Sudakov logarithms in dijet photoproduction at low *x*

Pieter Taels

Universiteit Antwerpen

Resummation Evolution Factorization

REF 2022 workshop

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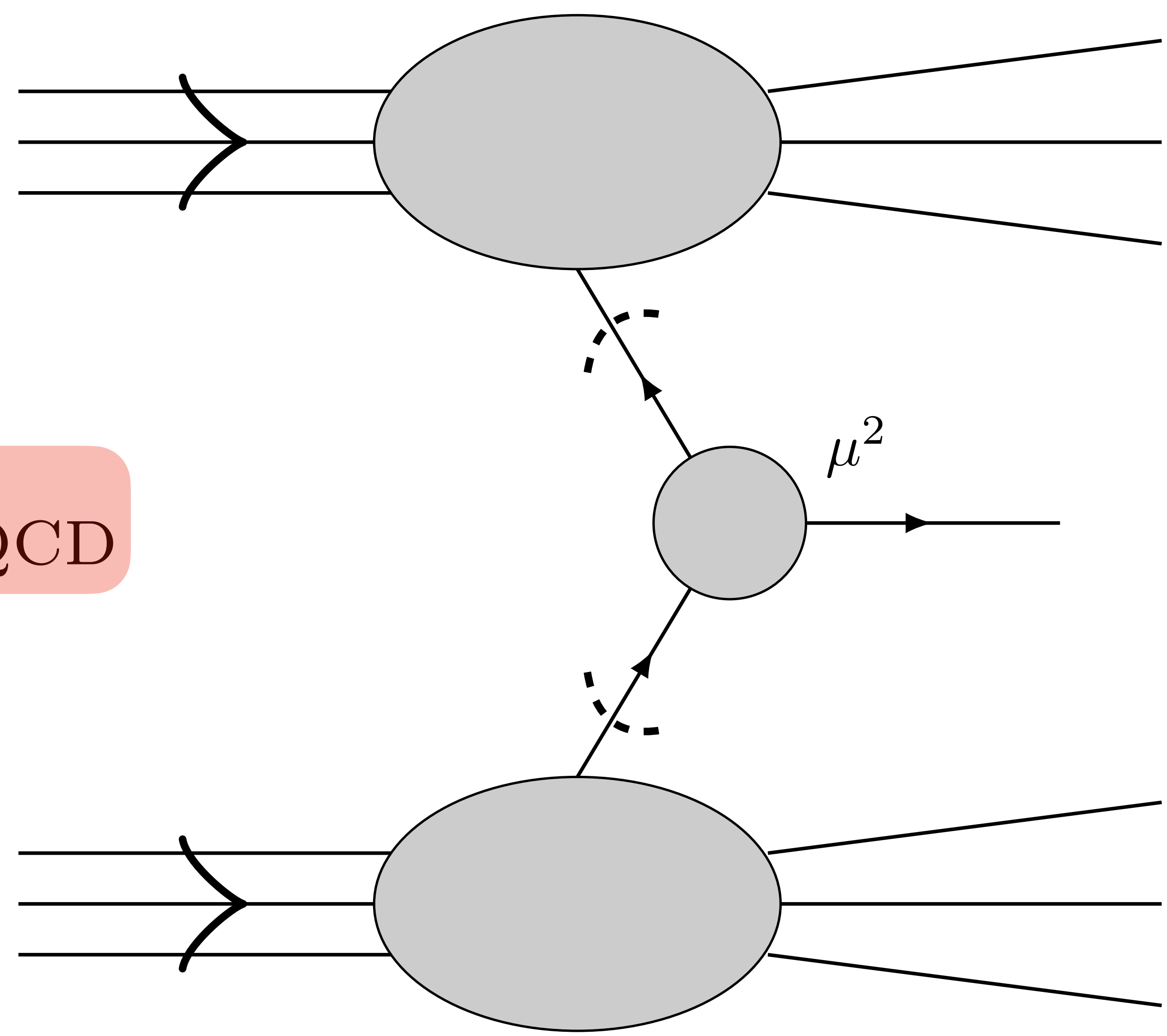
University of Antwerp

Particle Physics Group

Collinear factorisation

$s \sim \mu^2 \gg \Lambda_{\rm QCD}^2$



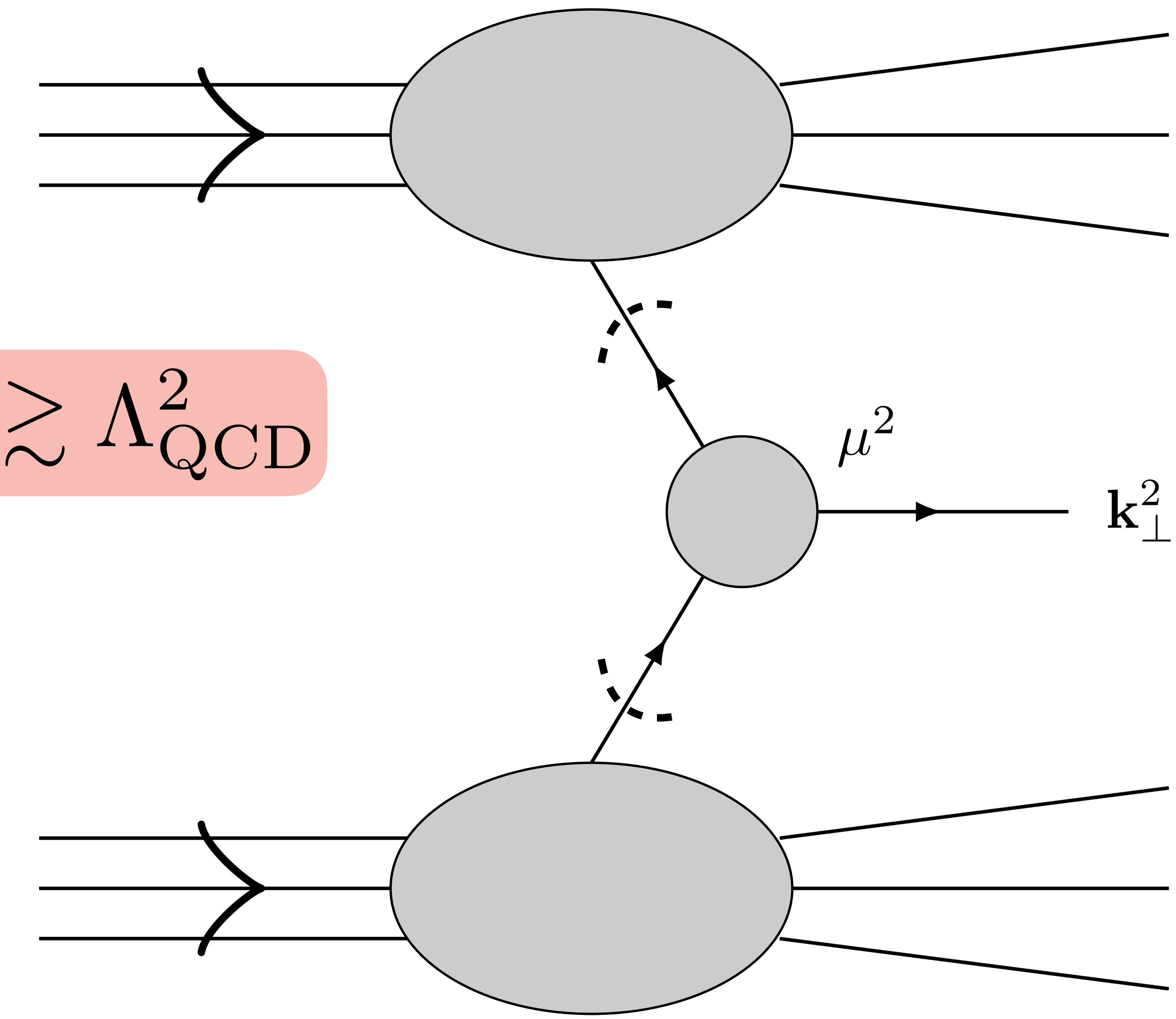
$$\sigma_{\rm coll} = \hat{\sigma}(\mu^2) \otimes f(x_a, \mu^2) \otimes f(x_b, \mu^2) + \mathcal{O}(\Lambda_{\rm QCD}/\mu)^n$$

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

Transverse-momentum dependent factorisation

Collinear factorisation needs to be generalised in presence of additional scale $\mu_b^2 \sim \mathbf{k}_\perp^2$

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

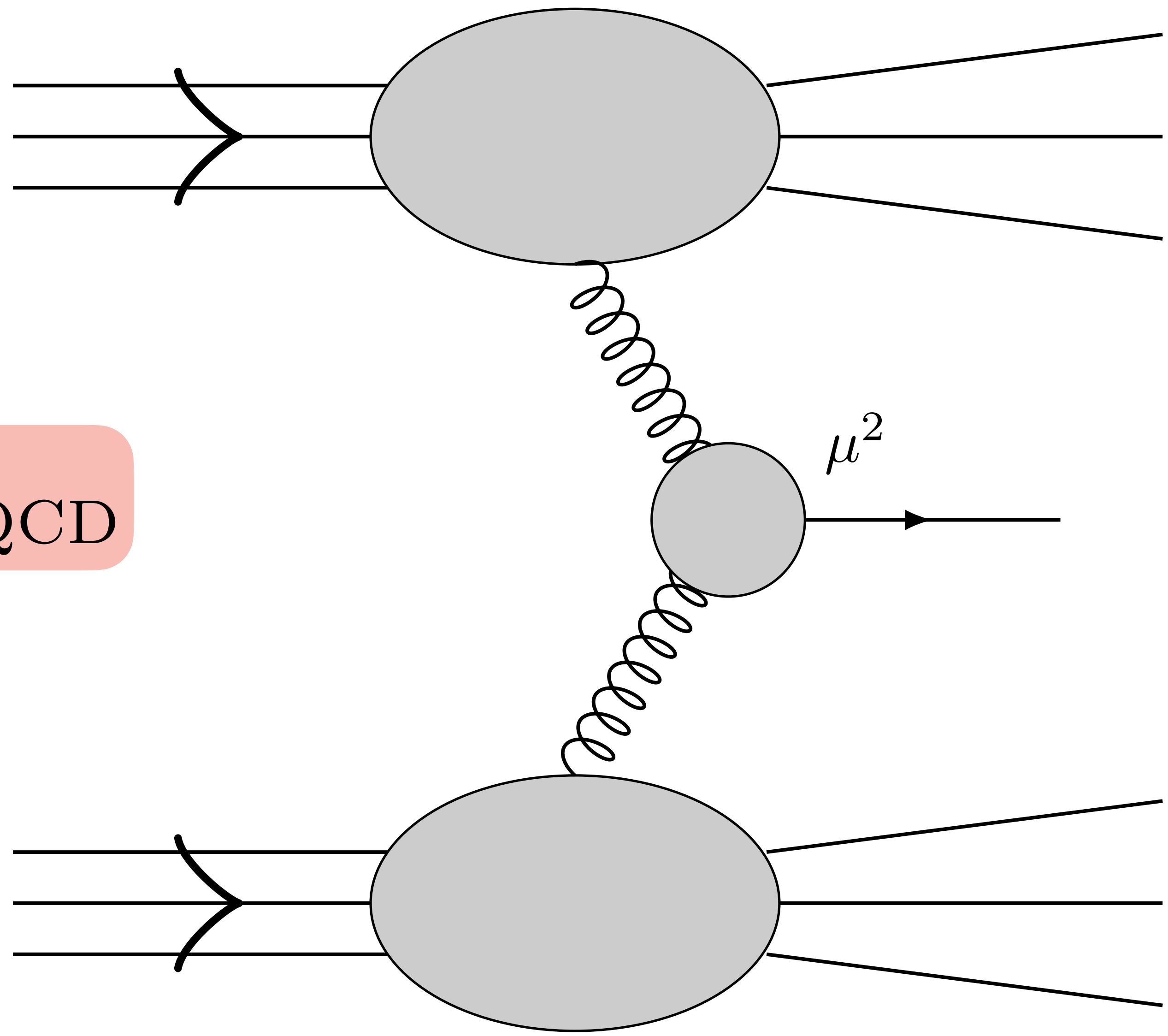


$$\sigma_{\rm TMD} = \hat{\sigma}(\mathbf{k}_\perp^2, \mu^2) \otimes f(x_a, \mathbf{k}_{a\perp}, \mu^2) \otimes f(x_b, \mathbf{k}_{b\perp}, \mu^2) + \mathcal{O}\left(\frac{\Lambda}{\mu}\right)^n$$

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

Collins, Soper, Sterman ('85-'89)
Collins (2011)
Echevarria, Idilbi, Scimemi (2012)

High-energy factorisation



$s \gg \mu^2 \gg \Lambda^2_{\mathrm{QCD}}$

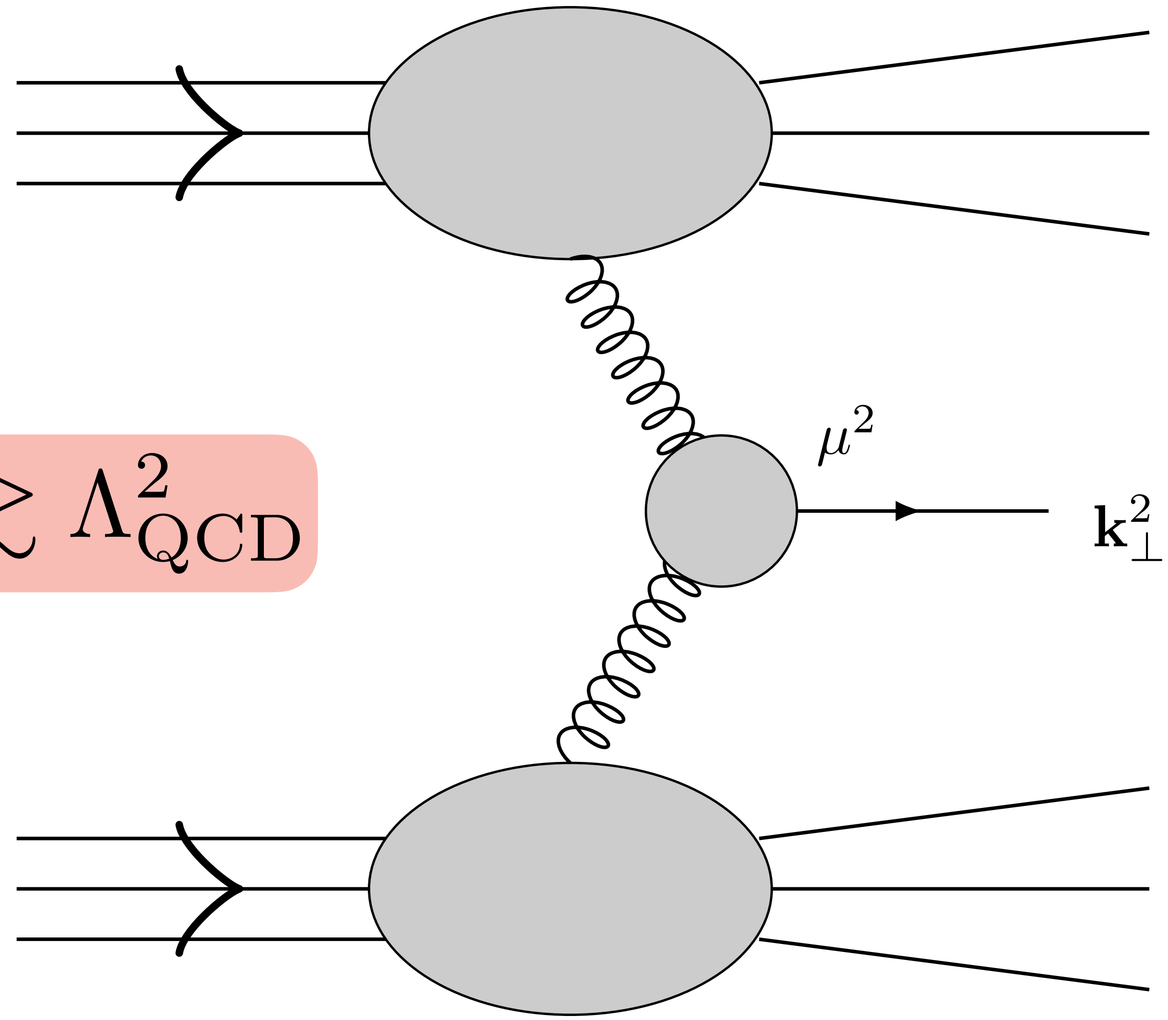
$$\sigma_{\mathrm{HEF}} = \hat{\sigma}\left(\frac{k_a^2}{\mu^2}, \frac{k_b^2}{\mu^2}, \mu^2\right) \otimes \mathcal{G}(x_a, \mathbf{k}_{a\perp}, \mu^2) \otimes \mathcal{G}(x_b, \mathbf{k}_{b\perp}, \mu^2) + \mathcal{O}\left(\frac{\Lambda}{\mu}\right)^n$$

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

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

Combining low-x and Sudakov resummation

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



Simultaneous resummation of $\ln(1/x)$ and $\ln(\mu^2/\mathbf{k}_\perp^2)$?

Many approaches and implementations:

SW: Balitsky, Tarasov (2015)

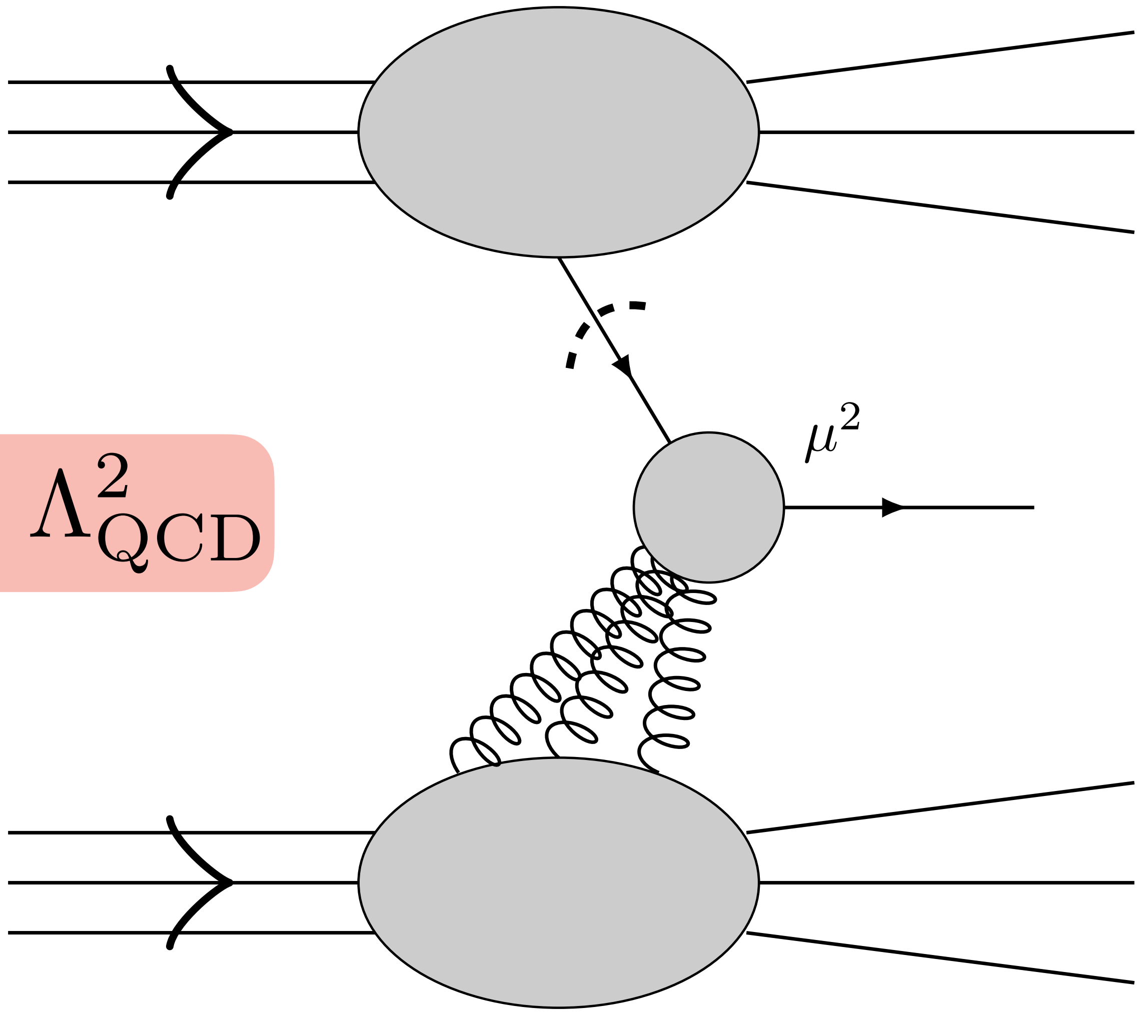
HEF: Deak, Hautmann, Jung, Kutak, van Hameren, Sapeta, Hentschinski (2016-2021)

BFKL: Nefedov (2021)

PB: Hautmann, Hentschinski, Keersmaekers, Kusina, Kutak, Lelek (2022)

CGC: Mueller, Xiao, Yuan (2011); Xiao, Yuan, Zhou (2017); Stasto, Wei, Xiao, Yuan (2018); PT, Altinoluk, Beuf, Marquet (2022); Caucal, Salazar, Schenke, Venugopalan (2022)

Why (not) the Colour Glass Condensate?



$$s \gg \mu^2 \gtrsim Q_s^2 \gtrsim \Lambda_{\mathrm{QCD}}^2$$

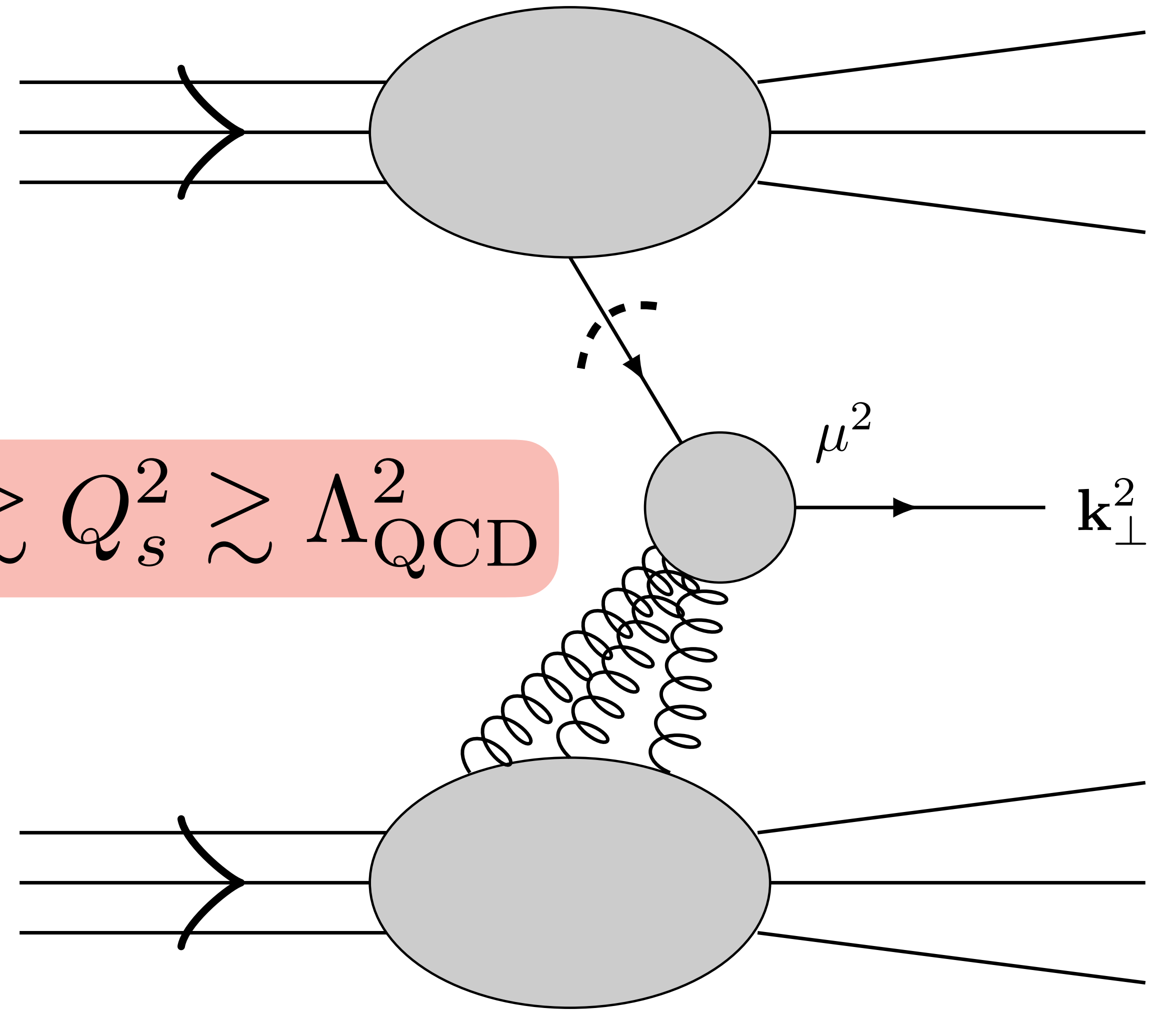
Saturation scale $Q_s^2(A,x) \simeq \dfrac{A^{1/3}}{x^{0.3}}$, e.g. $Q_s^2 \simeq 35\,\mathrm{GeV}^2$ for lead at $x = 10^{-3}$

All-twist framework, all hadronic operators $\sim Q_s^2/\mu^2$ included

$$\sigma_{\mathrm{CGC}} \neq \hat{\sigma} \otimes \mathcal{G}$$

Mueller, McLerran, Venugopalan, Jalilian-Marian, Kovner, Leonidov, Iancu, Weigert (1990-2001)

CGC in the TMD limit



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

$$\sigma_{\rm CGC,\,TMD} = \hat{\sigma}(\mathbf{k}_\perp^2, \mu_b^2) \otimes f(x_a, \mu^2) \otimes f(x_b, \mathbf{k}_\perp, \mu^2) + \mathcal{O}(Q_s^2/\mu^2) + \mathcal{O}(\alpha_s^n)$$

Dominguez, Marquet, Xiao, Yuan (2011)

CGC in the TMD limit

$$\Gamma^{\mu\nu}(x,\mathbf{k}) = \frac{2}{p_A^-}\int \frac{\mathrm{d}\xi^+\mathrm{d}^2\boldsymbol{\xi}}{(2\pi)^3} e^{i\xi^+k^-} e^{-i\boldsymbol{\xi}\mathbf{k}} \langle p_A|\mathrm{Tr}\, F^{-\mu}(0)\,\mathcal{U}(0,\xi^+,\boldsymbol{\xi})\,F^{-\nu}(\xi^+,\boldsymbol{\xi})|p_A\rangle$$

(Gluon) TMDs are process-dependent through gauge links / Wilson lines

$$\Gamma^{\mu\nu}(x,\mathbf{k}) = -\frac{g_T^{\mu\nu}}{2}\mathcal{F}_{\mathrm{WW}}(x,\mathbf{k}) + \left(\frac{k_T^{\mu}k_T^{\mu}}{\mathbf{k}^2} + \frac{g_T^{\mu\nu}}{2}\right)\mathcal{H}_{\mathrm{WW}}(x,\mathbf{k})$$

Contribution from linearly polarised gluons even in unpolarised hadron

Full Wilson-line and spin structure not included in k_t-factorisation

Unintegrated PDF

$$\mathcal{F}_i(x,\mathbf{k}_\perp) = \mathcal{G}(x,\mathbf{k}_\perp) + \mathcal{O}(Q_s^2/\mathbf{k}_\perp^2)$$

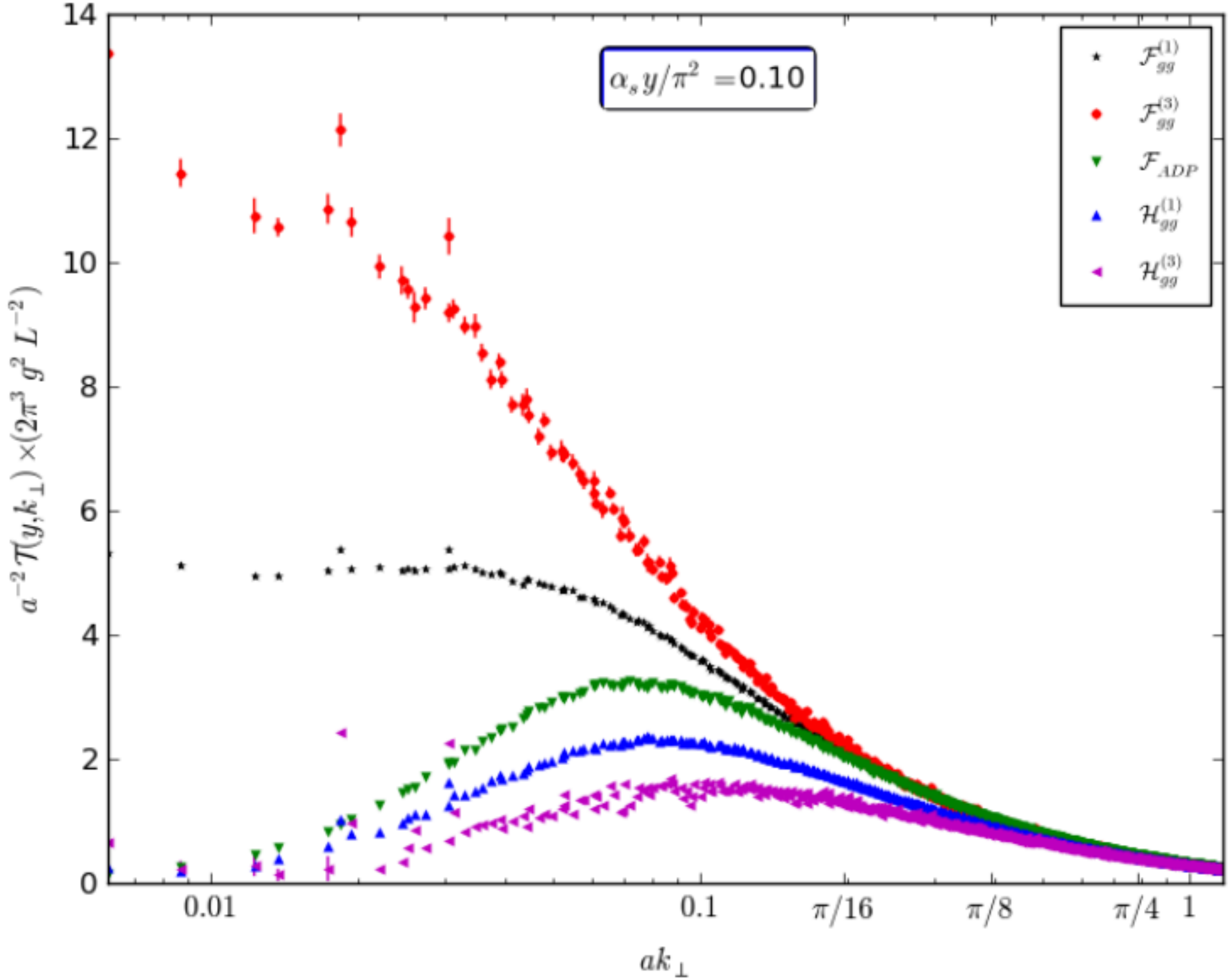
$$\mathcal{H}_i(x,\mathbf{k}_\perp) = \mathcal{G}(x,\mathbf{k}_\perp) + \mathcal{O}(Q_s^2/\mathbf{k}_\perp^2)$$

Unpolarised gluon TMD with gauge structure i

Linearly polarised gluon TMD with gauge structure i

Kotko, Kutak, Marquet, Petreska, Sapeta, van Hameren (2015)
Altinoluk, Boussarie, Kotko (2019)

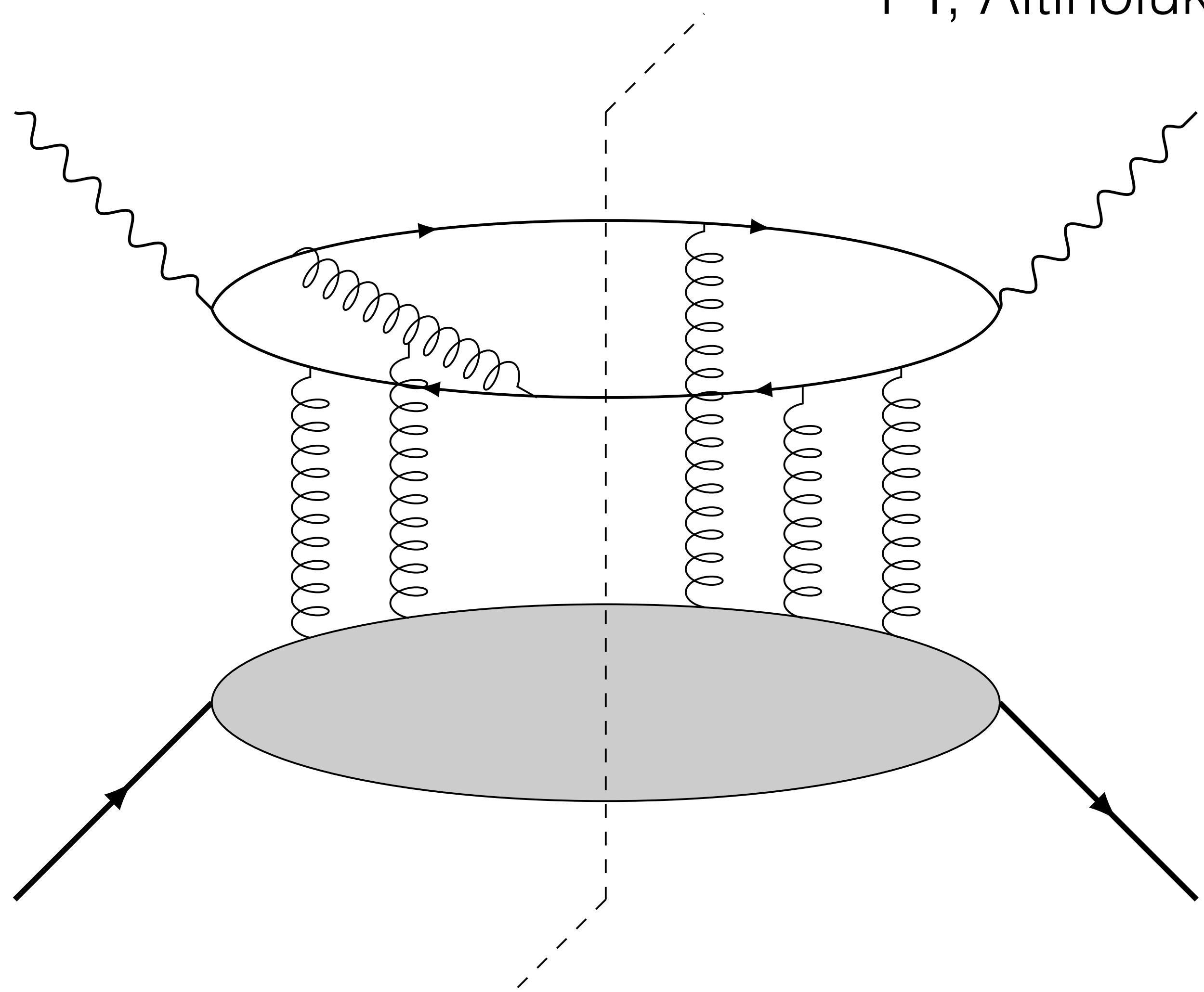
CGC in the TMD limit



Marquet, Roiesnel, PT (2018)

Dijet photoproduction at NLO in the CGC

PT, Altinoluk, Beuf, Marquet (2022)



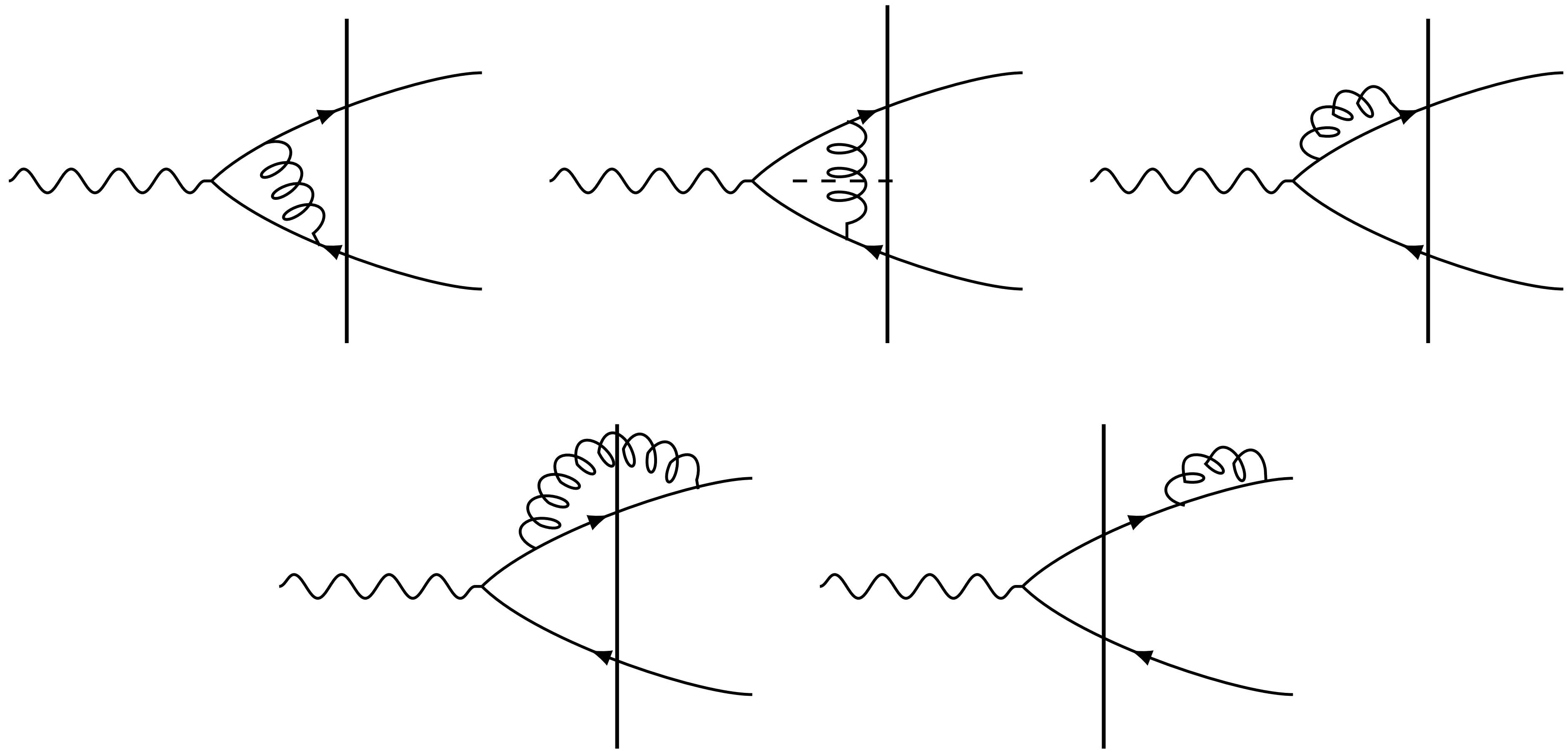
Framework: dipole formulation of CGC, light-cone perturbation theory

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

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

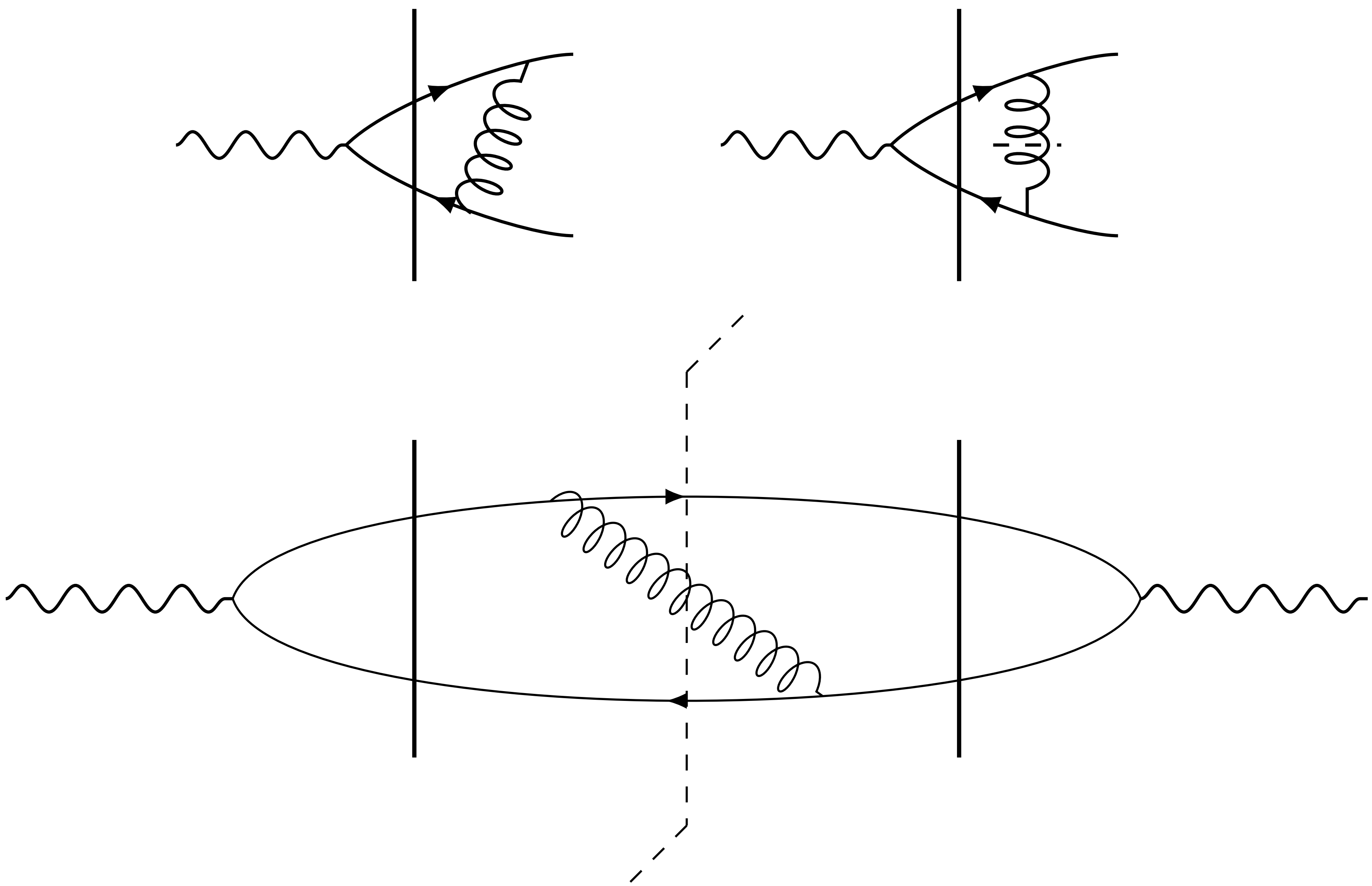
DIS: Caucal, Salazar, Venugopalan (2022)
Dihadron: Bergabo, Jalilian-Marian (2022)
Diffraction: Emilie Li (REF)

UV divergences



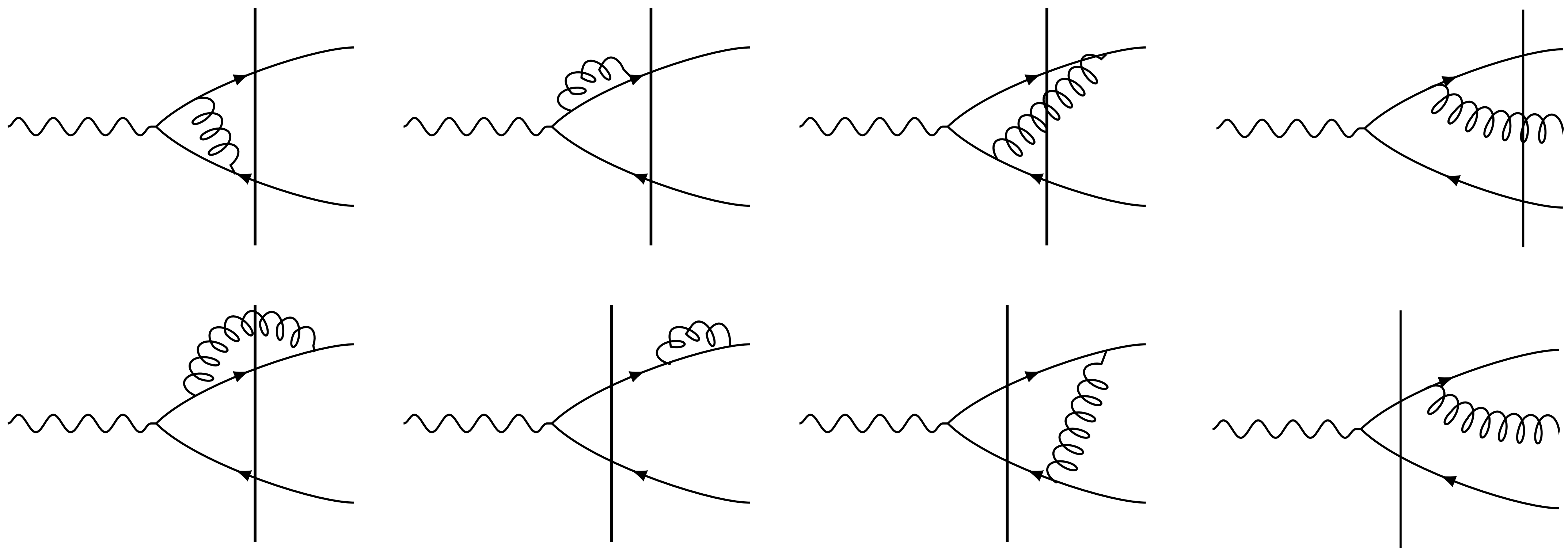
$\mathbf{k}_\perp \to \infty$ in loops, regulated with dimensional regularisation, no leftover logarithms

Soft divergences



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

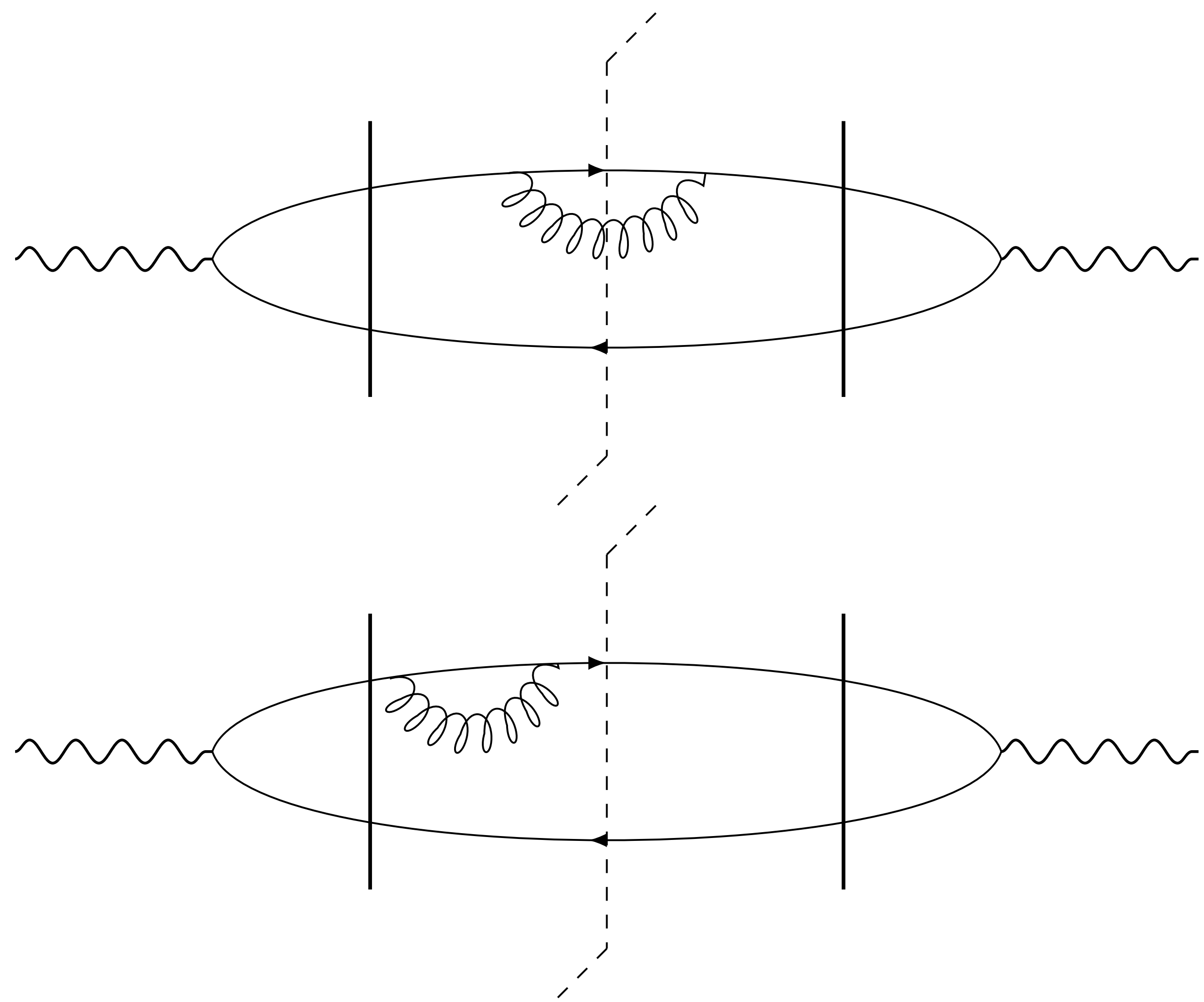
Rapidity divergences



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

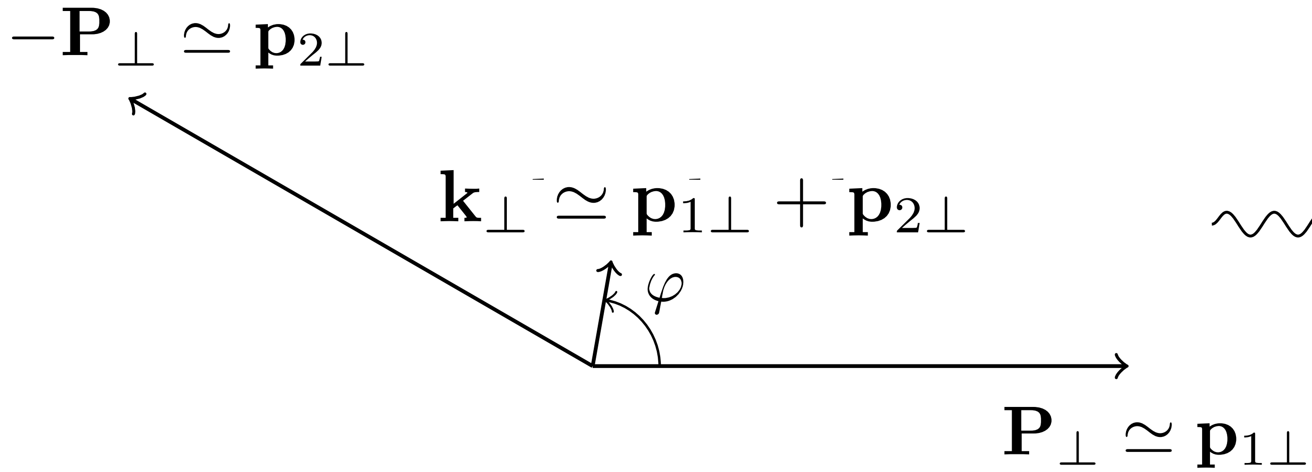
$$\mathrm{d}\sigma_{\mathrm{NLO}} = \int_{k^+_{\min}}^{k_f^+} \frac{\mathrm{d}p_3^+}{p_3^+} \hat{H}_{\mathrm{JIMWLK}} \mathrm{d}\sigma_{\mathrm{LO}} + \int_{k^+_{\min}}^{+\infty} \frac{\mathrm{d}p_3^+}{p_3^+} \left[\mathrm{d}\tilde{\sigma}_{\mathrm{NLO}} - \theta(k_f^+ - p_3^+) \hat{H}_{\mathrm{JIMWLK}}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

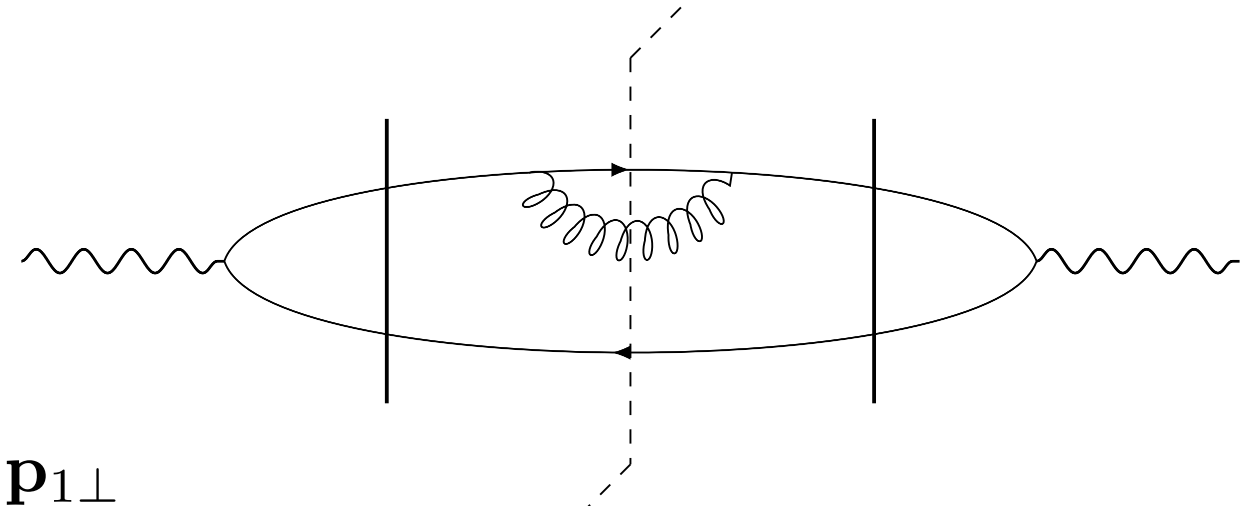
Collinear-soft divergences



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

Back-to-back limit: Sudakov logarithms





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

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

$$\mathbf{P}_\perp^2 \sim \mu^2$$
$$(\mathbf{b}-\mathbf{b}')^2 \sim 1/\mathbf{k}_\perp^2$$

… 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?

Caucal, Salazar, Schenke, Venugopalan (2022)

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!

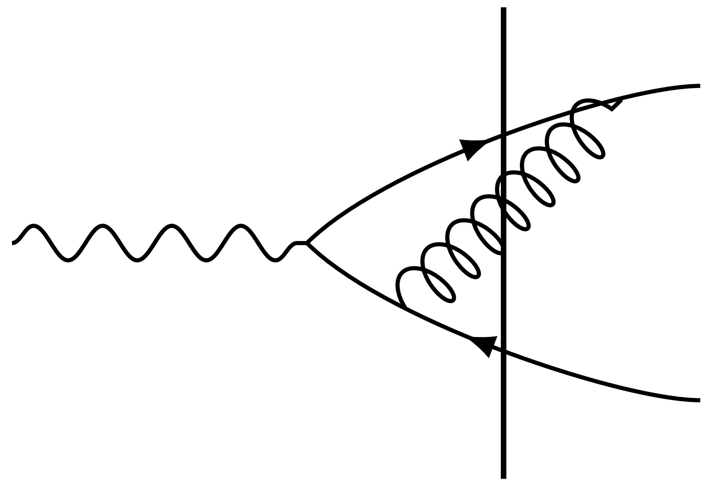
We end up with expected:

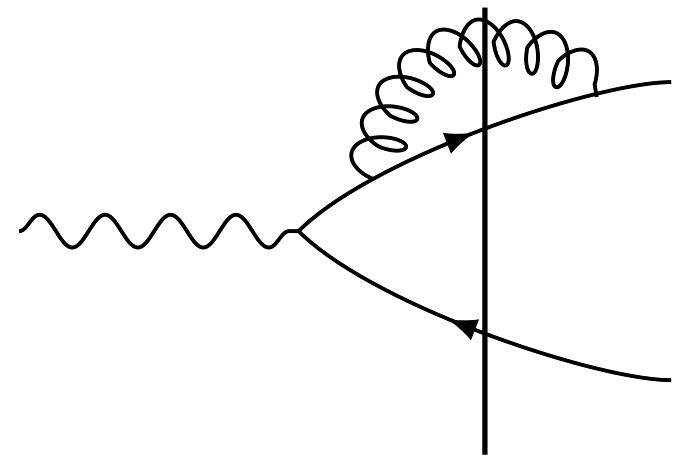
$$\mathrm{d}\sigma^{\mathrm{TMD}}_{\mathrm{NLO}} = \mathrm{d}\sigma^{\mathrm{TMD}}_{\mathrm{LO}} \times -\frac{\alpha_s N_c}{4\pi} \ln\left(\frac{\mathbf{P}^2_\perp (\mathbf{b}-\mathbf{b}')^2}{c_0^2}\right)^2$$

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)

Breaking of TMD factorisation (?)





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

At this point, we need rigorous power-counting à la SCET (Varun Vaidya’s talk)

Caucal, Salazar, Schenke, Venugopalan (2022)

Outlook

Computed full NLO dijet photoproduction cross section in CGC

Recover correct Sudakov logs in TMD limit provided kinematical improved JIMWLK

Argued that k_t -factorisation needs extension when $\mu^2 \gg \mathbf{k}_\perp^2 \sim Q_s^2$
… but then TMD factorisation is seemingly broken beyond LO

Thanks for your attention !