Odderon Mechanism for Transverse Single Spin Asymmetry in pp and pA collisions

Eric Andreas Vivoda (University of Zagreb, Faculty of Science)

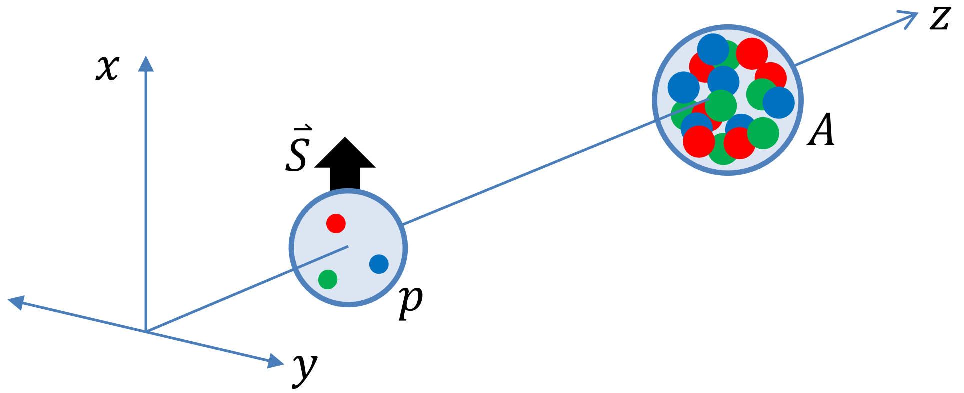
Workshop: REVESTRUCTURE workshop, Zagreb, July 10.-12. 2023.

S. Benić, D. Horvatić, A. Kaushik and **E. A. Vivoda**, Phys. Rev D **106**, 114025 (2022).

Transverse Single Spin Asymmetry

- Left-right asymmetry of produced particles in collisions involving polarized hadrons

- Known to be largest in forward region → small x effects in target



$$A_N \equiv \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$

$$A_N \sim \sin(\varphi_h - \varphi_S)$$

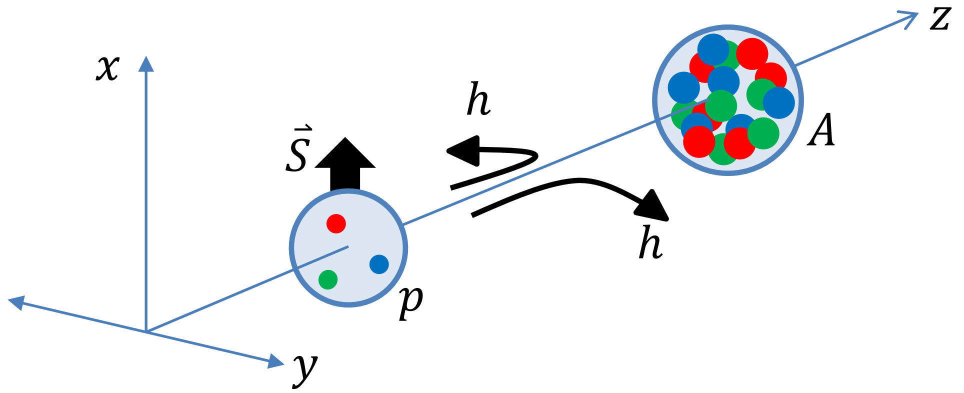
- **Spin vector comes with a factor of i, so to make cross section real, one has to find another factor of i from diagrams!**

S. Benić talk

A.V. Eferemov and O.V. Teryaev, Sov. J. Nucl. Phys. **36**, 140 (1982).

Transverse Single Spin Asymmetry

- Left-right asymmetry of produced particles in collisions involving polarized hadrons
- Known to be largest in forward region → small x effects in target



$$A_N \equiv \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$

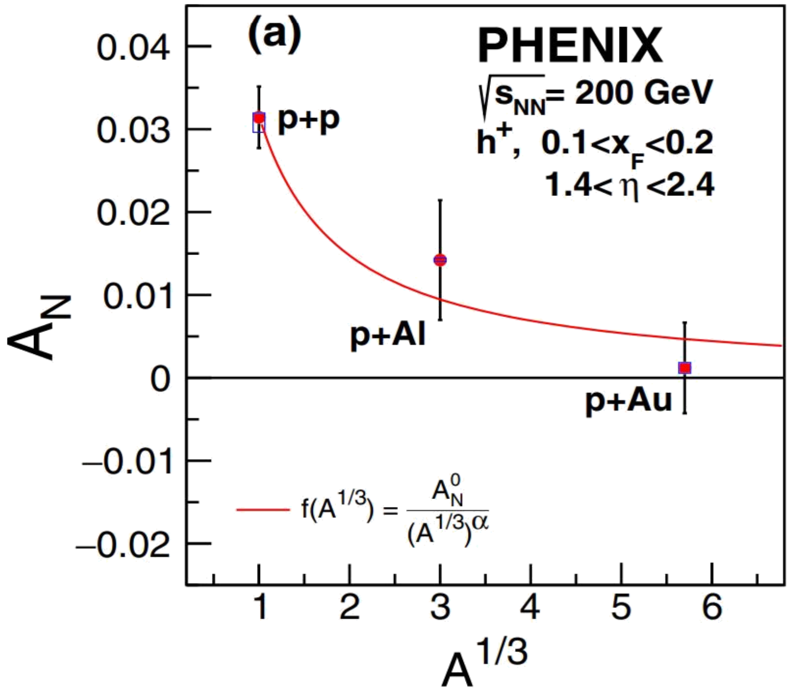
$$A_N \sim \sin(\varphi_h - \varphi_S)$$

- **Spin vector comes with a factor of i, so to make cross section real, one has to find another factor of i from diagrams!**

S. Benić talk

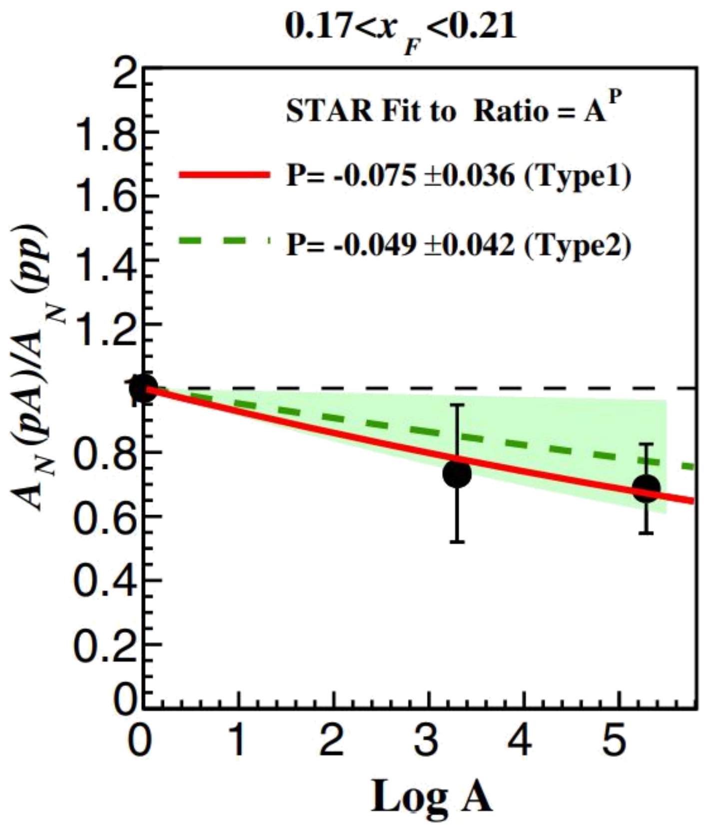
A.V. Eferemov and O.V. Teryaev, Sov. J. Nucl. Phys. **36**, 140 (1982).

TSSA in pA (data):



PHENIX Collaboration, C. Aidala et. al., Phys.Rev.Lett. **123**, 122001 (2019).

Star Collaboration, J. Adam et. al., Phys.Rev.D. **103**, 072005 (2021).



$1.8 < P_{hT} < 7.0$ GeV (integrated)

$0.004 \leq x \leq 0.1$

$$A_N \sim A^{-\frac{1}{3}}$$

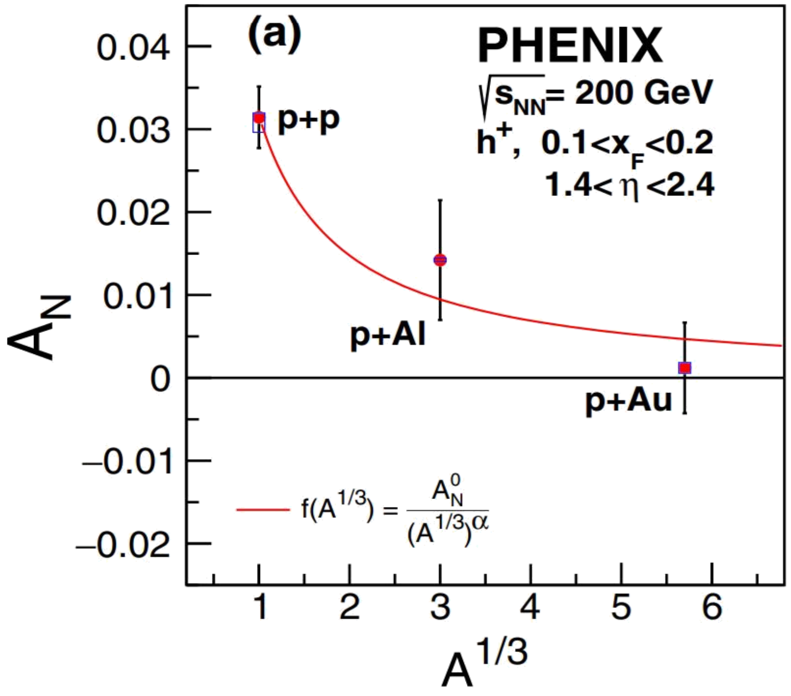
$1.5 < P_{hT} < 2.0$ GeV

$2.0 < P_{hT} < 3.0$ GeV…

$x < 0.005$

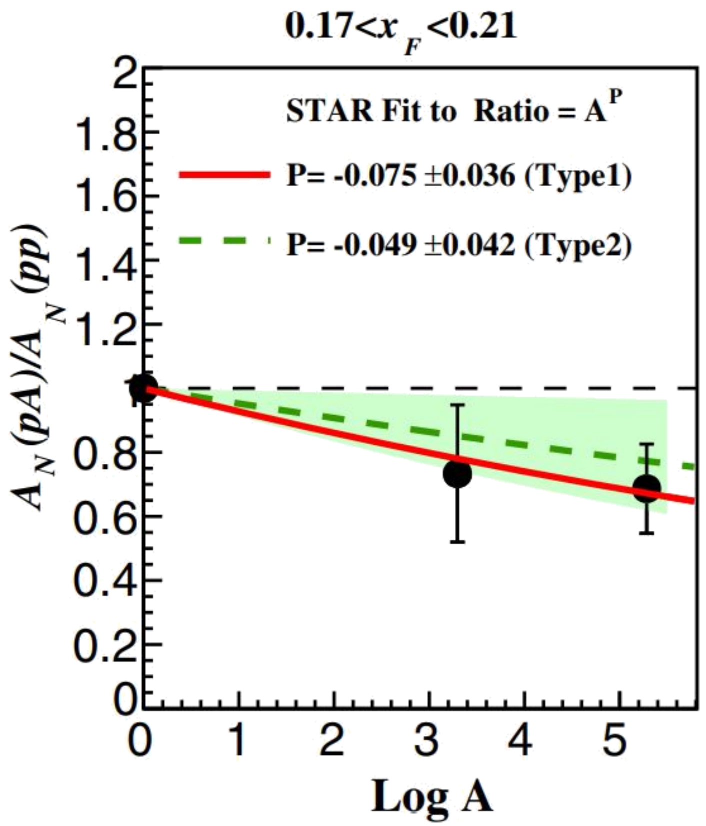
$$A_N \sim A^{-0.027 \pm 0.005}$$

TSSA in pA (data):



PHENIX Collaboration, C. Aidala et. al., Phys.Rev.Lett. **123**, 122001 (2019).

Star Collaboration, J. Adam et. al., Phys.Rev.D. **103**, 072005 (2021).



$1.8 < P_{hT} < 7.0$ GeV (integrated)

$0.004 \leq x \leq 0.1$

$$A_N \sim A^{-\frac{1}{3}}$$

A **dependance!**

$1.5 < P_{hT} < 2.0$ GeV

$2.0 < P_{hT} < 3.0$ GeV...

$x < 0.005$

$$A_N \sim A^{-0.027 \pm 0.005}$$

CGC in pA collisions:

C SU(3) charge

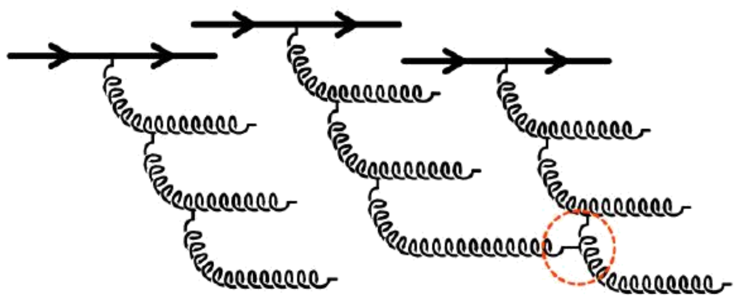
G $\Delta x^{+} \propto x$ (spin glass)

C Lot of gluons

↘

Classicall YM equations!

- Small x in nuclei (**Color Glass Condensate** (CGC) framework)
  - Effects of small-x and spin physics combined!
  - Small x gluons dominate in the description of collision



F. Gelis, 1211.3327

$$\Gamma_{gg\to g} = \frac{\alpha_S N_C}{(N_C^2-1)Q^2}\frac{x f_g(x,Q^2)}{\pi R^2} \approx 1 \longrightarrow$$ Q_s- Saturation scale

$$(Q_s^A)^2 = A^{\frac{1}{3}}(Q_s^p)^2 \longrightarrow$$ ***A* dependance!**

A. Perkov talk

S. Wallon talk

CGC in pA collisions:

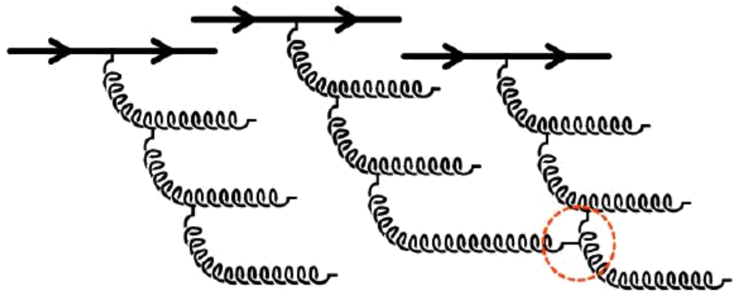
- Small x in nuclei (**Color Glass Condensate** (CGC) framework)
  - ➢ Effects of small-x and spin physics combined!
  - ➢ Small x gluons dominate in the description of collision

C SU(3) charge

G $\Delta x^+ \propto x$ (spin glass)

C Lot of gluons

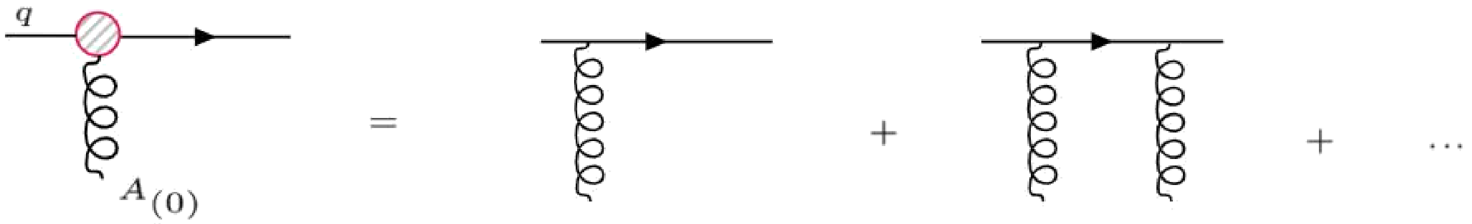
↘ Classicall YM equations!



F. Gelis, 1211.3327

$$\Gamma_{gg\to g} = \frac{\alpha_S N_C}{(N_C^2-1)Q^2}\frac{x f_g(x,Q^2)}{\pi R^2} \approx 1 \longrightarrow$$ Q_S- Saturation scale

$$(Q_S^A)^2 = A^{\frac{1}{3}}(Q_S^p)^2 \longrightarrow$$ **A dependance!**

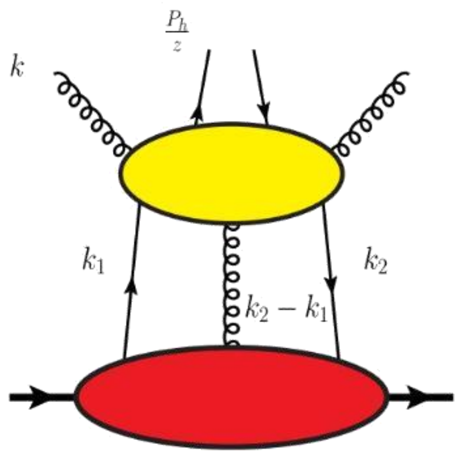


$\propto (V(x_\perp)-1) \longrightarrow$ Wilson line

ETQS mechanism in pA

Hybrid approach:

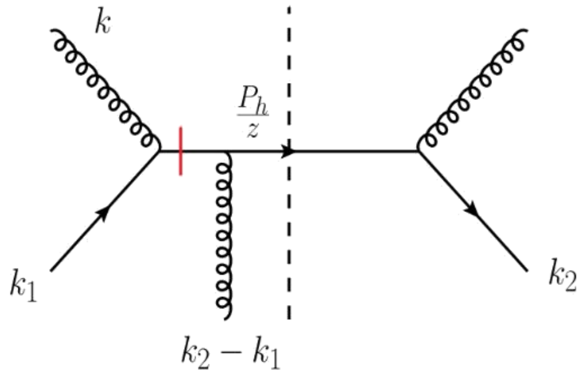
- Eferemov-Teryaev-Qiu-Sterman (ETQS) functions for projectile
- Unintegrated gluon distribution for target



$$\frac{d^3\Delta\sigma(p^\uparrow A \to hX)}{dy_h d^2 P_{h\perp}} = \epsilon^{\alpha\beta} P_{h\alpha} S_{\perp\beta} \times \int_{x_f} \frac{dz}{z^2} D_{h/q}(z) G_F(x_p, x_p) \otimes F(x_g, P_{h\perp}/z)$$

$$G_F \propto \langle \psi F \bar{\psi} \rangle$$

$$\frac{d\sigma^{SGP}}{dy_h d^2 P_{h\perp}} = \frac{\pi M x_F}{2(N_C^2 - 1)} \epsilon^{\alpha\beta} S_{\perp\beta} \int_{x_F}^{1} \frac{dz}{z^3} D(z) \left\{ -\frac{1}{(P_{h\perp}/z)^2} \times \frac{\partial}{\partial(P_h^\alpha/z)} \left(\frac{P_{h\perp}^2}{z^2} F(x_g, P_{h\perp}/z) \right) G_F(x,x) + \frac{2P_{h\alpha}/z}{(P_{h\perp}/z)^2} F(x_g, P_{h\perp}/z) x \frac{d}{dx} G_F(x,x) \right\}$$



SGP = Soft-gluon pole

$$\frac{A_N^{pp}}{A_N^{pA}} \approx 1$$

Phenix data can't be explained

Y. Hatta, B.-W. Xiao, S. Yoshida and F. Yuan, Phys. Rev. D **94**, 054013 (2016).

J. W. Qiu and G.F. Sterman, Phys. Rev. Lett. **67**, 2264 (1991).

A.V. Efremov and O.V. Teryaev, Phys. Lett. B **150**, 383 (1985).

Odderon mechanism for TSSA

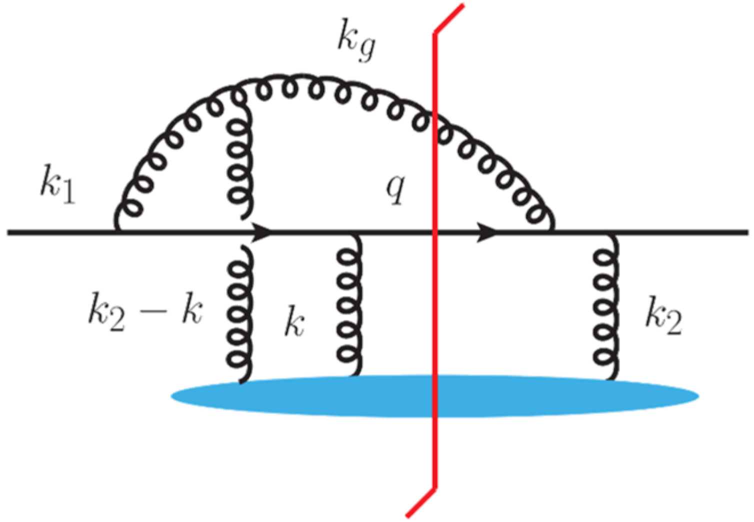
- **Odderon** = imaginary part of **dipole distribution function**

$$\mathcal{S}(\boldsymbol{x}_\perp, \boldsymbol{x}'_\perp) \equiv \frac{1}{N_C} \mathrm{tr}\left\langle V(\boldsymbol{x}_\perp) V^\dagger(\boldsymbol{x}'_\perp) \right\rangle \qquad \mathcal{S}(\boldsymbol{x}_\perp, \boldsymbol{x}'_\perp) \equiv \mathcal{P}(\boldsymbol{x}_\perp, \boldsymbol{x}'_\perp) + i\mathcal{O}(\boldsymbol{x}_\perp, \boldsymbol{x}'_\perp)$$

- Wilson lines come from the CGC propagator
- Odderon can supply necessary phase!
- Calculated at parton level (qA collisions)

Y. V. Kovchegov and M. D. Sievert, Phys. Rev. D **86**, 034028 (2012).

- We need interference diagrams to get non-zero contributions to TSSA (there is no LO contribution)



$$E_q \frac{d\Delta\sigma}{d^3 q} \propto i\alpha_S \int_{\boldsymbol{k}_\perp \boldsymbol{k}_{2\perp}} \int_{\boldsymbol{r}_\perp \boldsymbol{b}_\perp \boldsymbol{r'}_\perp}$$

$$\times \left[\mathcal{P}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp)\mathcal{O}(\boldsymbol{r'}_\perp, \boldsymbol{b'}_\perp) - \mathcal{O}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp)\mathcal{P}(\boldsymbol{r'}_\perp, \boldsymbol{b'}_\perp)\right] \mathcal{H}(\boldsymbol{r}_\perp, \boldsymbol{r'}_\perp, \boldsymbol{S}_\perp)$$

- Result: $A_N \propto A^{-\frac{7}{6}}$

- What will change when we go from partonic to hadronic level?

- What is responsible PDF?

$$\boldsymbol{r}_\perp = \boldsymbol{x}_\perp - \boldsymbol{y}_\perp$$

$$\boldsymbol{b}_\perp = \frac{1}{2}(\boldsymbol{x}_\perp + \boldsymbol{y}_\perp)$$

$$\boldsymbol{b}_\perp - \boldsymbol{b'}_\perp = \frac{1}{2}(\boldsymbol{r}_\perp + \boldsymbol{r'}_\perp)$$

Y. V. Kovchegov and M. D. Sievert, Phys. Rev. D **86**, 034028 (2012).

Polarized cross section in pA collisions

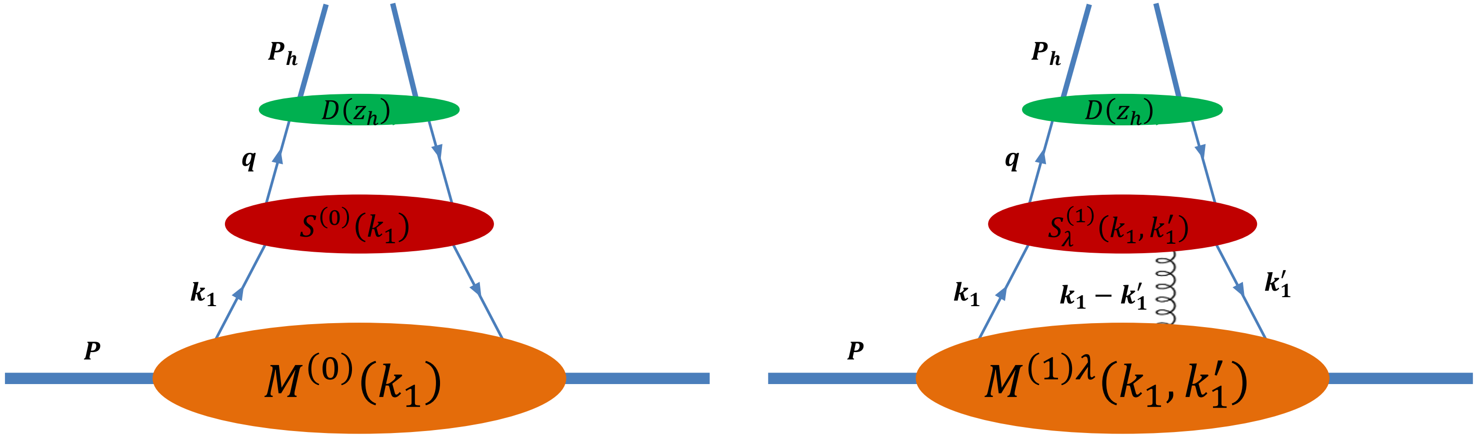
S. Benić, Y. Hatta, H. Li, D.J. Yang,
Phys. Rev. D **100**, 094027 (2019).

All order formula for twist-3 cross section:

$$E_h \frac{d\Delta\sigma}{d^3P_h} = \frac{1}{2(2\pi)^3}\int \frac{dz_h}{z_h^2} D(z_h)\left\{\frac{M_N}{2}\int dx_p g_T(x_p) \mathrm{Tr}[\gamma_5 \not{S}_\perp S^{(0)}(p_1)] + \right. \quad \longrightarrow \text{Intrinsic}$$

$$\frac{M_N}{2}\int dx_p \mathrm{Tr}\left[\left(\gamma_5 \not{P}_p S_\perp^\lambda g_{1T}^{(1)}(x_p) + \epsilon^{\lambda\bar{n}nS_\perp}\not{P}_p f_{1T}^{(1)}(x_p)\right)\left(\frac{\partial S^{(0)}(k_1)}{\partial k_{1\perp}^\lambda}\right)_{k_1=p_1}\right] + \quad \longrightarrow \text{Kinematical}$$

$$\left.\frac{iM_N}{4}\int dx_p dx_p' \mathrm{Tr}\left[\left(\not{P}_p \epsilon^{\bar{n}n\lambda S_\perp}\frac{G_F(x_p,x_p')}{x_p - x_p'} + i\gamma_5 \not{P}_p S_\perp^\lambda \frac{\tilde{G}_F(x_p,x_p')}{x_p - x_p'}\right) S_\lambda^{(1)}(x_p P_p, x_p' P_p)\right]\right\} \quad \longrightarrow \text{Dynamical}$$



$$g_T(x) = \int_x^1 \frac{dx'}{x'}\Delta_q(x') + \cdots$$

↓ Helicity quark PDF

Wandzura – Wilczek approximation

- Neglect all genuine twist-3 contributions $x g_T(x) \approx g_{1T}^{(1)}(x)$ + Twist-3

$$E_h \frac{\mathrm{d}\Delta\sigma}{\mathrm{d}^3 P_h} \simeq \frac{1}{2(2\pi)^3} \frac{M_N}{2} \int \frac{\mathrm{d}z_h}{z_h^2} D(z_h) \int dx_p\, g_T(x_p) \times \left(S_\perp^\lambda \frac{\partial}{\partial k_{1\perp}^\lambda} \mathrm{tr}[\gamma_5 \not{k}_1 S^{(0)}(k_1)] \right)_{k_1 = p_1}$$

- This is our MASTER formula

- $S^{(0)}(\mathrm{k}_1)$ is calculated in perturbation theory

- First two contributions
  1. $q \to q$ Real contribution (integration over final state gluon)
  2. $q \to q$ Virtual contribution

Wandzura – Wilczek approximation

- Neglect all genuine twist-3 contributions

$x g_T(x) \approx g_{1T}^{(1)}(x) + \text{Twist-3}$

$$E_h \frac{d\Delta\sigma}{d^3 P_h} \simeq \frac{1}{2(2\pi)^3} \frac{M_N}{2} \int \frac{dz_h}{z_h^2} D(z_h) \int dx_p\, g_T(x_p) \times \left(S_\perp^\lambda \frac{\partial}{\partial k_{1\perp}^\lambda} \mathrm{tr}\left[\gamma_5 \not{k}_1 S^{(0)}(k_1)\right] \right)_{k_1 = p_1}$$

- This is our MASTER formula

- $S^{(0)}(\mathrm{k}_1)$ is calculated in perturbation theory

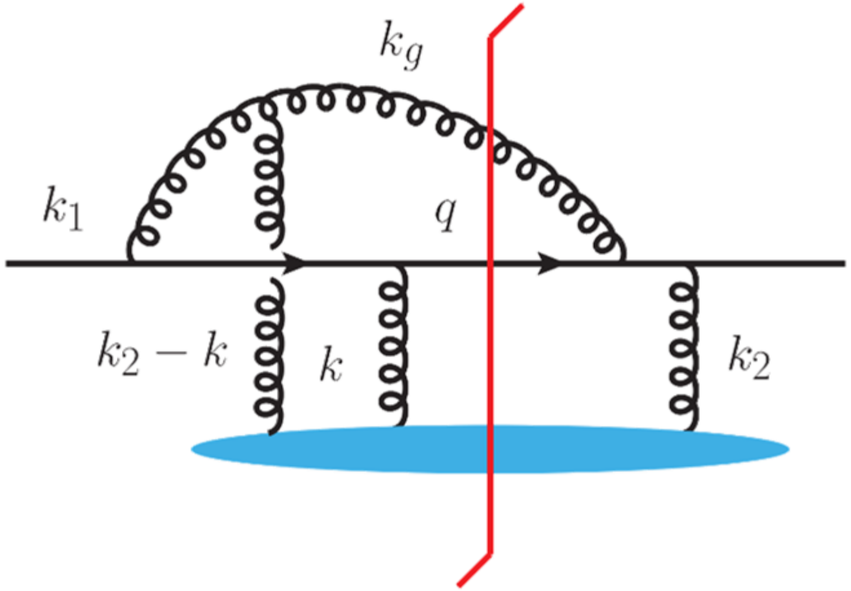
- First two contributions
  1. $q \to q$ Real contribution (integration over final state gluon)
  2. $q \to q$ Virtual contribution

Diagrams!

$q \to q$ Real contribution

S. Benić, D. Horvatić, A. Kaushik and E. A. Vivoda, Phys. Rev D **106**, 114025 (2022).

- We need interference diagrams:



- Extraction of $S^0(k_1)$:

$$S^{(0)}(k_1) = \frac{q^+}{P_p^+}\frac{g^2 C_F}{4q^+k_g^+}\int_{\boldsymbol{k}_{g\perp}\boldsymbol{k}_\perp\boldsymbol{k}'_\perp}\int_{\boldsymbol{x}_\perp\boldsymbol{x}'_\perp\boldsymbol{y}_\perp\boldsymbol{y}'_\perp} e^{i\boldsymbol{k}_\perp\cdot\boldsymbol{x}_\perp}\, e^{i(\boldsymbol{k}_{2\perp}-\boldsymbol{k}_\perp)\cdot\boldsymbol{y}_\perp} \times e^{-i\boldsymbol{k}'_\perp\cdot\boldsymbol{x}'_\perp} e^{-i(\boldsymbol{k}_{2\perp}-\boldsymbol{k}'_\perp)\cdot\boldsymbol{y}'_\perp} d_{\mu\mu'}(k_g)$$

$$\times\Big[\mathcal{S}(\boldsymbol{x}_\perp,\boldsymbol{x}'_\perp)\bar{T}_q^{\mu'}\not{q}T_q^{\mu} + \mathcal{S}_{qqg}(\boldsymbol{x}'_\perp,\boldsymbol{x}_\perp,\boldsymbol{y}'_\perp)\bar{T}_{qg}^{\mu'}(\boldsymbol{k}'_\perp)\not{q}T_q^{\mu}$$

$$+\mathcal{S}_{qqg}(\boldsymbol{x}'_\perp,\boldsymbol{x}_\perp,\boldsymbol{y}_\perp)\bar{T}_q^{\mu'}\not{q}T_{qg}^{\mu}(\boldsymbol{k}_\perp) + \mathcal{S}_{qgqg}(\boldsymbol{x}'_\perp,\boldsymbol{y}'_\perp,\boldsymbol{x}_\perp,\boldsymbol{y}_\perp)\bar{T}_{qg}^{\mu'}(\boldsymbol{k}'_\perp)\not{q}T_{qg}^{\mu}(\boldsymbol{k}_\perp)\Big]$$

- After final state gluon integration (and due to C-parity) only interference terms survive, so the trace takes following form:

$$\mathrm{tr}\big[\gamma_5 \not{k}_1 S^{(0)}(k_1)\big] = \frac{q^+}{P_p^+} g^2 C_F \int_{\boldsymbol{k}_{g\perp}\boldsymbol{k}_\perp \boldsymbol{k}'_\perp} \int_{\boldsymbol{x}_\perp \boldsymbol{x}'_\perp \boldsymbol{y}_\perp \boldsymbol{y}'_\perp} e^{i\boldsymbol{k}_\perp\cdot\boldsymbol{x}_\perp} e^{i(\boldsymbol{k}_{2\perp}-\boldsymbol{k}_\perp)\cdot\boldsymbol{y}_\perp} e^{-i\boldsymbol{k}'_\perp\cdot\boldsymbol{x}'_\perp} e^{-i(\boldsymbol{k}_{2\perp}-\boldsymbol{k}'_\perp)\cdot\boldsymbol{y}'_\perp} \times \left[-\mathcal{S}_{qqg}(\boldsymbol{x}'_\perp,\boldsymbol{x}_\perp,\boldsymbol{y}'_\perp)\mathcal{H}(\boldsymbol{k}'_\perp,\boldsymbol{k}_{1\perp}) + \mathcal{S}_{qqg}(\boldsymbol{x}'_\perp,\boldsymbol{x}_\perp,\boldsymbol{y}_\perp)\mathcal{H}(\boldsymbol{k}_\perp,\boldsymbol{k}_{1\perp})\right]$$

$$\mathcal{H}(\boldsymbol{k}_\perp,\boldsymbol{k}_{1\perp}) \equiv \frac{1}{4q^+k_g^+} d_{\mu\mu'}(k_g)\mathrm{Tr}[\gamma_5 \not{k}_1 \bar{T}_q^{\mu} \not{q} \bar{T}_{qg}^{\mu'}(\boldsymbol{k}_\perp)]$$

$$\mathcal{S}_{qqg}(\boldsymbol{x}'_\perp,\boldsymbol{x}_\perp,\boldsymbol{y}'_\perp) = \frac{1}{2C_F N_C}\left(N_C^2 \mathcal{S}(\boldsymbol{y}'_\perp,\boldsymbol{x}'_\perp)\mathcal{S}(\boldsymbol{x}_\perp,\boldsymbol{y}'_\perp) - \mathcal{S}(\boldsymbol{x}_\perp,\boldsymbol{x}'_\perp)\right)$$

→ Dipole distribution

S. Benić, D. Horvatić, A. Kaushik and E. A. Vivoda, Phys. Rev D **106**, 114025 (2022).

- Hard factor is easy to calculate:

$$\mathrm{tr}[\gamma_5 \not{k}_1 S^{(0)}(k_1)] = ig^2 N_C \frac{q^+}{P_p^+} \int_{\boldsymbol{k}_{2\perp}\boldsymbol{k}_\perp} \int_{\boldsymbol{x}_\perp \boldsymbol{x}'_\perp \boldsymbol{y}_\perp} \mathrm{e}^{i\boldsymbol{k}_\perp \cdot (\boldsymbol{x}_\perp - \boldsymbol{y}_\perp)} \mathrm{e}^{-i\boldsymbol{k}_{2\perp} \cdot (\boldsymbol{x}'_\perp - \boldsymbol{y}_\perp)}$$
$$\times [\mathcal{P}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp) \mathcal{O}(\boldsymbol{x}'_\perp, \boldsymbol{y}_\perp) - \mathcal{O}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp) \mathcal{P}(\boldsymbol{x}'_\perp, \boldsymbol{y}_\perp)] \mathcal{H}(\boldsymbol{k}_\perp, \boldsymbol{k}_{1\perp})$$

$$\mathcal{H}(\boldsymbol{k}_\perp, \boldsymbol{k}_{1\perp}) = 4i(\bar{z}+1) \frac{\boldsymbol{v}_{1\perp} \times \boldsymbol{v}_{2\perp}}{\boldsymbol{v}_{1\perp}^2 \boldsymbol{v}_{2\perp}^2}$$

→ Manifestly finite

$$\boldsymbol{v}_{1\perp} \equiv \boxed{\boldsymbol{q}_\perp - \bar{z}\boldsymbol{k}_{1\perp}} - \bar{z}\boldsymbol{k}_{2\perp}$$
$$\boldsymbol{v}_{2\perp} \equiv \boxed{\boldsymbol{q}_\perp - \bar{z}\boldsymbol{k}_{1\perp}} - \boldsymbol{k}_\perp$$

⇒ **Same vectors!**

S. Benić, D. Horvatić, A. Kaushik and E. A. Vivoda, Phys. Rev D **106**, 114025 (2022).

There is no polarized cross section!

- To get a usual sine modulation we need a **reference vector**:

$$q_\perp \times S_\perp$$

- Our proxy for $S_\perp$ is $k_{1\perp}$ (because of the derivative)

- In our calculation $q_\perp$ and $k_{1\perp}$ appear in unique combination:

$$q_{1\perp} = q_\perp - \bar{z} k_{1\perp}$$

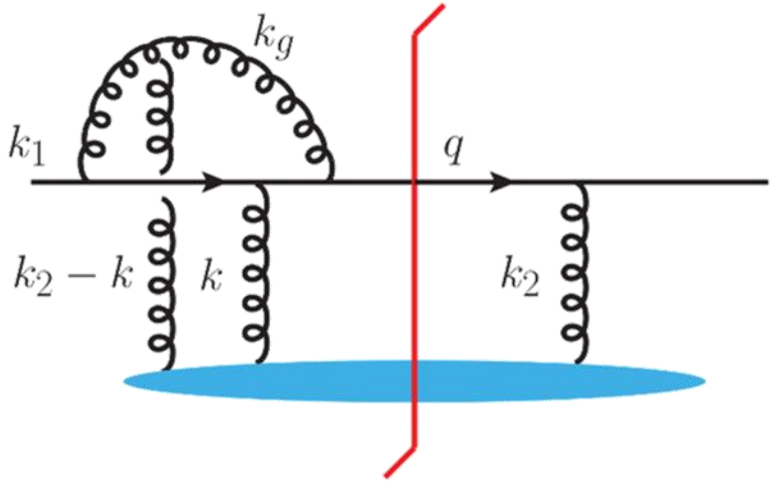
$$\mathbf{d\Delta\sigma_{WW} = 0}$$

➢ There is no polarized cross section in this channel!

S. Benić, D. Horvatić, A. Kaushik and E. A. Vivoda, Phys. Rev D **106**, 114025 (2022).

$q \to q$ Virtual contribution

- Interference with leading order amplitude:



$$\boldsymbol{v}_{1\perp} \equiv y\boldsymbol{q}_\perp - \boldsymbol{k}_{g\perp}$$

$$\boldsymbol{v}_{2\perp} \equiv \boldsymbol{k}_\perp + \bar{y}\boldsymbol{k}_{1\perp} + \boldsymbol{k}_{g\perp} - \boldsymbol{q}_\perp$$

$$y = \frac{z}{\bar{z}}$$

- Same manipulations as before lead to:

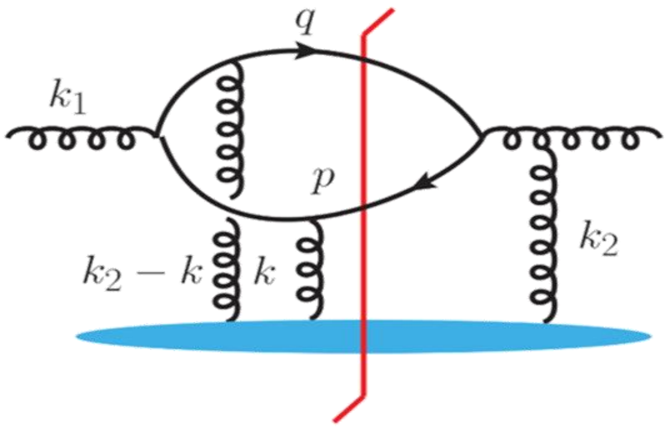
$$\mathcal{H}(\boldsymbol{k}_\perp, \boldsymbol{k}_{1\perp}) = -4i(\bar{y} + 1)\frac{\boldsymbol{v}_{1\perp} \times \boldsymbol{v}_{2\perp}}{\boldsymbol{v}_{1\perp}^2 \boldsymbol{v}_{2\perp}^2}$$

Integration over virtual gluon transverse momentum:

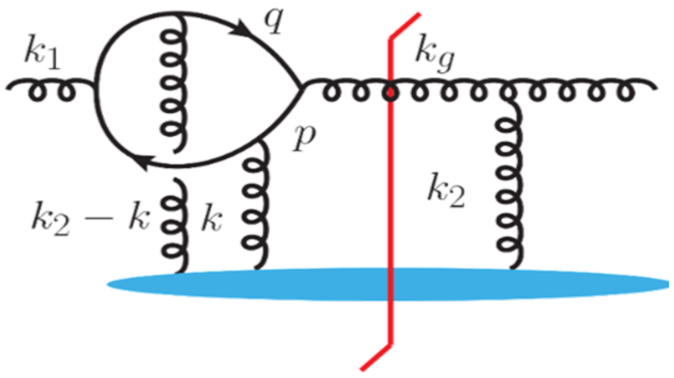
$$\mathbf{d}\Delta\boldsymbol{\sigma}_{WW} = \mathbf{0}$$

S. Benić, D. Horvatić, A. Kaushik and E. A. Vivoda, Phys. Rev D **106**, 114025 (2022).

Gluon initiated channels



$g \to q\bar{q}$



$g \to g$

- There is no $g \to gg$ contribution because adjoint Wilson lines are real
- In Wandzura – Wilczek approximation there is no TSSA in above channels

$$\mathbf{d\Delta\sigma_{WW} = 0}$$

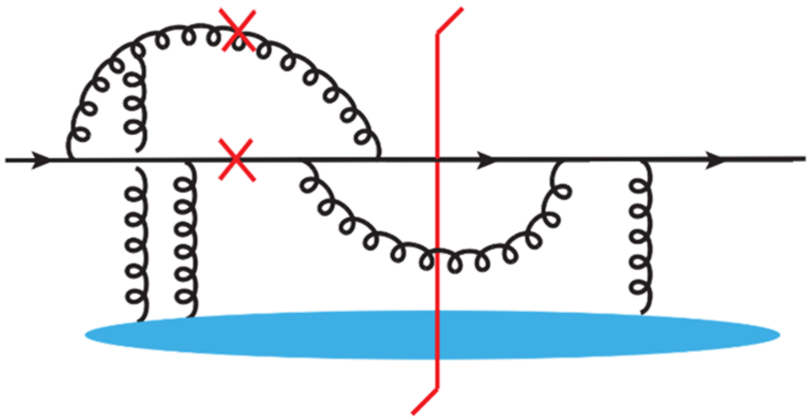
S. Benić, D. Horvatić, A. Kaushik and E. A. Vivoda, Phys. Rev D **106**, 114025 (2022).

Is there any odderon contribution?

1. Going beyond WW approximation
   a) Taking the real distribution in target (pomeron) and the phase from the cut of the propagator
   b) Principal value of the propagator and phase from the odderon

$$\frac{1}{k^2 + i\epsilon} = P\frac{1}{k^2} - i\pi\delta(k^2)$$

2. NNLO -> competing mechanisms (lensing vs. odderon)



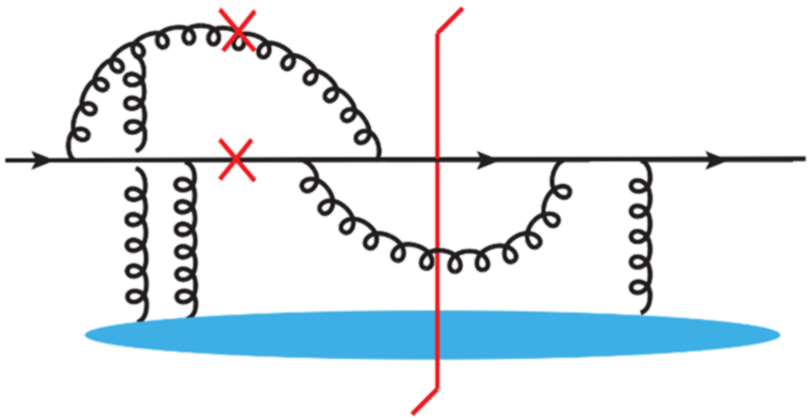
Y.V. Kovchegov and M.G. Santiago, Phys. Rev D **102**, 014022 (2020).

Is there any odderon contribution?

1. Going beyond WW approximation
   a) Taking the real distribution in target (pomeron) and the phase from the cut of the propagator
   b) Principal value of the propagator and phase from the odderon

$$\frac{1}{k^2 + i\epsilon} = P\frac{1}{k^2} - i\pi\delta(k^2)$$

2. NNLO -> competing mechanisms (lensing vs. odderon)



Y.V. Kovchegov and M.G. Santiago, Phys. Rev D **102**, 014022 (2020).

Going beyond WW approximation

- Possible LO contribution

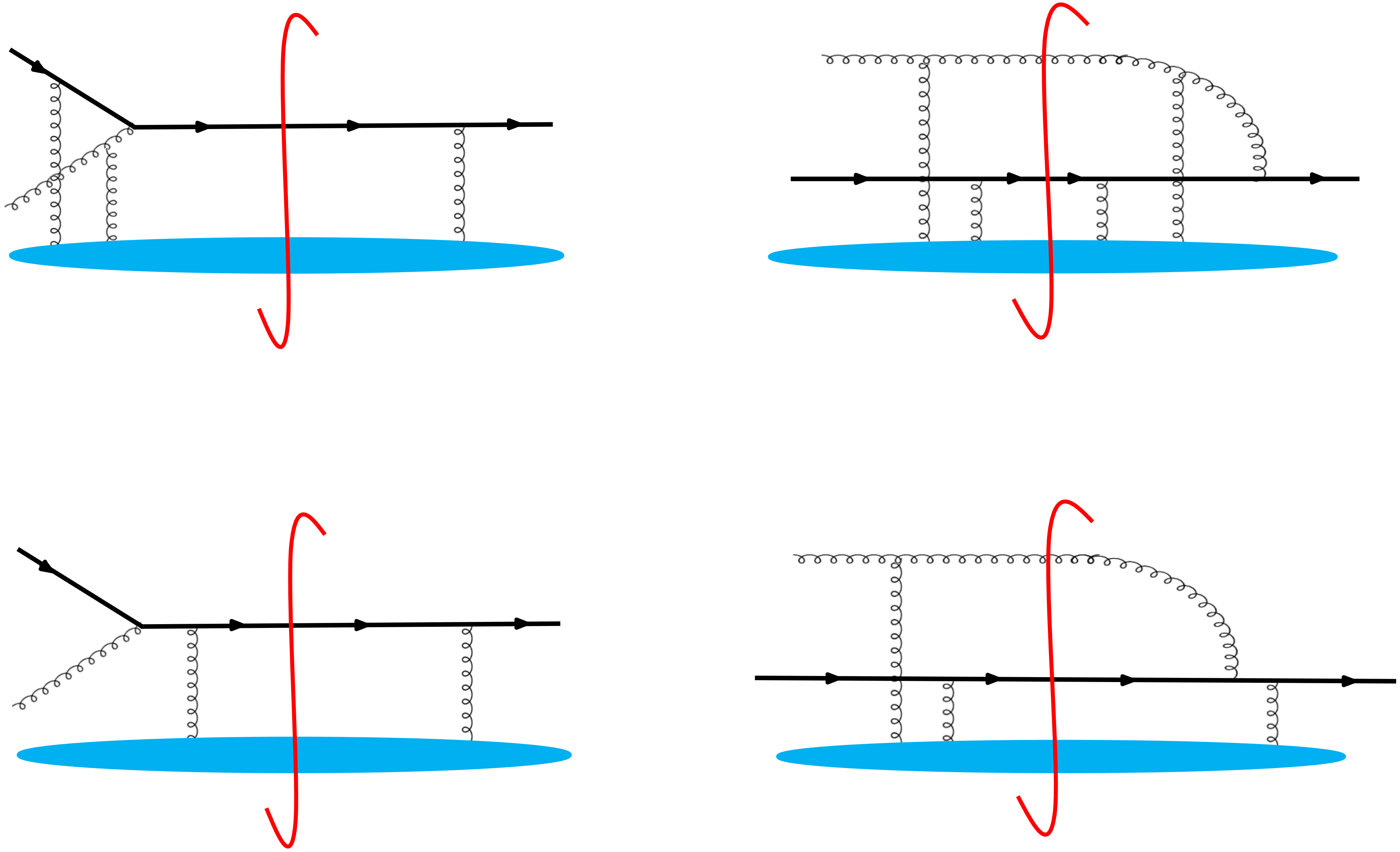
- In LO $S^{(0)}(k_1)$ can contribute only by Sievers term:

$$E_h \frac{d\Delta\sigma}{d^3P_h} = \frac{1}{2(2\pi)^3} \frac{M_N}{2} \int \frac{dz_h}{z_h^2} D(z_h) \int dx_p dx_p' \,\mathrm{Tr}\left[\epsilon^{\lambda\bar{n}nS_\perp} \not{P}_p f_{1T}^{\perp(1)}(x_p) \left(\frac{\partial S^{(0)}(k_1)}{\partial k_{1\perp}^{\lambda}}\right)_{k_1=p_1} \right.$$

$$\left. + \frac{i}{2}\left(\not{P}_p \epsilon^{\bar{n}n\lambda S_\perp} \frac{G_F(x_p, x_p')}{x_p - x_p'} + i\gamma_5 \not{P}_p S_\perp^{\lambda} \frac{\tilde{G}_F(x_p, x_p')}{x_p - x_p'}\right) S_\lambda^{(1)}(x_p P_p, x_p' P_p)\right]$$

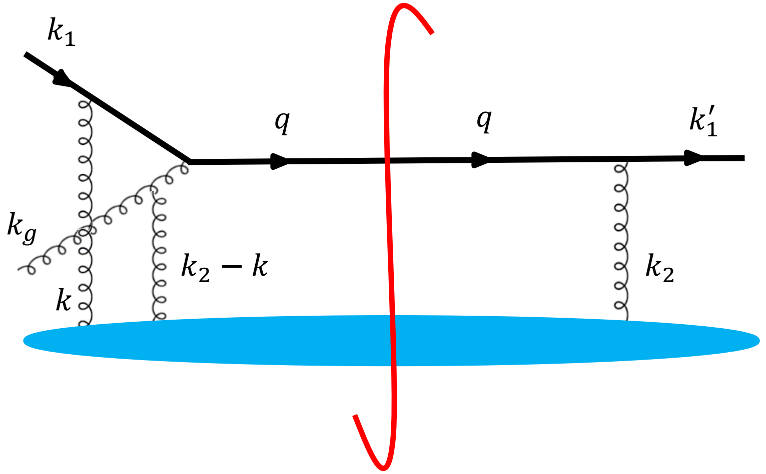
- We need to calculate $S_\lambda^{(1)}(x_p P_p, x_p' P_p)$ from perturbation theory

Possible LO contributions:



Amplitudes:

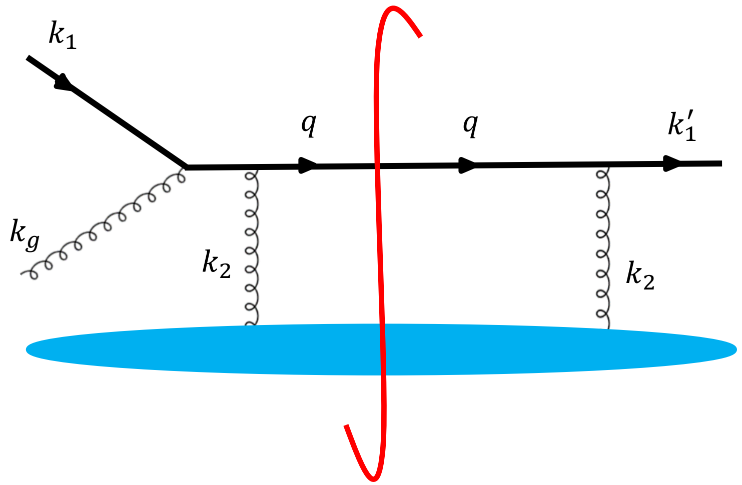
$$T^{\mu}_{qg}(k_\perp) = q^+ k_g^+ \gamma^\nu (\not{k}_1 + \not{k}) \gamma^+ \times \frac{d^{\mu}_{\nu}(q - k_1 - k)}{\left(k_1^+ \boldsymbol{q}_\perp - q^+(\boldsymbol{k}_{1\perp} + \boldsymbol{k}_\perp)\right)}$$

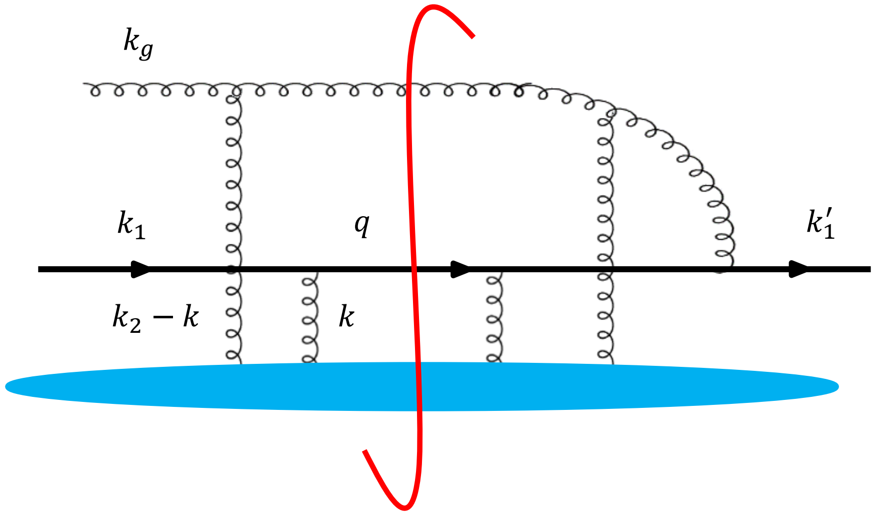


$$\mathcal{M}^{\mu}_{qg\to q} = ig \int_{\boldsymbol{k}_\perp} \int_{\boldsymbol{x}_\perp} \int_{\boldsymbol{y}_\perp} e^{i\boldsymbol{k}_\perp \cdot \boldsymbol{x}_\perp} e^{i(\boldsymbol{k}_{2\perp} - \boldsymbol{k}_\perp)\cdot \boldsymbol{y}_\perp} \left[T^{\mu}_{q} V(\boldsymbol{x}_\perp) t^a + T^{\mu}_{qg}(\boldsymbol{k}_\perp) t^b V(\boldsymbol{x}_\perp) U^{ba}(\boldsymbol{y}_\perp)\right]$$

$$\mathcal{M}_{q\to q} = -i\gamma^+ V(\boldsymbol{k}_{2\perp})$$

$$T^{\mu}_{q} = \gamma^+ \frac{\not{k}_1 + \not{k}_g}{(k_1 + k_g)^2} \gamma^\mu$$

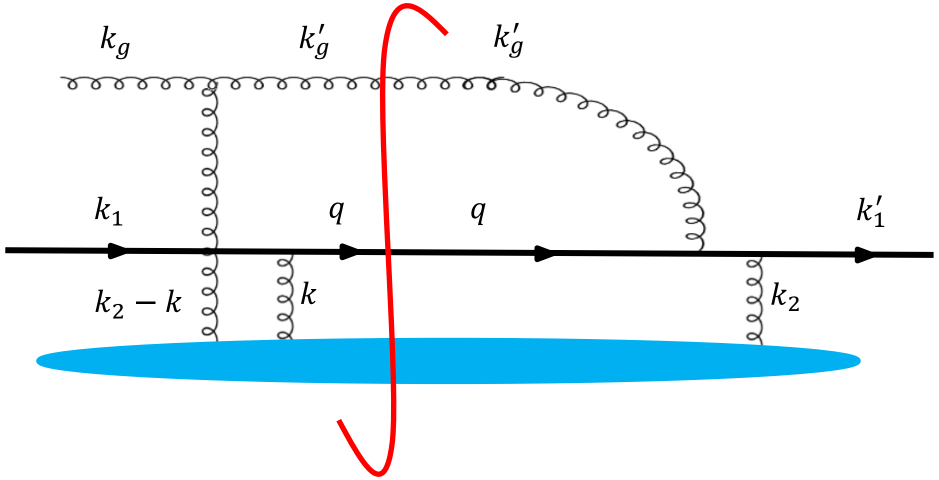




$$T^{\mu}_{qg}(k_\perp) = k_1^+ k_g^+ \gamma^+ (\not{q} - \not{k}) \gamma^\nu \times \frac{d^\mu_{\ \nu}(k_1 - q + k)}{\left(q^+ \boldsymbol{k}_{1\perp} + k_1^+ (\boldsymbol{k}_\perp - \boldsymbol{q}_\perp)\right)}$$

$$\mathcal{M}_{qg\to qg} = -2k_g^+ \gamma^+ \times V(\boldsymbol{k}_\perp) U^{ab}(\boldsymbol{k}_{2\perp} - \boldsymbol{k}_\perp)$$

$$\mathcal{M}^{\mu}_{q\to qg} = ig \int_{\boldsymbol{k}_\perp} \int_{\boldsymbol{x}_\perp} \int_{\boldsymbol{y}_\perp} e^{i\boldsymbol{k}_\perp \cdot \boldsymbol{x}_\perp} e^{i(\boldsymbol{k}_{2\perp} - \boldsymbol{k}_\perp)\cdot \boldsymbol{y}_\perp} \left[T^{\mu}_{q} t^a V(\boldsymbol{x}_\perp) + T^{\mu}_{qg}(\boldsymbol{k}_\perp) V(\boldsymbol{x}_\perp) t^b U^{ab}(\boldsymbol{y}_\perp) \right]$$



$$T^{\mu}_{q} = \gamma^\mu \frac{\not{q} + \not{k}_g}{(q + k_g)^2} \gamma^+$$

Further tasks:

1. Extract $S_{\lambda}^{(1)}\left(x_p P_p, x_p' P_p\right)$

2. Check for possible pole contribution and compare with old results

3. Calculate Odderon contribution

Conclusions:

- Odderon mechanism for TSSA at hadron level
- Wandzura – Wilczek approximation (intrinsic and kinematical contribution)
- There is no TSSA at LO and NLO
- Going beyond WW approximation

THANK YOU!