

PROBING GLUON SATURATION WITH PHOTON PRODUCTION IN PROTON-NUCLEUS COLLISIONS

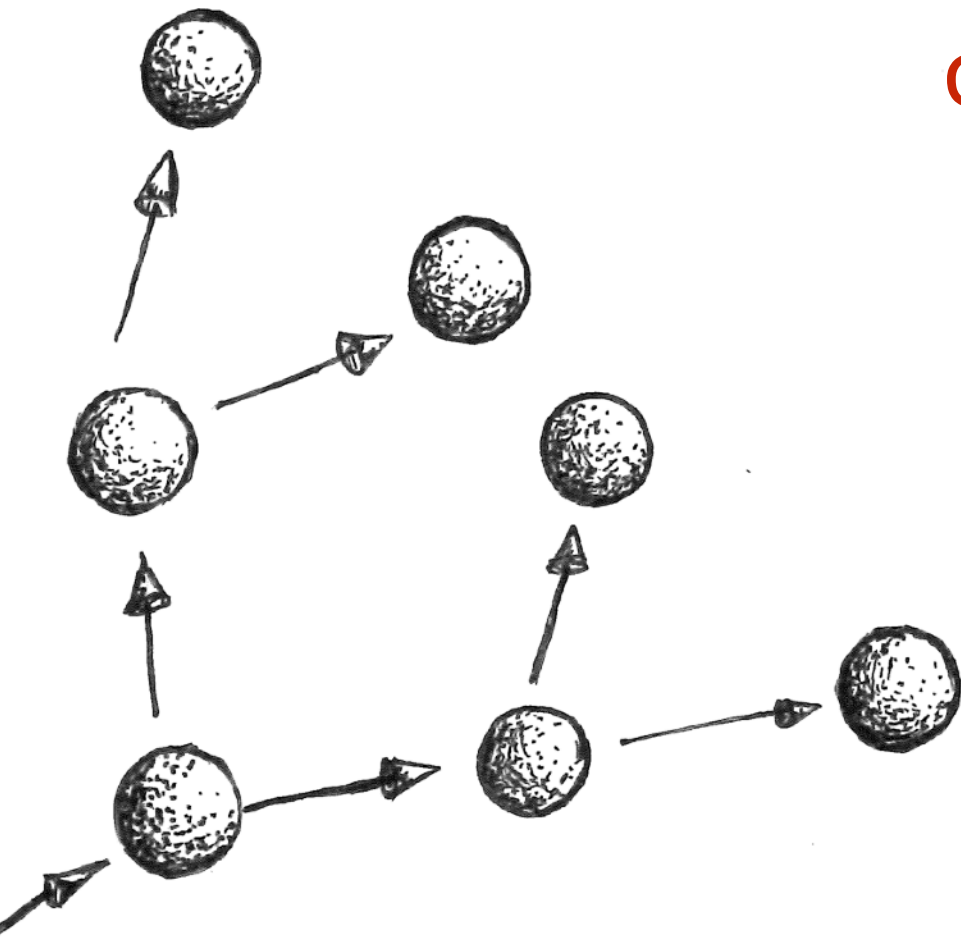
OSCAR GARCIA-MONTERO

In collaboration with

Sanjin Benic

Kenji Fukushima

Raju Venugopalan



HOW TO TAKE A PHOTO OF A GLUON SOUP

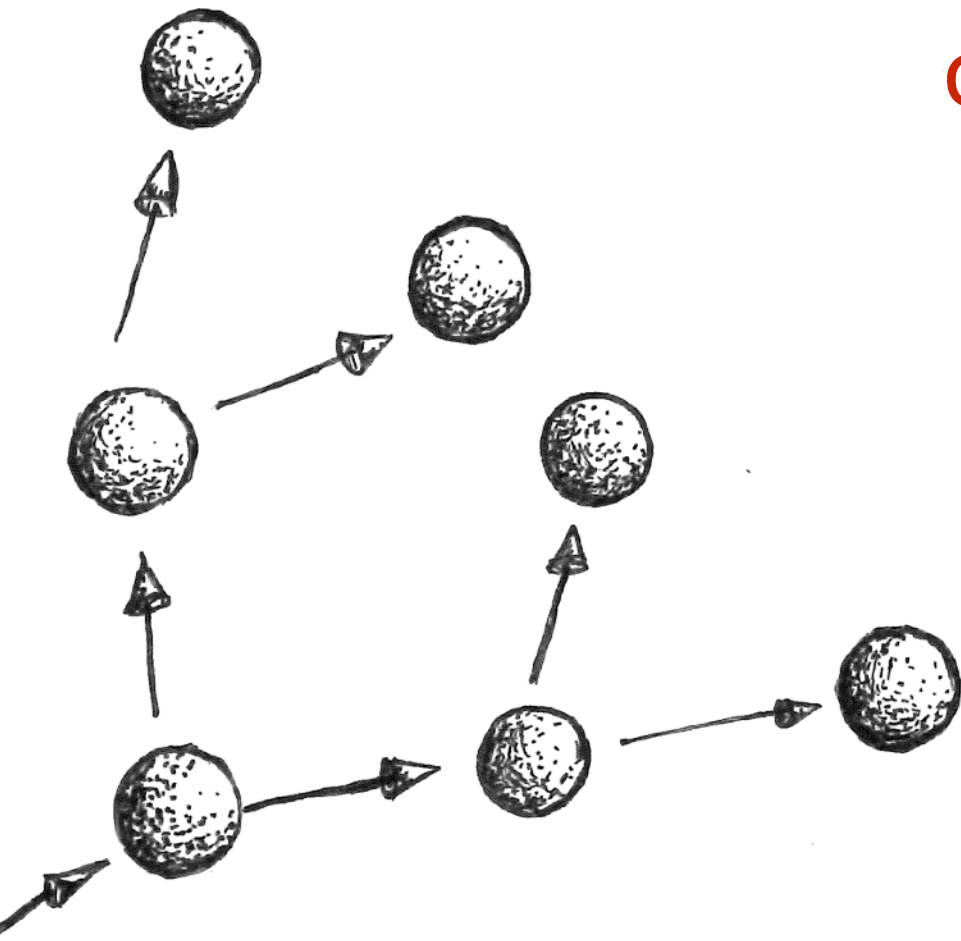
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CONTENTS



Motivation



Saturation



Color Glass Condensate



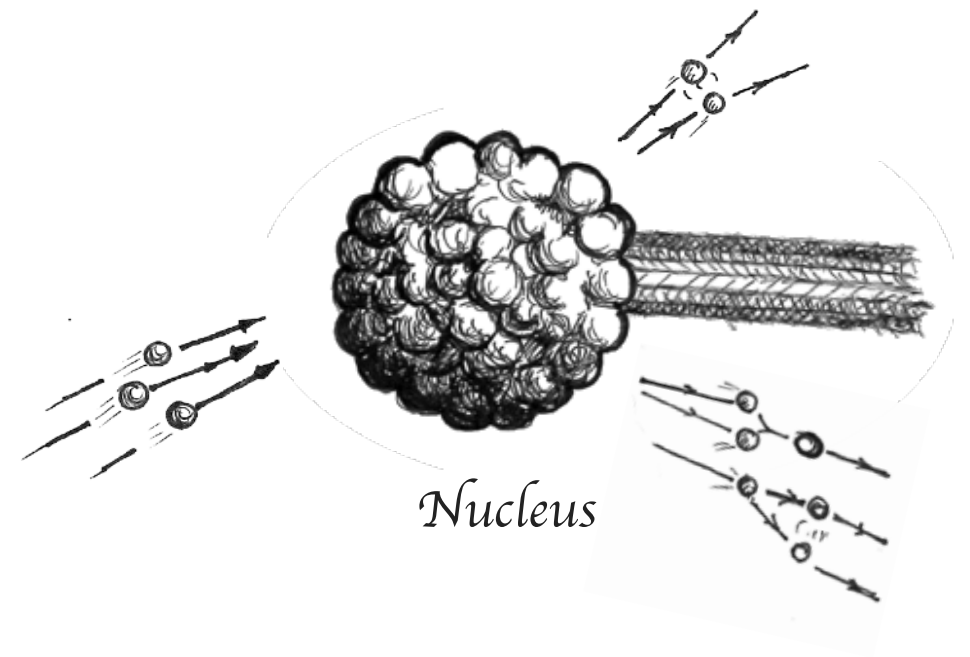
Photon Production



Summary and Outlook

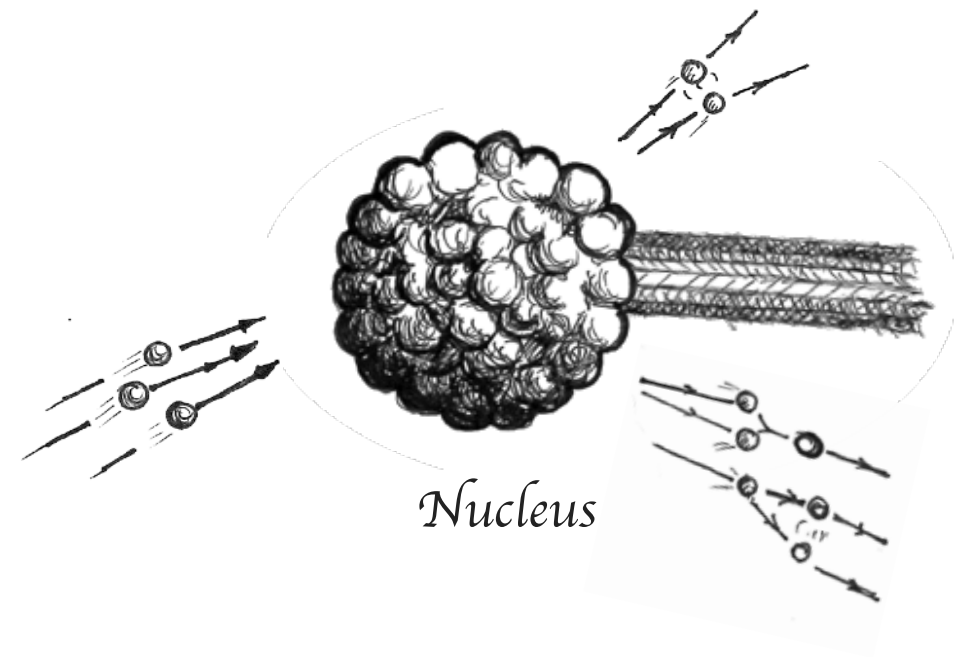
GLOBAL GOAL

Understand nuclear matter under
extreme conditions



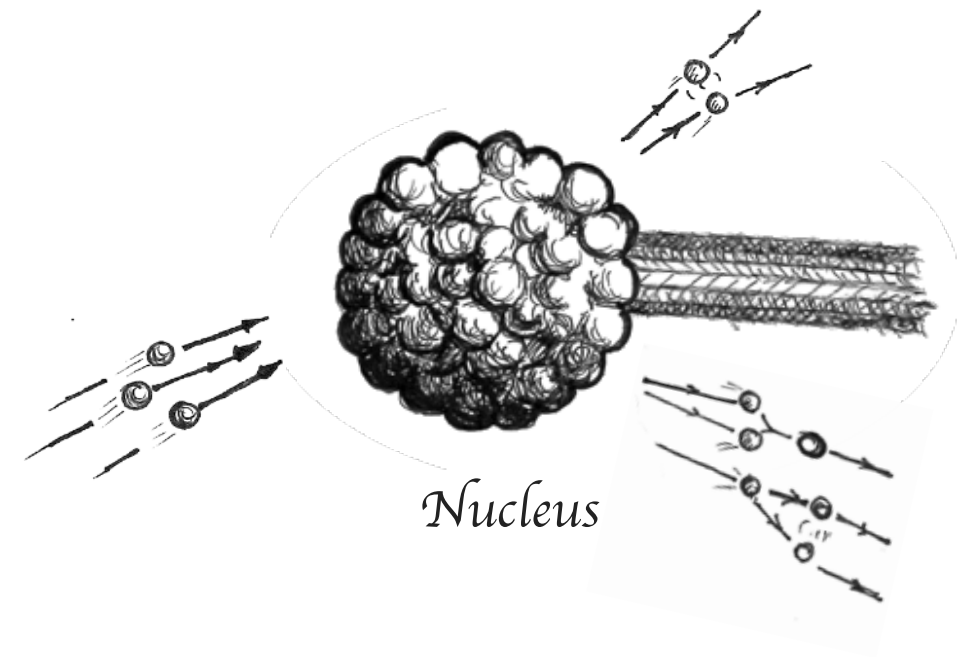
LOCAL GOAL

Use photons as probes for saturation
in highly energetic p+A collisions



LOCAL GOAL

Use photons as probes for saturation
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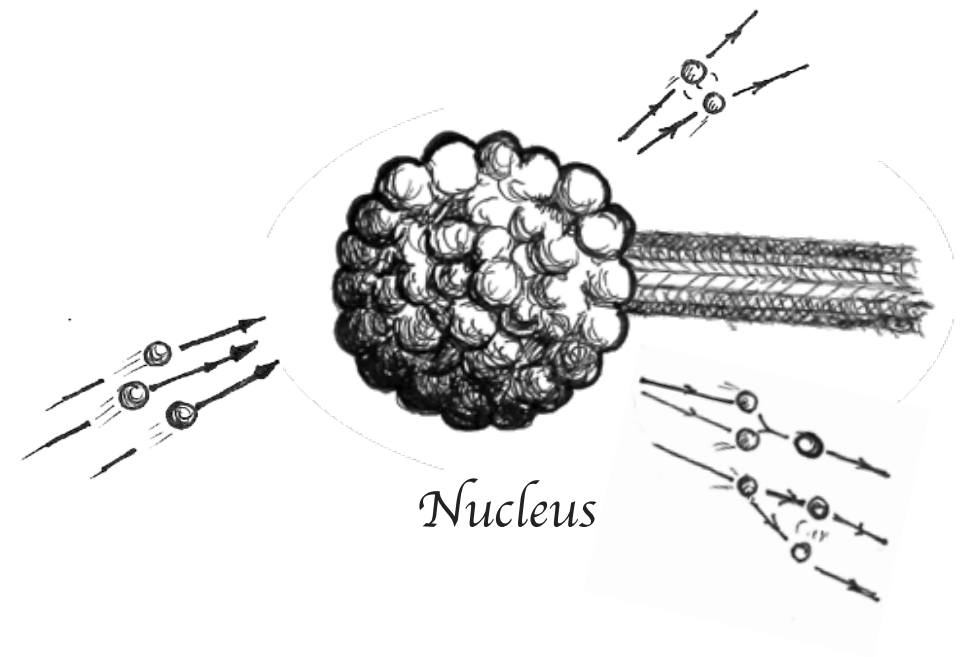


WHY PHOTONS?

No strong interaction

LOCAL GOAL

Use photons as probes for saturation
in highly energetic p+A collisions



WHY PHOTONS?

No strong interaction

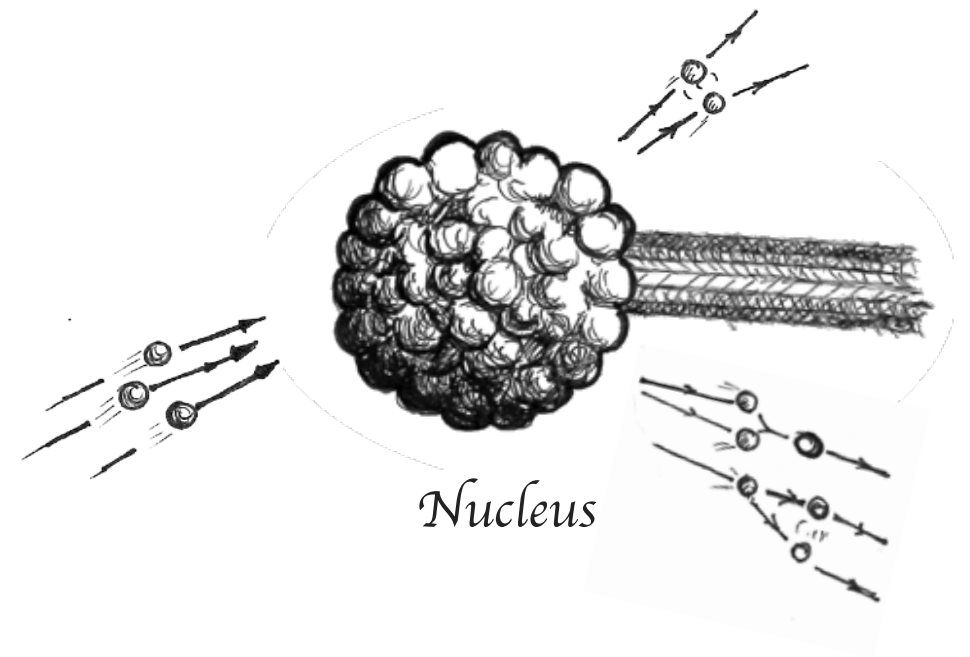


Clean probes.



LOCAL GOAL

Use photons as probes for saturation
in highly energetic p+A collisions



WHY PHOTONS?

No strong interaction



Clean probes.



WHY P+A?

Use known probes to probe the "unknown"

DEEP INELASTIC SCATTERING

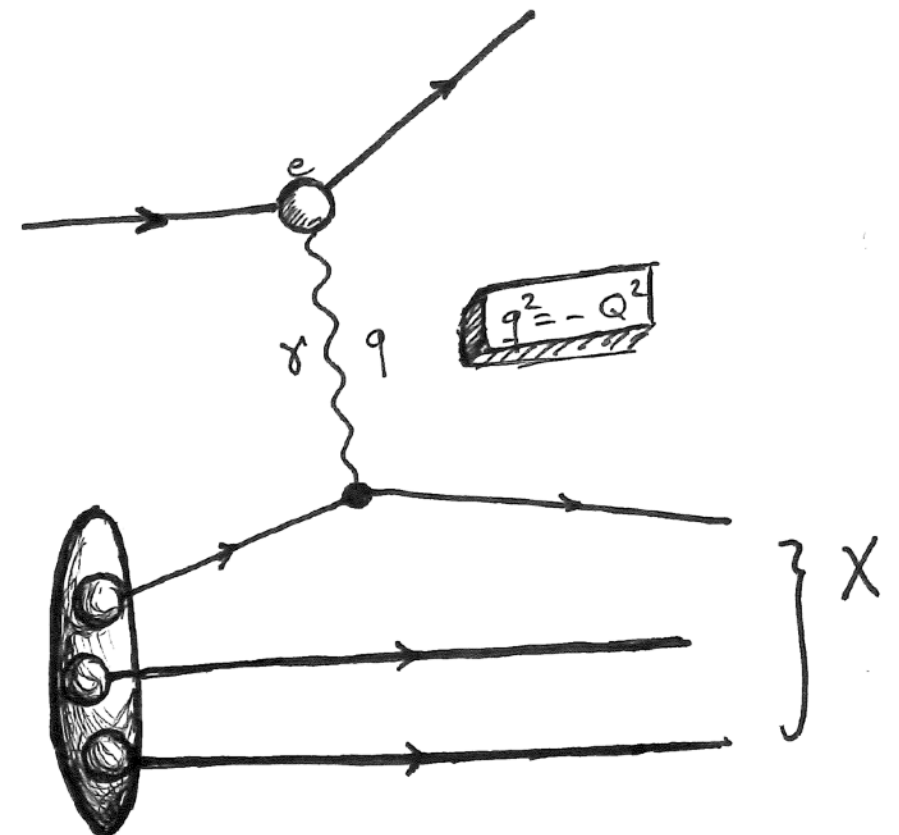
Probe (e, μ , ν) used to test internal structure of nucleons

Q^2 as a measure of the minimum probing area

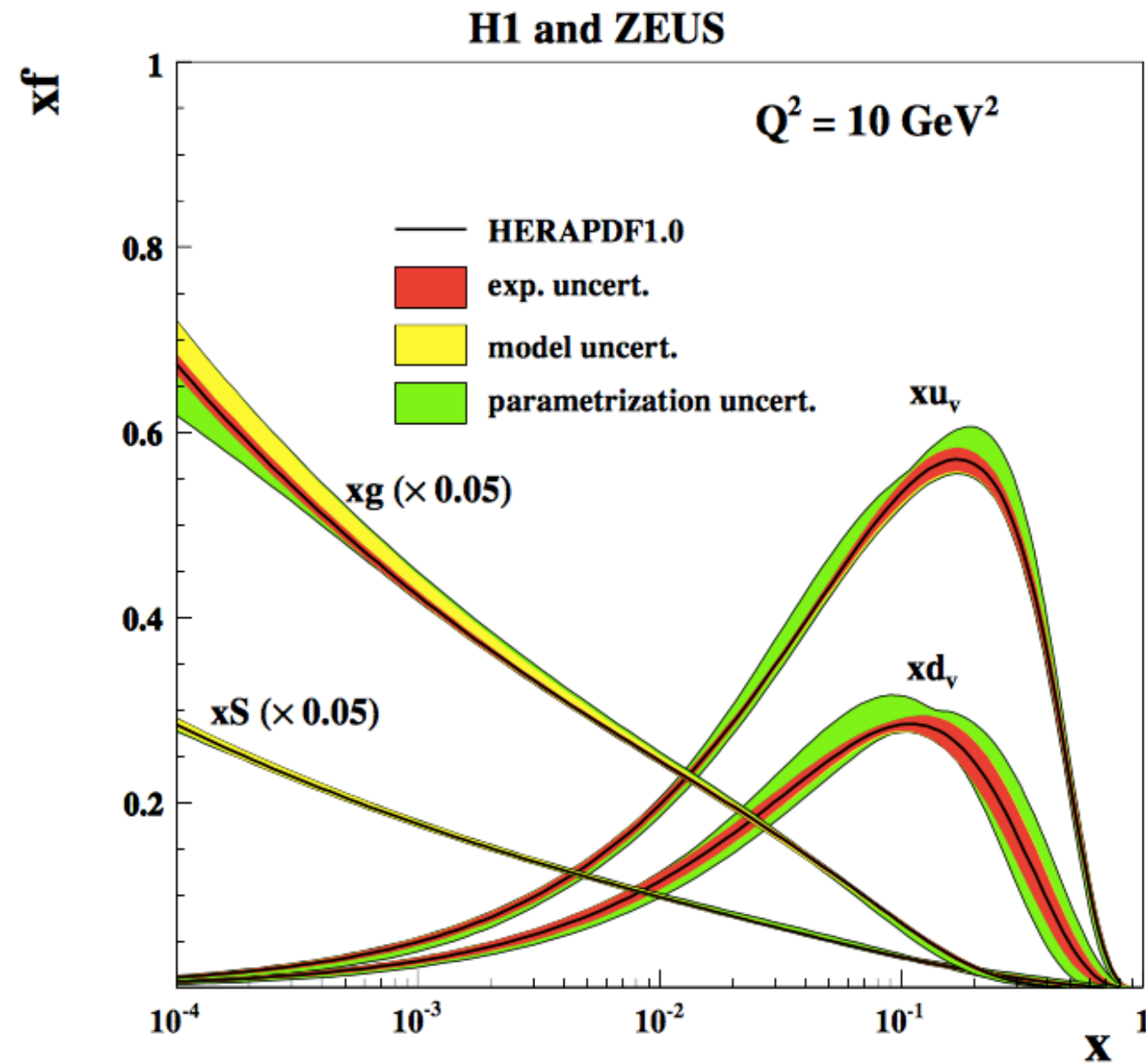
$x = \frac{Q^2}{2P \cdot q} \sim \frac{p_z}{\sqrt{s}}$, the parton's longitudinal momentum fraction

Asymptotic freedom was discovered

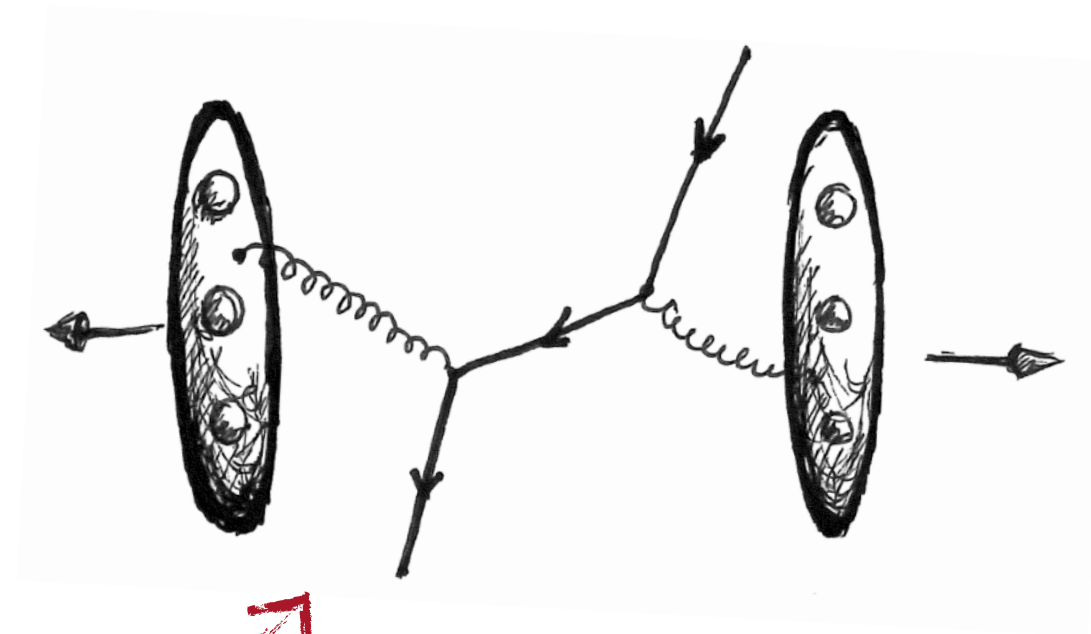
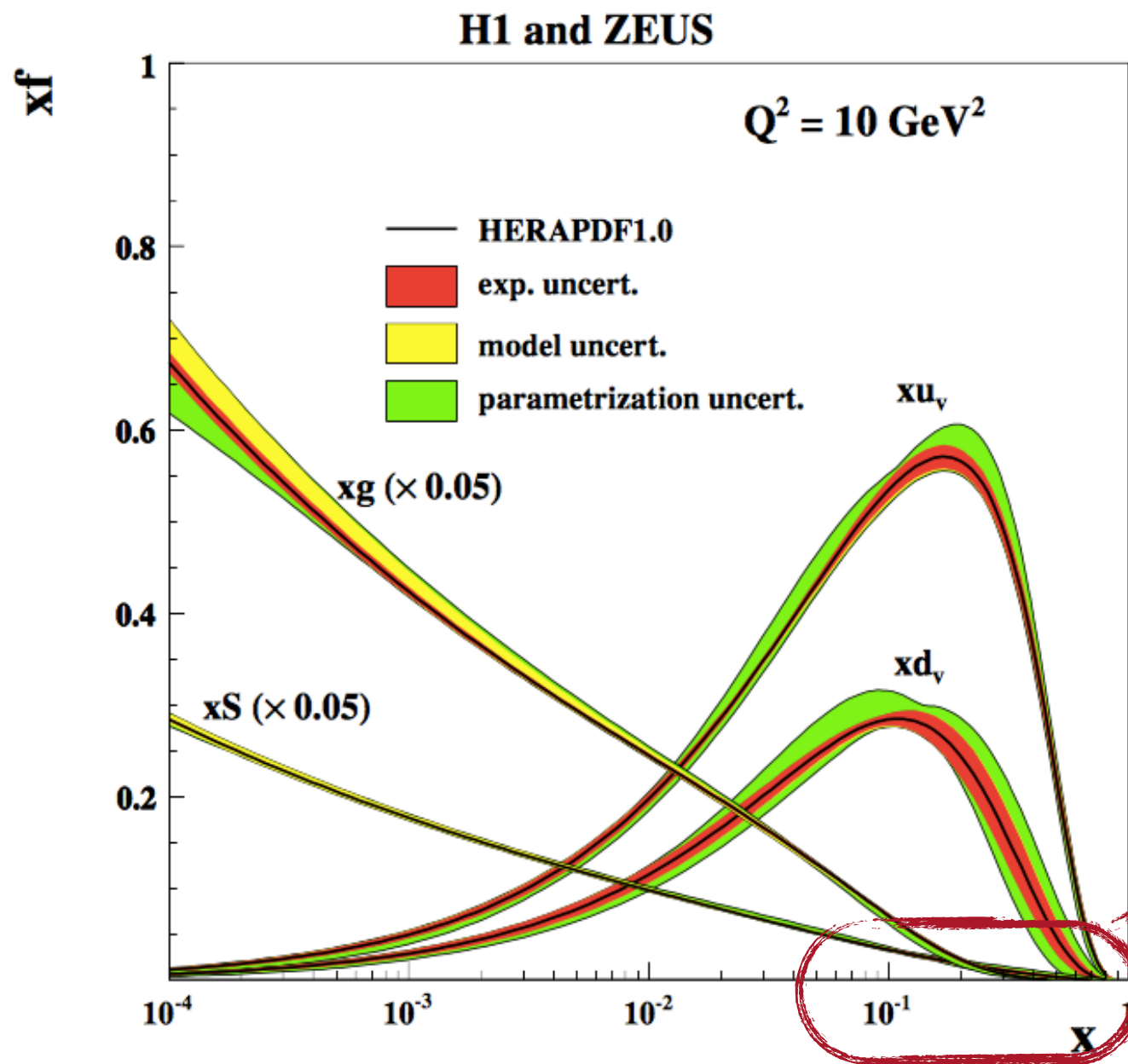
But also...



PARTON DISTRIBUTION FUNCTIONS



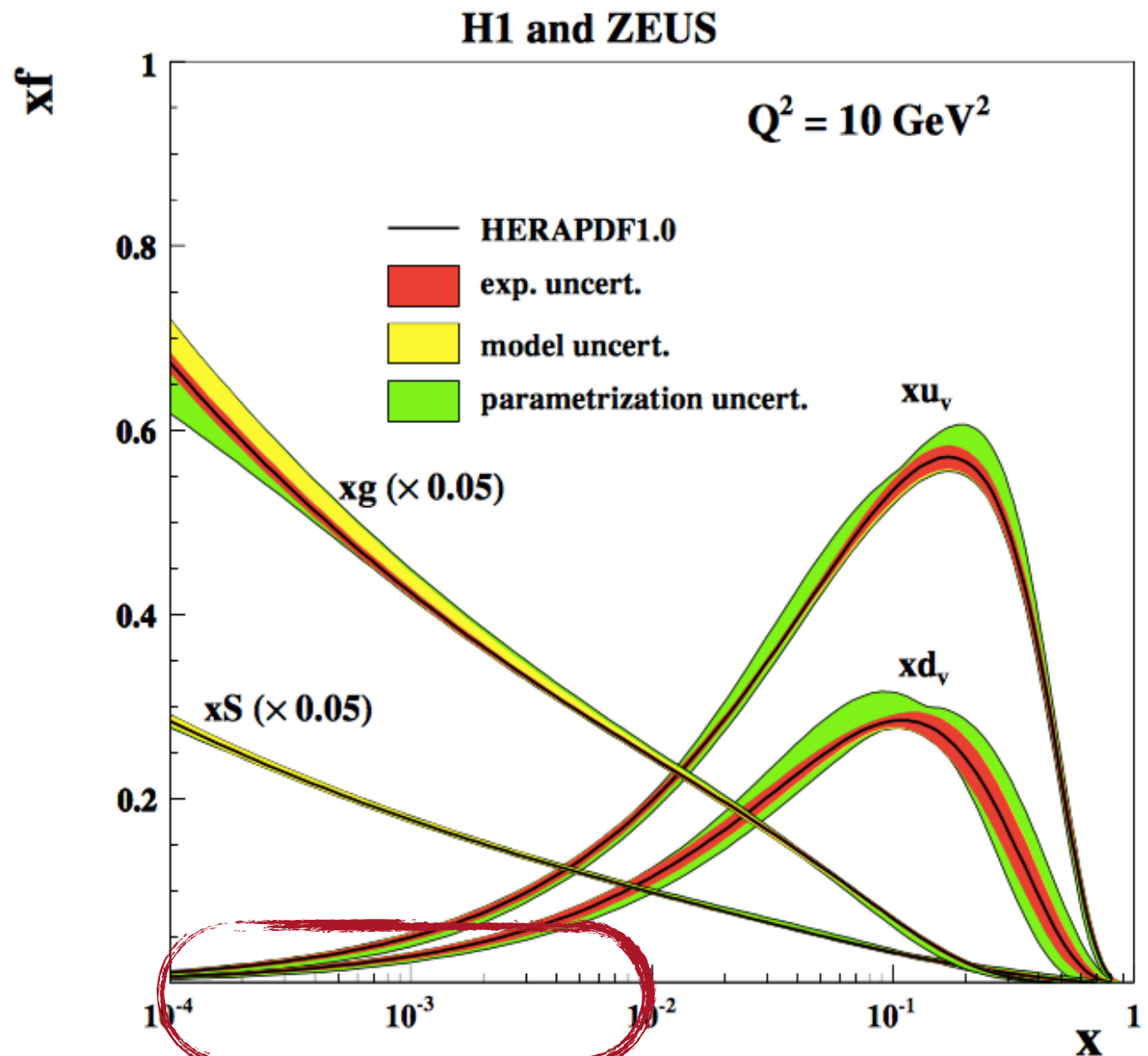
$$x = p_z / \sqrt{s}$$



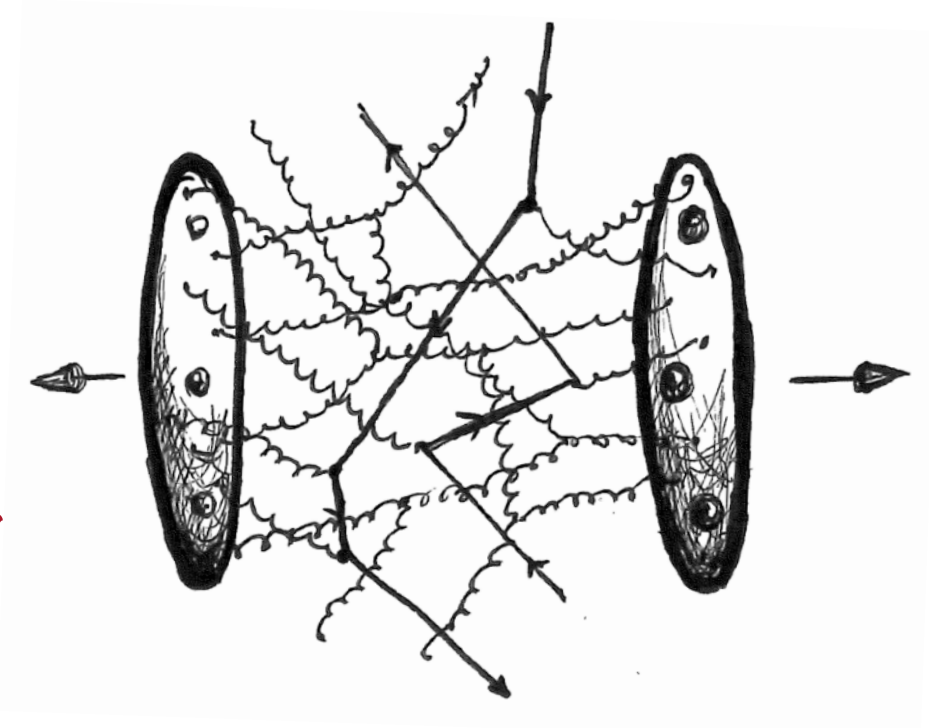
Low gluons densities

Standard pQCD

$$x = p_z / \sqrt{s}$$

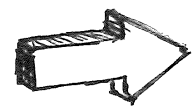
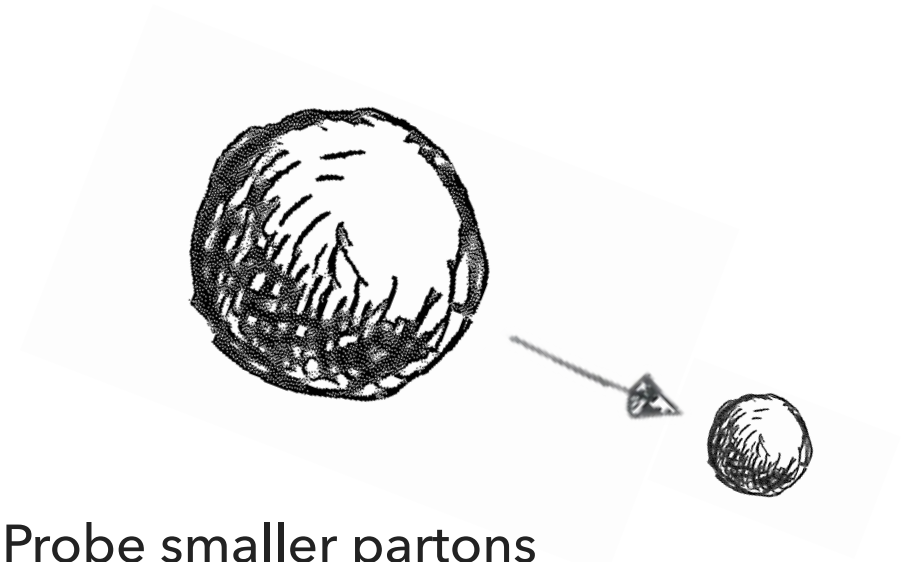


High gluon densities
Multi-particle scatterings



$$x = p_z / \sqrt{s}$$

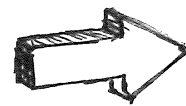
SATURATION



Evolve distribution in Q^2



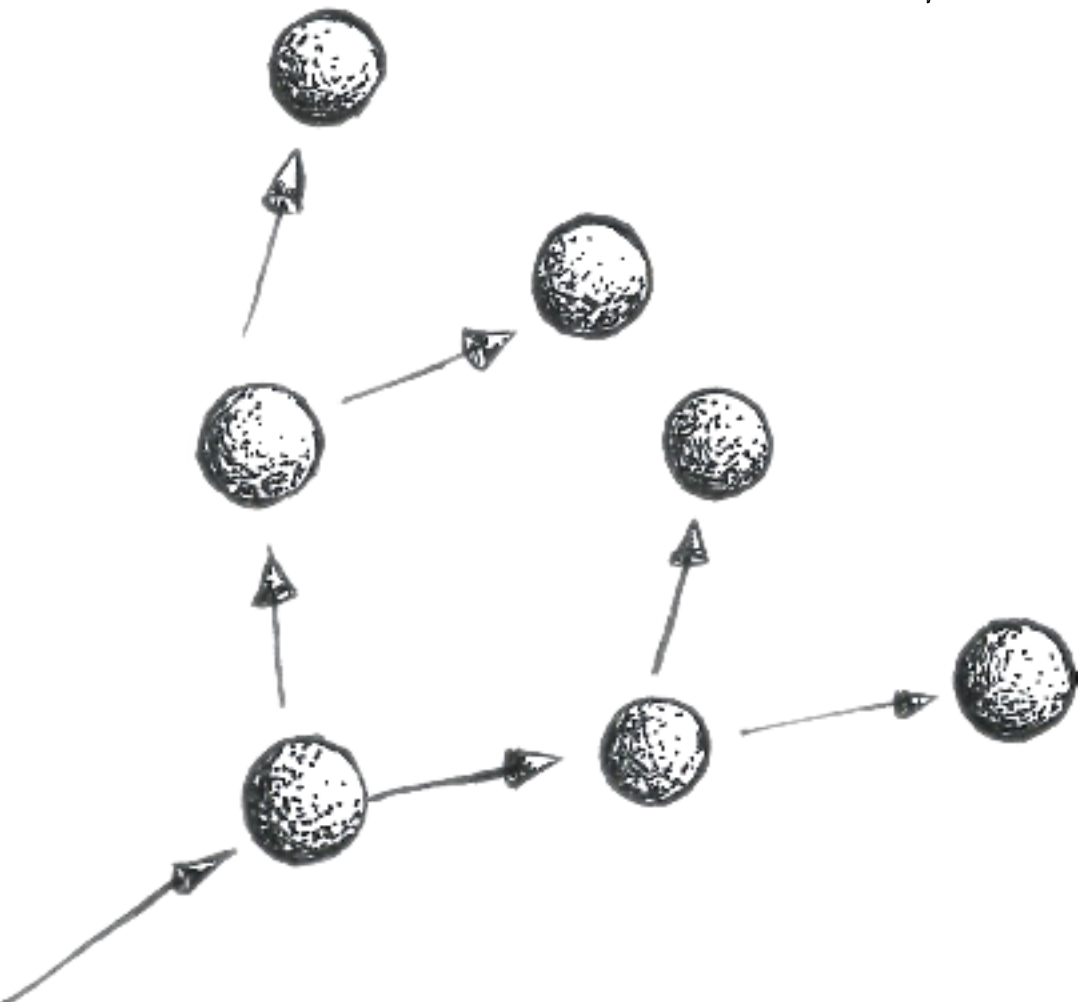
Probe smaller partons



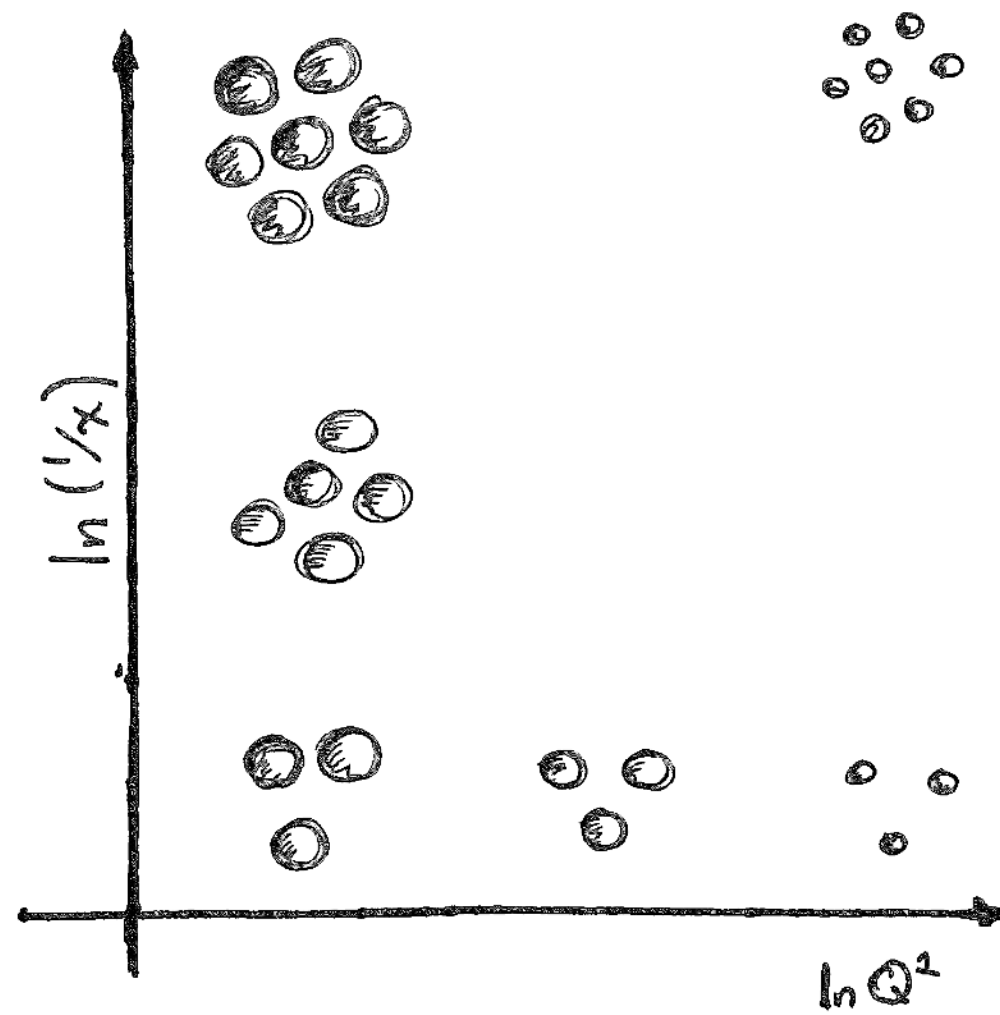
Evolve distribution in x



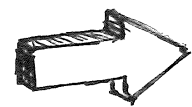
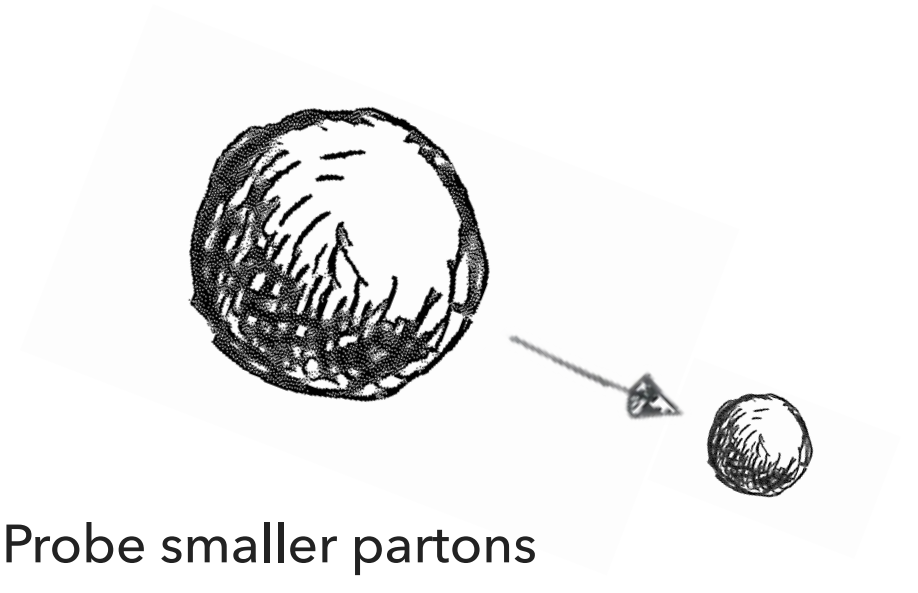
Partons fill phase space



SATURATION



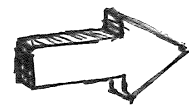
SATURATION



Evolve distribution in Q^2



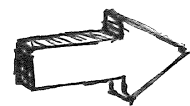
Probe smaller partons



Evolve distribution in x



Partons fill phase space



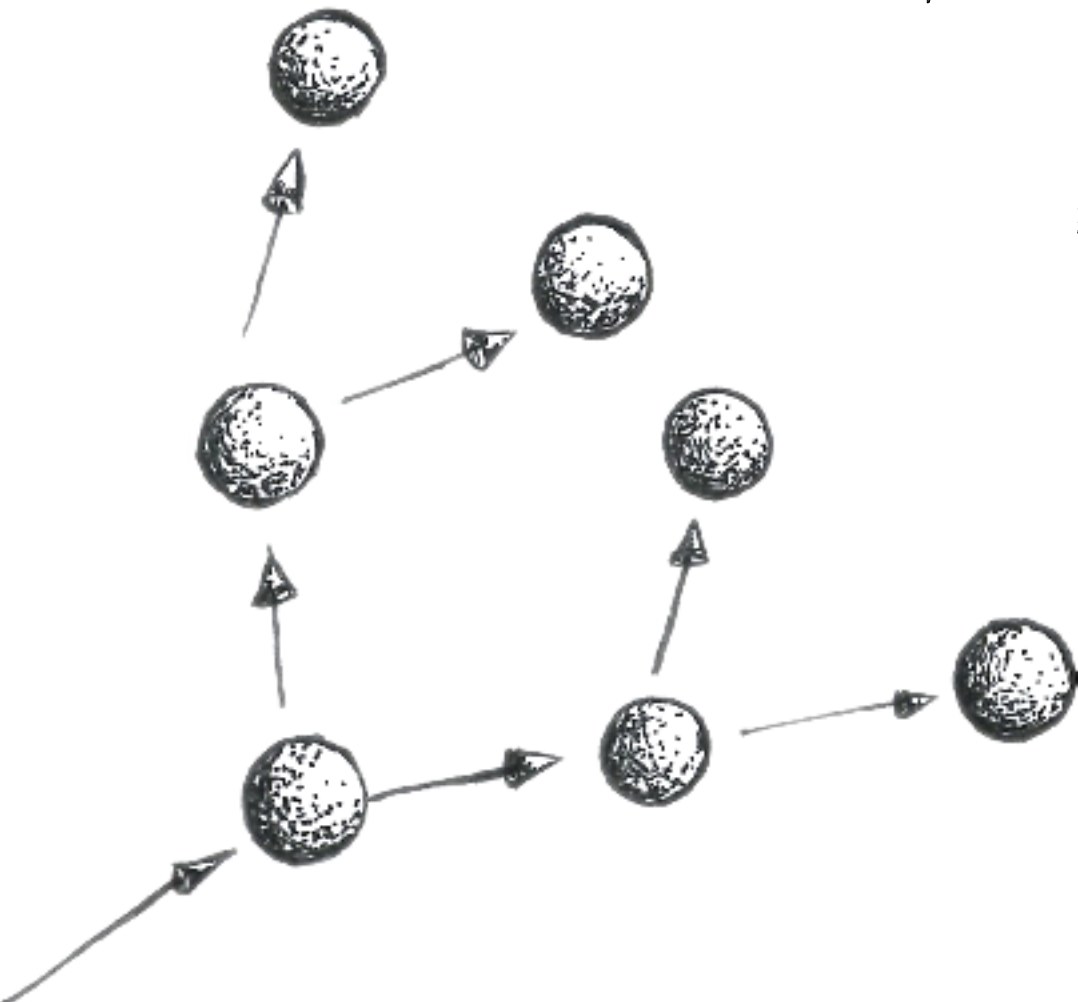
Distribution reaches $\mathcal{O}(1/\alpha_S)$



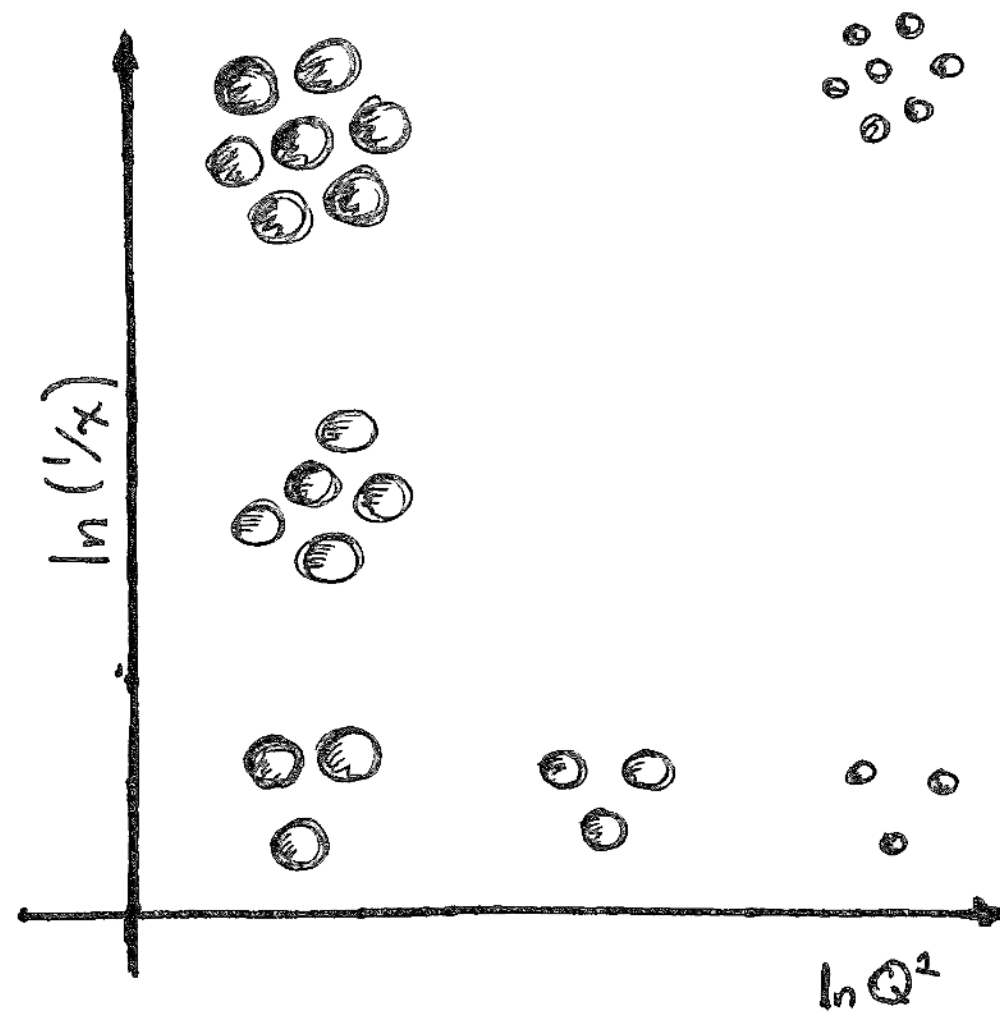
gluon fusion



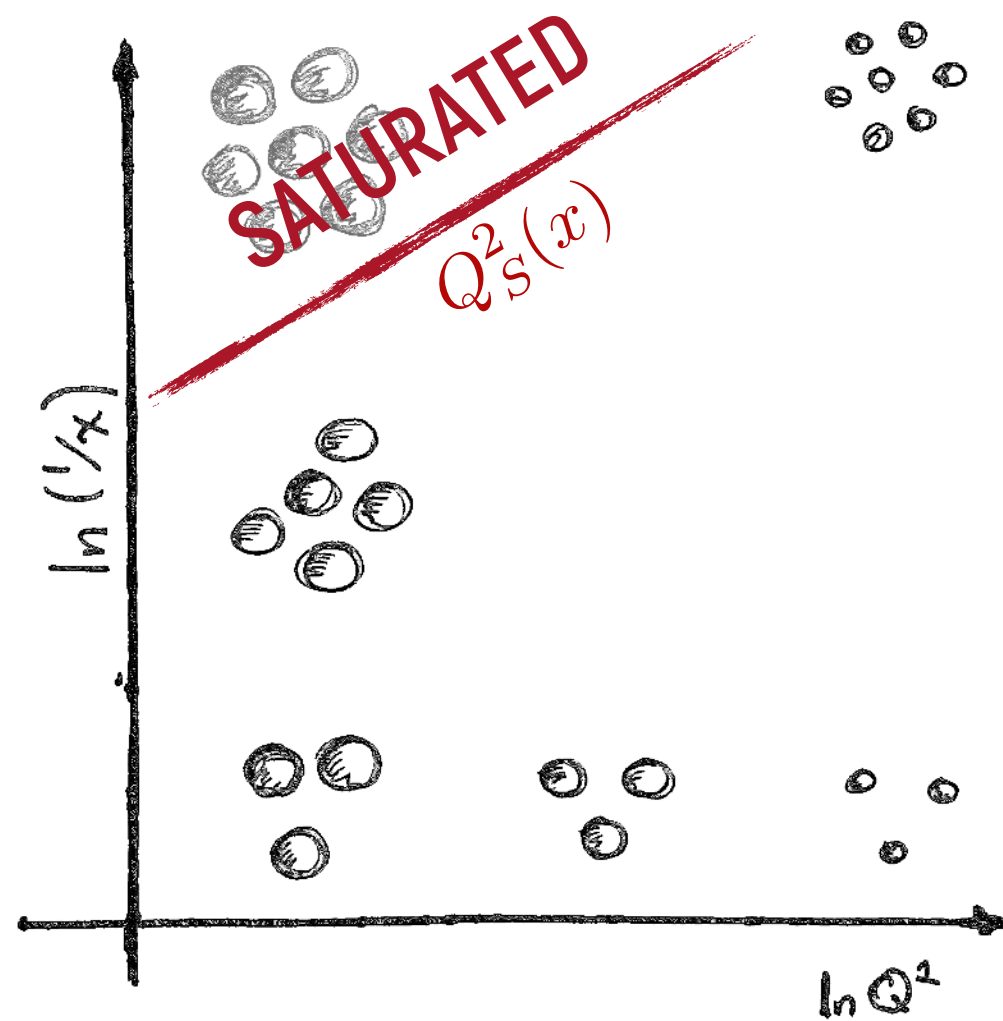
Growth stops !



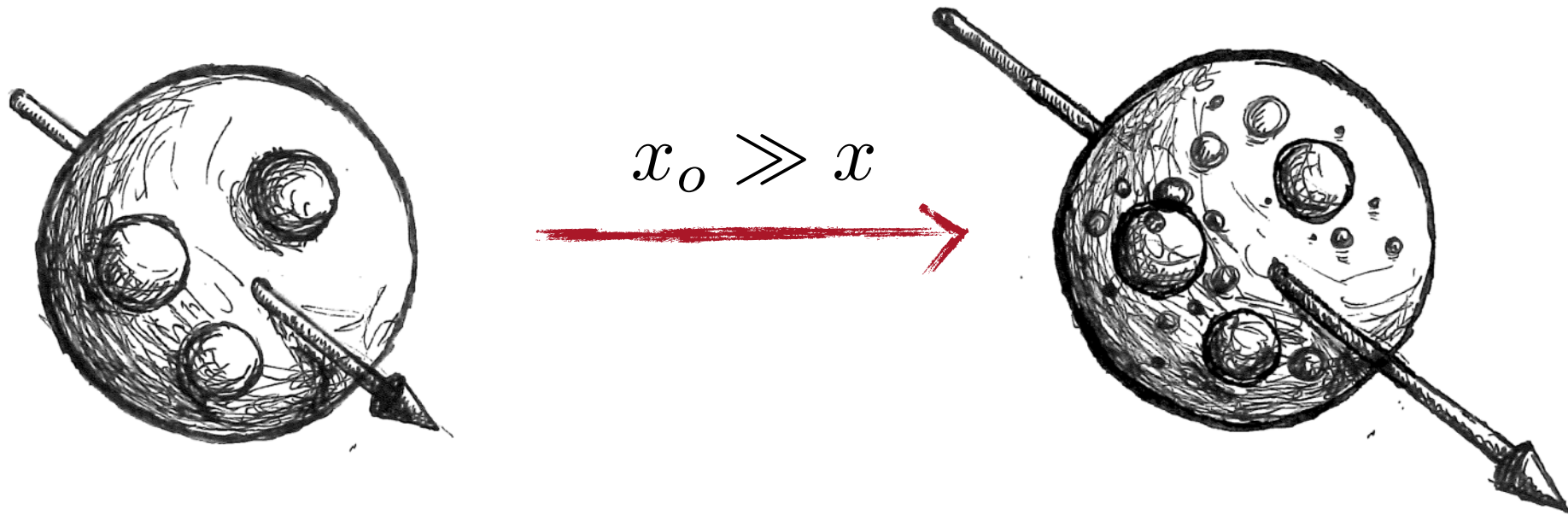
SATURATION



SATURATION



SATURATION



PHOTON PRODUCTION

Expansion in α_e and α_s

LO CONTRIBUTION

 $q \rightarrow q \gamma$

$O(\alpha_e)$

NLO CONTRIBUTIONS

 $q \rightarrow q g \gamma$

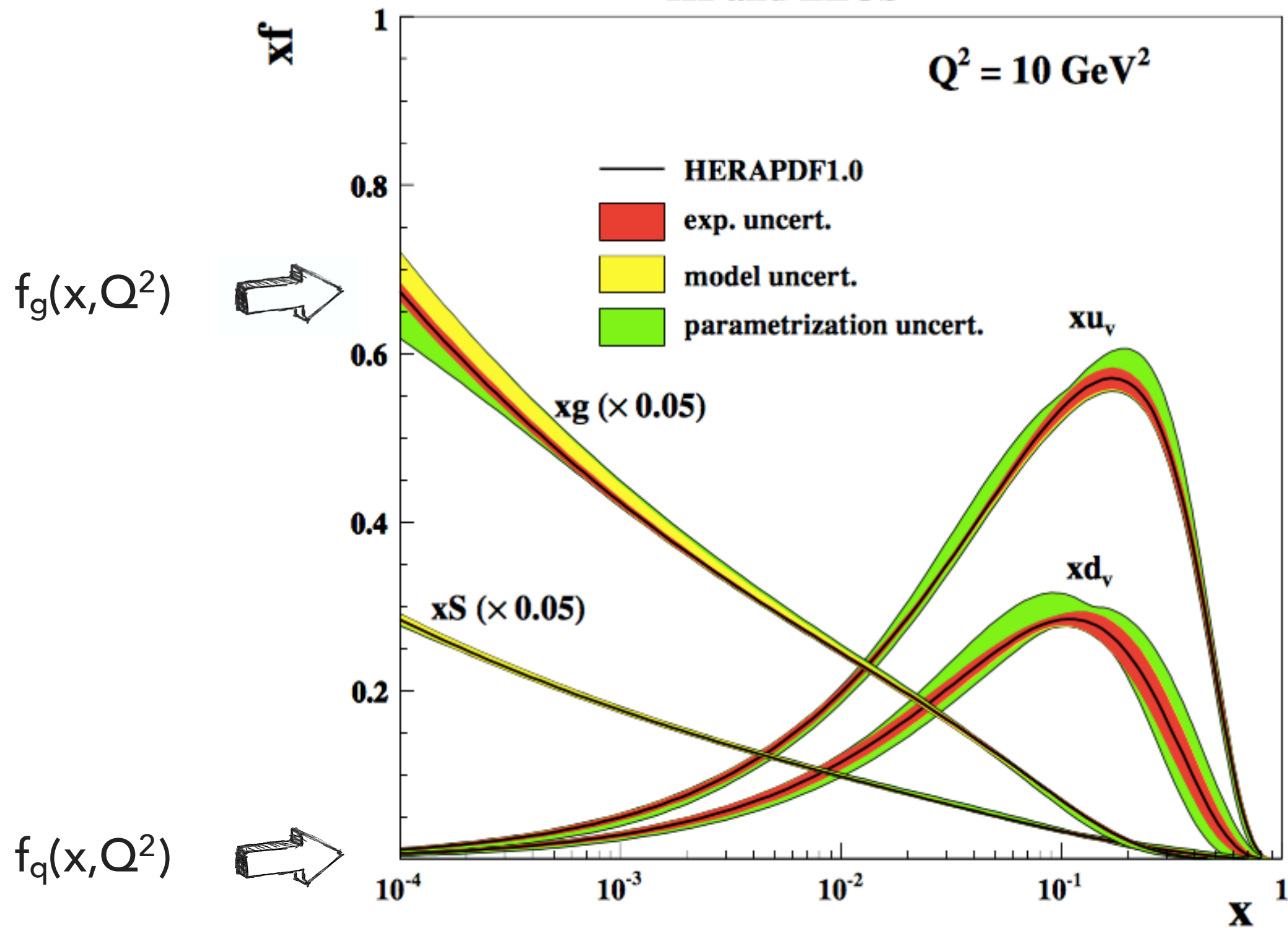
 $g \rightarrow q \bar{q} \gamma$

 $g \rightarrow q \bar{q} \rightarrow \gamma$

 $O(\alpha_e \alpha_s)$

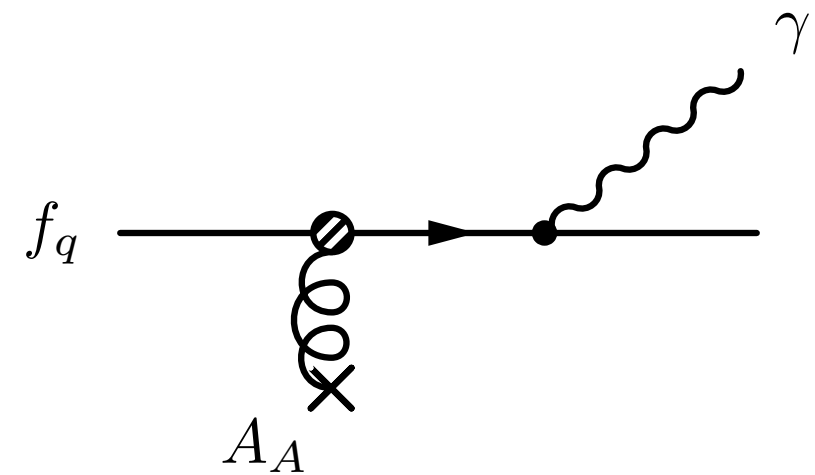
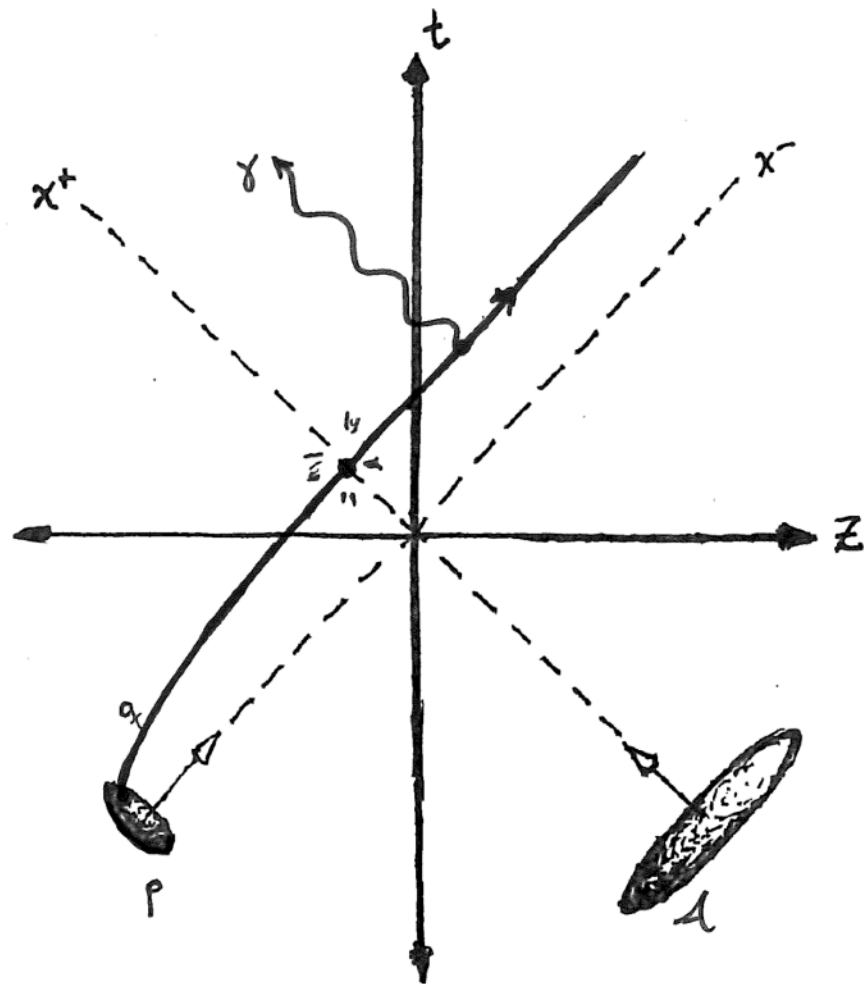
Phys. Rev. C 59 (**1999**) 1609
Phys. Rev. D 66 (**2002**) 014021
Nucl. Phys. A 741 (**2004**) 358

H1 and ZEUS



$$x = p_z / \sqrt{s}$$

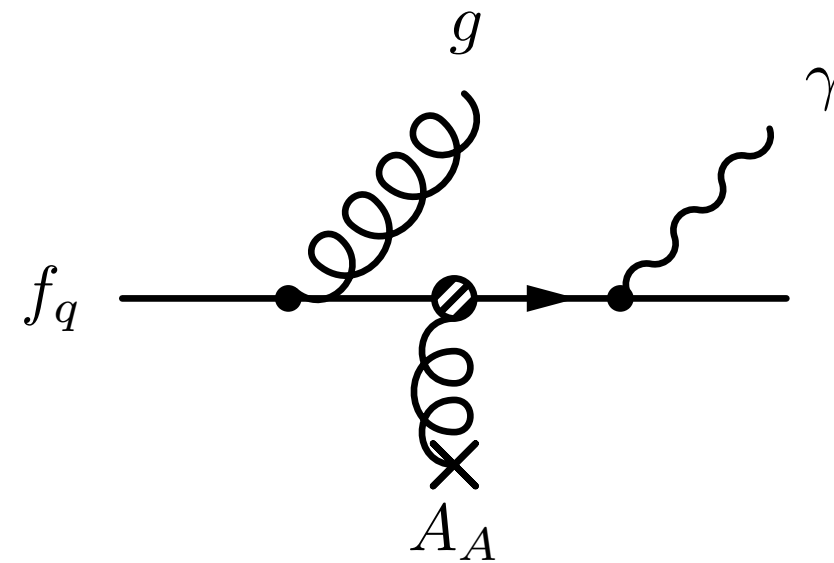
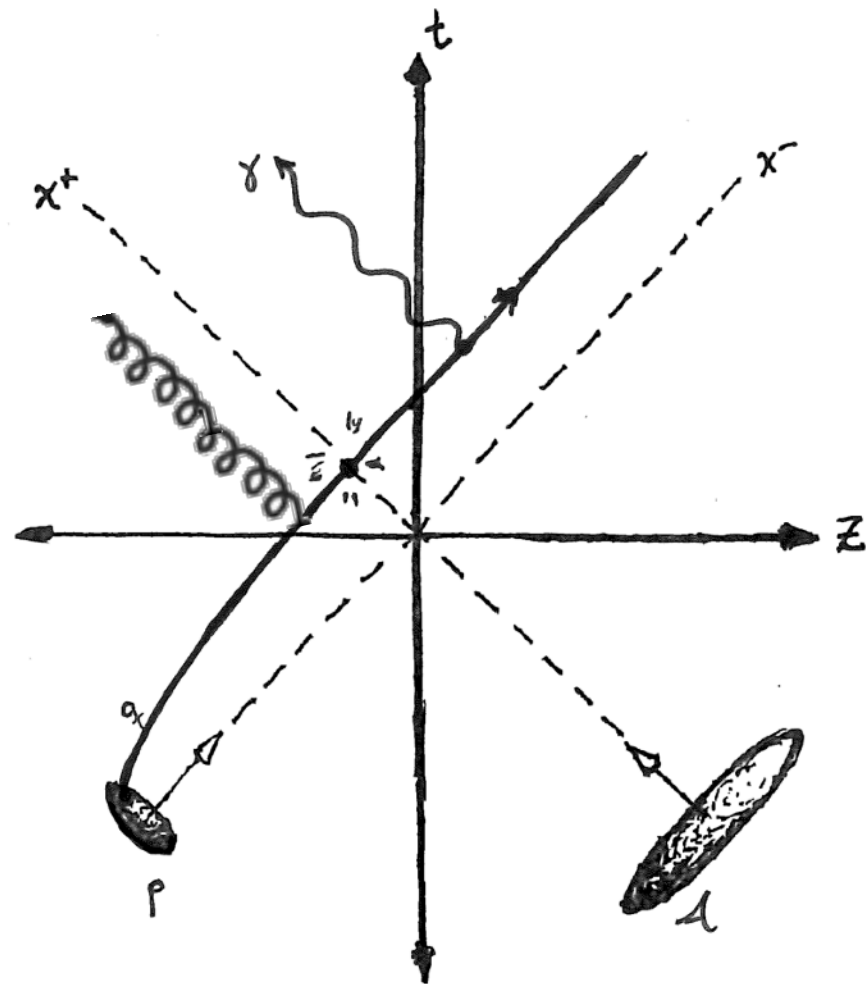
LO CONTRIBUTION



⇒ At $x \sim 10^{-2}$, $f_g(x, Q^2) \gg f_q(x, Q^2)$

Phys. Rev. C 59 (**1999**) 1609
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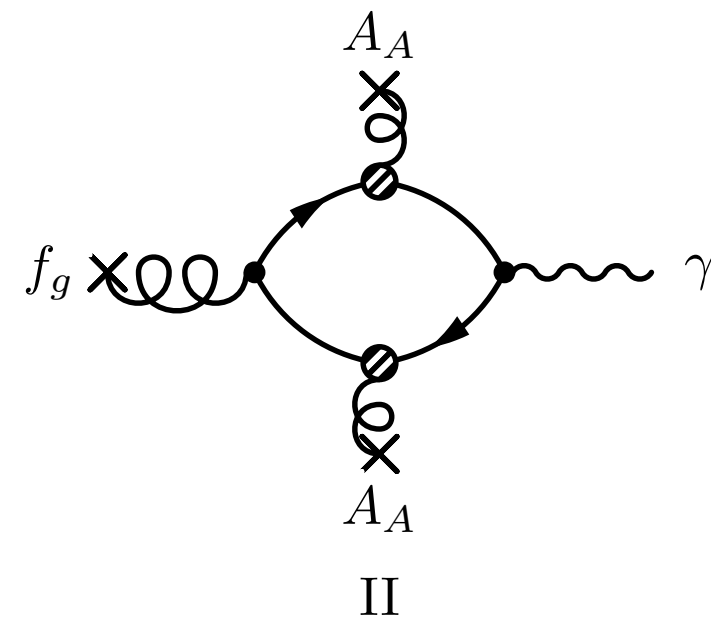
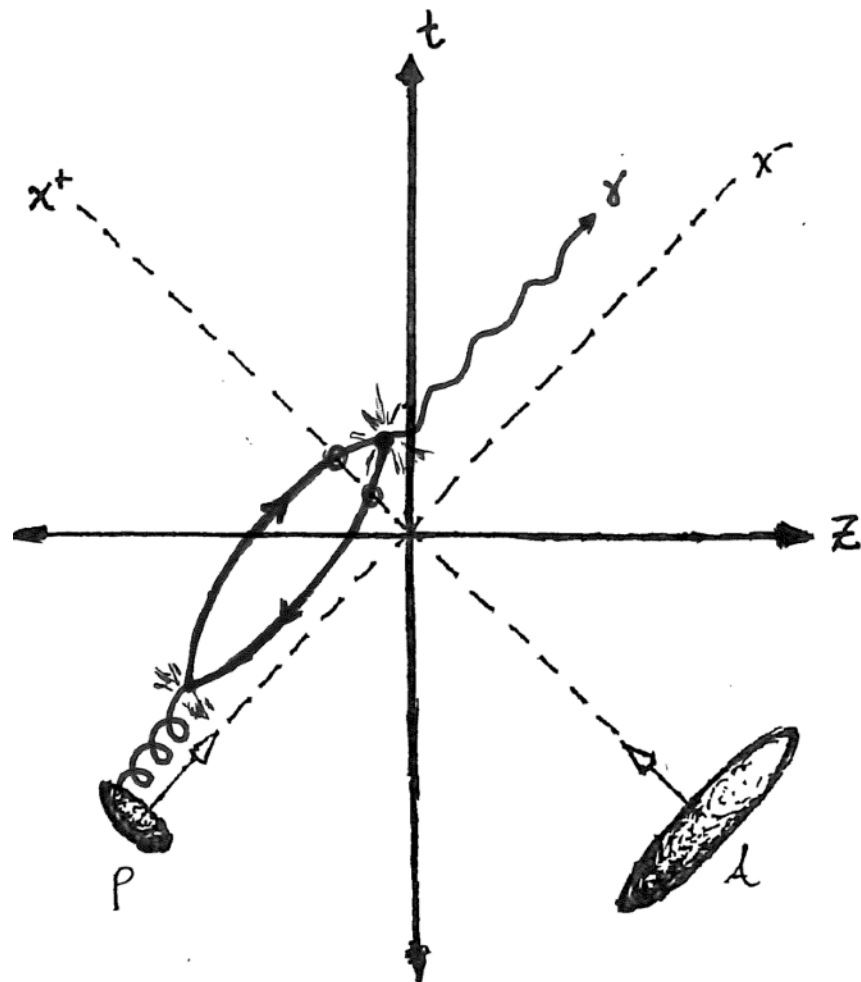
NLO: PHOTON + GLUON BREMSSTRAHLUNG



At $x \sim 10^{-2}$, $f_g(x, Q^2) \gg f_q(x, Q^2)$

⇒ Suppressed by $f_q(x, Q^2)$

NLO: ANNIHILATION

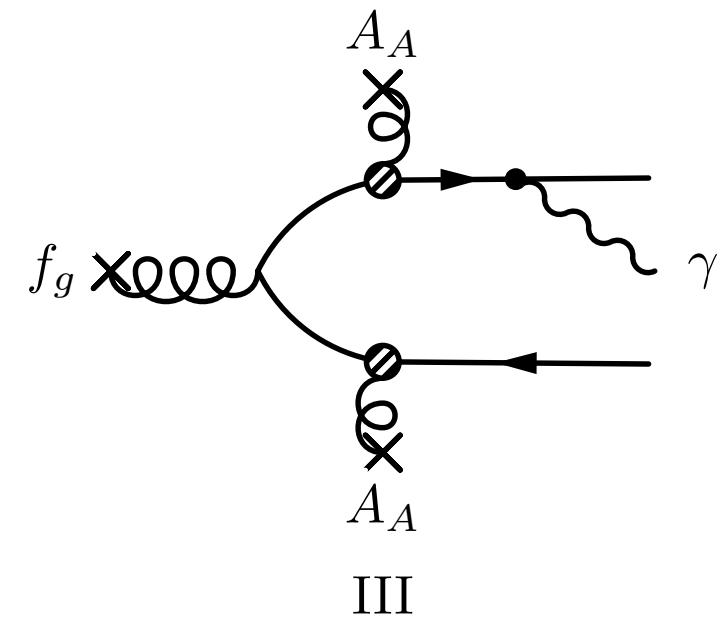
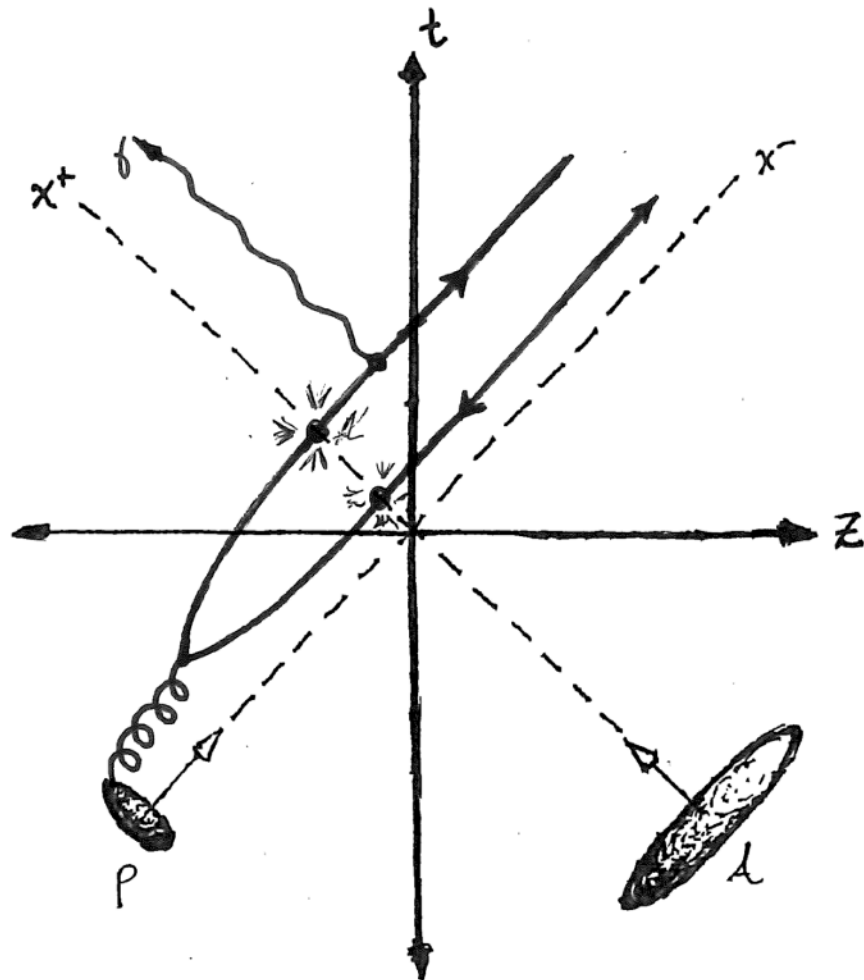


Enhanced by $f_g(x, Q^2)$

⇒ Kinematically constrained

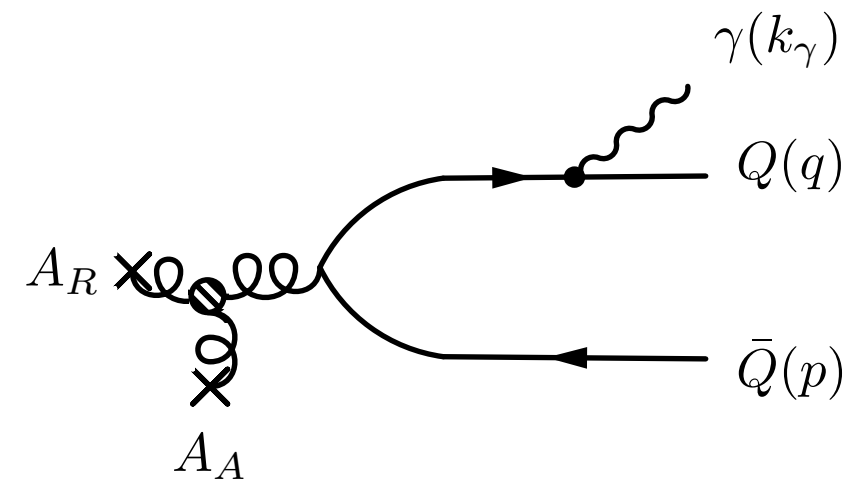
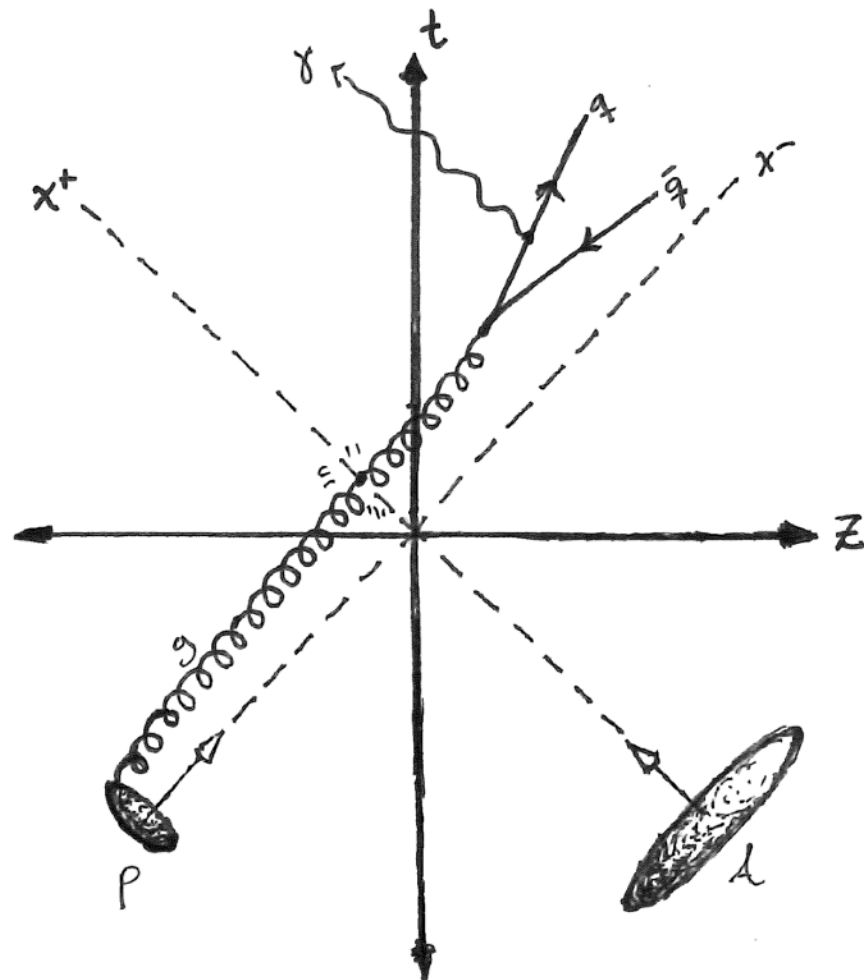
⇒ Dominated by $k_{\perp}^2 \sim Q_{S,A}^2$

NLO: PHOTON BREMSSTRAHLUNG



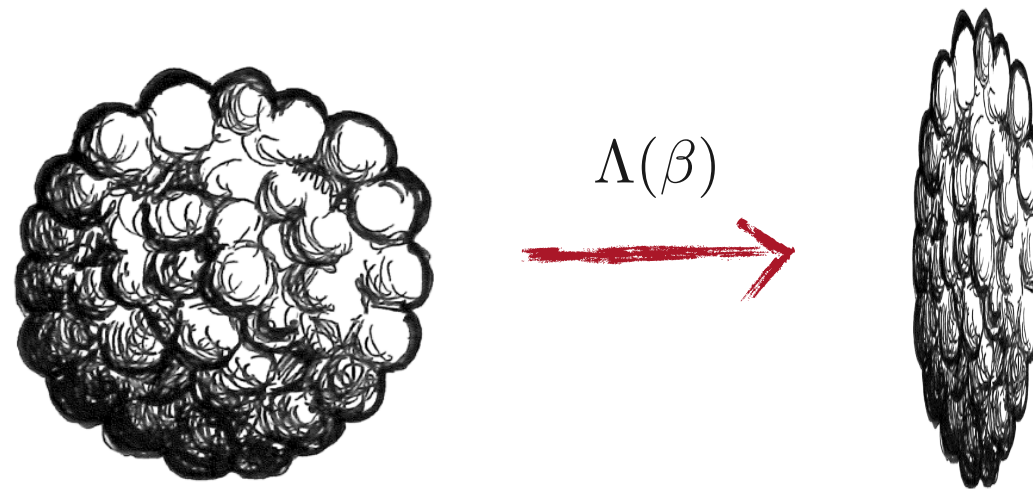
- ➡ Enhanced by $f_g(x, Q^2)$
- ➡ Dominated by low momenta

NLO: PHOTON BREMSSTRAHLUNG



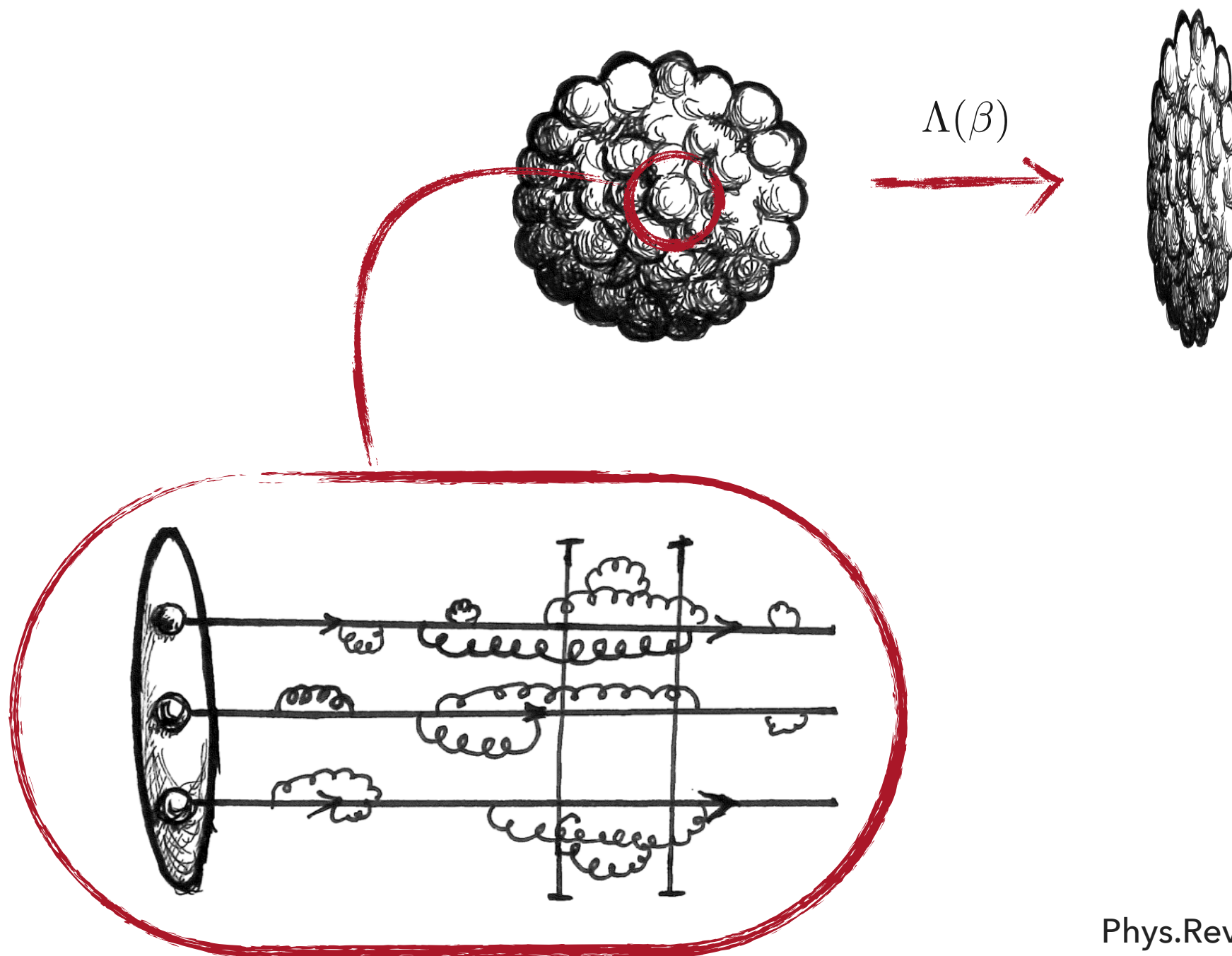
- ➡ Enhanced by $f_g(x, Q^2)$
- ➡ Dominated by low momenta

COLOR GLASS CONDENSATE



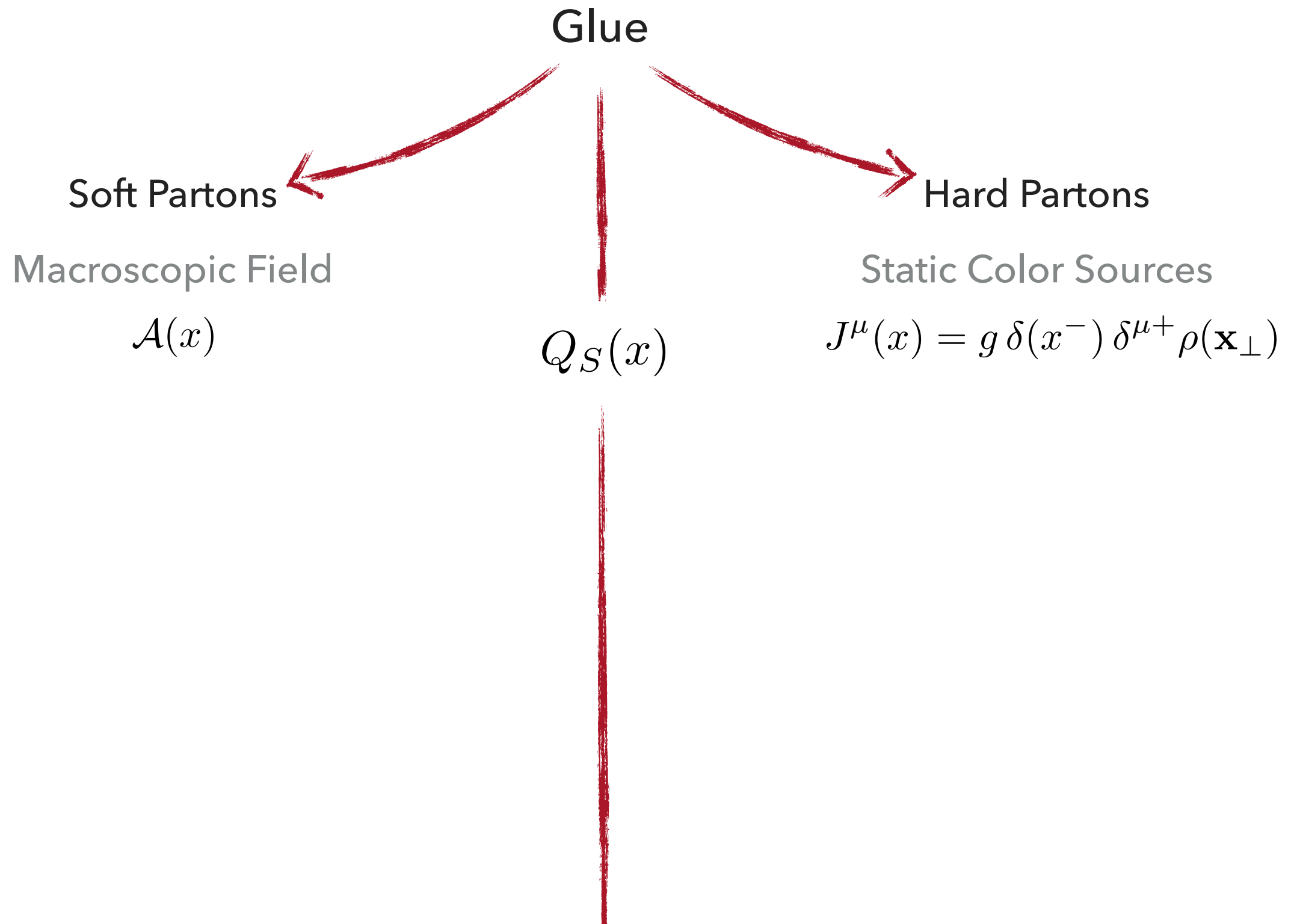
Phys.Rev. D49 (**1994**) 2233-2241
Phys.Rev. D49 (**1994**) 3352-3355
Phys.Rev. D50 (**1994**) 2225-2233

COLOR GLASS CONDENSATE

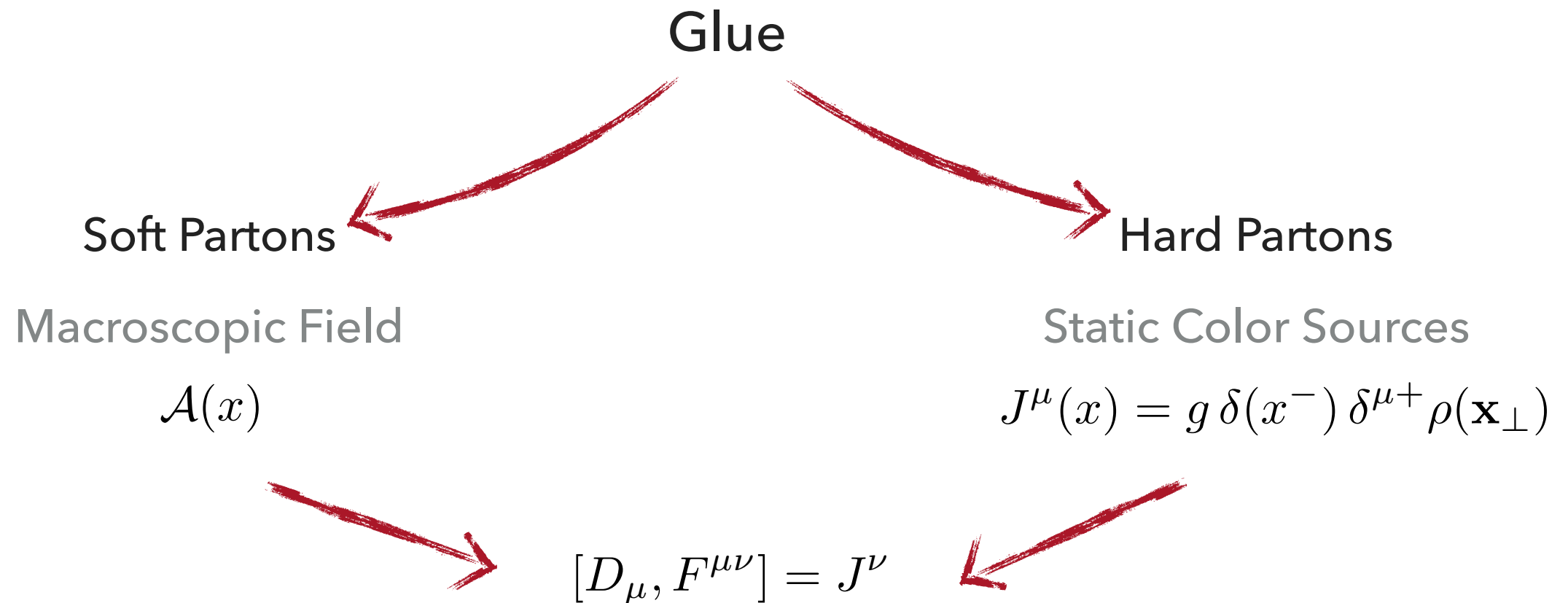


Phys.Rev. D49 (**1994**) 2233-2241
Phys.Rev. D49 (**1994**) 3352-3355
Phys.Rev. D50 (**1994**) 2225-2233

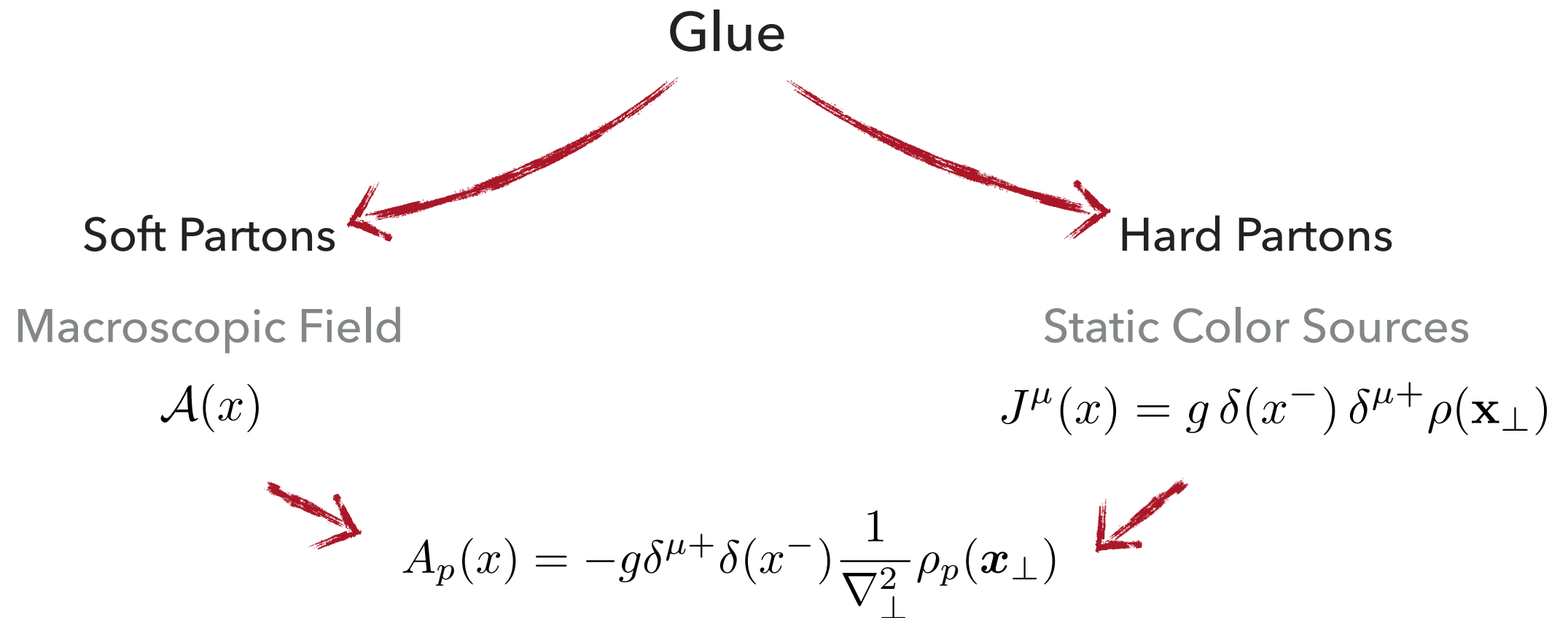
COLOR GLASS CONDENSATE



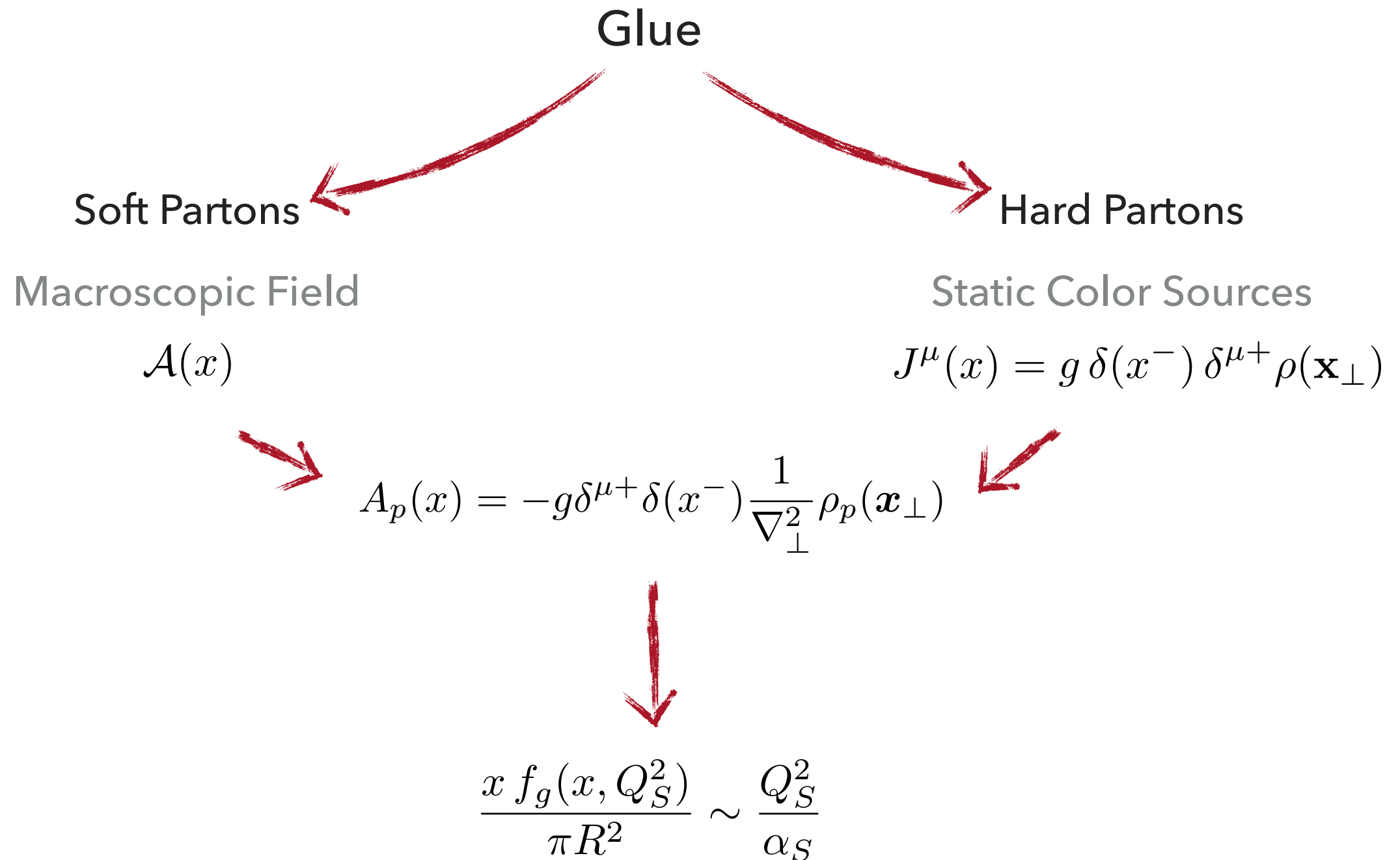
COLOR GLASS CONDENSATE



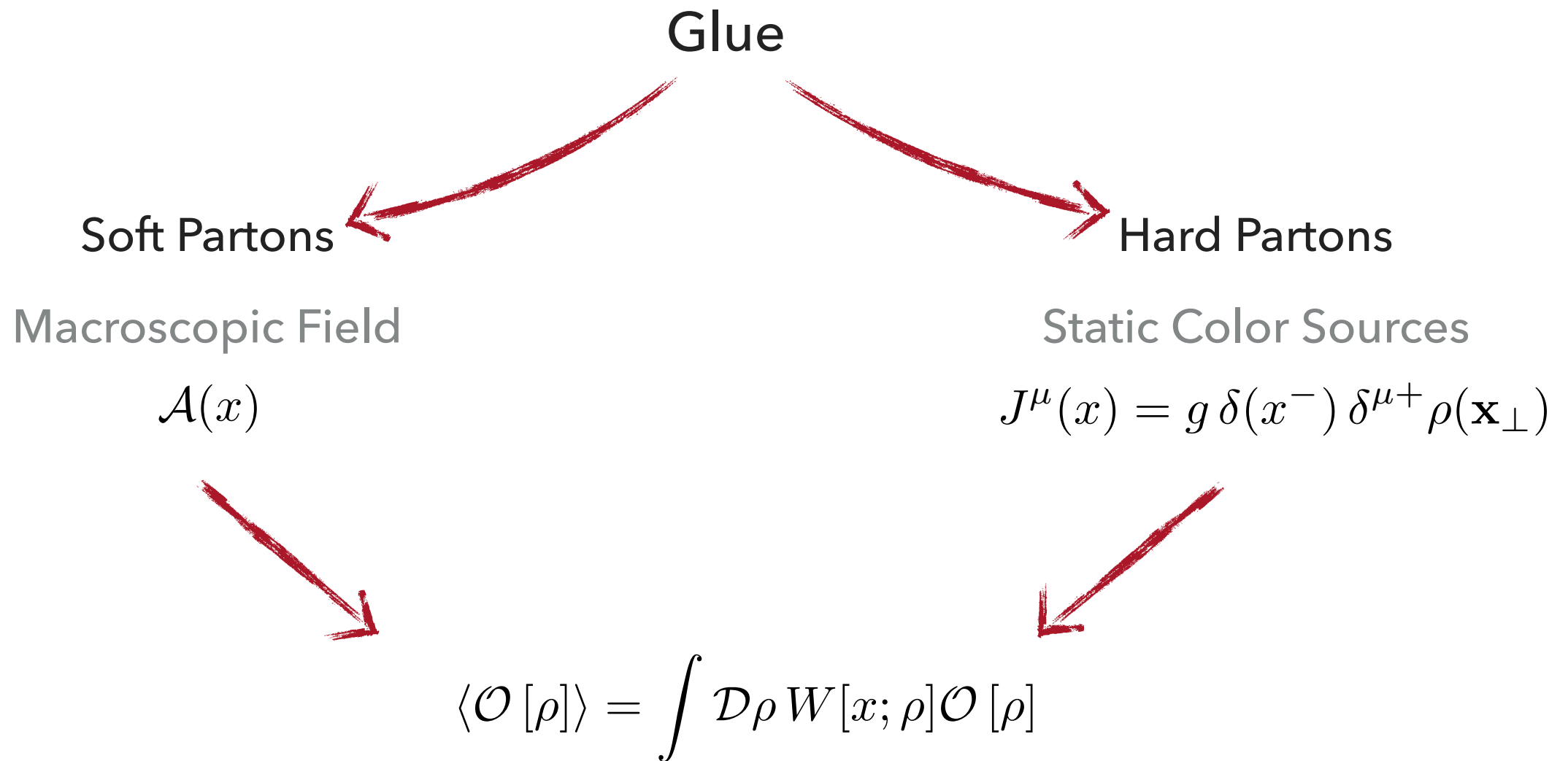
COLOR GLASS CONDENSATE



COLOR GLASS CONDENSATE

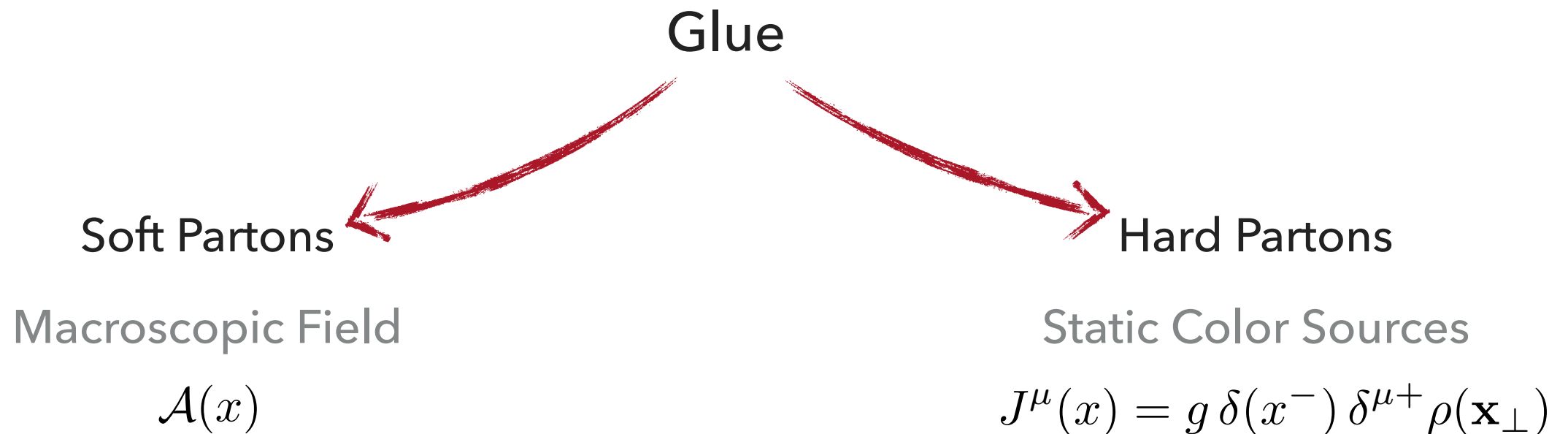


COLOR GLASS CONDENSATE



$W[x; \rho]$: gauge invariant probability distribution

COLOR GLASS CONDENSATE

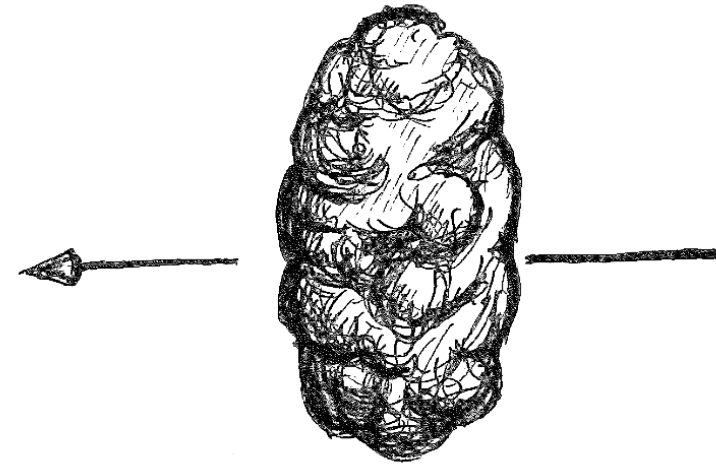


SPECIAL CASE

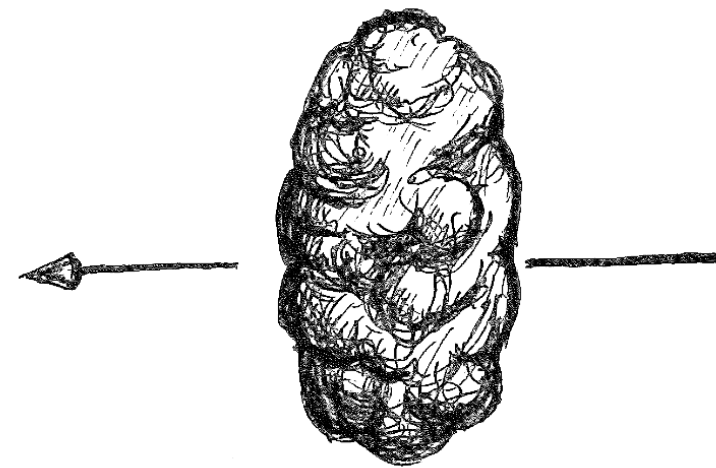
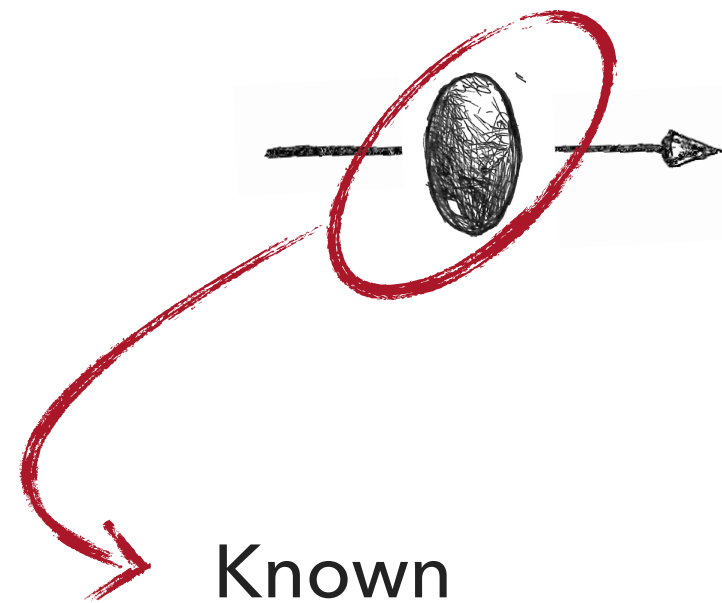
McLerran-Venugopalan Model

$$\langle \rho^a(\mathbf{x}_\perp) \rho^b(\mathbf{y}_\perp) \rangle = g^2 \delta^{ab} \mu^2 \delta^{(2)}(\mathbf{x}_\perp - \mathbf{y}_\perp)$$

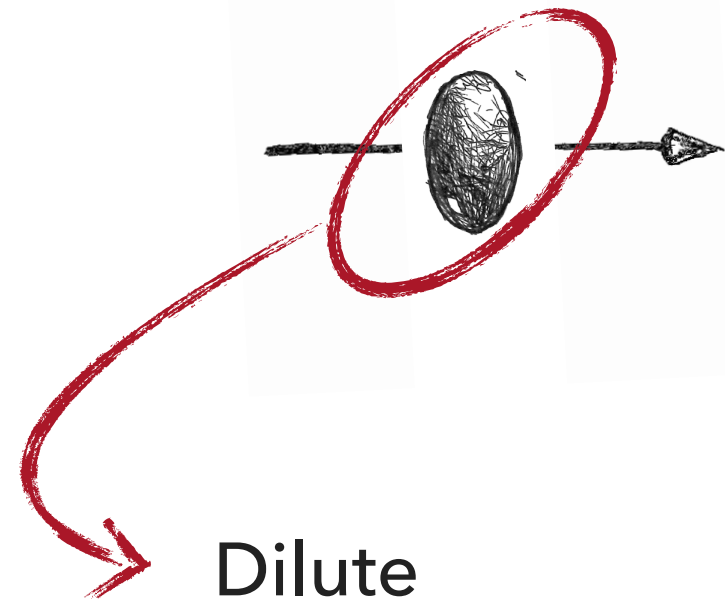
Our turf: $p+A$



Our turf: $p+A$

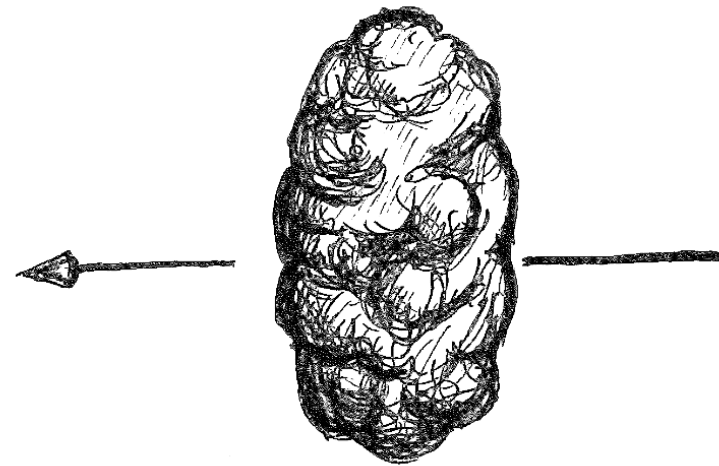


Our turf: p+A

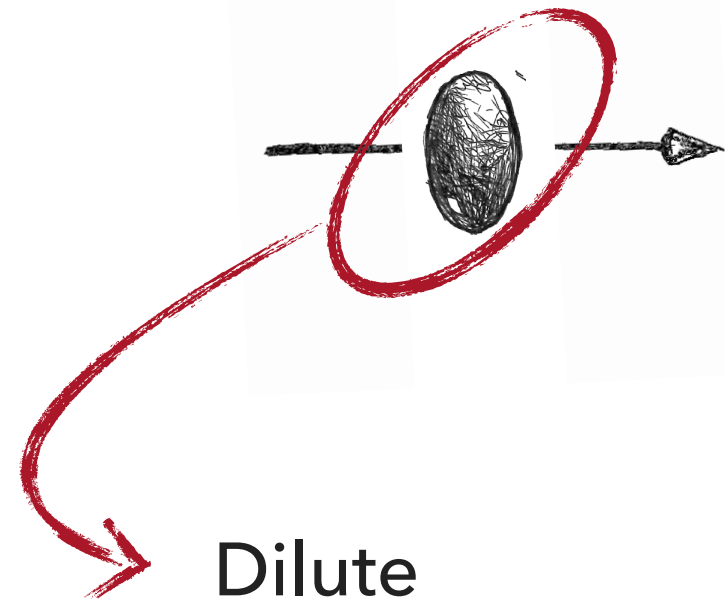


Dilute

$$J_p^\mu(x) = g \delta(x^-) \delta^{\mu+} \rho_p(\mathbf{x}_\perp)$$

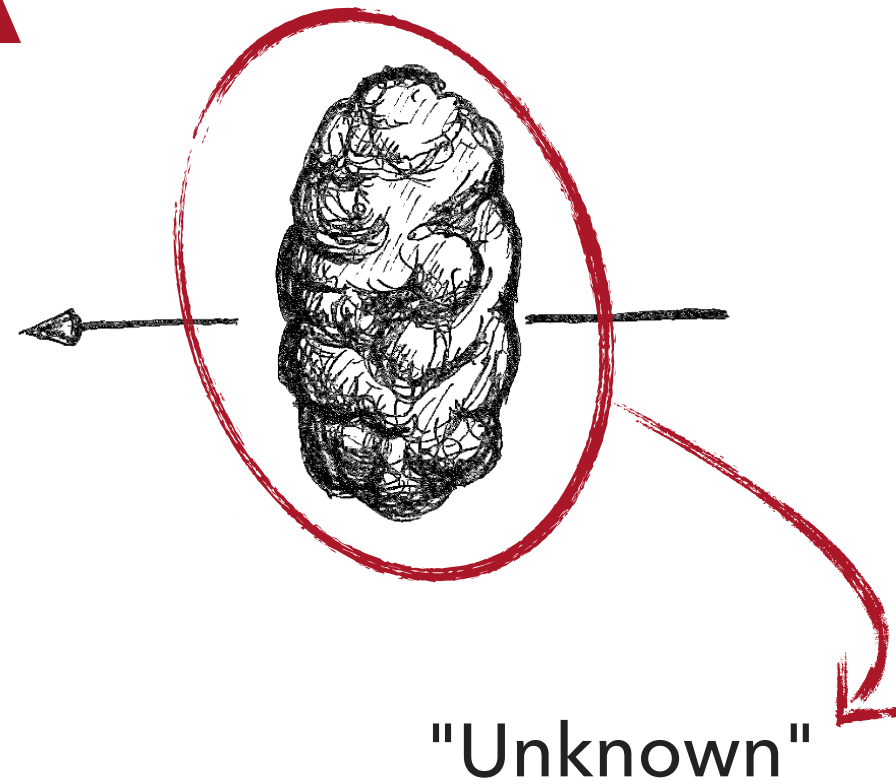


Our turf: p+A



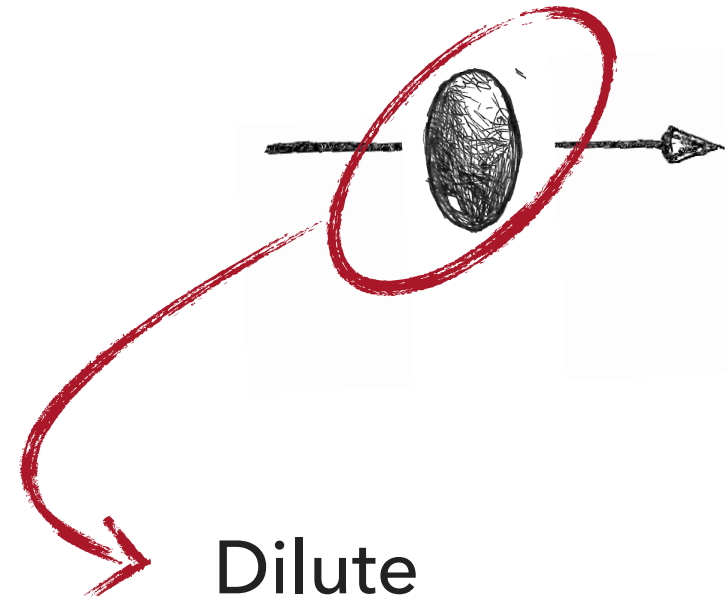
Dilute

$$J_p^\mu(x) = g \delta(x^-) \delta^{\mu+} \rho_p(\mathbf{x}_\perp)$$



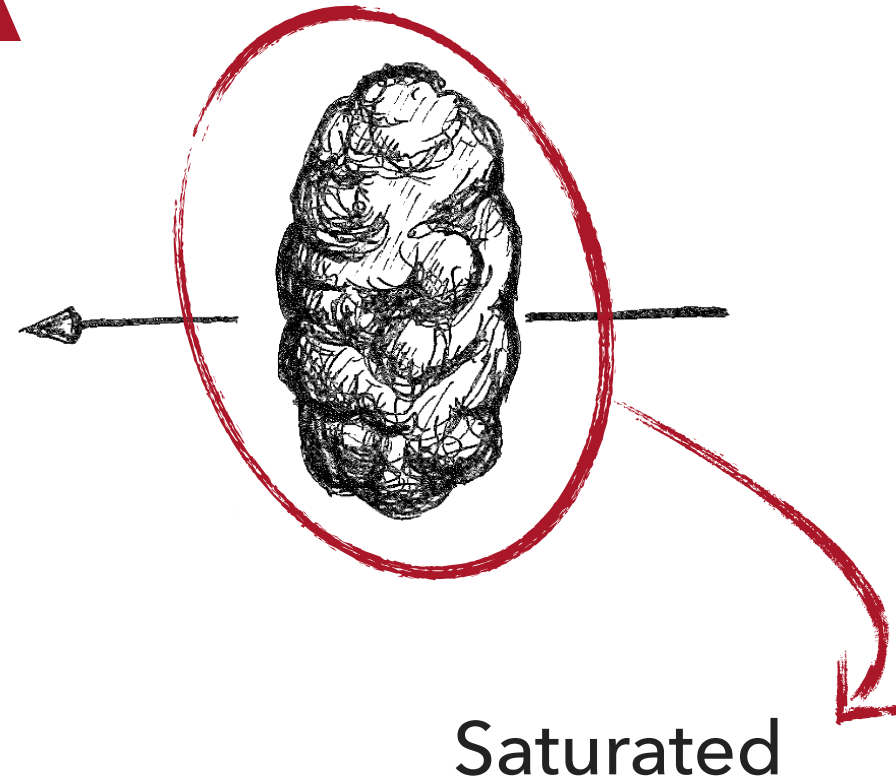
"Unknown"

Our turf: p+A



Dilute

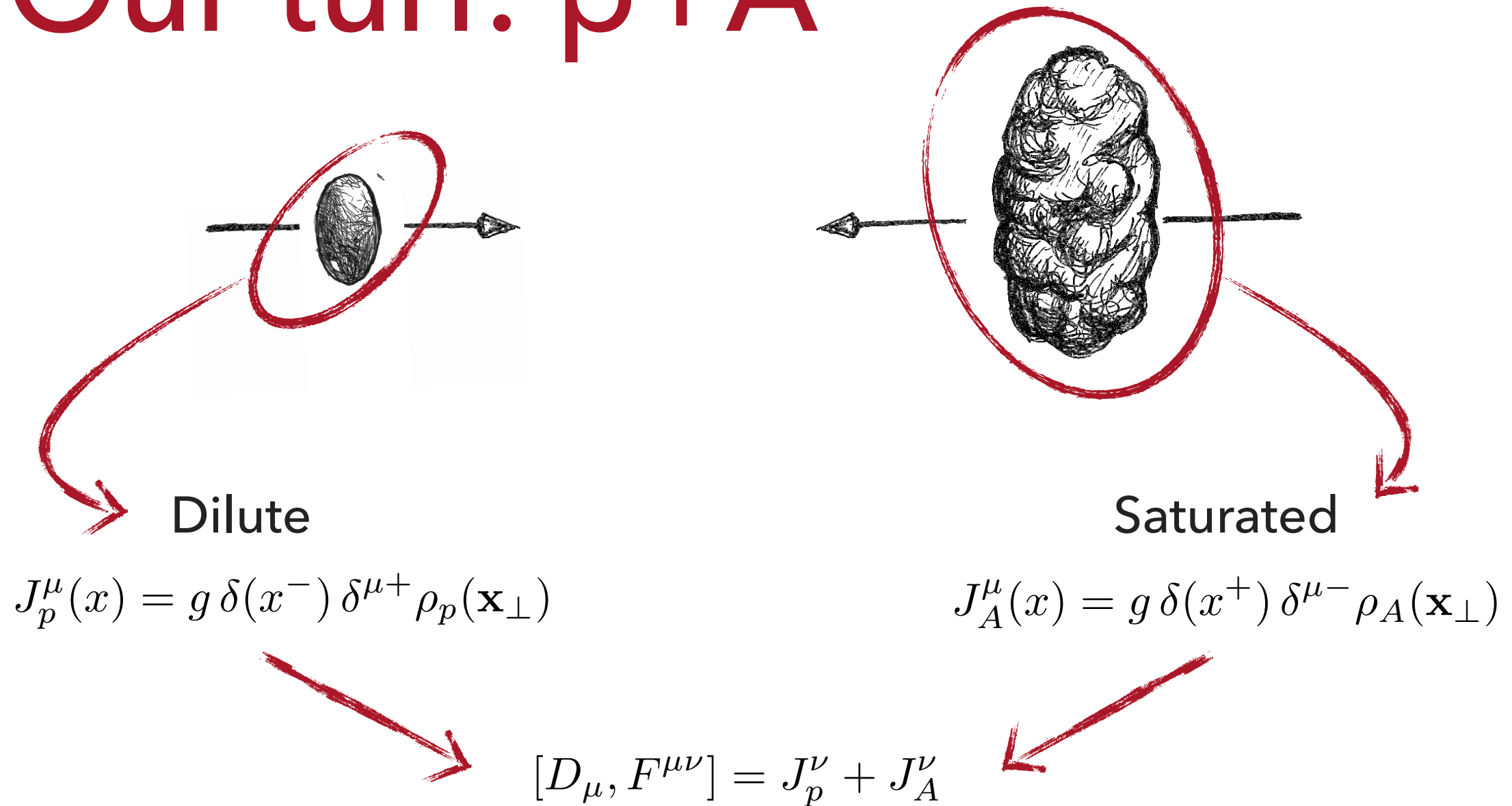
$$J_p^\mu(x) = g \delta(x^-) \delta^{\mu+} \rho_p(\mathbf{x}_\perp)$$



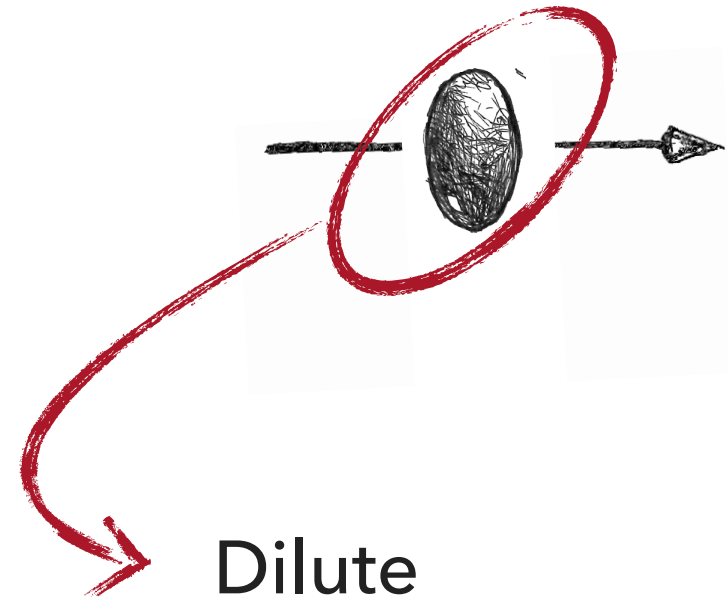
Saturated

$$J_A^\mu(x) = g \delta(x^+) \delta^{\mu-} \rho_A(\mathbf{x}_\perp)$$

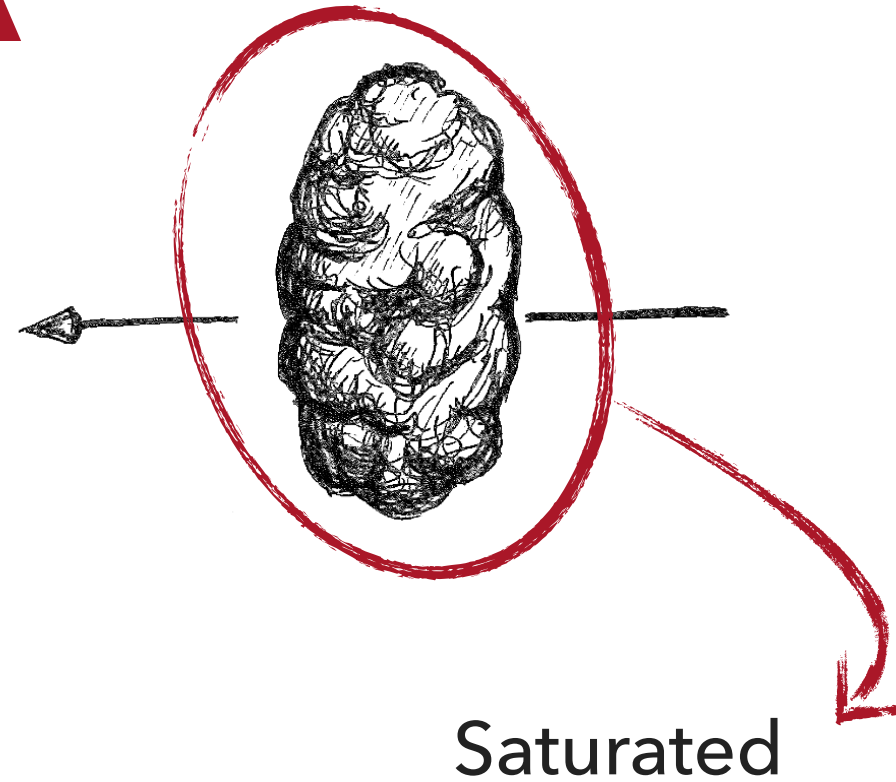
Our turf: p+A



Our turf: p+A



$$J_p^\mu(x) = g \delta(x^-) \delta^{\mu+} \rho_p(\mathbf{x}_\perp)$$



$$J_A^\mu(x) = g \delta(x^+) \delta^{\mu-} \rho_A(\mathbf{x}_\perp)$$

$$[D_\mu, F^{\mu\nu}] = J_p^\nu + J_A^\nu$$

$$\langle \mathcal{O}[\rho_p, \rho_A] \rangle = \int \mathcal{D}\rho_p \mathcal{D}\rho_A W[x_p; \rho_p] W[x_A; \rho_A] \mathcal{O}[\rho_p, \rho_A]$$

Our turf: p+A

$$A^\mu(q) = A_p^\mu(q) + \frac{ig}{q^2 + iq^+\epsilon} \int \frac{\mathbf{k}_{1\perp}}{(2\pi)^2} \int d^2\mathbf{x}_\perp e^{i(\mathbf{q}_\perp - \mathbf{k}_{1\perp}) \cdot \mathbf{x}_\perp} \\ \times \left\{ C_U^\mu(q, \mathbf{k}_{1\perp}) [U(\mathbf{x}_\perp) - 1] + C_V^\mu(q) [V(\mathbf{x}_\perp) - 1] \right\} \frac{\rho_p(\mathbf{k}_{1\perp})}{k_{1\perp}^2}$$



$$U(\mathbf{x}_\perp) = \mathcal{P}_+ \exp \left[ig \int dz^+ A_A^-(z^+, \mathbf{x}_\perp) \cdot T \right]$$

Our turf: p+A

$$A^\mu(q) = A_p^\mu(q) + \frac{ig}{q^2 + iq^+\epsilon} \int \frac{\mathbf{k}_{1\perp}}{(2\pi)^2} \int d^2\mathbf{x}_\perp e^{i(\mathbf{q}_\perp - \mathbf{k}_{1\perp}) \cdot \mathbf{x}_\perp} \\ \times \left\{ C_U^\mu(q, \mathbf{k}_{1\perp}) [U(\mathbf{x}_\perp) - 1] + C_V^\mu(q) [V(\mathbf{x}_\perp) - 1] \right\} \frac{\rho_p(\mathbf{k}_{1\perp})}{k_{1\perp}^2}$$



$$U(\mathbf{x}_\perp) = \mathcal{P}_+ \exp \left[ig \int dz^+ A_A^-(z^+, \mathbf{x}_\perp) \cdot T \right]$$

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$$A^\mu(q) = A_p^\mu(q) + \frac{ig}{q^2 + iq^+\epsilon} \int \frac{\mathbf{k}_{1\perp}}{(2\pi)^2} \int d^2\mathbf{x}_\perp e^{i(\mathbf{q}_\perp - \mathbf{k}_{1\perp}) \cdot \mathbf{x}_\perp} \\ \times \left\{ C_U^\mu(q, \mathbf{k}_{1\perp}) [U(\mathbf{x}_\perp) - 1] + C_V^\mu(q) [V(\mathbf{x}_\perp) - 1] \right\} \frac{\rho_p(\mathbf{k}_{1\perp})}{k_{1\perp}^2}$$



$$V(\mathbf{x}_\perp) = \mathcal{P}_+ \exp \left[\frac{ig}{2} \int dz^+ A_A^-(z^+, \mathbf{x}_\perp) \cdot T \right]$$

Gauge Artifact

Our turf: p+A

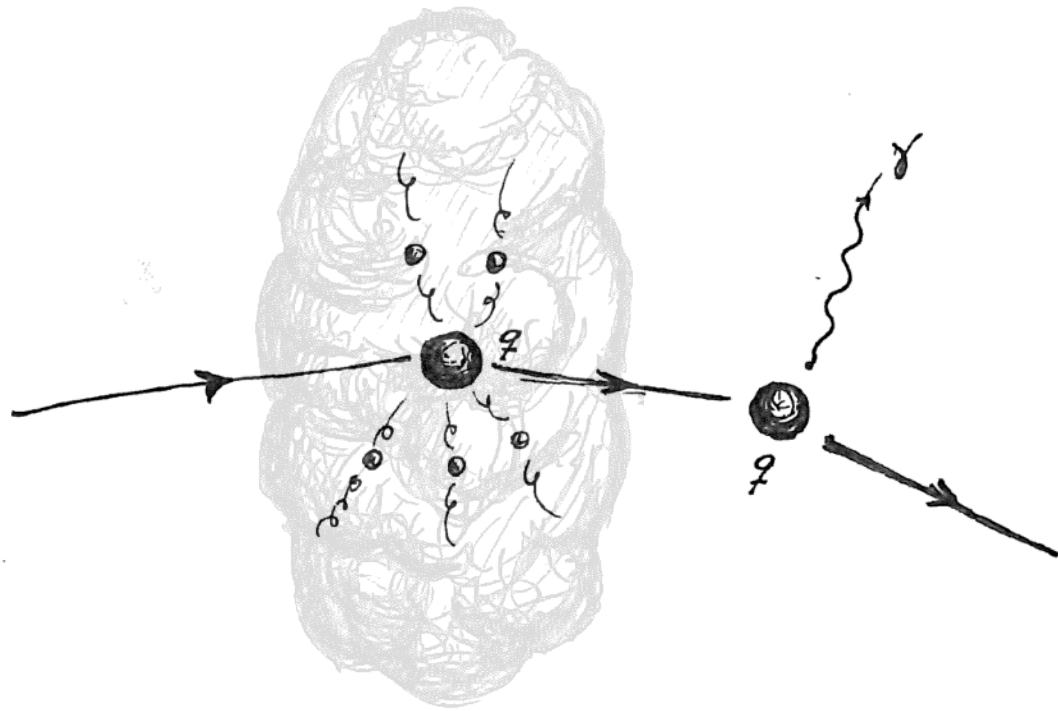
$$A^\mu(q) = A_p^\mu(q) + \frac{ig}{q^2 + i\epsilon} \int \frac{k_{1\perp}}{(2\pi)^2} \int d^2\mathbf{x}_\perp e^{i(\mathbf{q}_\perp - \mathbf{k}_{1\perp}) \cdot \mathbf{x}_\perp} \\ \times \left\{ C_U^\mu(q, \mathbf{k}_{1\perp}) [U(\mathbf{x}_\perp) - 1] + C_V^\mu(q) [V(\mathbf{x}_\perp) - 1] \right\} \frac{\rho_p(\mathbf{k}_{1\perp})}{k_{1\perp}^2}$$

Superposition

$$A \times \text{wavy line} = \rho_p \times \text{wavy line} + A_p \times \text{wavy line} \otimes \text{wavy line}$$

proton CGC mixed field

COLOR GLASS CONDENSATE



How do quarks behave
through the CGC?



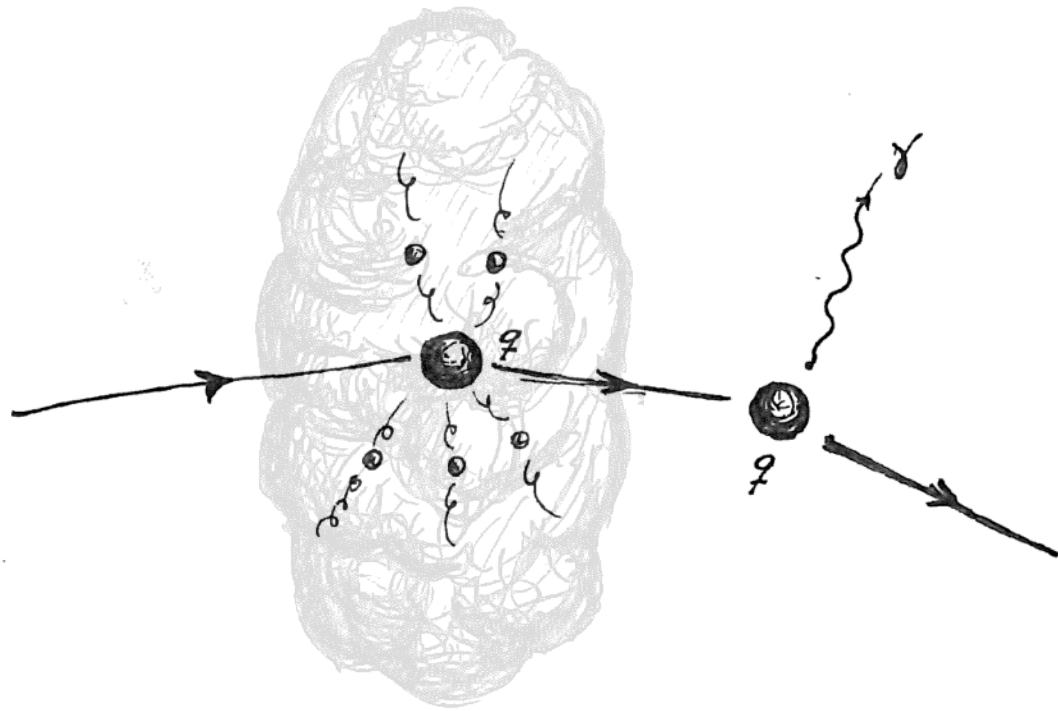
Multiple Scatterings



Dressed propagator



COLOR GLASS CONDENSATE



How do quarks behave through the CGC?



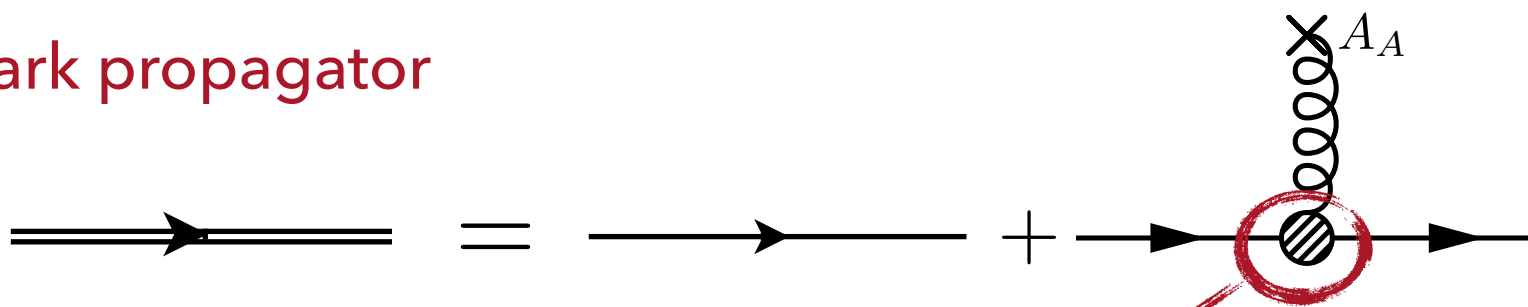
Multiple Scatterings



Dressed propagator

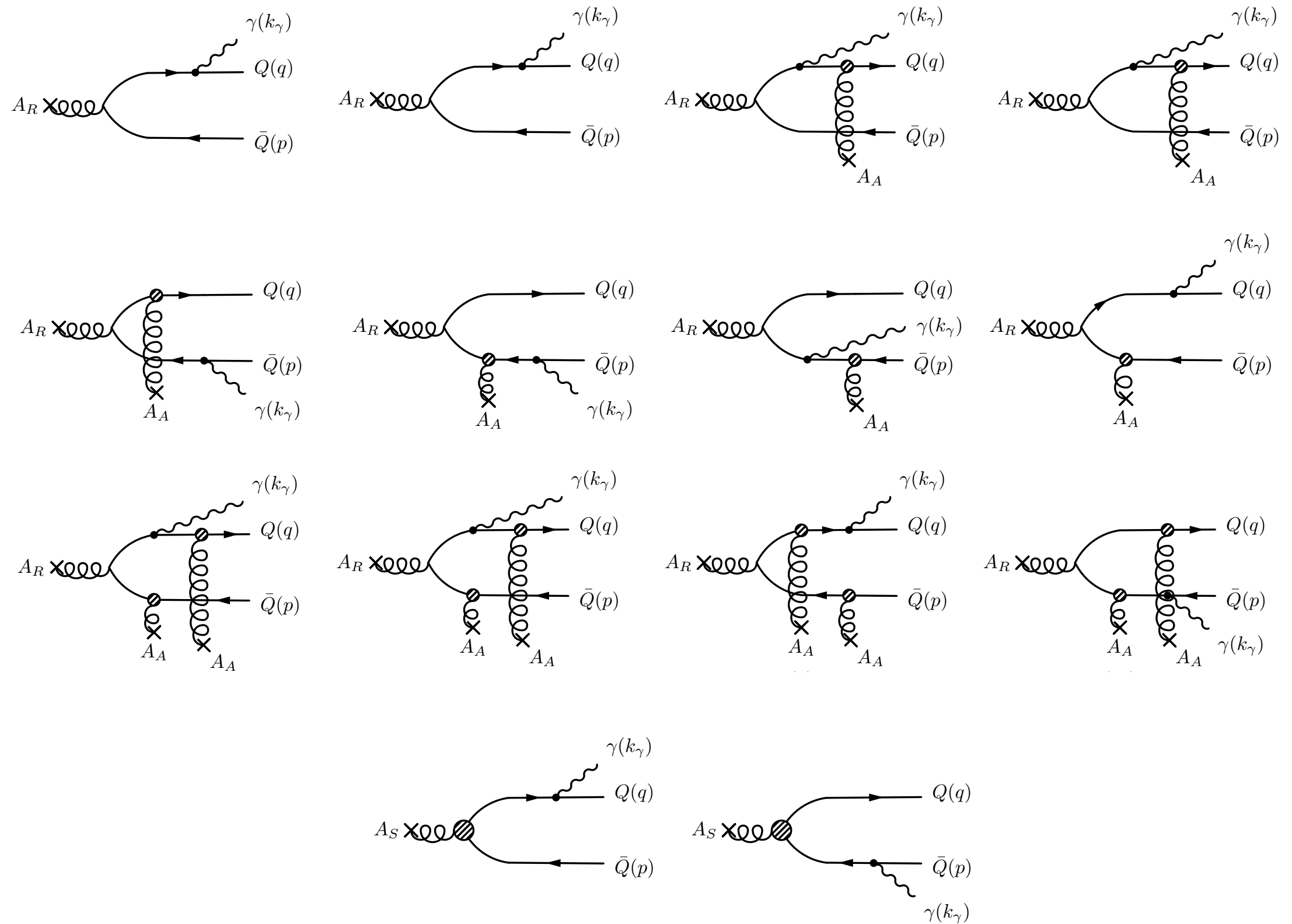


Quark propagator



$$\mathcal{T}(k, p) = 2\pi \operatorname{sgn}(p^+) \gamma^+ \int d^2 \mathbf{x}_\perp e^{i \mathbf{x}_\perp \cdot \mathbf{k}_\perp} \left[U^{\operatorname{sgn}(p^+)}(\mathbf{x}_\perp) - 1 \right]$$

ALL CONTRIBUTIONS

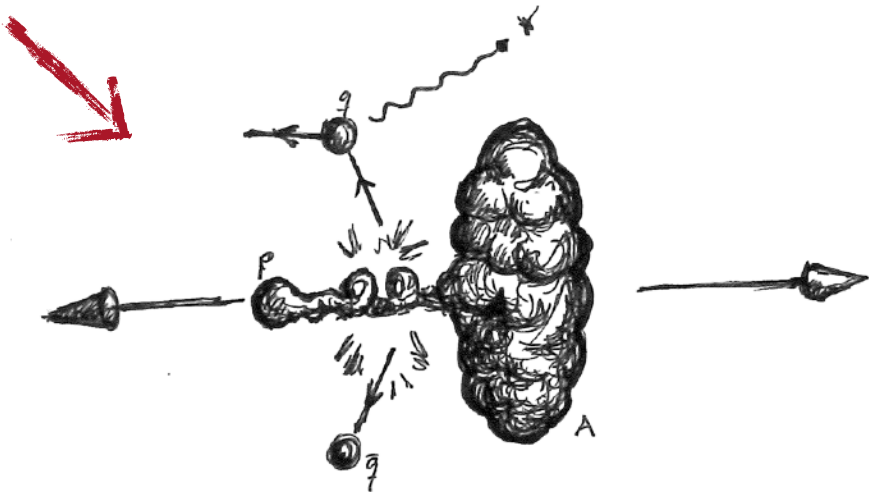


AMPLITUDE

$$\begin{aligned}
 \mathcal{M} = & -q_f e g^2 \epsilon_\mu(\mathbf{k}_\gamma) \int d^2 \mathbf{k}_\perp d^2 \mathbf{k}_{1\perp} \int d^2 \mathbf{x}_\perp d^2 \mathbf{y}_\perp e^{i \mathbf{k}_\perp \cdot \mathbf{x}_\perp} e^{i \mathbf{y}_\perp \cdot (\mathbf{P}_\perp - \mathbf{k}_\perp - \mathbf{k}_{1\perp})} \frac{\rho_p^a(\mathbf{k}_{1\perp})}{k_{1\perp}^2} \\
 & \times \bar{u}(\mathbf{q}) \left\{ T_g^\mu(\mathbf{k}_{1\perp}) U^{ba}(\mathbf{x}_\perp) t^b \right. \\
 & \left. + T_{q\bar{q}}^\mu(\mathbf{k}_\perp, \mathbf{k}_{1\perp}) \tilde{U}(\mathbf{x}_\perp) t^a \tilde{U}^\dagger(\mathbf{y}_\perp) \right\} v(\mathbf{p})
 \end{aligned}$$

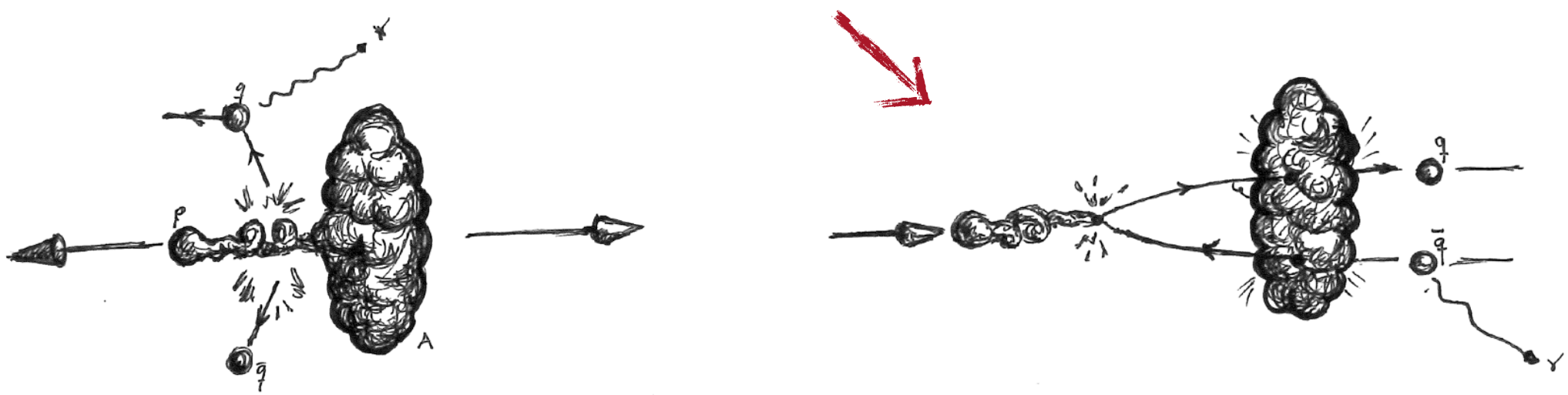
AMPLITUDE

$$\begin{aligned} \mathcal{M} = & -q_f e g^2 \epsilon_\mu(\mathbf{k}_\gamma) \int d^2 \mathbf{k}_\perp d^2 \mathbf{k}_{1\perp} \int d^2 \mathbf{x}_\perp d^2 \mathbf{y}_\perp e^{i \mathbf{k}_\perp \cdot \mathbf{x}_\perp} e^{i \mathbf{y}_\perp \cdot (\mathbf{P}_\perp - \mathbf{k}_\perp - \mathbf{k}_{1\perp})} \frac{\rho_p^a(\mathbf{k}_{1\perp})}{k_{1\perp}^2} \\ & \times \bar{u}(\mathbf{q}) \left\{ \underline{T_g^\mu(\mathbf{k}_{1\perp}) U^{ba}(\mathbf{x}_\perp) t^b} \right. \\ & \left. + T_{q\bar{q}}^\mu(\mathbf{k}_\perp, \mathbf{k}_{1\perp}) \tilde{U}(\mathbf{x}_\perp) t^a \tilde{U}^\dagger(\mathbf{y}_\perp) \right\} v(\mathbf{p}) \end{aligned}$$



AMPLITUDE

$$\begin{aligned} \mathcal{M} = & -q_f e g^2 \epsilon_\mu(\mathbf{k}_\gamma) \int d^2 \mathbf{k}_\perp d^2 \mathbf{k}_{1\perp} \int d^2 \mathbf{x}_\perp d^2 \mathbf{y}_\perp e^{i \mathbf{k}_\perp \cdot \mathbf{x}_\perp} e^{i \mathbf{y}_\perp \cdot (\mathbf{P}_\perp - \mathbf{k}_\perp - \mathbf{k}_{1\perp})} \frac{\rho_p^a(\mathbf{k}_{1\perp})}{k_{1\perp}^2} \\ & \times \bar{u}(\mathbf{q}) \left\{ T_g^\mu(\mathbf{k}_{1\perp}) U^{ba}(\mathbf{x}_\perp) t^b \right. \\ & \left. + T_{q\bar{q}}^\mu(\mathbf{k}_\perp, \mathbf{k}_{1\perp}) \tilde{U}(\mathbf{x}_\perp) t^a \tilde{U}^\dagger(\mathbf{y}_\perp) \right\} v(\mathbf{p}) \end{aligned}$$



CROSS-SECTION

$$\begin{aligned}
 \frac{d\sigma^\gamma}{d^2\mathbf{k}_{\gamma\perp} dy_\gamma d^2\mathbf{q}_\perp dy_q d^2\mathbf{p}_\perp dy_p} &= \frac{\alpha_e \alpha_S^2 q_f^2}{(2\pi)^8 C_F} \int \frac{d^2\mathbf{k}_{1\perp}}{(2\pi)^2} \frac{d^2\mathbf{k}_{2\perp}}{(2\pi)^2} \delta^{(2)}(\mathbf{P}_\perp - \mathbf{k}_{1\perp} - \mathbf{k}_{2\perp}) \frac{\varphi_p(\mathbf{k}_{1\perp})}{k_{1\perp}^2} \\
 &\times \left\{ \tau_{g,g}(\mathbf{k}_{1\perp}; \mathbf{k}_{1\perp}) \frac{\phi_A^{g,g}(\mathbf{k}_{2\perp})}{k_{2\perp}^2} \right. \\
 &\quad + 2\text{Re} [\tau_{g,qq}(\mathbf{k}_{1\perp}; \mathbf{k}_\perp, \mathbf{k}_{1\perp})] \frac{\phi_A^{qq,g}(\mathbf{k}_{2\perp}, \mathbf{k}_{2\perp} - \mathbf{k}_\perp; \mathbf{k}_{2\perp})}{k_{2\perp}^2} \\
 &\quad \left. + \tau_{qq,qq}(\mathbf{k}'_\perp, \mathbf{k}_{1\perp}; \mathbf{k}_\perp, \mathbf{k}_{1\perp}) \frac{\phi_A^{qq,qq}(\mathbf{k}_\perp, \mathbf{k}_{2\perp} - \mathbf{k}_\perp, \mathbf{k}'_\perp, \mathbf{k}_{2\perp} - \mathbf{k}'_\perp)}{k_{2\perp}^2} \right\}
 \end{aligned}$$

COLOR AVERAGING

Two-point Correlator

$$\begin{aligned} \frac{\phi^{g,g}(\mathbf{k}_{2\perp})}{k_{2\perp}^2} = & \frac{1}{2N_c\alpha_S} \int \frac{d^2\mathbf{k}_\perp}{(2\pi)^2} \frac{d^2\mathbf{k}'_\perp}{(2\pi)^2} \int d^2\mathbf{x}_\perp d^2\mathbf{y}_\perp d^2\mathbf{x}'_\perp d^2\mathbf{y}'_\perp e^{i(\mathbf{k}_\perp \cdot \mathbf{x}_\perp - \mathbf{k}'_\perp \cdot \mathbf{x}'_\perp)} e^{i(\mathbf{k}_{2\perp} - \mathbf{k}_\perp) \cdot \mathbf{y}_\perp} \\ & \times e^{-i(\mathbf{k}_{2\perp} - \mathbf{k}'_\perp) \cdot \mathbf{y}'_\perp} \delta^{aa'} \text{tr}_c \langle t^b U^{ba}(\mathbf{x}_\perp) t^b U^{\dagger ba}(\mathbf{x}_\perp) \rangle \end{aligned}$$

COLOR AVERAGING

Three-point Correlator

$$\frac{\phi^{qq,g}(\mathbf{k}_\perp, \mathbf{k}_\perp - \mathbf{k}_{2\perp}; \mathbf{k}_{2\perp})}{k_{2\perp}^2} = \frac{1}{2N_c\alpha_S} \int \frac{d^2\mathbf{k}'_\perp}{(2\pi)^2} \int d^2\mathbf{x}_\perp d^2\mathbf{y}_\perp d^2\mathbf{x}'_\perp d^2\mathbf{y}'_\perp e^{i(\mathbf{k}_\perp \cdot \mathbf{x}_\perp - \mathbf{k}'_\perp \cdot \mathbf{x}'_\perp)} e^{i(\mathbf{k}_{2\perp} - \mathbf{k}_\perp) \cdot \mathbf{y}_\perp} \\ \times e^{-i(\mathbf{k}_{2\perp} - \mathbf{k}'_\perp) \cdot \mathbf{y}'_\perp} \delta^{aa'} \text{tr}_c \left\langle \tilde{U}(\mathbf{x}_\perp) t^a \tilde{U}^\dagger(\mathbf{x}_\perp) t^{b'} U^{\dagger a' b'}(\mathbf{x}'_\perp) \right\rangle$$

COLOR AVERAGING

Four-point Correlator

$$\frac{\phi^{qq,qq}(\mathbf{k}_\perp, \mathbf{k}_{2\perp} - \mathbf{k}_\perp; \mathbf{k}'_\perp, \mathbf{k}_{2\perp} - \mathbf{k}'_\perp)}{k_{2\perp}^2} = \frac{1}{2N_c\alpha_S} \int d^2\mathbf{x}_\perp d^2\mathbf{y}_\perp d^2\mathbf{x}'_\perp d^2\mathbf{y}'_\perp e^{i(\mathbf{k}_\perp \cdot \mathbf{x}_\perp - \mathbf{k}'_\perp \cdot \mathbf{x}'_\perp)} e^{i(\mathbf{k}_{2\perp} - \mathbf{k}_\perp) \cdot \mathbf{y}_\perp} \\ \times e^{-i(\mathbf{k}_{2\perp} - \mathbf{k}'_\perp) \cdot \mathbf{y}'_\perp} \delta^{aa'} \text{tr}_c \left\langle \tilde{U}(\mathbf{x}_\perp) t^a \tilde{U}^\dagger(\mathbf{x}_\perp) t^{b'} U^{\dagger a' b'}(\mathbf{x}'_\perp) \right\rangle$$

COLOR AVERAGING

EXAMPLE: DIPOLE

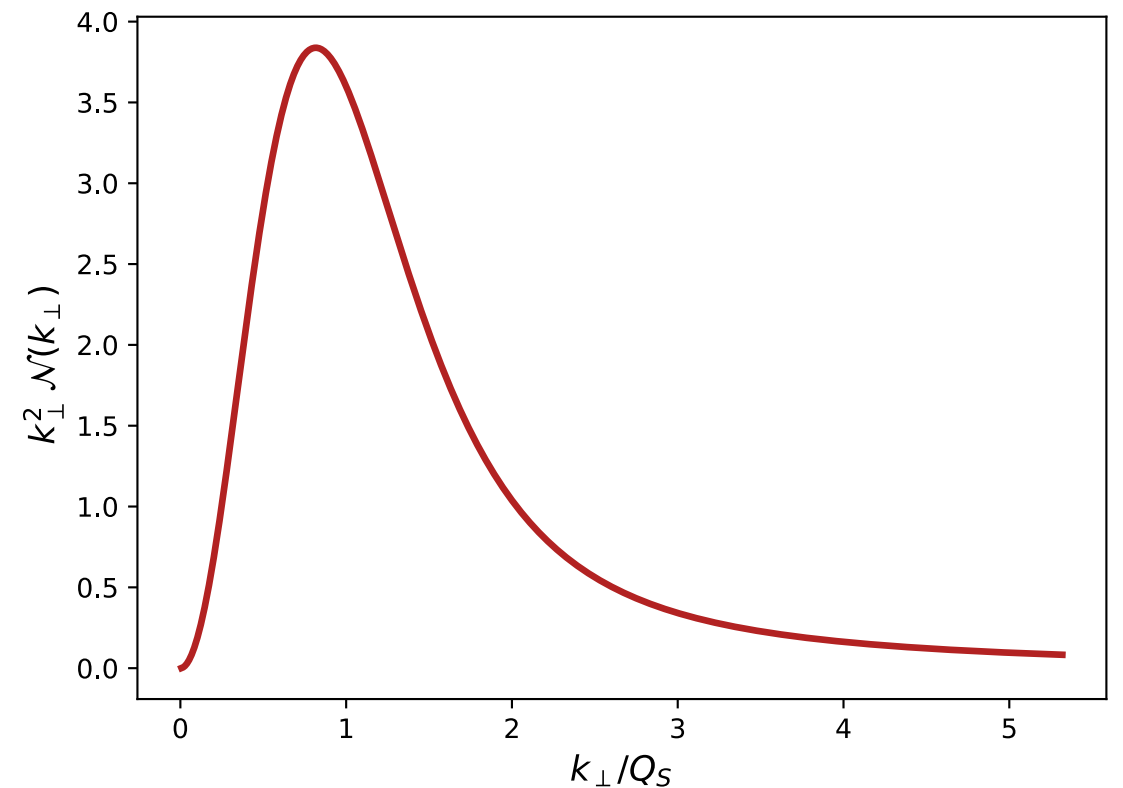
$$\tilde{\mathcal{N}}(\mathbf{k}_\perp) = \int d^2\mathbf{x}_\perp e^{i\mathbf{k}_\perp \cdot \mathbf{x}_\perp} \left\langle \tilde{U}(0) \tilde{U}^\dagger(\mathbf{x}_\perp) \right\rangle$$

An involved process of gaussian averaging the sources

COLOR AVERAGING

EXAMPLE: DIPOLE

$$\begin{aligned}\tilde{\mathcal{N}}(\mathbf{k}_\perp) &= \int d^2\mathbf{x}_\perp e^{i\mathbf{k}_\perp \cdot \mathbf{x}_\perp} \left\langle \tilde{U}(0) \tilde{U}^\dagger(\mathbf{x}_\perp) \right\rangle \\ &= \int d^2\mathbf{x}_\perp e^{i\mathbf{k}_\perp \cdot \mathbf{x}_\perp} e^{-B_2(\mathbf{x}_\perp)}\end{aligned}$$



An involved process of gaussian averaging the sources

$$B_2(\mathbf{x}_\perp) = \frac{1}{2\pi} \left(\frac{Q_s}{\Lambda_{QCD}} \right)^2 [1 - x_\perp \Lambda_{QCD} K_1(x_\perp \Lambda_{QCD})]$$

Nucl.Phys. A697 (**2002**) 879-901

Nucl.Phys. A695 (**2001**) 395-429

COLOR AVERAGING

Large N limit

Dynamics dictated

by forward dipole
amplitude

$$\frac{\phi^{g,g}(\mathbf{k}_{2\perp})}{k_{2\perp}^2} = \frac{N_c}{4\alpha_S} (\pi R_A)^2 \int \frac{d^2 \mathbf{k}_\perp}{(2\pi)^2} \tilde{\mathcal{N}}_A(\mathbf{k}_\perp) \tilde{\mathcal{N}}_A(\mathbf{k}_{2\perp} - \mathbf{k}_\perp)$$

$$\frac{\phi^{qq,g}(\mathbf{k}_\perp, \mathbf{k}_\perp - \mathbf{k}_{2\perp}; \mathbf{k}_{2\perp})}{k_{2\perp}^2} = \frac{N_c}{4\alpha_S} (\pi R_A)^2 \tilde{\mathcal{N}}_A(\mathbf{k}_\perp) \tilde{\mathcal{N}}_A(\mathbf{k}_{2\perp} - \mathbf{k}_\perp)$$

$$\begin{aligned} \frac{\phi^{qq,qq}(\mathbf{k}_\perp, \mathbf{k}_{2\perp} - \mathbf{k}_\perp; \mathbf{k}'_\perp, \mathbf{k}_{2\perp} - \mathbf{k}'_\perp)}{k_{2\perp}^2} &= \frac{N_c}{4\alpha_S} (2\pi)^2 \delta^{(2)}(\mathbf{k}_\perp - \mathbf{k}'_\perp) (\pi R_A)^2 \\ &\quad \times \tilde{\mathcal{N}}_A(\mathbf{k}_\perp) \tilde{\mathcal{N}}_A(\mathbf{k}_{2\perp} - \mathbf{k}_\perp) \end{aligned}$$

LEADING TWIST APPROXIMATION

● $\mathbf{k}_\perp$ Factorization

$$\begin{aligned} \frac{d\sigma^\gamma}{d^2\mathbf{k}_{\gamma\perp} dy_\gamma} &= \frac{\alpha_e \alpha_S^2 q_f^2}{(2\pi)^4 N_c (N_c^2 - 1)} \int_0^\infty \frac{dq^+}{q^+} \frac{dp^+}{p^+} \int \frac{d^2\mathbf{q}_\perp}{(2\pi)^2} \frac{d^2\mathbf{p}_\perp}{(2\pi)^2} (2\pi)^2 \\ &\times (2\pi)^2 \delta^{(2)}(\mathbf{P}_\perp - \mathbf{k}_{1\perp} - \mathbf{k}_{2\perp}) \frac{\varphi_p(\mathbf{k}_{1\perp})}{\mathbf{k}_{1\perp}} \frac{\varphi_A(\mathbf{k}_{2\perp})}{\mathbf{k}_{2\perp}} \Theta(\mathbf{k}_{1\perp}, \mathbf{k}_{2\perp}) \end{aligned}$$

LEADING TWIST APPROXIMATION

● $\mathbf{k}_\perp$ Factorization

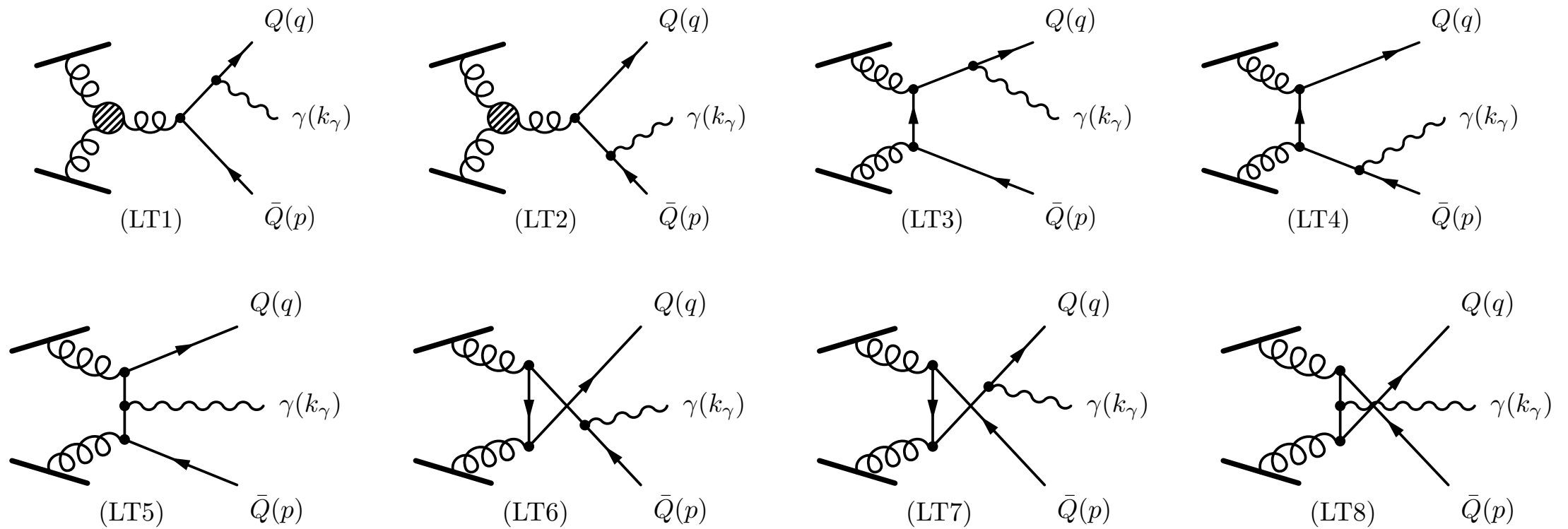
$$\begin{aligned} \frac{d\sigma^\gamma}{d^2\mathbf{k}_{\gamma\perp} dy_\gamma} &= \frac{\alpha_e \alpha_S^2 q_f^2}{(2\pi)^4 N_c (N_c^2 - 1)} \int_0^\infty \frac{dq^+}{q^+} \frac{dp^+}{p^+} \int \frac{d^2\mathbf{q}_\perp}{(2\pi)^2} \frac{d^2\mathbf{p}_\perp}{(2\pi)^2} (2\pi)^2 \\ &\times (2\pi)^2 \delta^{(2)}(\mathbf{P}_\perp - \mathbf{k}_{1\perp} - \mathbf{k}_{2\perp}) \frac{\varphi_p(\mathbf{k}_{1\perp})}{\mathbf{k}_{1\perp}} \frac{\varphi_A(\mathbf{k}_{2\perp})}{\mathbf{k}_{2\perp}} \Theta(\mathbf{k}_{1\perp}, \mathbf{k}_{2\perp}) \end{aligned}$$

LEADING TWIST APPROXIMATION

● $\mathbf{k}_\perp$ Factorization

$$\frac{d\sigma^\gamma}{d^2\mathbf{k}_{\gamma\perp} dy_\gamma} = \frac{\alpha_e \alpha_S^2 q_f^2}{(2\pi)^4 N_c (N_c^2 - 1)} \int_0^\infty \frac{dq^+}{q^+} \frac{dp^+}{p^+} \int \frac{d^2\mathbf{q}_\perp}{(2\pi)^2} \frac{d^2\mathbf{p}_\perp}{(2\pi)^2} (2\pi)^2$$

$$\times (2\pi)^2 \delta^{(2)}(\mathbf{P}_\perp - \mathbf{k}_{1\perp} - \mathbf{k}_{2\perp}) \frac{\varphi_p(\mathbf{k}_{1\perp})}{\mathbf{k}_{1\perp}} \frac{\varphi_A(\mathbf{k}_{2\perp})}{\mathbf{k}_{2\perp}} \Theta(\mathbf{k}_{1\perp}, \mathbf{k}_{2\perp})$$



LEADING TWIST APPROXIMATION

$\mathbf{k}_\perp$ Factorization

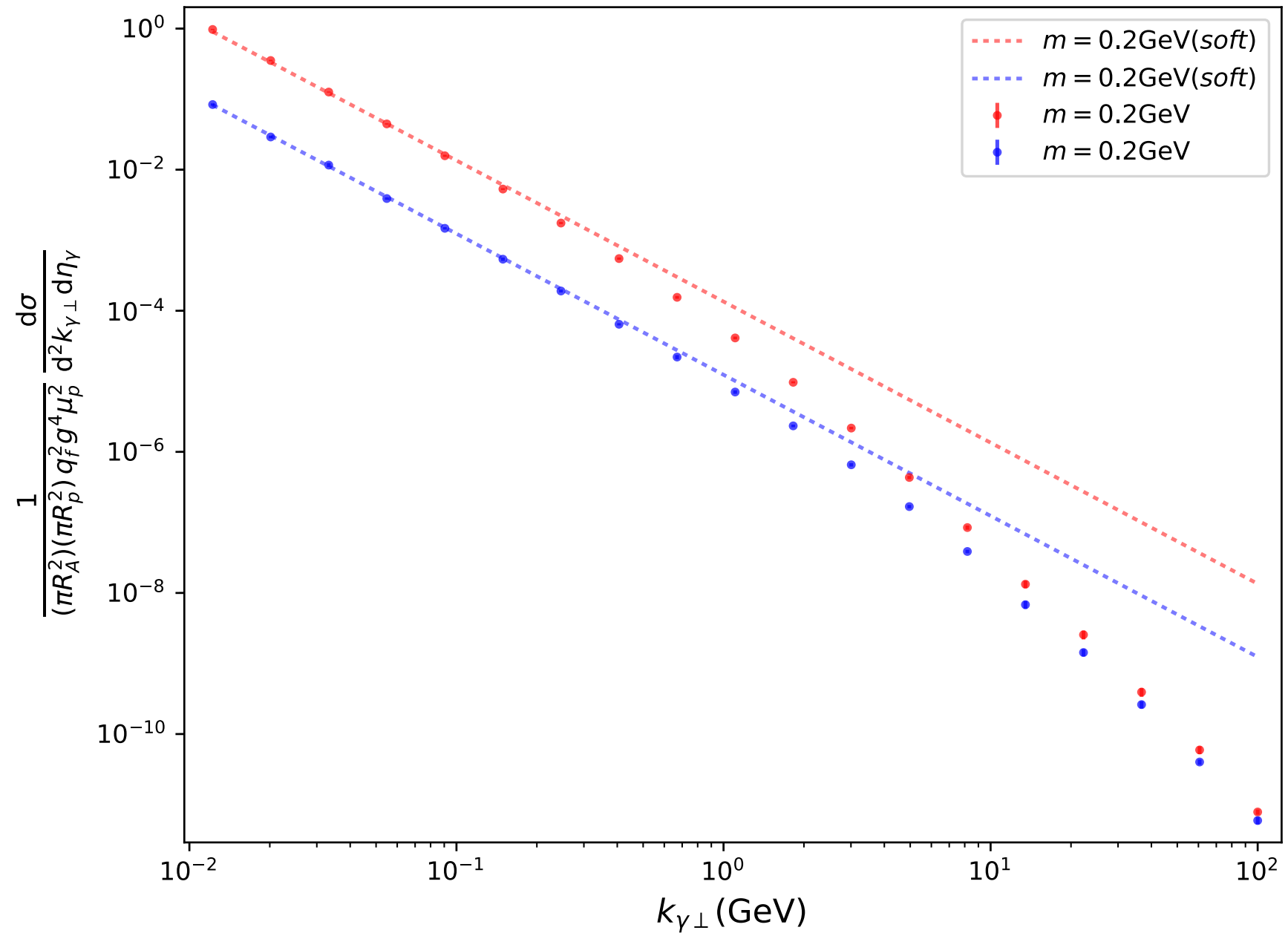
$$\begin{aligned} \frac{d\sigma^\gamma}{d^2\mathbf{k}_{\gamma\perp} dy_\gamma} &= \frac{\alpha_e \alpha_S^2 q_f^2}{(2\pi)^4 N_c (N_c^2 - 1)} \int_0^\infty \frac{dq^+}{q^+} \frac{dp^+}{p^+} \int \frac{d^2\mathbf{q}_\perp}{(2\pi)^2} \frac{d^2\mathbf{p}_\perp}{(2\pi)^2} (2\pi)^2 \\ &\times (2\pi)^2 \delta^{(2)}(\mathbf{P}_\perp - \mathbf{k}_{1\perp} - \mathbf{k}_{2\perp}) \frac{\varphi_p(\mathbf{k}_{1\perp})}{\mathbf{k}_{1\perp}} \frac{\varphi_A(\mathbf{k}_{2\perp})}{\mathbf{k}_{2\perp}} \Theta(\mathbf{k}_{1\perp}, \mathbf{k}_{2\perp}) \end{aligned}$$

ArXiv:1609.04300

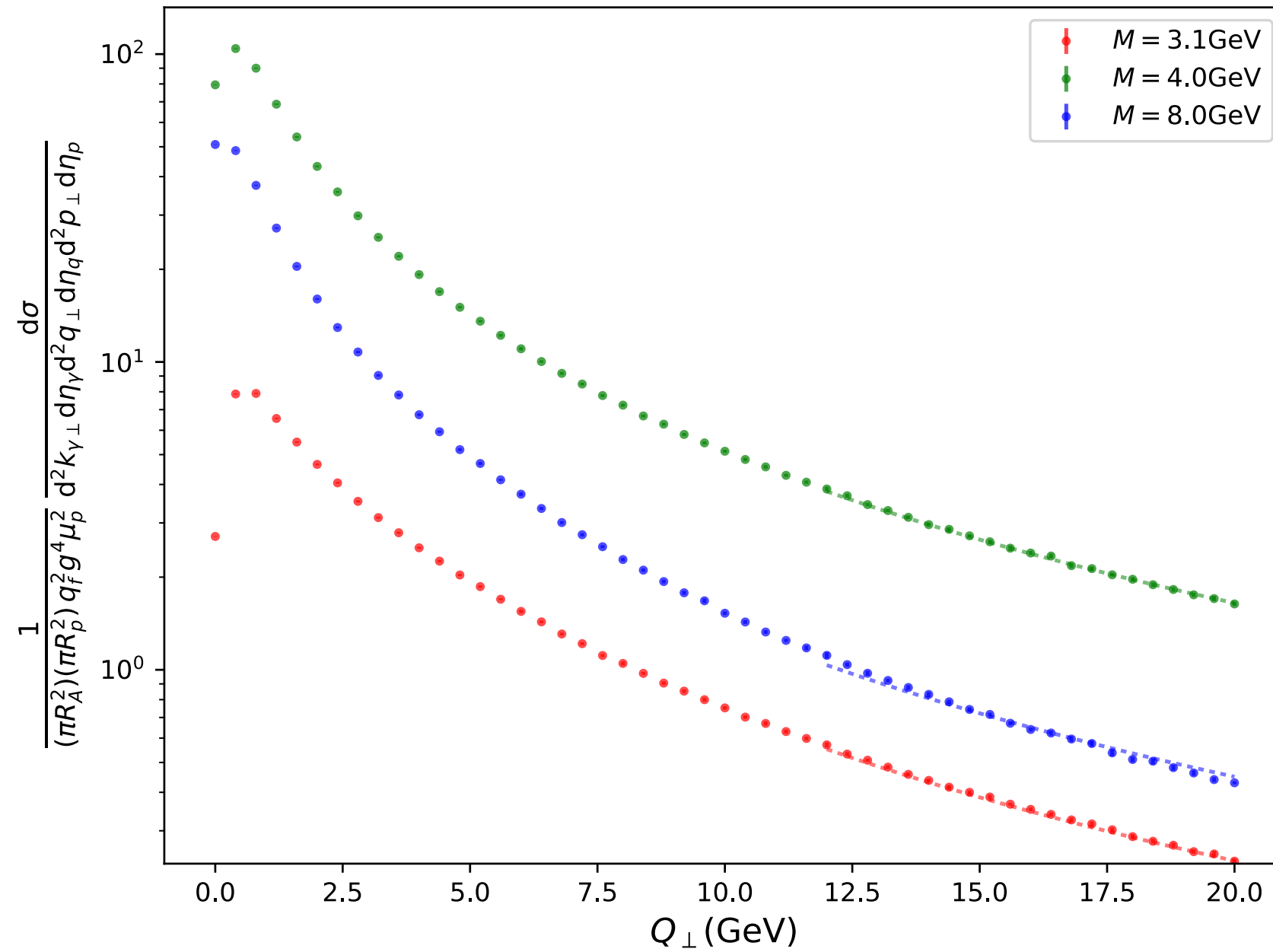
Collinear Factorization

$$\begin{aligned} \frac{d\sigma^\gamma}{d^2\mathbf{k}_{\gamma\perp} dy_\gamma} &= \frac{1}{16} \int_0^\infty \frac{dq^+}{q^+} \frac{dp^+}{p^+} \int \frac{d^2\mathbf{q}_\perp}{(2\pi)^2} \frac{d^2\mathbf{p}_\perp}{(2\pi)^2} \delta^{(2)}(\mathbf{q}_\perp + \mathbf{p}_\perp + \mathbf{k}_{\gamma\perp}) \\ &\times x_p f_{g,p}(x_p, Q^2) x_p f_{g,p}(x_p, Q^2) |\mathcal{M}_{gg \rightarrow q\bar{q}\gamma}|^2 \end{aligned}$$

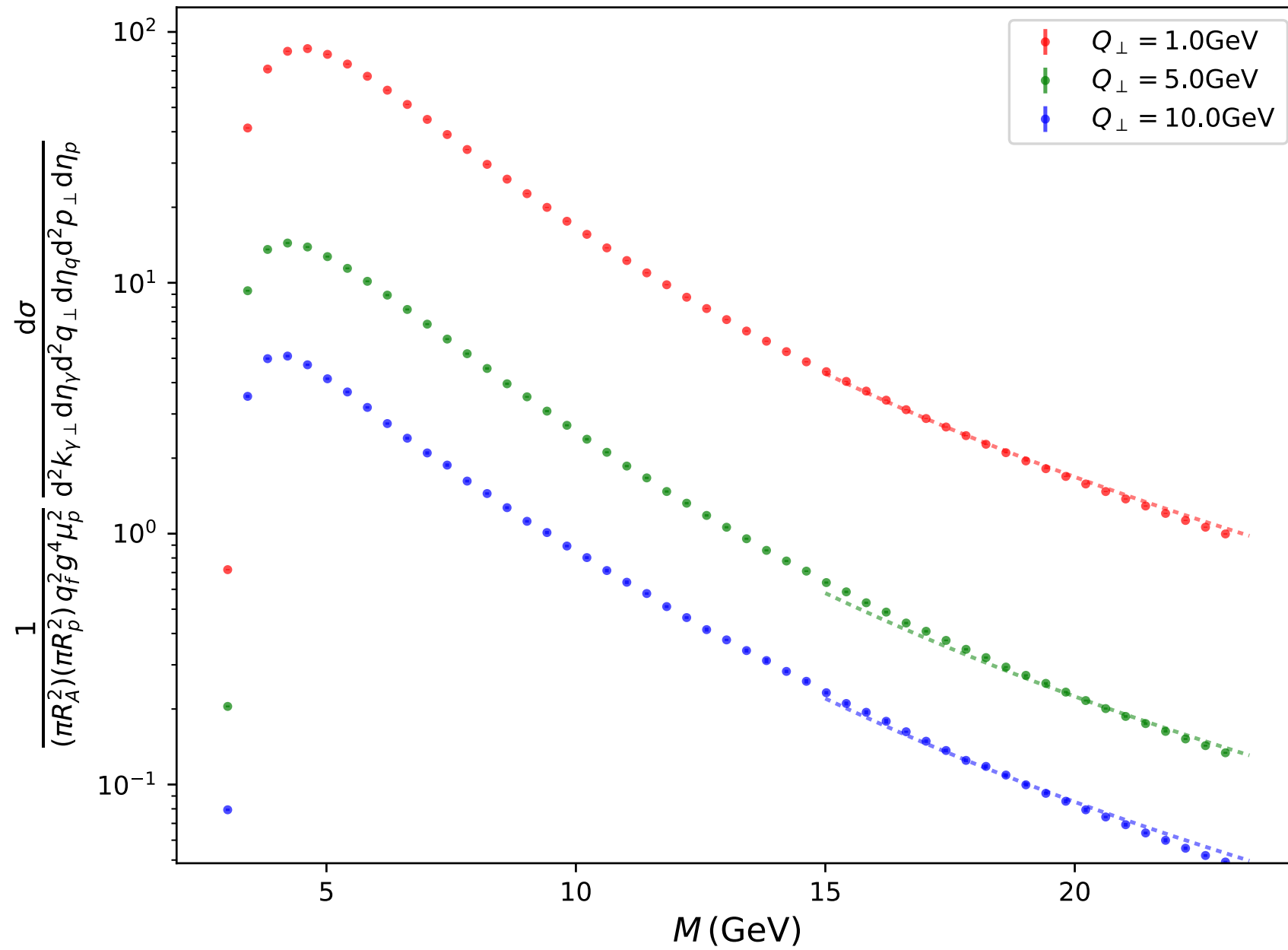
RESULTS (PRELIMINARY)



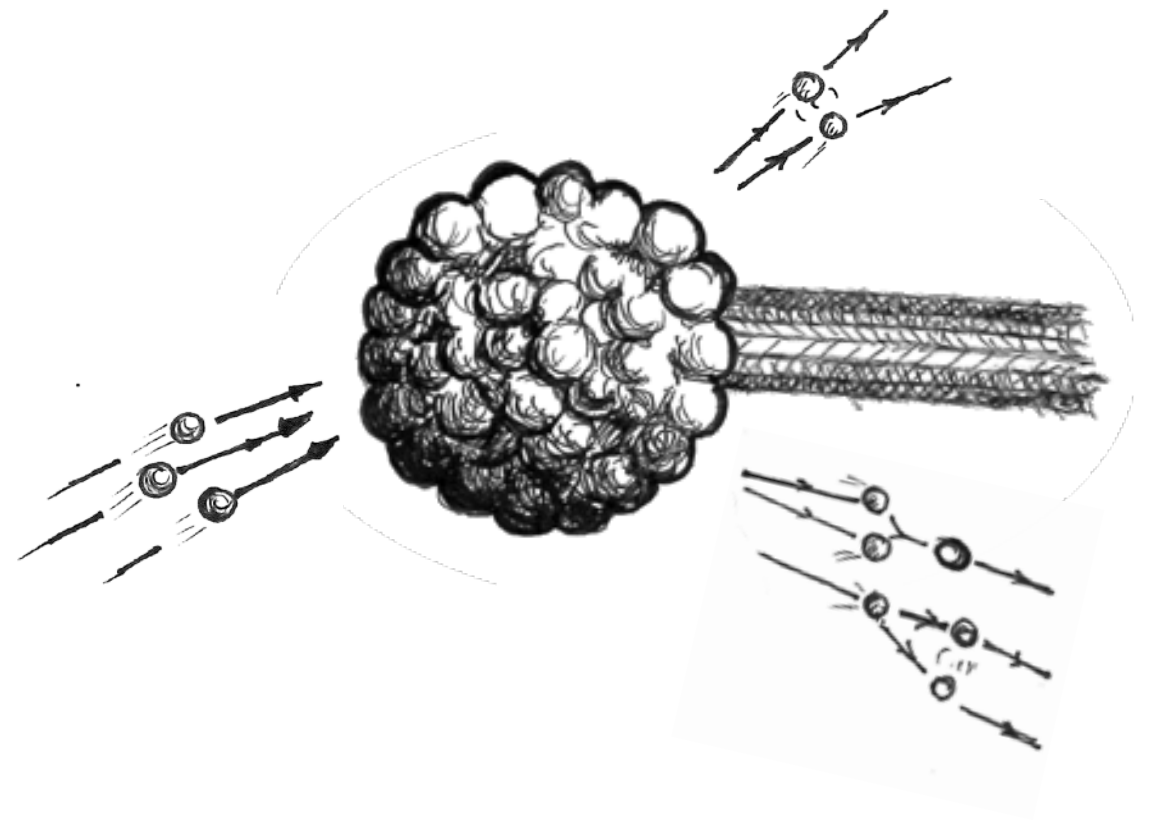
RESULTS (PRELIMINARY)



RESULTS (PRELIMINARY)

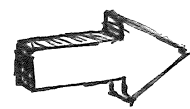


SUMMARY

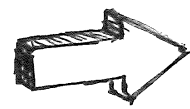


- Saturation modifies the emission process thanks to multi-particle scatterings
- CGC formalism yields correct limits to the pQCD results
- Complete analytical result at NLO, $\mathcal{O}(\alpha_e \alpha_s)$

OUTLOOK



Rapidity evolution (BK) for the cross-section will give photon multiplicity predictions for the next run of the ALICE experiment.

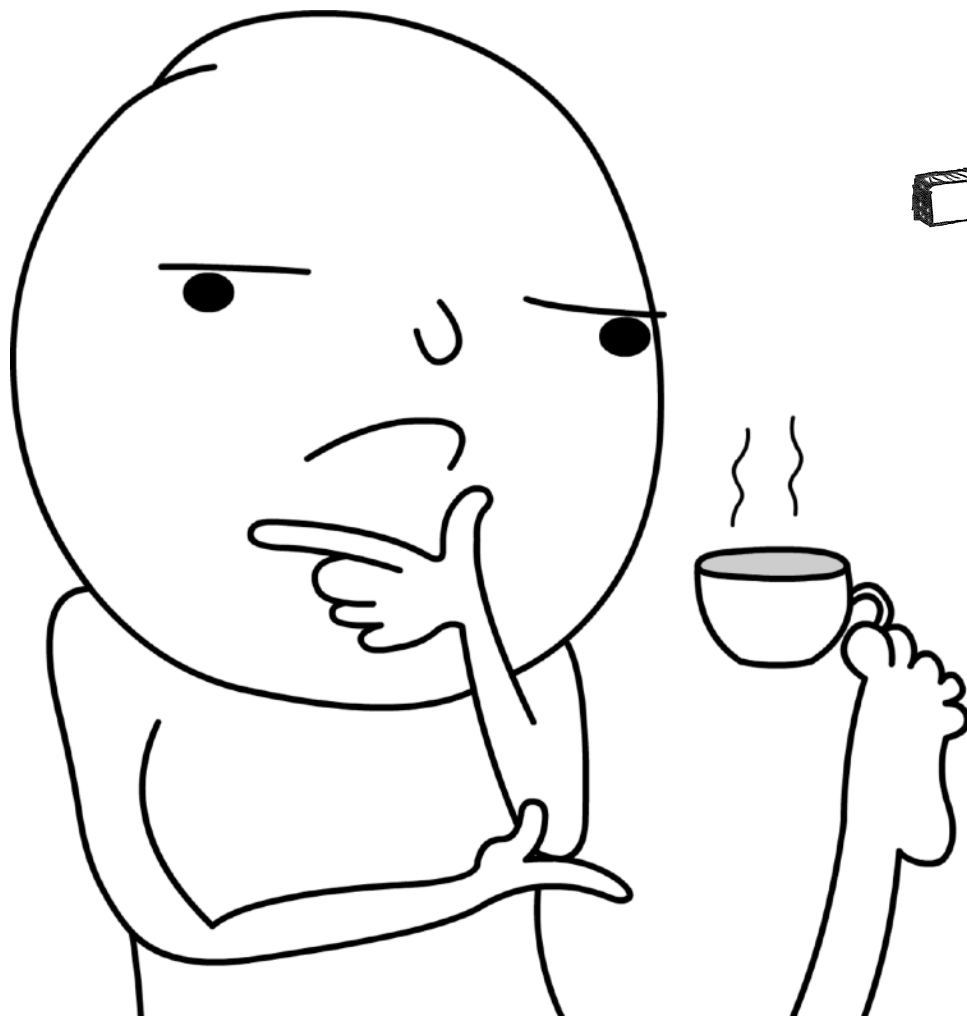


Photon-hadron correlations are sensitive to saturation.



More exciting studies:

- NNLO?
- Higher particle correlations?
- Saturation and Anomalies?





THANK YOU