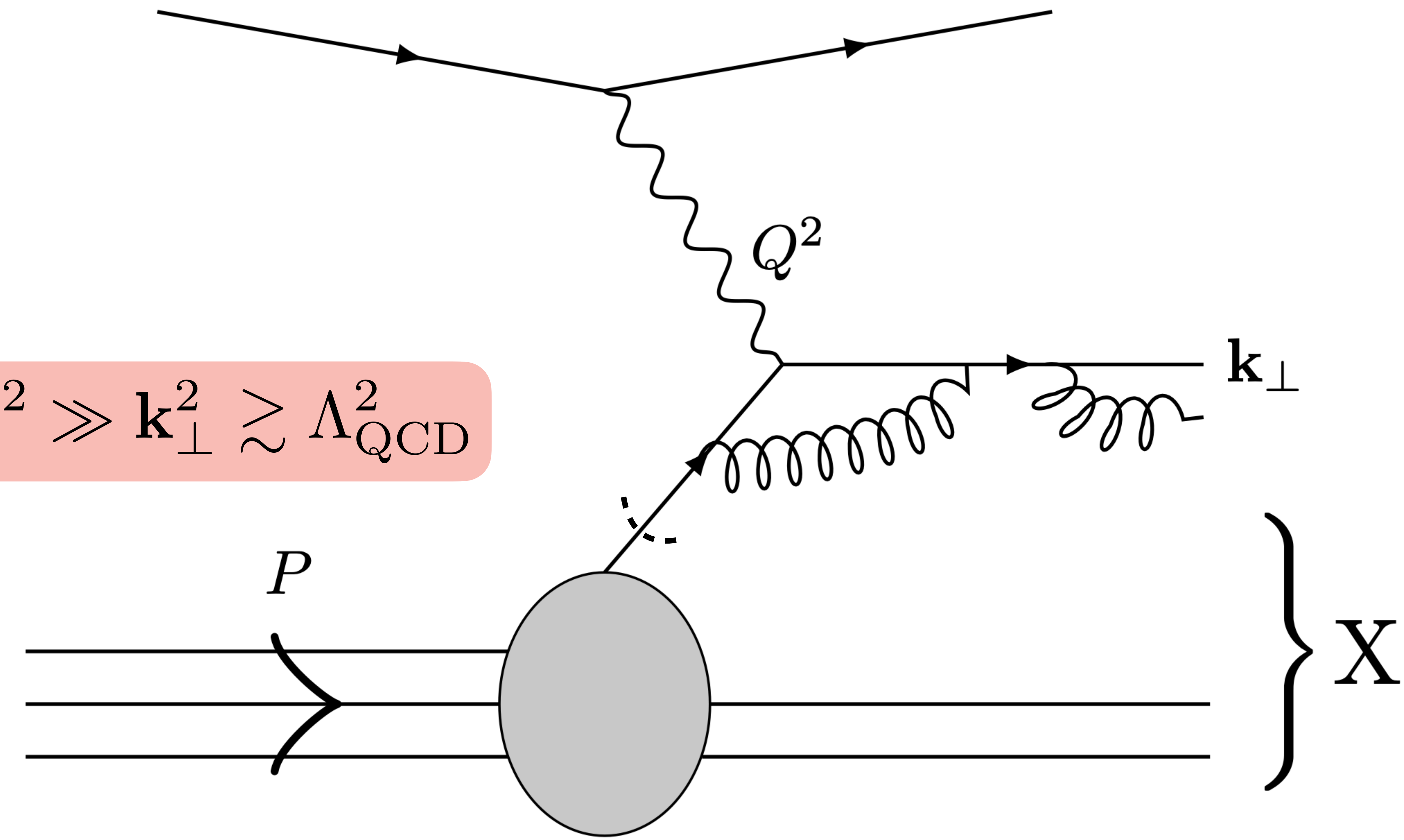
$$s \sim Q^2 \sim \mathbf{k}_\perp^2 \gg \Lambda_{\mathrm{QCD}}^2$$



$$\sigma_{\mathrm{coll}} = \hat{\sigma}(Q^2) \otimes f(x, Q^2) + \mathcal{O}(\Lambda_{\mathrm{QCD}}/Q)^n$$

Large logarithms $\ln(Q^2/\Lambda_{\mathrm{QCD}}^2)$ resummed using DGLAP

Transverse-momentum dependent (TMD) factorisation



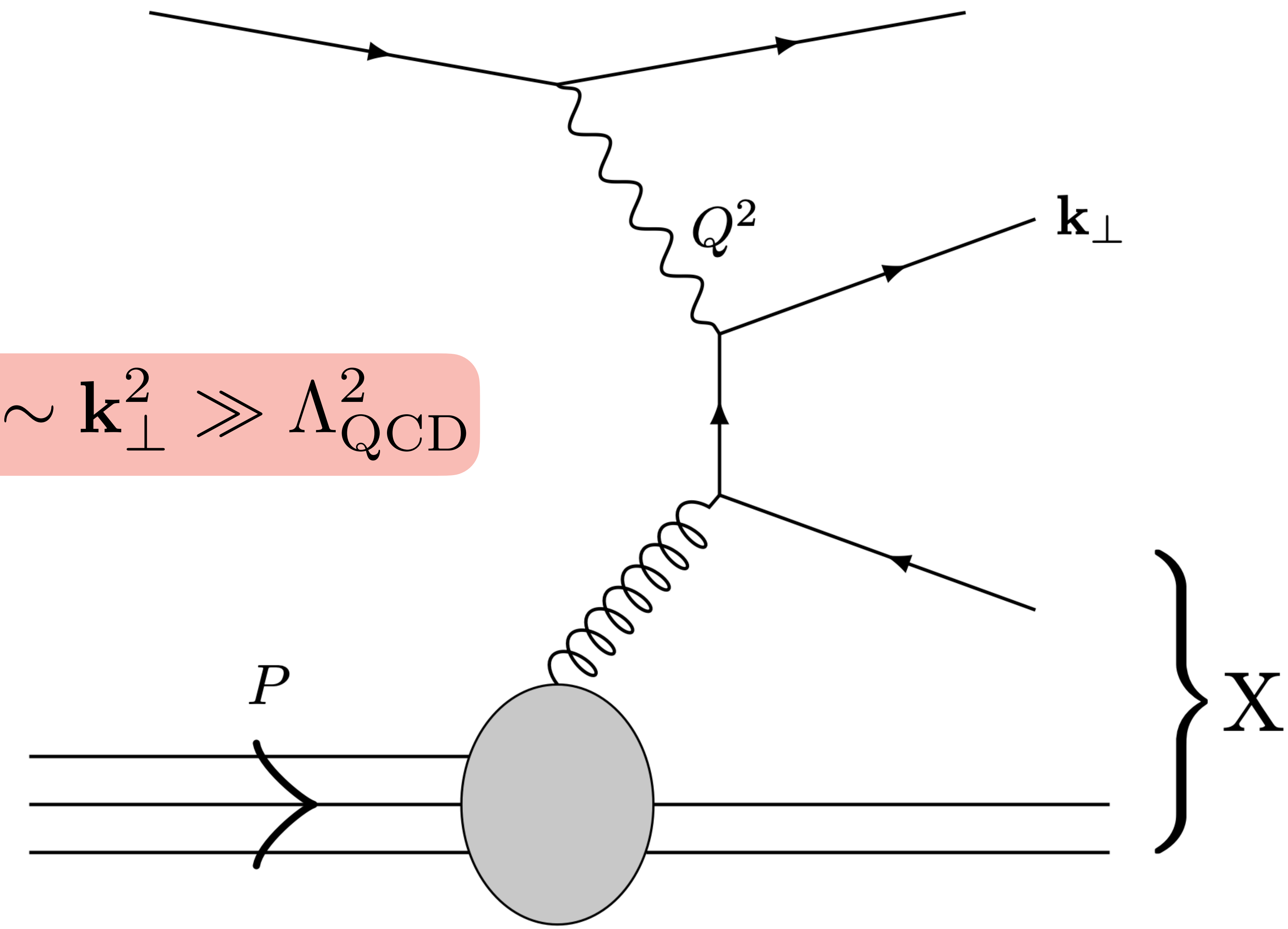
$s \sim Q^2 \gg \mathbf{k}_\perp^2 \gtrsim \Lambda_{\rm QCD}^2$

$$\sigma_{\rm TMD} = \hat{\sigma}(Q^2) \otimes f(x, \mathbf{k}_\perp, Q^2) \otimes + \mathcal{O}\left(\frac{\Lambda_{\rm QCD}}{Q}, \frac{\mathbf{k}_\perp}{Q}\right)^n$$

Additional Sudakov logarithms $\ln(Q^2/\mathbf{k}_\perp^2)$ resummed using CSS

Collins, Soper, Sterman ('85-'89); Ji, Ma, Yuan (2005); Collins (2011); Echevarria, Idilbi, Scimemi (2012)

High-energy factorisation



$$s \gg Q^2 \sim \mathbf{k}_\perp^2 \gg \Lambda^2_{\rm QCD}$$

$$\sigma_{\rm HEF} = \hat{\sigma}\left(\mathbf{k}_\perp^2, Q^2\right) \otimes \mathcal{G}(x, \mathbf{k}_\perp, Q^2) + \mathcal{O}\left(\frac{\Lambda_{\rm QCD}}{Q}\right)^n$$

Additional logarithms $\ln(s/Q^2) \sim \ln(1/x)$ resummed using BFKL

Catani, Ciafaloni, Hautmann ('90-'94)

Combining low-x and Sudakov resummation

$$s \gg Q^2 \gg \mathbf{k}_\perp^2 \gtrsim \Lambda_{\mathrm{QCD}}^2$$

Simultaneous resummation of high-energy $\ln(1/x)$ and Sudakov $\ln(Q^2/\mathbf{k}_\perp^2)$ logarithms?

Longstanding problem, studied using many different approaches, including recently:

SW: Balitsky, Tarasov (2015)
RO: Balitsky (2021-2023)
HEF: Deak, Hautmann, Jung, Kutak, van Hameren, Sapeta, Hentschinski (2016-2021)
BFKL: Nefedov (2021)
PB: Hautmann, Hentschinski, Keersmaekers, Kusina, Kutak, Lelek (2022)
CGC: Mueller, Xiao, Yuan (2011); Hatta, Xiao, Yuan, Zhou (2017-2021); Stasto, Wei, Xiao, Yuan (2018); PT, Altinoluk, Beuf, Marquet (2022); Caucal, Salazar, Schenke, Venugopalan (2022-2023)

(Gluon) TMDs

PDFs parameterize longitudinal structure of hadron

TMDs parameterize 3D momentum structure + spin correlations

Ultimate goal: extracting TMDs from few theoretically clean processes

No extractions of gluon TMDs yet

GLUONS	*unpolarized*	*circular*	*linear*
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	h_{1T}^g, $h_{1T}^{\perp g}$

→ coincide with unintegrated gluon distribution at high k_T and low x

Kutak, Sapeta (2012)

two TMDs survive kT integration: $f_g(x,Q^2) \propto \int \mathrm{d}k_\perp^2 \, f_1^g(x,k_\perp;Q^2)$

$$\Delta G \propto \int \mathrm{d}x\mathrm{d}k_\perp^2 \, g_{1L}^g(x,k_\perp;Q^2)$$

Mulders & Rodrigues (2001) Collins (2011) Angelez-Martinez et al. (2015)

Operator definitions of (TMD) PDFs

Collins (2011)

Collinear gluon PDF:

$$xg\left(x,Q^2\right) \equiv \int \frac{\mathrm{d}\xi^-}{\pi p^+} e^{ixp^+\xi^-} \mathrm{Tr}\Big\langle P\Big| F^{i+}\left(\xi^-\right) U^\dagger_{[\xi^-,0^-]}\left(\mathbf{0}\right) F^{i+}\left(0^-\right) U_{[\xi^-,0^-]}\left(\mathbf{0}\right)\Big| P\Big\rangle$$

Wilson lines to preserve gauge invariance

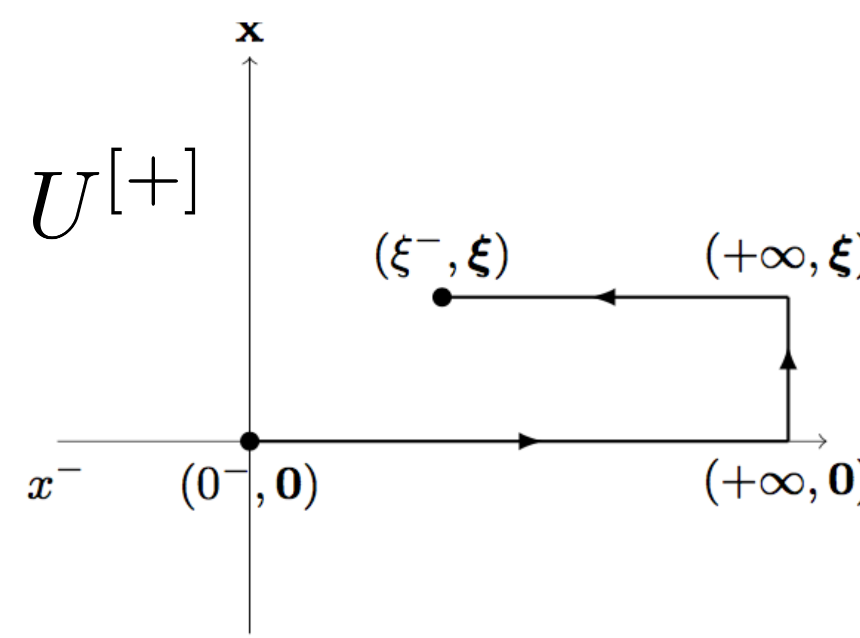
$$U^\dagger_{[\xi^-,0^-]}(\mathbf{0}) = \mathcal{P} e^{-ig_s \int \mathrm{d}z^- A^+(z^-,\mathbf{0})}$$

Gluon TMD:

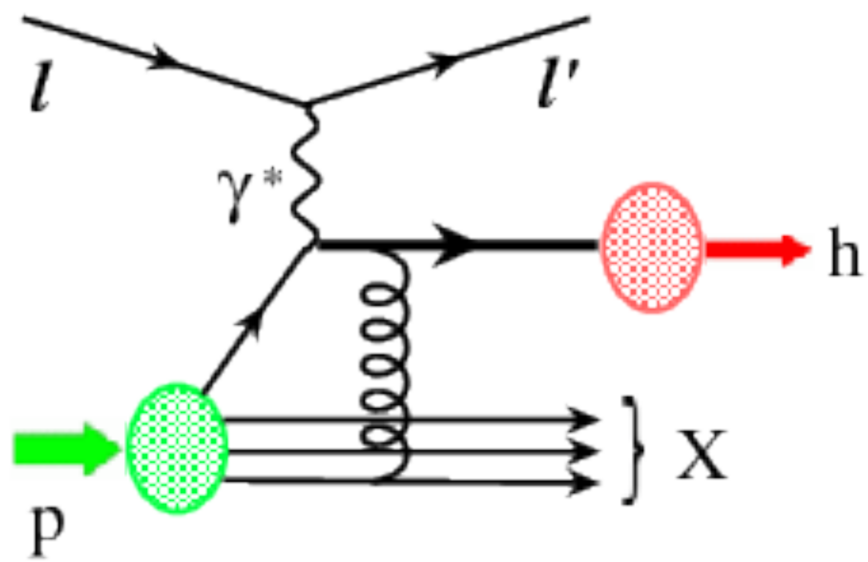
$$f_1^g(x,\mathbf{q}_T^2) = 2\int \frac{\mathrm{d}^3\vec{\xi}}{(2\pi)^3 p^+} e^{ixp^+\xi^-} e^{-i\mathbf{q}_T\boldsymbol{\xi}} \mathrm{Tr}\langle P|F^{i+}(\vec{\xi})U^{[+]\dagger}F^{i+}(\vec{0})U^{[+]}|P\rangle$$

$$U_\Gamma^\dagger = \mathcal{P}\exp\Big(-ig_s\int_\Gamma \mathrm{d}x^\mu A_\mu(x)\Big)$$

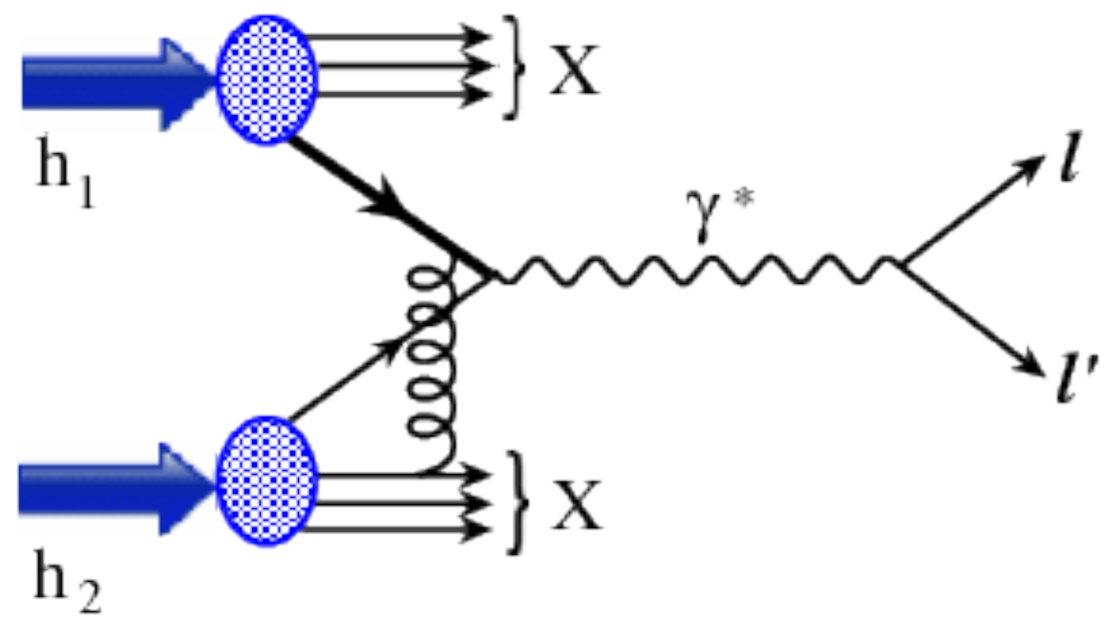
different possible paths in $(x^-, x_\perp)$-plane to connect field strengths



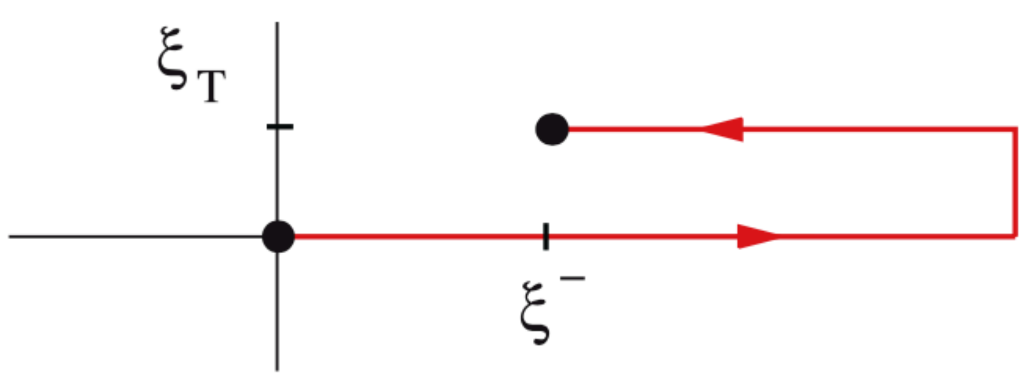
Path dependence

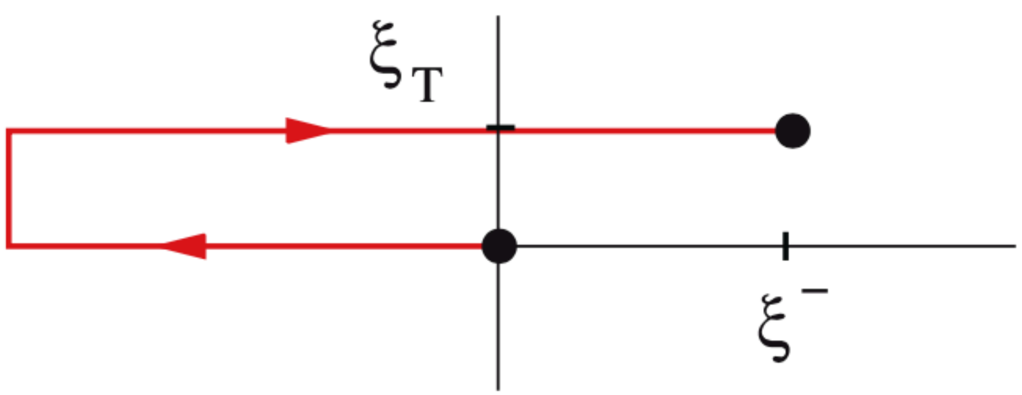


SIDIS (Final state radiation)



DY (Initial state radiation)





$$f_{1T}^{\perp,SIDIS}(x,\mathbf{q}_T^2) = -f_{1T}^{\perp,DY}(x,\mathbf{q}_T^2)$$

Bomhof, Mulders, Pijlman (2006)

Why the Colour Glass Condensate?

$$s \gg Q^2 \gtrsim \mathbf{k}_\perp^2 \gtrsim Q_s^2$$

$$\Gamma_i^{\mu\nu}(x,\mathbf{k}_\perp) = \frac{x}{2}\left[-g_T^{\mu\nu} f_{1i}^g(x,\mathbf{k}_\perp) + \left(\frac{k_\perp^\mu k_\perp^\nu}{M_p^2} + g_T^{\mu\nu}\frac{\mathbf{k}_\perp^2}{2M_p^2}\right) h_{1i}^{\perp g}(x,\mathbf{k}_\perp)\right]$$

Polarisation + gauge structure disappears in large $k_\perp$ limit

$$f_{1i}^g(x,\mathbf{k}_\perp,Q^2) = \mathcal{G}(x,\mathbf{k}_\perp,Q^2) + \mathcal{O}(Q_s^2/\mathbf{k}_\perp^2)$$

$$h_{1i}^{\perp g}(x,\mathbf{k}_\perp,Q^2) = \mathcal{G}(x,\mathbf{k}_\perp,Q^2) + \mathcal{O}(Q_s^2/\mathbf{k}_\perp^2)$$

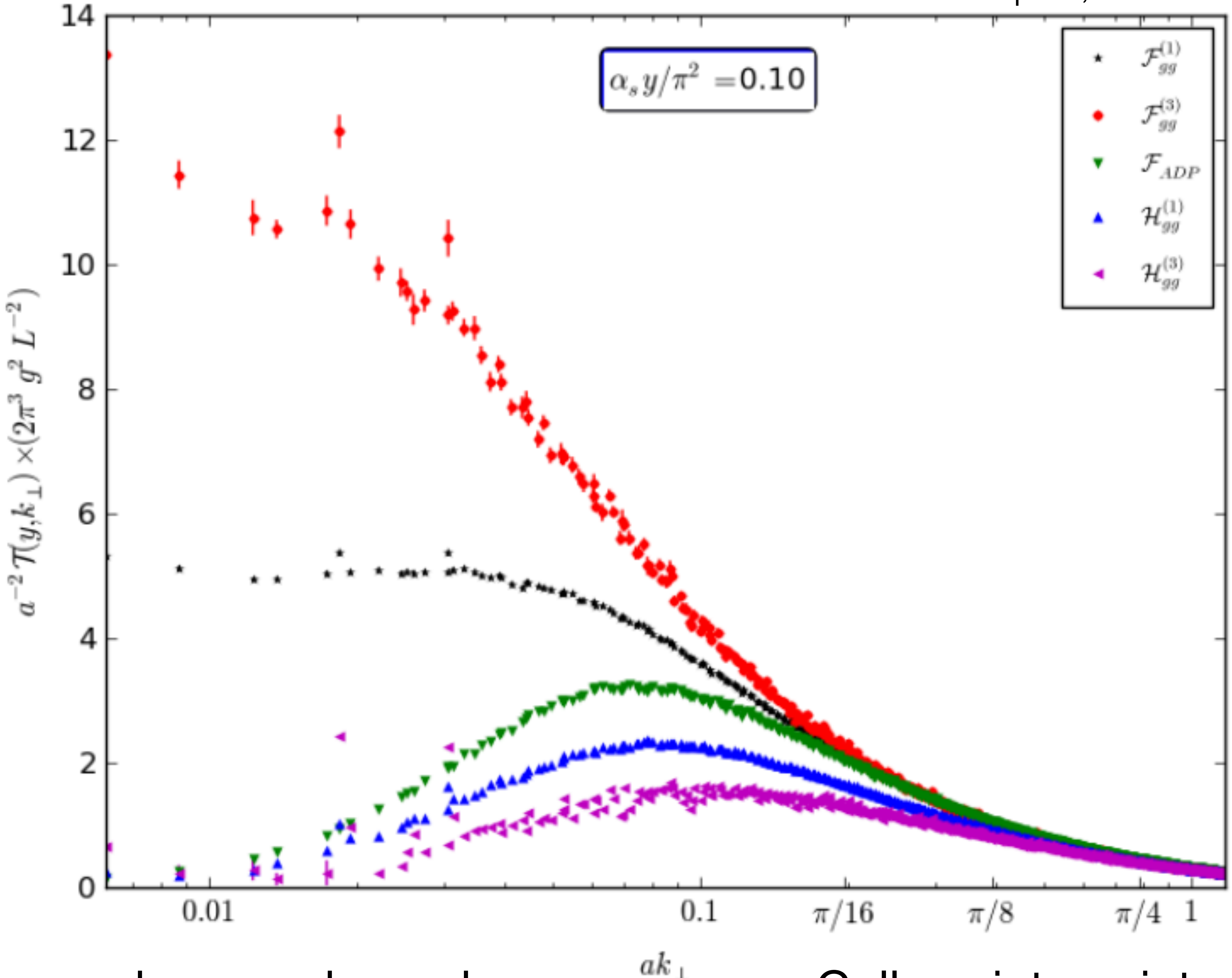
Unpolarised gluon TMD with gauge structure i

Linearly polarised gluon TMD with gauge structure i

Dominguez, Marquet, Xiao, Yuan (2011)
Kotko, Kutak, Marquet, Petreska, Sapeta, van Hameren (2015-2016); Dumitru, Lappi, Skokov (2015); Zhou (2016); Benic, Dumitru (2017); Marquet, Roiesnel, PT (2017)
Altinoluk, Boussarie, Marquet, PT (2018-2020)
Altinoluk, Boussarie, Kotko, Mehtar-Tani (2019-2020)

Model + nonlinear high-energy evolution of low-x gluon TMDs

Marquet, Roiesnel, PT (2018)

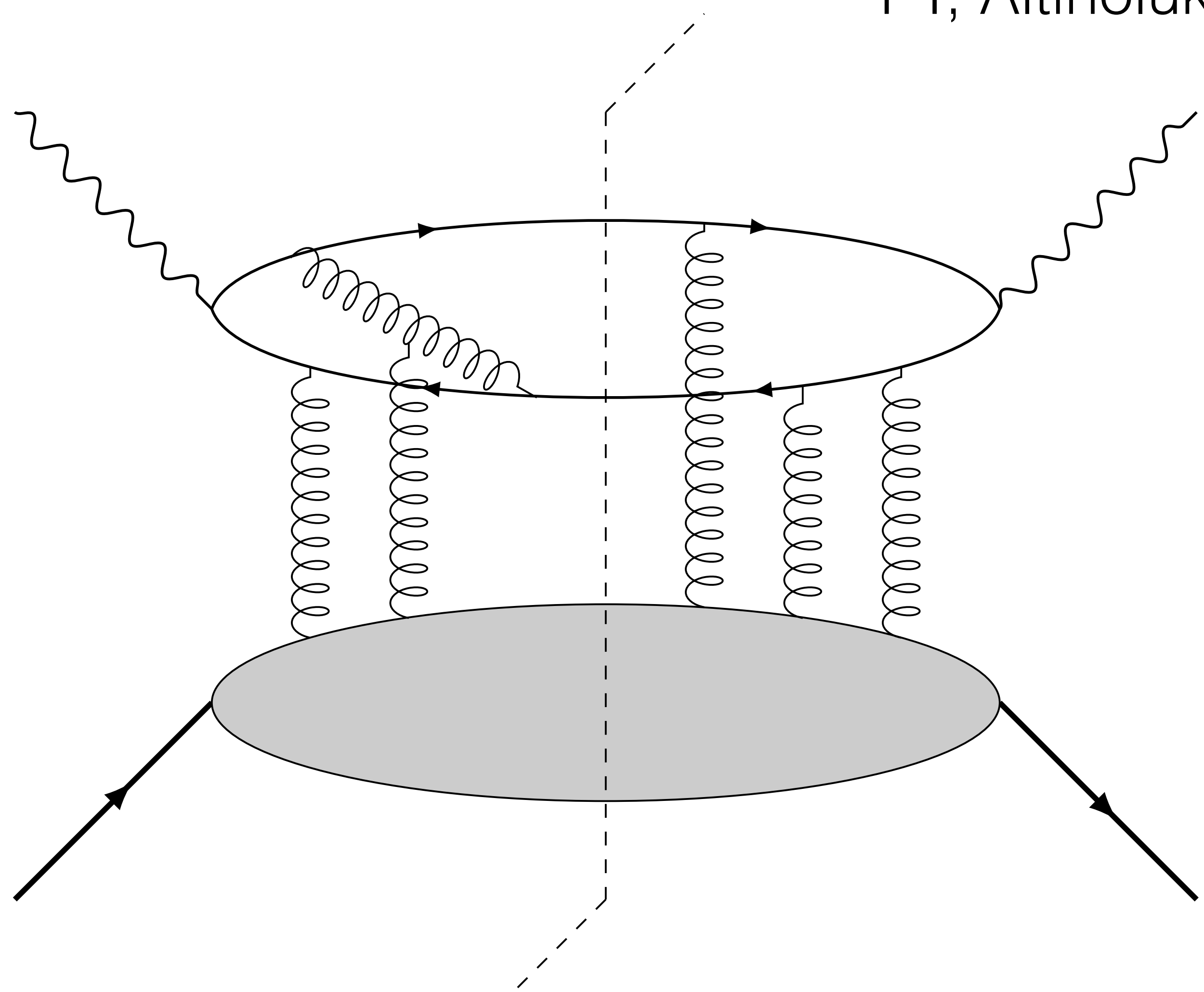


Polarisation and gauge dependence critical when $k_\perp \lesssim Q_s$

Collaps into unintegrated gluon distribution when $k_\perp \gg Q_s$

Dijet photoproduction at NLO in the CGC

PT, Altinoluk, Beuf, Marquet (2022)



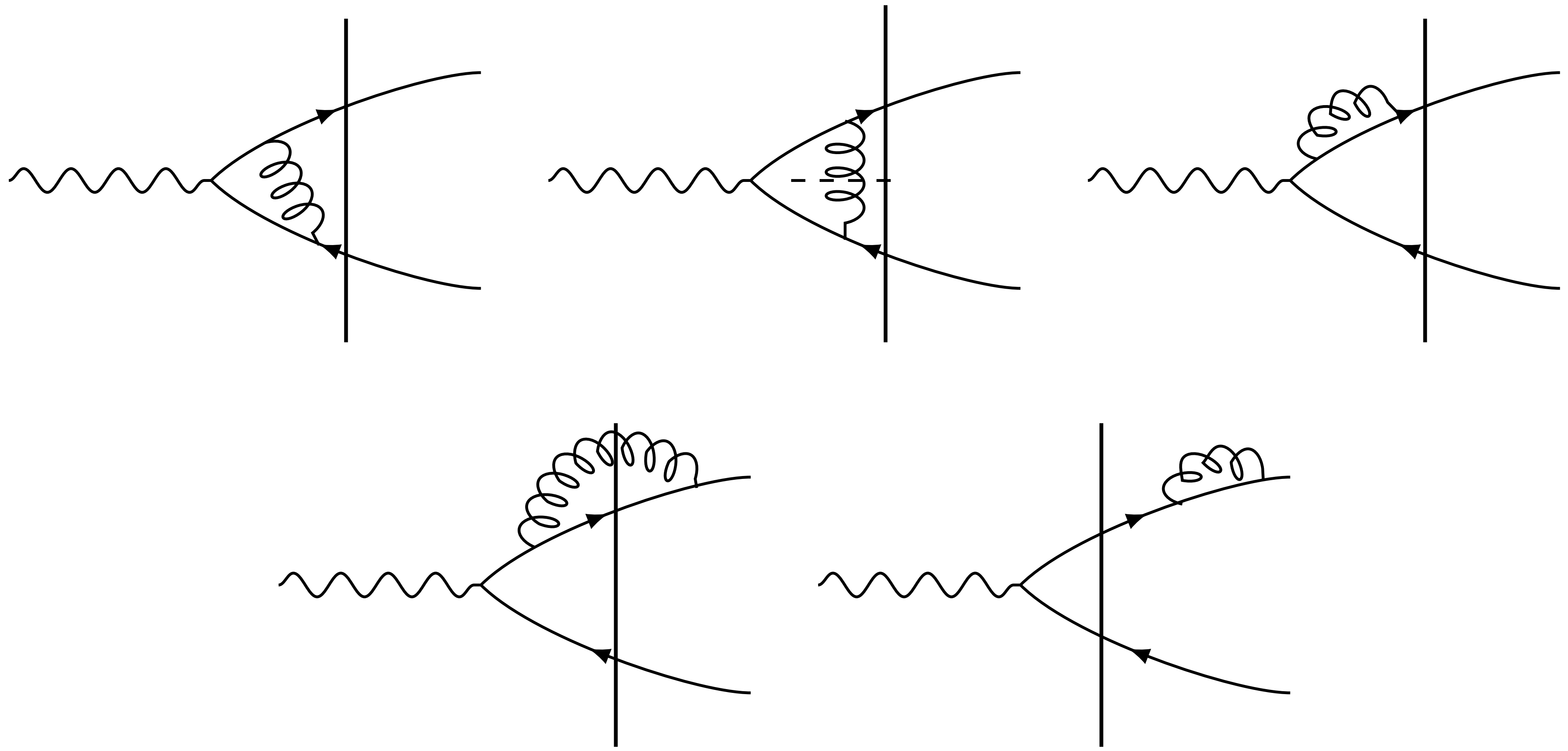
Framework: dipole formulation of CGC, light-cone perturbation theory

$$
{}_f\langle(\mathbf{q})[\vec{p}_1]_{s_1};(\bar{\mathbf{q}})[\vec{p}_2]_{s_2}|\hat{F}-1|(\boldsymbol{\gamma})[\vec{q}]_\lambda\rangle_i
$$
$$
=\langle(\mathbf{q})[\vec{p}_1]_{s_1};(\bar{\mathbf{q}})[\vec{p}_2]_{s_2}|\mathcal{U}(+\infty,0)(\hat{F}-1)\mathcal{U}(0,-\infty)|(\boldsymbol{\gamma})[\vec{q}]_\lambda\rangle
$$

LCPT: Bjorken, Kogut, Soper (1971)
Inclusive DIS: Beuf (2016-2017)

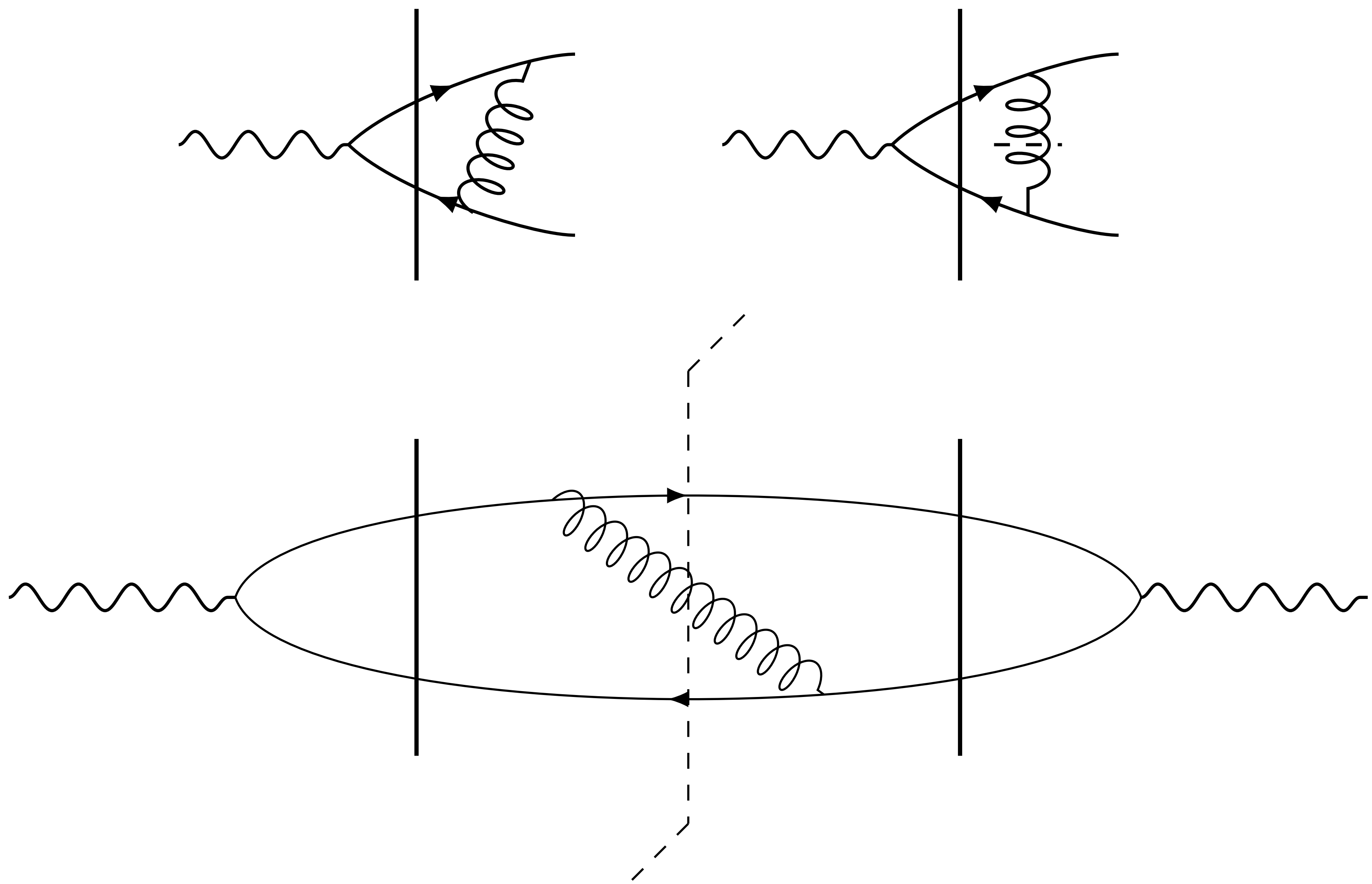
DIS: Caucal, Salazar, Venugopalan (2022)
Dihadron: Bergabo, Jalilian-Marian (2022)
Diffraction: Boussarie et al. (2017),
Fucilla et al. (2022)

UV divergences



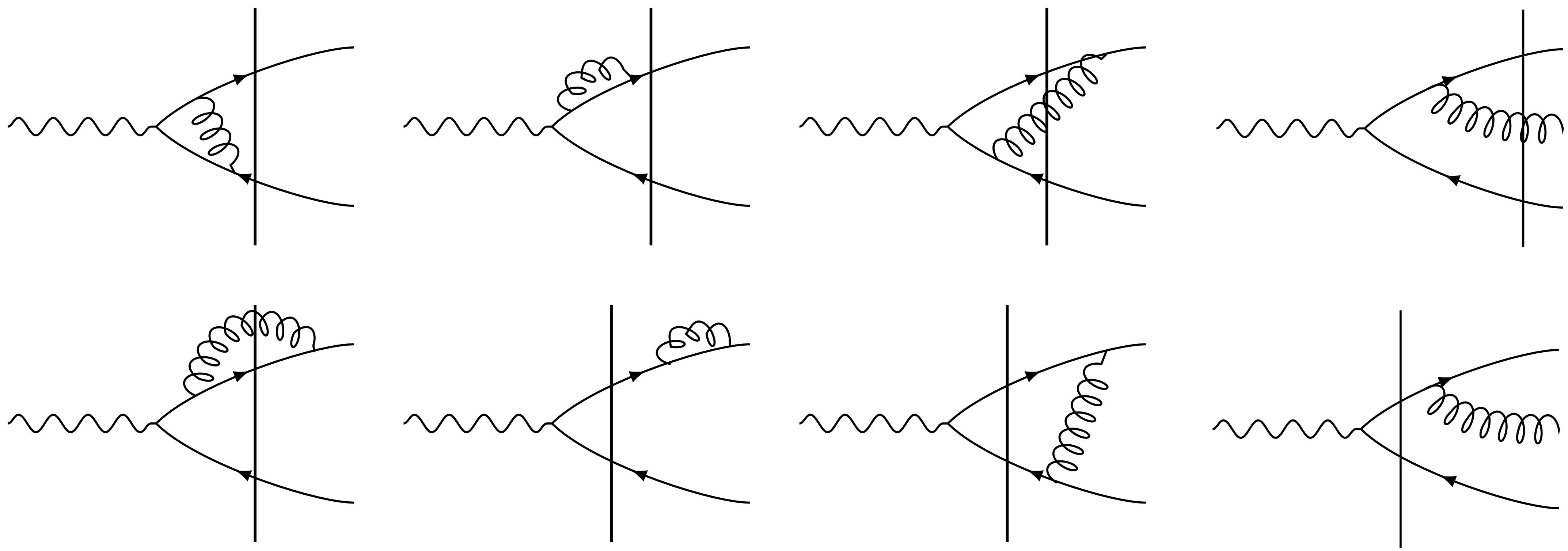
$\mathbf{k}_\perp \to \infty$ in loops, regulated with dimensional regularisation, no leftover logarithms

Soft divergences



$(k^+, \mathbf{k}_\perp) \to 0$ in final state, regulated with dimensional regularisation, no leftover logarithms

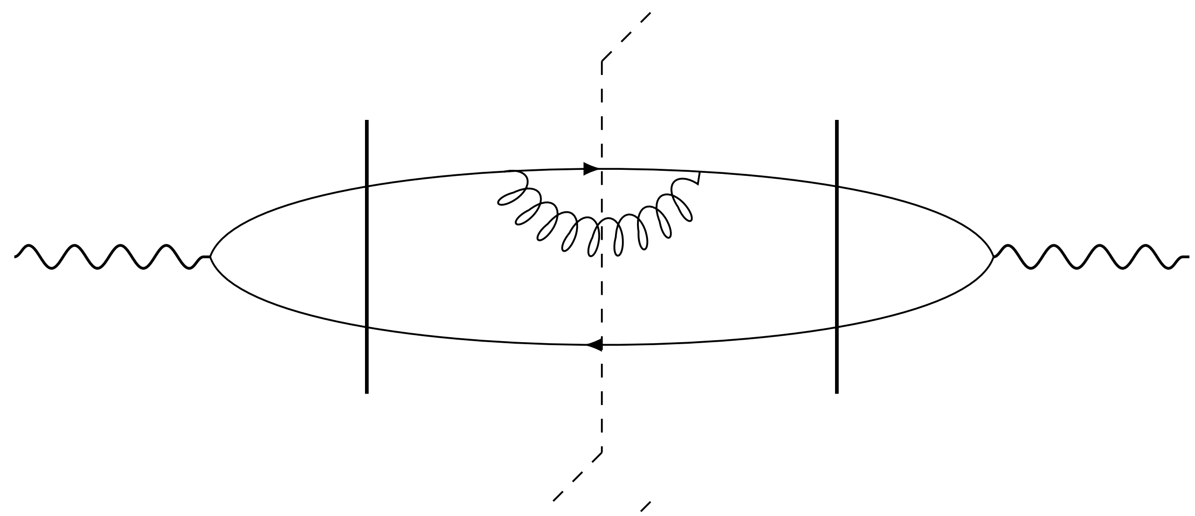
Rapidity divergences

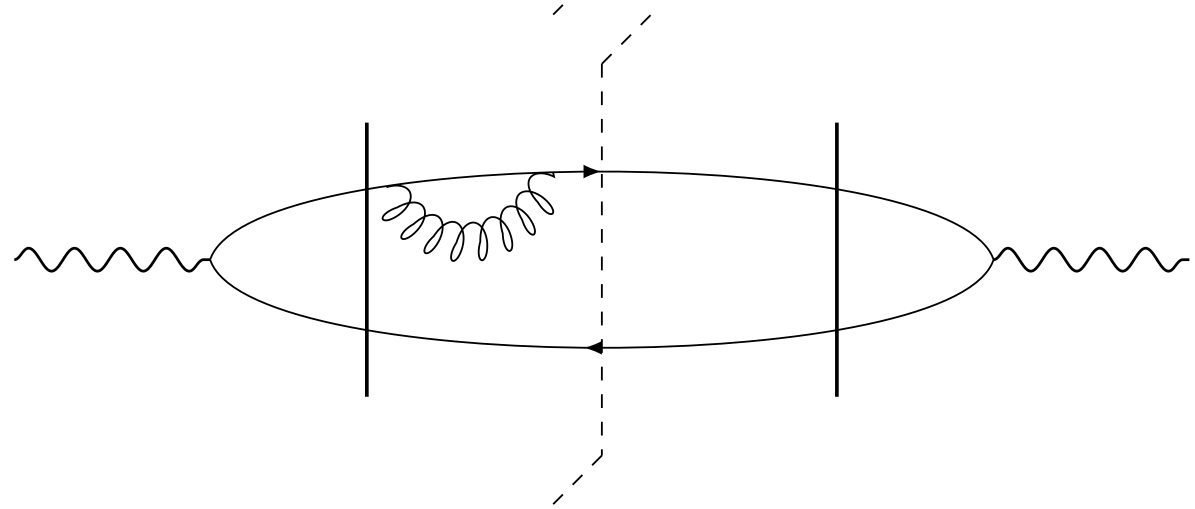


$k^+ \to 0$, regulated with cutoff $k^+_{\rm min}$, 'renormalisation scale' k^+_f, absorbed into JIMWLK evolution of LO cross section

$$\mathrm{d}\sigma_{\rm NLO} = \int_{k^+_{\rm min}}^{k^+_f} \frac{\mathrm{d}p_3^+}{p_3^+} \hat{H}_{\rm JIMWLK}\mathrm{d}\sigma_{\rm LO} + \int_{k^+_{\rm min}}^{+\infty} \frac{\mathrm{d}p_3^+}{p_3^+}\left[\mathrm{d}\tilde{\sigma}_{\rm NLO} - \theta(k^+_f - p^+_3)\hat{H}_{\rm JIMWLK}\mathrm{d}\sigma_{\rm LO}\right]$$

Collinear-soft divergences



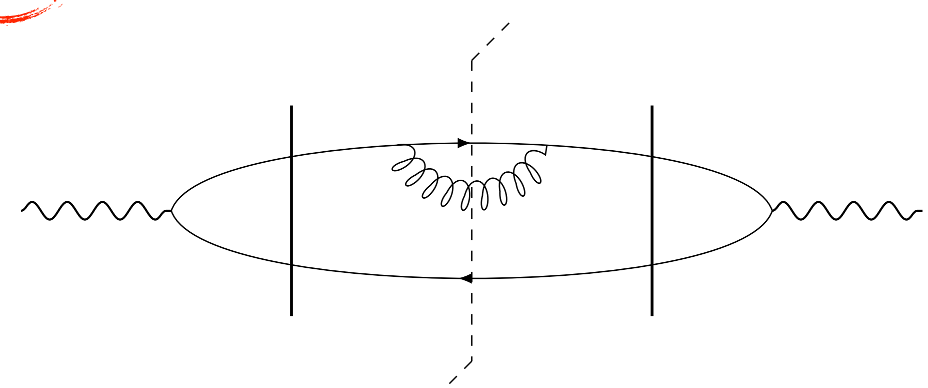


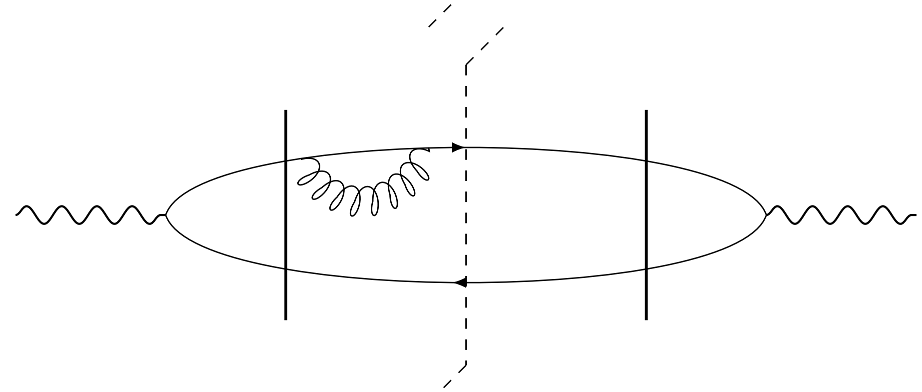
Mix of dimensional regularisation and cutoff method
Collinear divergences cancel between inside-jet radiation and self-energy
Leftover soft divergences cancel between radiation in-and outside the jet

Collinear-soft divergences

$$\mathcal{V}^{\text{in}}_{|\text{QFS}|^2} = \left(-\frac{3}{2} + 2\ln\frac{p^+_{j1}}{k^+_{\text{min}}}\right)\left(-\frac{1}{\epsilon_{\text{coll}}} + \gamma_E + \ln\frac{\mathbf{p}^2_{j1}}{4\pi\mu^2} + 2\ln R\right) - 2\left(\ln\frac{p^+_{j1}}{k^+_{\text{min}}}\right)^2 - \frac{2\pi^2}{3} + \frac{13}{2} + \mathcal{O}(\epsilon)\ .$$

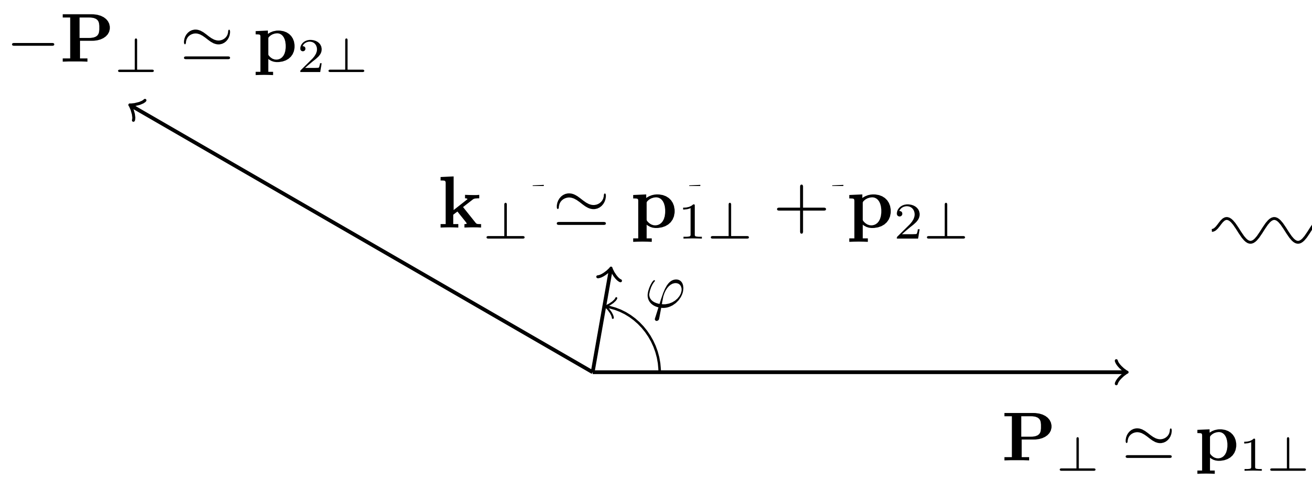
$$\mathcal{V}^{\text{out; soft}}_{|\text{QFS}|^2} = 2\left(\ln\frac{p^+_{j1}}{k^+_{\text{min}}}\right)^2 - 4\ln\left(\frac{p^+_{j1}}{k^+_{\text{min}}}\right)\ln R - 2\ln\left(\frac{p^+_{j1}}{k^+_{\text{min}}}\right)\ln\left(\frac{\mathbf{p}^2_{j1}\mathbf{x}^2_{11'}}{c_0^2}\right)$$

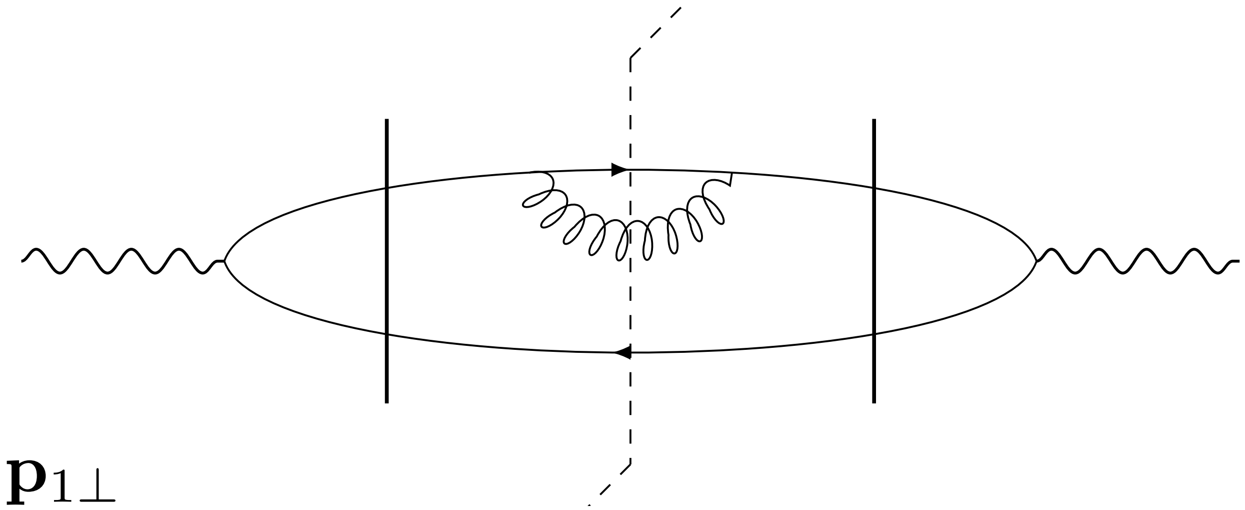




$$\mathcal{V}_{\text{FSIR}} = \left[\frac{1}{\epsilon_{\text{coll}}} + \gamma_E + \ln(\pi\mu^2\mathbf{x}^2_{12})\right]\left[-\frac{3}{2} + \ln\left(\frac{p^+_{j1}}{k^+_{\text{min}}}\right) + \ln\left(\frac{p^+_{j2}}{k^+_{\text{min}}}\right)\right]$$

Back-to-back limit: Sudakov logarithms





Remnants of soft-collinear generate Sudakov double log with wrong sign!

$$\mathrm{d}\sigma_{\mathrm{NLO}}^{\mathrm{TMD}} = \mathrm{d}\sigma_{\mathrm{LO}}^{\mathrm{TMD}} \times \frac{\alpha_s N_c}{4\pi} \ln\left(\frac{\mathbf{P}_\perp^2(\mathbf{b}-\mathbf{b}')^2}{c_0^2}\right)^2 \qquad \begin{array}{l} \mathbf{P}_\perp^2 \sim \mu^2 \\ (\mathbf{b}-\mathbf{b}')^2 \sim 1/\mathbf{k}_\perp^2 \end{array}$$

… but in our framework hard to distinguish soft $(k^+, \mathbf{k}_\perp) \to 0$ and rapidity $k^+ \to 0$ divergences

oversubtraction of high-energy logs via JIMWLK?

Kinematically consistent low-x resummation

JIMWLK evolution along p^+ in interval $k^+_{\min} \to k^+_f$

'Naive' approach: strong ordering in p^+ only, implicitely assumes $s \to \infty$

More realistic approach calls for additional ordering in p^-, and additional renormalisation scale k^-_f

Implementing this ordering in final-state diagrams with suitable choice $k^+_f = \frac{p^+_{j1} p^+_{j2}}{q^+}$ and $k^-_f = \frac{\mathbf{P}^2_\perp}{2k^+_f}$ exactly compensates for wrong sign!

We end up with expected:

$$\mathrm{d}\sigma^{\mathrm{TMD}}_{\mathrm{NLO}} = \mathrm{d}\sigma^{\mathrm{TMD}}_{\mathrm{LO}} \times -\frac{\alpha_s N_c}{4\pi} \ln\left(\frac{\mathbf{P}^2_\perp (\mathbf{b}-\mathbf{b}')^2}{c_0^2}\right)^2$$

Beyond large-N_c and double log: see Farid Salazar's talk tomorrow

Ciafaloni ('88); Andersson, Gustafson, Samuelsson ('96); Kwiecinski, Martin, Sutton ('96); Salam ('98); Motyka, Stasto (2009); Kutak, Golec-Biernat, Jadach (2011); Beuf (2014); Iancu, Madrigal, Mueller, Soyez, Triantafyllopoulos (2019); Hatta, Iancu (2016) Nefedov (2022)

Outlook

Computed full NLO dijet photoproduction cross section in CGC

Kinematical improved high-energy evolution is crucial in order to recover correct Sudakov logs

Towards the LHC: forward DY + jet production at NLO in the CGC

Thanks for your attention !