INCLUSIVE PROMPT PHOTON PRODUCTION FROM THE CGC

OSCAR GARCIA MONTERO

In collaboration with
SANJIN BENIC
KENJI FUKUSHIMA
RAJU VENUGOPALAN

GARCIA@THPHYS.UNI-HEIDELBERG.DE

1 **MOTIVATION**

2 **FRAMEWORK: CGC**

3 **POWER COUNTING?**

4 **SOME RESULTS**

5 **SUMMARY AND OUTLOOK**

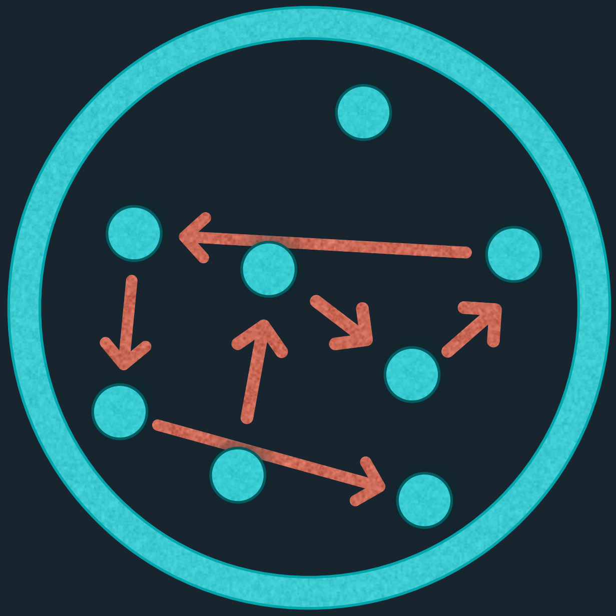
GLOBAL GOAL

Understand (nuclear) matter under extreme conditions

LOCAL GOAL

Use photons as probes for saturation
in dilute-dense collisions

LOCAL GOAL



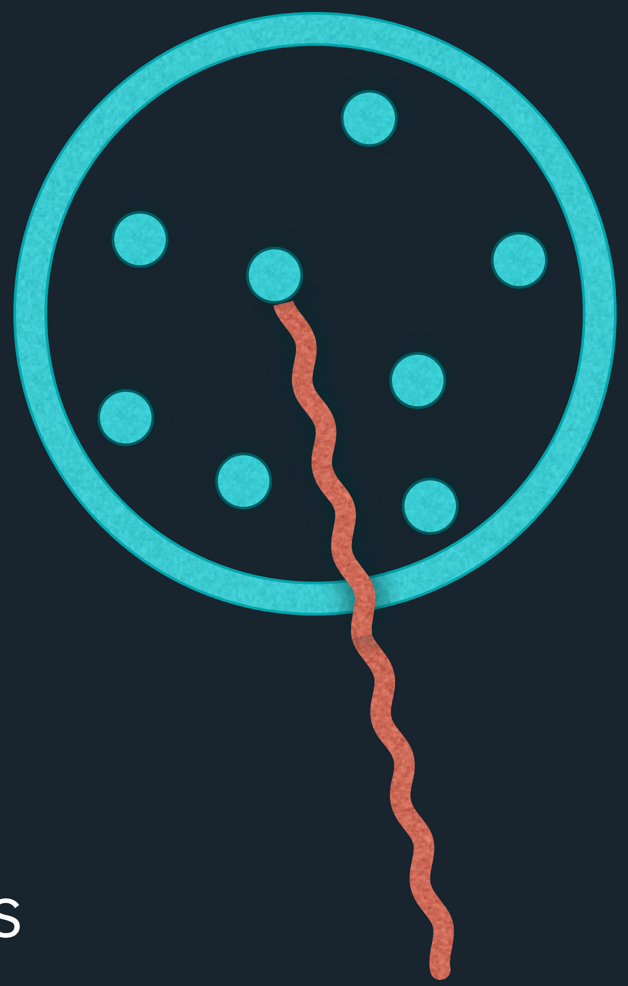
Use photons as probes for saturation in dilute-dense collisions

WHY PHOTONS?

No strong interaction

LOCAL GOAL

Use photons as probes for saturation in dilute-dense collisions

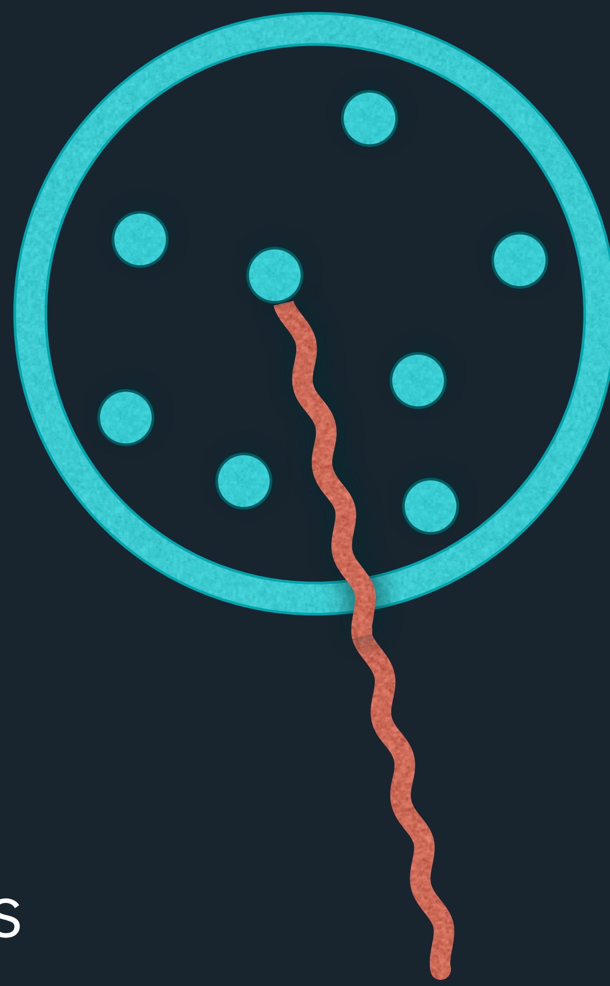


WHY PHOTONS?

No strong interaction → Clean Probes

LOCAL GOAL

Use photons as probes for saturation
in dilute-dense collisions



WHY PHOTONS?

No strong interaction → Clean Probes

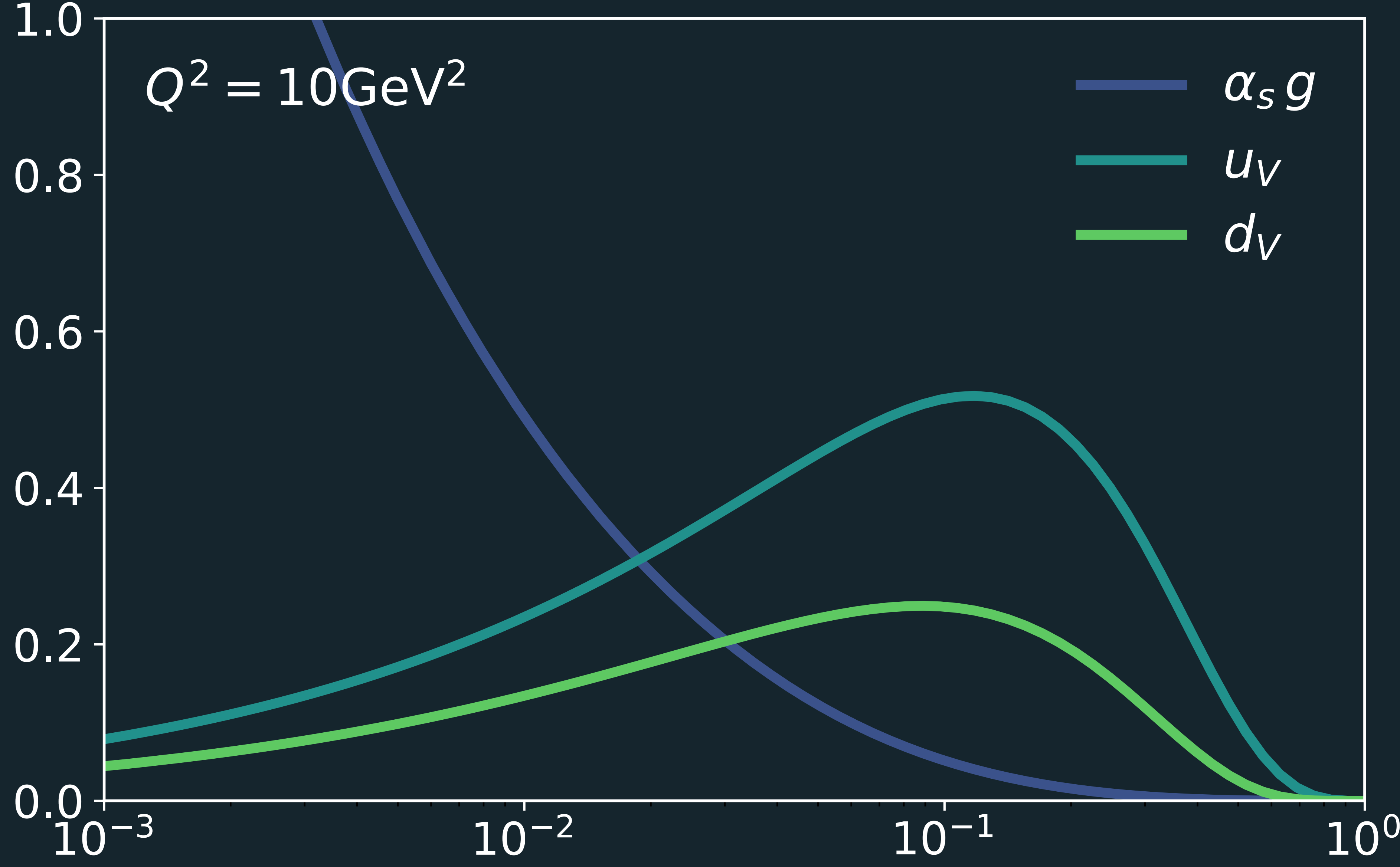
WHY DILUTE-DENSE?

Use the 'known' to probe the 'unknown'

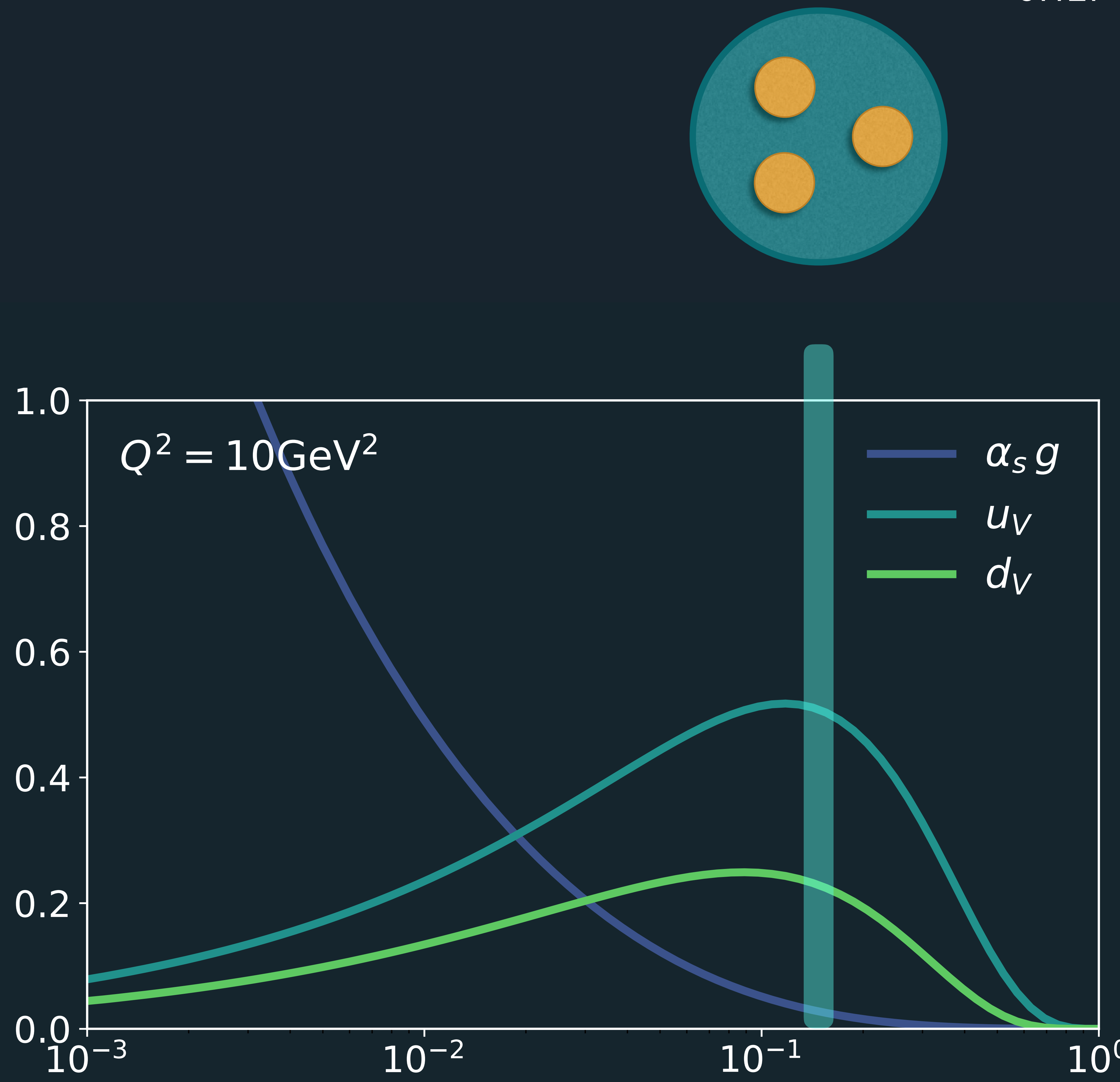
WHAT IS DILUTE-DENSE?

JHEP 07 (2002) 012

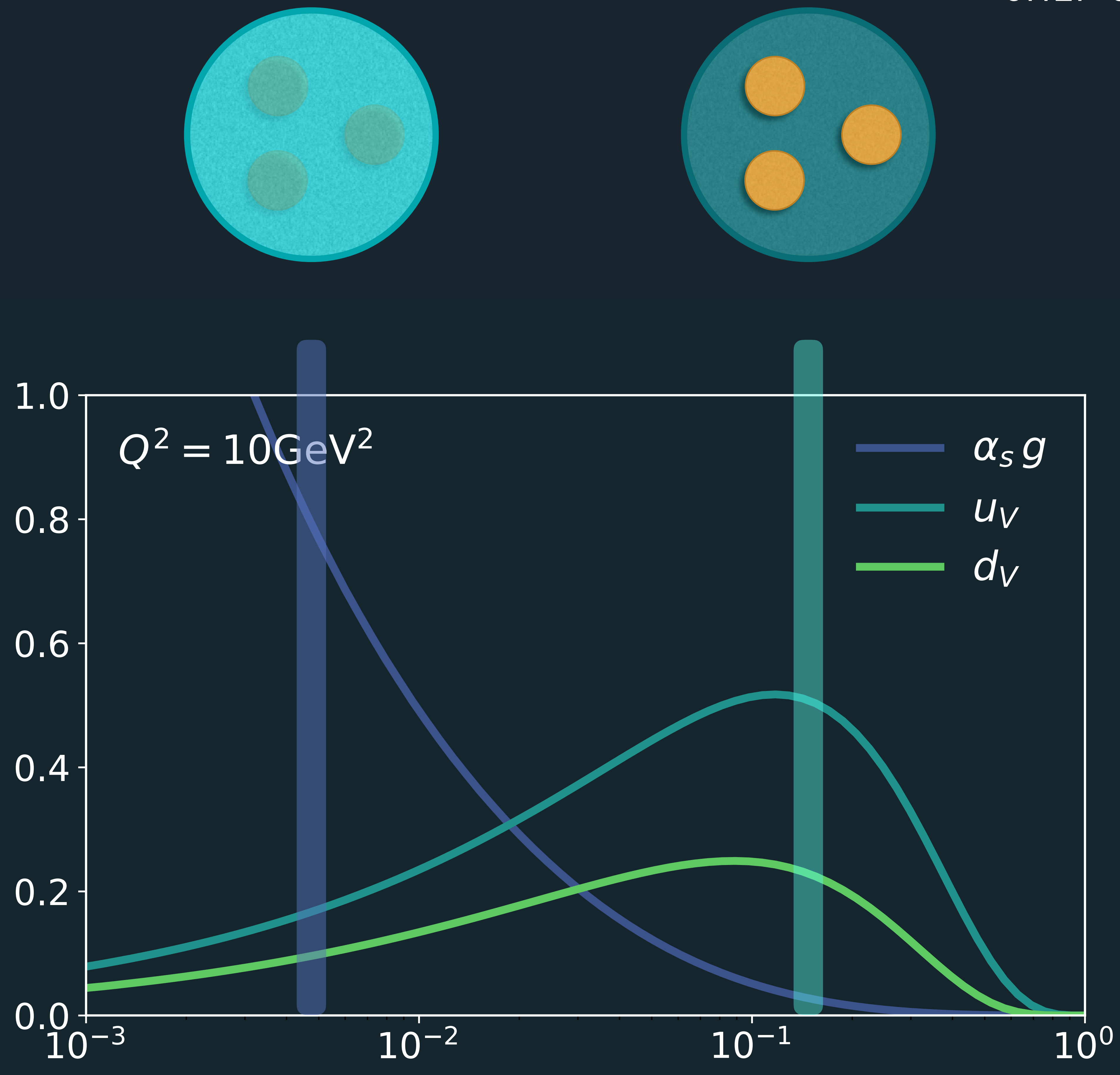
PARTON DISTRIBUTION FUNCTIONS



JHEP 07 (2002) 012



JHEP 07 (2002) 012



GLUON RISE

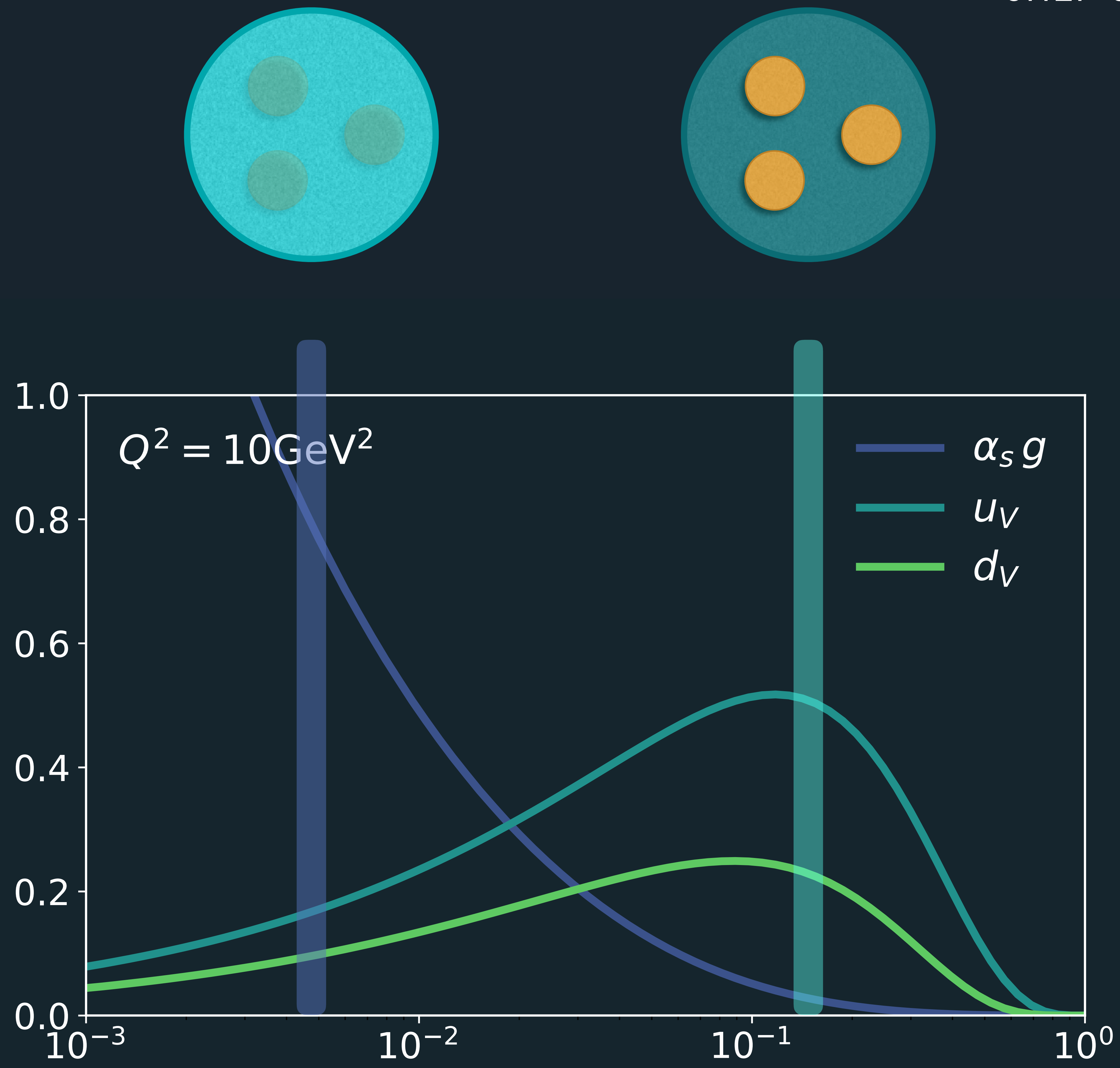
↓

GLUON RECOMBINATION

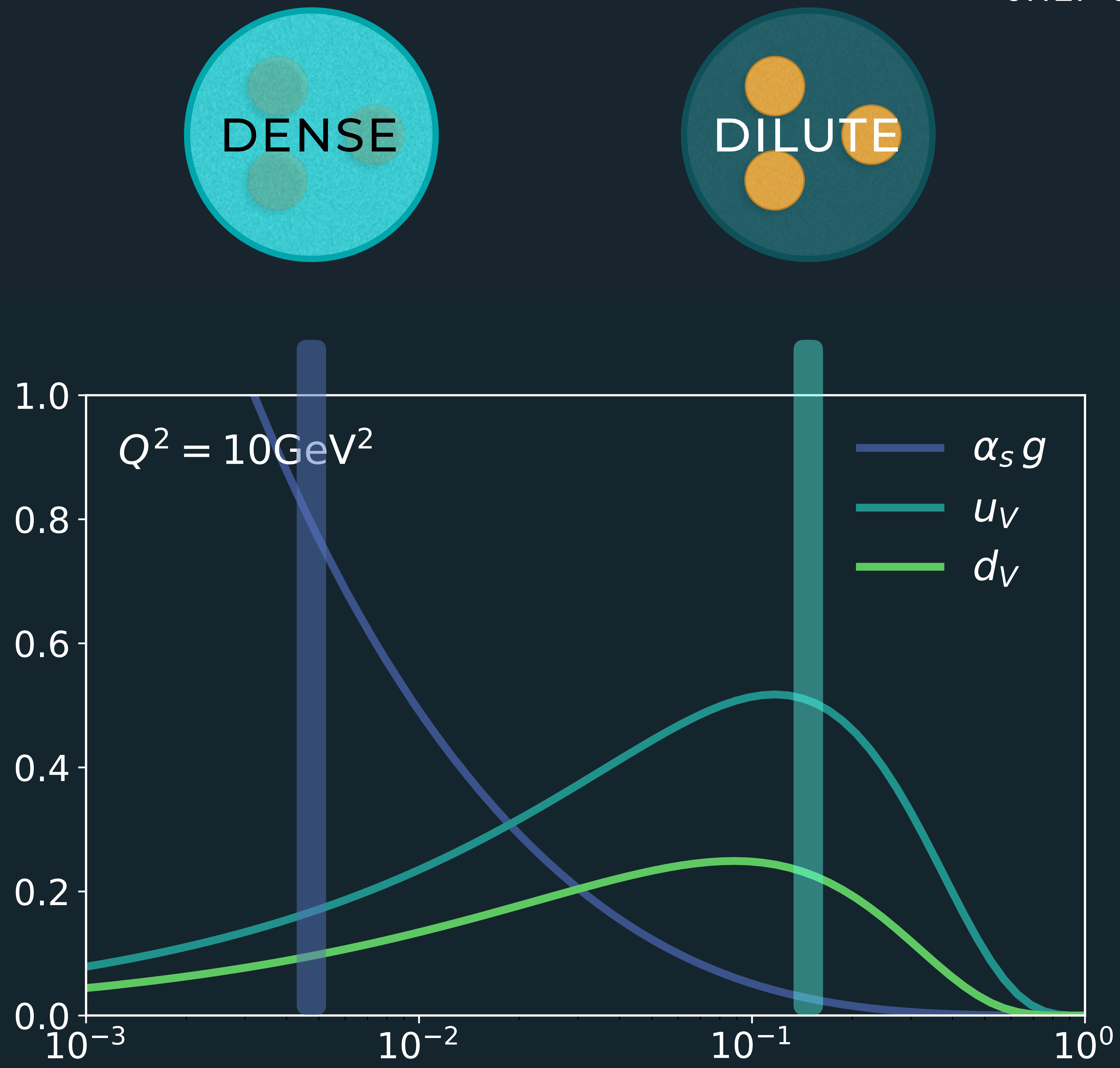
↓

SATURATION

JHEP 07 (2002) 012



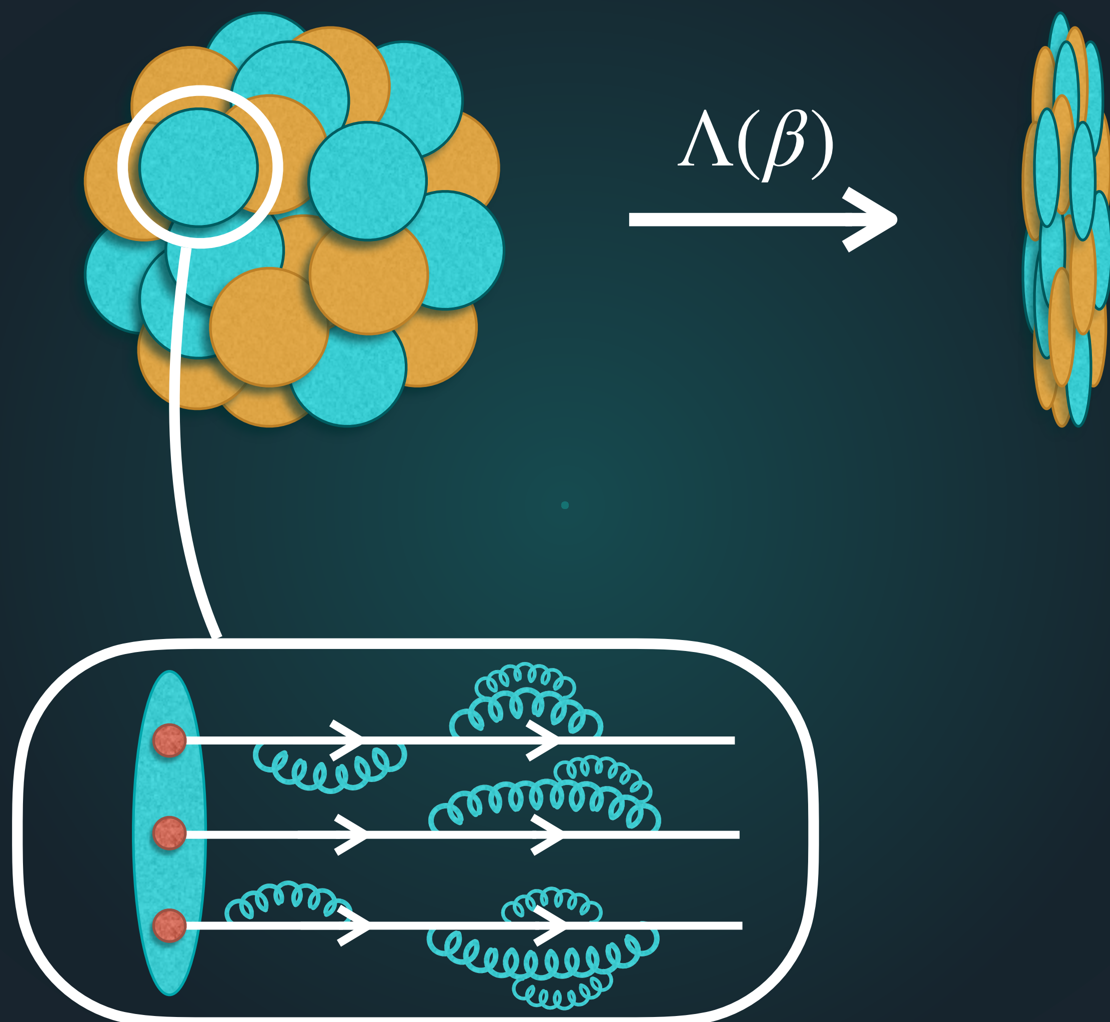
JHEP 07 (2002) 012



HOW TO CATCH A GLUON SOUP?

1. MOTIVATION
2. FRAMEWORK: CGC
3. POWER COUNTING?
4. SOME RESULTS
5. SUMMARY AND OUTLOOK

COLOR GLASS CONDENSATE



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

COLOR GLASS CONDENSATE

GLUE

COLOR GLASS CONDENSATE

GLUE

Soft Partons

Macroscopic Field

$A(x)$

COLOR GLASS CONDENSATE

GLUE

Soft Partons

Macroscopic Field

$$A(x)$$

Hard Partons

Static Color Sources

$$J^{\mu}(x) = g\,\delta(x^{-})\,\delta^{\mu +}\,\rho(\boldsymbol{x}_{\perp})$$

COLOR GLASS CONDENSATE

GLUE

Soft Partons

Macroscopic Field

$A(x)$

Q_s

Hard Partons

Static Color Sources

$J^{\mu}(x) = g\,\delta(x^{-})\,\delta^{\mu+}\,\rho(\boldsymbol{x}_{\perp})$

COLOR GLASS CONDENSATE

GLUE

Soft Partons

Macroscopic Field

$A(x)$

Hard Partons

Static Color Sources

$J^{\mu}(x) = g\,\delta(x^{-})\,\delta^{\mu +}\,\rho(\boldsymbol{x}_{\perp})$

$$[D_{\mu}, F^{\mu\nu}] = J^{\nu}$$

COLOR GLASS CONDENSATE

GLUE

Soft Partons

Macroscopic Field

$$A(x)$$

Hard Partons

Static Color Sources

$$J^{\mu}(x) = g\,\delta(x^-)\,\delta^{\mu +}\,\rho(\boldsymbol{x}_\perp)$$

$$A_p^{\mu}(x) = -\,g\,\delta^{\mu +}\,\delta(x^-)\,\frac{1}{\nabla_\perp^2}\,\rho(\boldsymbol{x}_\perp)$$

COLOR GLASS CONDENSATE

GLUE

Soft Partons

Macroscopic Field

$A(x)$

Hard Partons

Static Color Sources

$J^{\mu}(x) = g\,\delta(x^{-})\,\delta^{\mu +}\,\rho(\boldsymbol{x}_{\perp})$

$$A_{p}^{\mu}(x) = -\,g\,\delta^{\mu +}\,\delta(x^{-})\,\frac{1}{\nabla_{\perp}^{2}}\,\rho(\boldsymbol{x}_{\perp})$$

$$\frac{\alpha_s}{Q_S^2(x)}\,\frac{x\,f_g(x, Q_S^2)}{\pi R^2} \sim 1$$

COLOR GLASS CONDENSATE

GLUE

Soft Partons

Macroscopic Field

$$A(x)$$

Hard Partons

Static Color Sources

$$J^{\mu}(x) = g\,\delta(x^{-})\,\delta^{\mu +}\,\rho(\boldsymbol{x}_{\perp})$$

$$\langle \mathcal{O}[\rho] \rangle = \int \mathcal{D}\rho\, W[x;\rho]\mathcal{O}[\rho]$$

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

COLOR GLASS CONDENSATE

GLUE

Soft Partons

Macroscopic Field

$A(x)$

Hard Partons

Static Color Sources

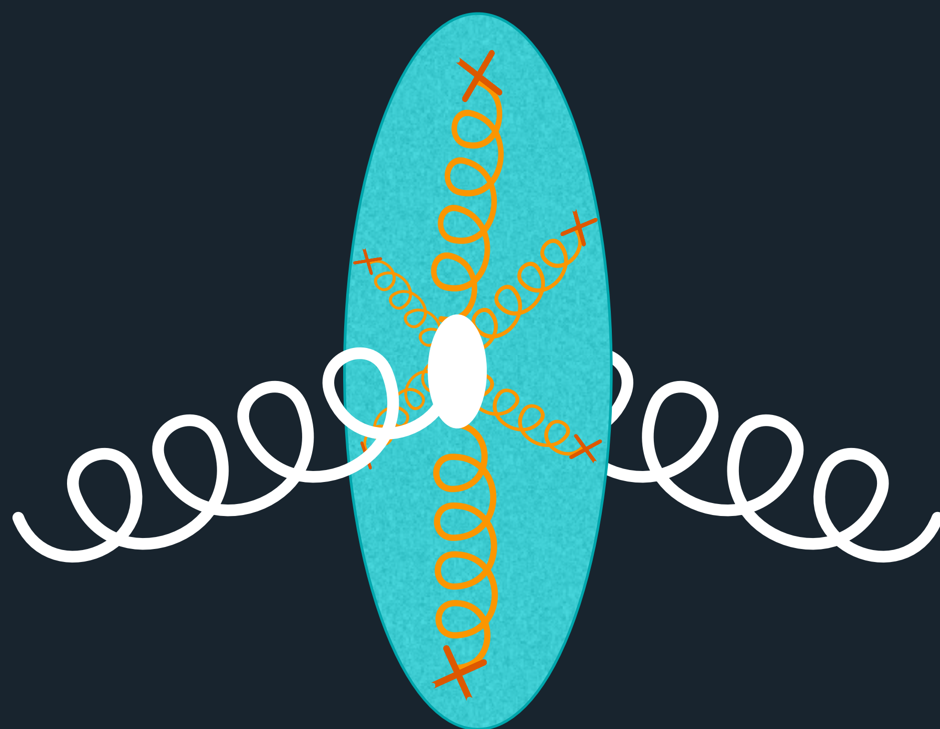
$J^{\mu}(x) = g\,\delta(x^{-})\,\delta^{\mu +}\rho(\boldsymbol{x}_{\perp})$

SPECIAL CASE

McLerran-Venugopalan Model

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

PROPAGATION: GLUE



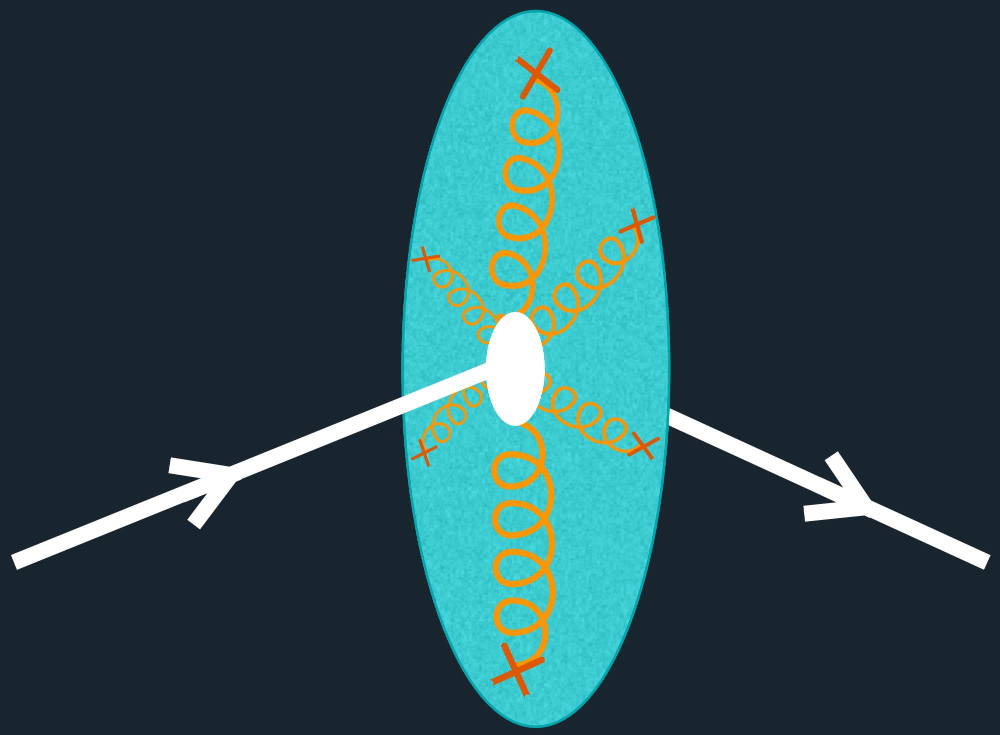
Is the gluon field (projectile) modified by the nuclear CGC?

Multiple Scatterings

$$A^{\mu}(q) = A^{\mu}(q) + \frac{i\,g}{q^2 + iq^+\epsilon} \int_{\boldsymbol{k}_\perp} \int_{\boldsymbol{x}_\perp} e^{\mathrm{i}(\boldsymbol{q}_\perp - \boldsymbol{k}_\perp)\cdot \boldsymbol{x}}\, C^{\mu}(q, \boldsymbol{k}_\perp))\, U(\boldsymbol{x}_\perp) \frac{\rho_p(\boldsymbol{k}_\perp)}{k_\perp^2}$$

Nucl.Phys. A743 (**2004**) 57-91
Nucl.Phys. A743 (**2004**) 13-56

PROPAGATION: QUARKS



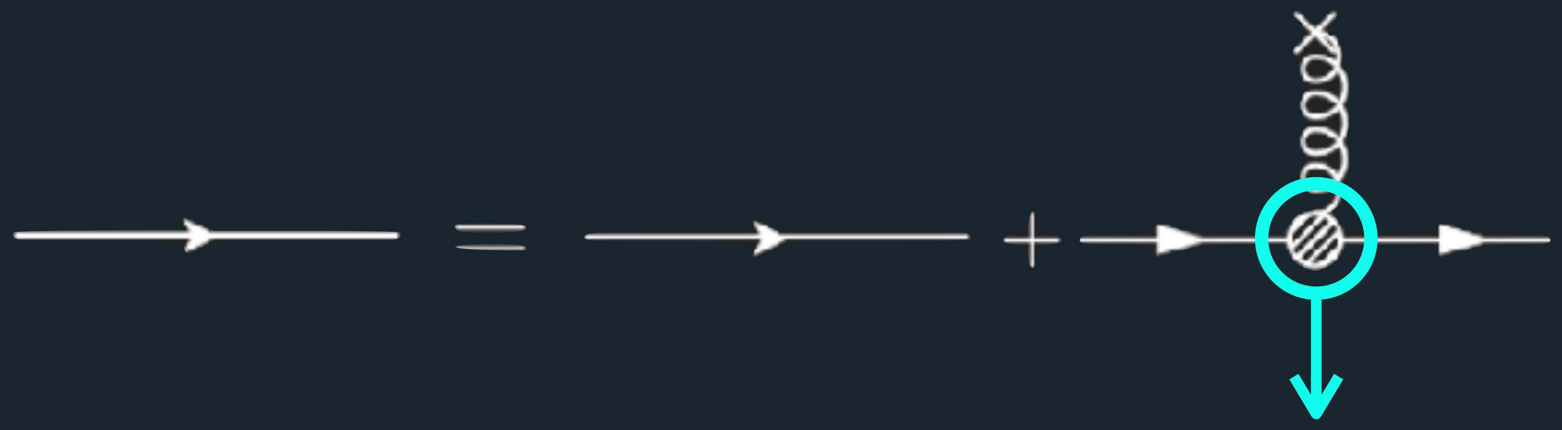
How do quarks behave through the CGC?

↓

Multiple Scatterings

↓

Dressed propagator



$$\mathcal{T}(k,p) = 2\pi\,\mathrm{sgn}(p^+)\,\gamma^+ \int_{\boldsymbol{x}_\perp} e^{i\boldsymbol{x}_\perp\cdot\boldsymbol{k}_\perp}\,\left[\tilde{U}(\boldsymbol{x}_\perp) - 1\right]$$

Nucl.Phys. A743 (**2004**) 57-91
Nucl.Phys. A743 (**2004**) 13-56

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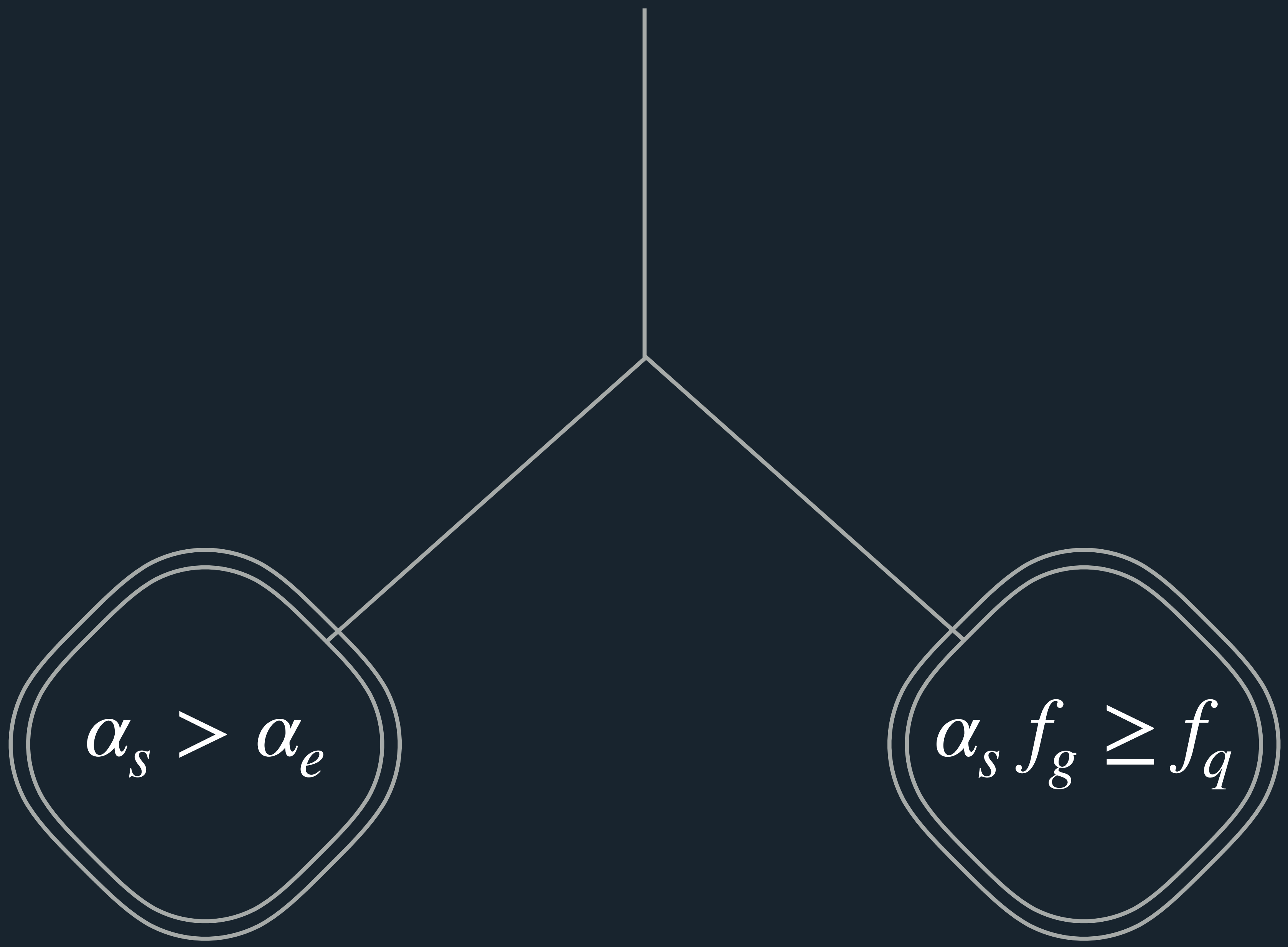
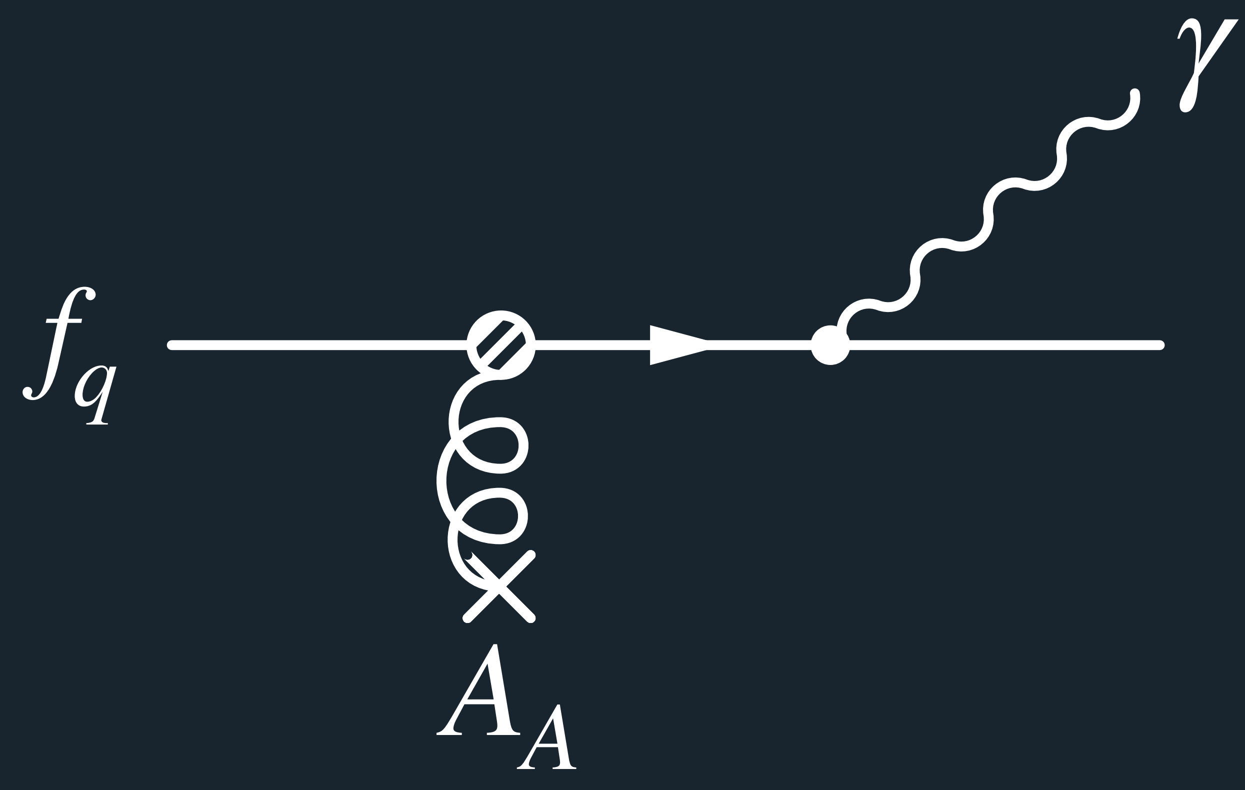
POWER COUNTING

$$\alpha_s > \alpha_e$$

POWER COUNTING



LO [$\mathcal{O}(\alpha_e)$]



$x \sim 10^{-2}$

$\alpha_s f_g \geq f_q$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}^2\boldsymbol{k}_{\gamma_\perp}\mathrm{d}\eta_\gamma} = \frac{\alpha\alpha_S^2 q_f^2}{(2\pi)^8 C_F}\int_{\eta_q}\int_{\boldsymbol{q}_\perp}\int_{x_p}(2\pi)\,\delta(l^+ - q^+ - k_\gamma^+)$$

$$\times\; f_{q,p}(x_p, Q^2)\;\; \mathcal{N}_A(x_A, \boldsymbol{q}_\perp + \boldsymbol{k}_{\gamma\perp})\;\; \theta_{LO}(q, k_\gamma)$$

with $N(x_0, k) = \frac{1}{N_C}\left\langle U(k)\, U^\dagger(0)\right\rangle$

Phys.Rev. D97 (2018) 054023
Phys. Rev. C 59 (1999) 1609
Phys. Rev. D 66 (2002) 014021
Nucl. Phys. A 741 (2004) 358

LO [$\mathcal{O}(\alpha_e)$]

SUPPRESSED

$x \sim 10^{-2}$

$\alpha_s f_g \geq f_q$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}^2 \boldsymbol{k}_{\gamma_\perp} \mathrm{d}\eta_\gamma} = \frac{\alpha \alpha_s^2 q_f^2}{(2\pi)^8 C_F} \int_{\eta_q} \int_{\boldsymbol{q}_\perp} \int_{x_p} (2\pi)\, \delta(l^+ - q^+ - k_\gamma^+)$$

$$\times\ f_{q,p}(x_p, Q^2)\ \ \mathcal{N}_A(x_A, \boldsymbol{q}_\perp + \boldsymbol{k}_{\gamma\perp})\ \ \theta_{LO}(q, k_\gamma)$$

Phys.Rev. D97 (2018) 054023
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LO [$\mathcal{O}(\alpha_e)$]

$x \sim 10^{-2}$

$\alpha_s f_g \geq f_q$

SUPPRESSED
(DEPENDING ON X)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}^2\boldsymbol{k}_{\gamma_\perp}\mathrm{d}\eta_\gamma} = \frac{\alpha\alpha_s^2 q_f^2}{(2\pi)^8 C_F}\int_{\eta_q}\int_{\boldsymbol{q}_\perp}\int_{x_p}(2\pi)\,\delta(l^+ - q^+ - k_\gamma^+)$$

$$\times\; f_{q,p}(x_p, Q^2)\;\; \mathcal{N}_A(x_A, \boldsymbol{q}_\perp + \boldsymbol{k}_{\gamma\perp})\;\; \theta_{LO}(q, k_\gamma)$$

Phys.Rev. D97 (2018) 054023
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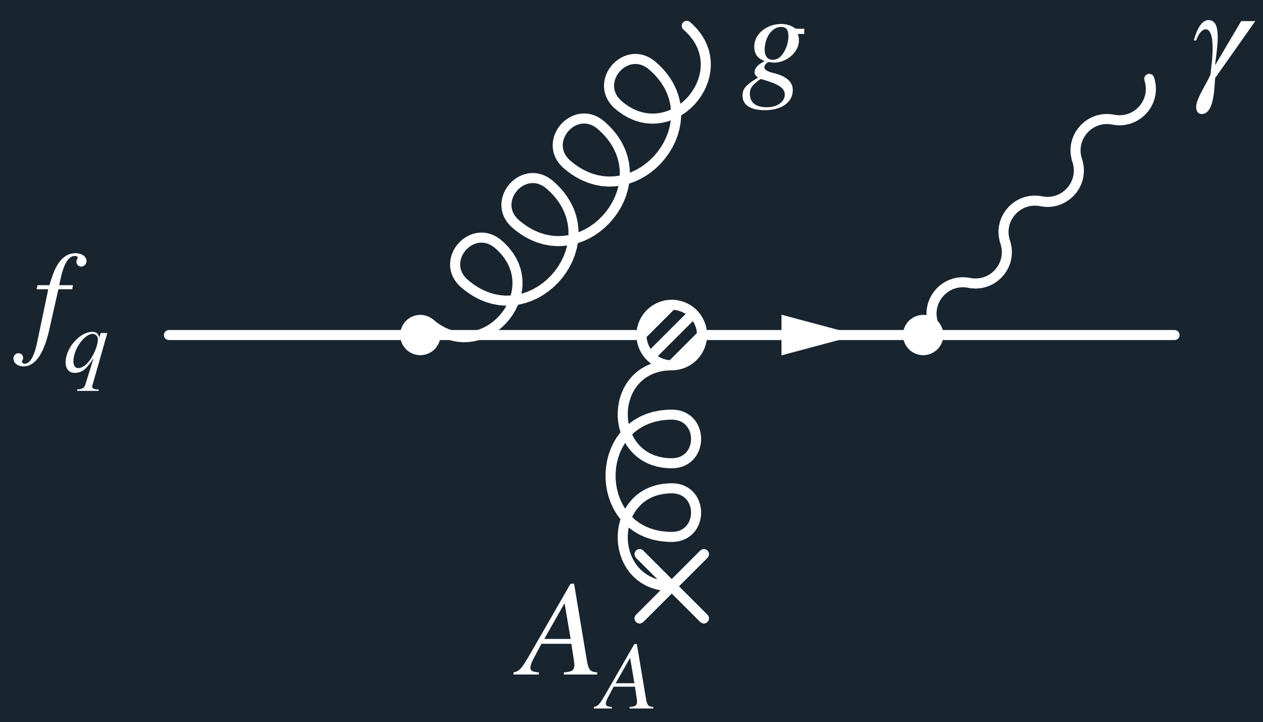
Nucl. Phys. A 741 (2004) 358

NLO I[$\mathcal{O}(\alpha_s \alpha_e)$]

$x \sim 10^{-2}$

$\alpha_s f_g \geq f_q$



*** For inclusive photon, it can be included as evolution of the quark distributions

NLO II[$\mathcal{O}(\alpha_s \alpha_e)$]

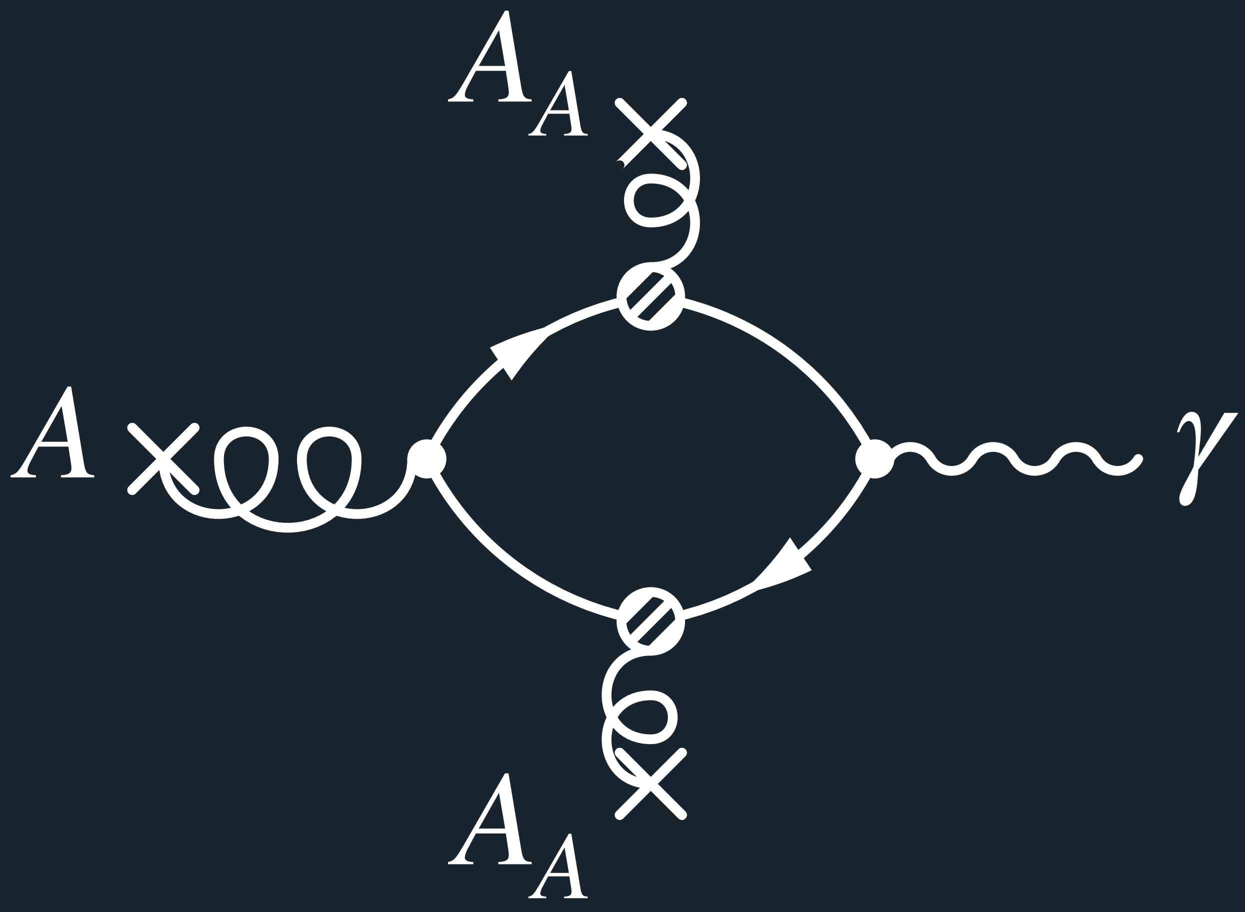
$x \sim 10^{-2}$

Enhanced by

$\alpha_s f_g \geq f_q$

Kinematically constrained

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



Nucl.Phys. A958 (**2017**) 1-24

NLO II [$\mathcal{O}(\alpha_s \alpha_e)$]

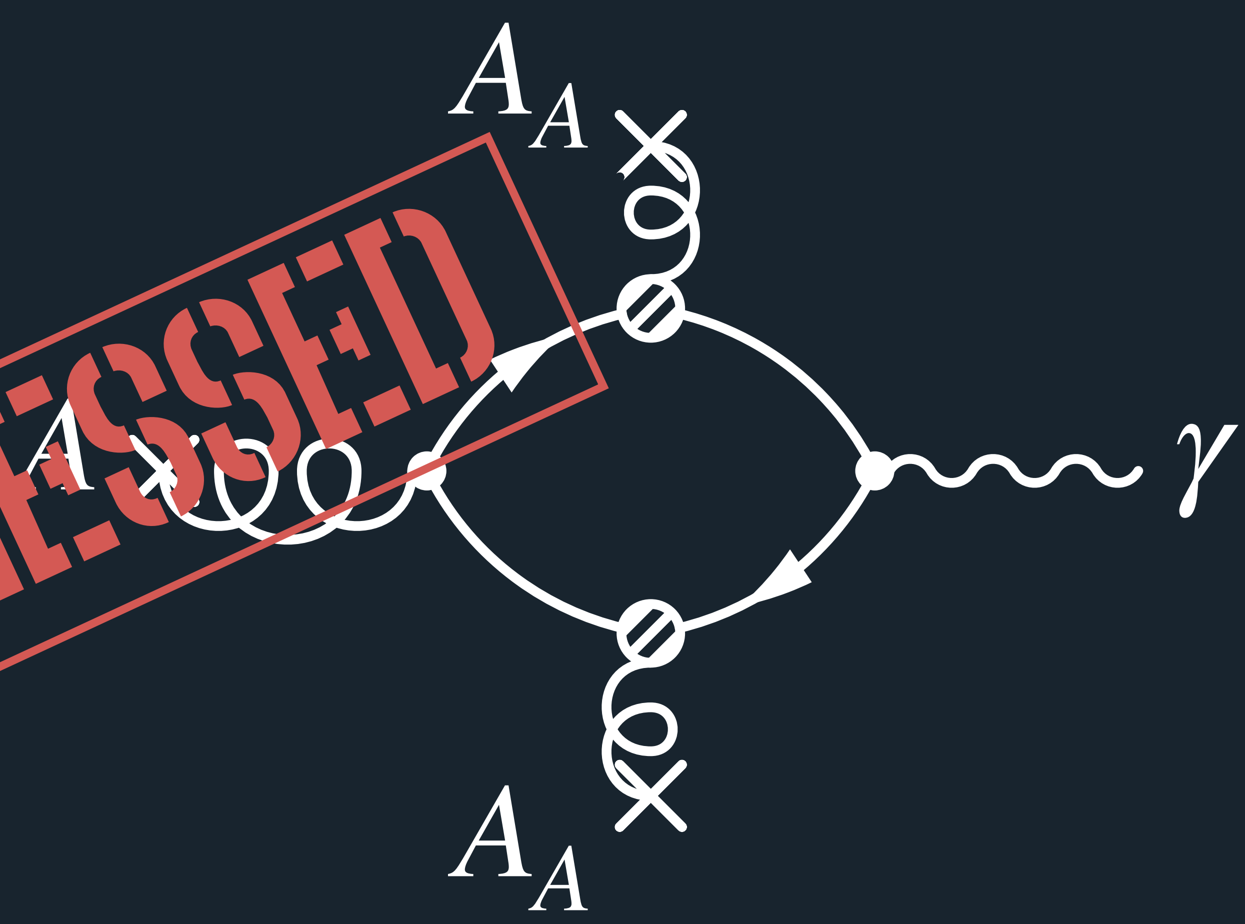
$x \sim 10^{-2}$

Enhanced by

$$\alpha_s f_g \geq f_q$$

Kinematically constrained

Dominated by $k_\perp^2 = Q_{s,A}^2$



Nucl.Phys. A958 (**2017**) 1-24

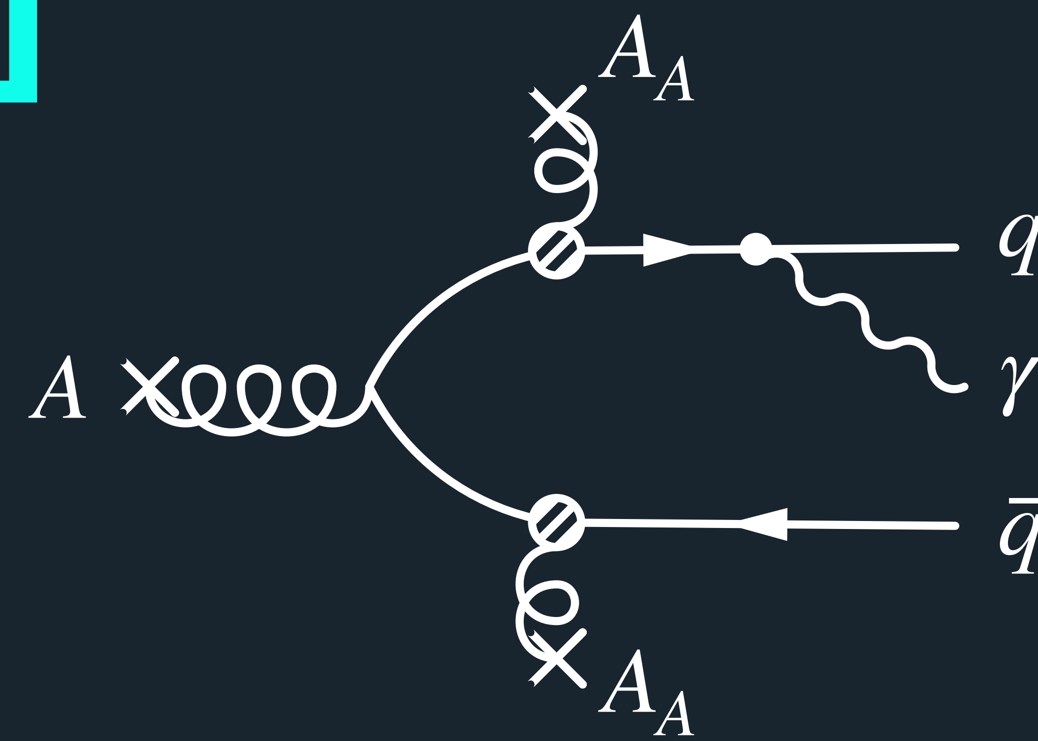
JHEP 1701 (**2017**) 115
arXiv:1807.03806

NLO III[$\mathcal{O}(\alpha_s \alpha_e)$]

$x \sim 10^{-2}$

Enhanced by

$\alpha_s f_g \geq f_q$



$$\frac{\mathrm{d}\sigma}{\mathrm{d}^2 \boldsymbol{k}_{\gamma_\perp} \mathrm{d}\eta_\gamma} = \frac{\alpha \alpha_S^2 \, q_f^2}{(2\pi)^8 C_F} \int_{\eta_q,\eta_p} \int_{\boldsymbol{q}_\perp,\boldsymbol{p}_\perp,\boldsymbol{k}_\perp,\boldsymbol{k}_{1\perp},\boldsymbol{k}_{2\perp}} \delta^{(2)}(\boldsymbol{P}_\perp - \boldsymbol{k}_{1\perp} - \boldsymbol{k}_{2\perp}) \; \frac{\varphi_p(\boldsymbol{k}_{1\perp})}{k_{1\perp}^2}$$

$$\times \Bigg\{ \tau_{g,g}(\boldsymbol{k}_{1\perp}) \frac{\phi_A^{g,g}(\boldsymbol{k}_{2\perp})}{\boldsymbol{k}_{2\perp}} + 2\tau_{g,qq}(\boldsymbol{k}_{1\perp}, \boldsymbol{k}_\perp) \frac{\phi_A^{qq,g}(\boldsymbol{k}_\perp, \boldsymbol{k}_{2\perp})}{\boldsymbol{k}_{2\perp}} + \tau_{qq,qq}(\boldsymbol{k}_{1\perp}, \boldsymbol{k}_\perp, \boldsymbol{k}_\perp) \; \frac{\phi_A^{qq,qq}(\boldsymbol{k}_\perp, \boldsymbol{k}_{2\perp})}{\boldsymbol{k}_{2\perp}} \Bigg\}$$

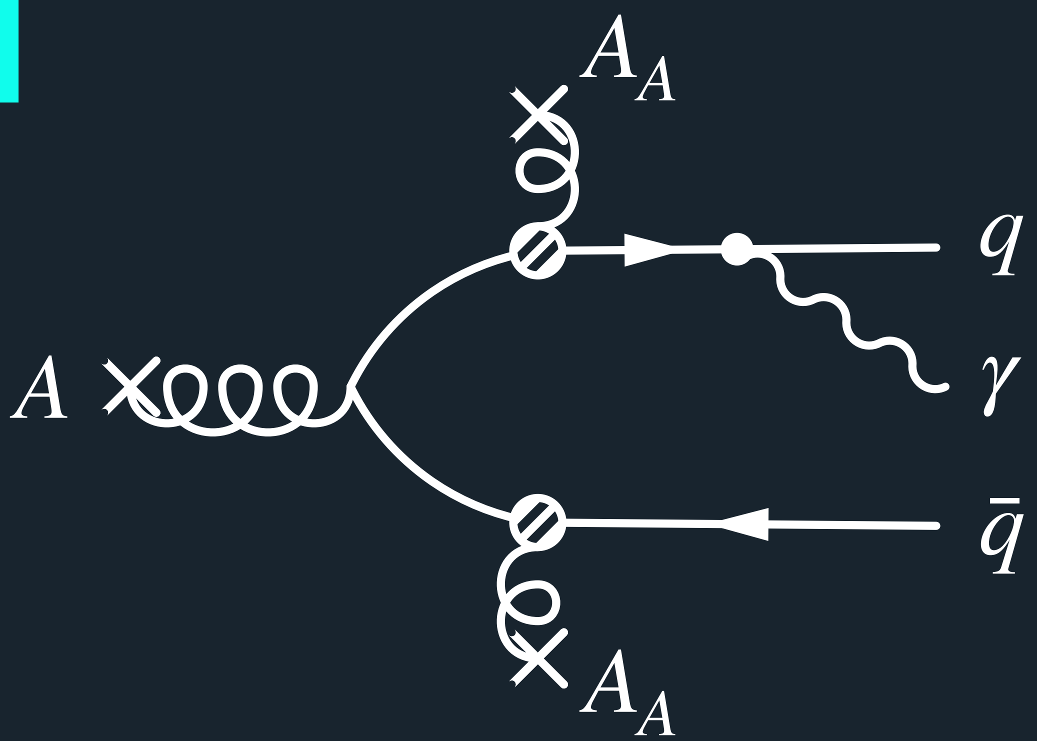
JHEP 1701 (**2017**) 115
arXiv:1807.03806

NLO III [$\mathcal{O}(\alpha_s \alpha_e)$]

$x \sim 10^{-2}$

Enhanced by

$\alpha_s f_g \geq f_q$



$$\frac{\mathrm{d}\sigma}{\mathrm{d}^2 \boldsymbol{k}_{\gamma_\perp} \mathrm{d}\eta_\gamma} = \frac{\alpha \alpha_S^2 q_f^2}{(2\pi)^8 C_F} \int_{\eta_q, \eta_p} \int_{\boldsymbol{q}_\perp, \boldsymbol{p}_\perp, \boldsymbol{k}_\perp, \boldsymbol{k}_{1\perp}, \boldsymbol{k}_{2\perp}} \delta^{(2)}(\boldsymbol{P}_\perp - \boldsymbol{k}_{1\perp} - \boldsymbol{k}_{2\perp}) \; \frac{\varphi_p(\boldsymbol{k}_{1\perp})}{k_{1\perp}^2}$$

$$\times \theta_{NLO}(\boldsymbol{k}_{1\perp}, \boldsymbol{k}_\perp, \boldsymbol{k}'_\perp) \, \mathcal{N}(x_0, \boldsymbol{k}_{2\perp}) \, \mathcal{N}(x_0, \boldsymbol{k}_\perp - \boldsymbol{k}_{2\perp})$$

AT LARGE N_c

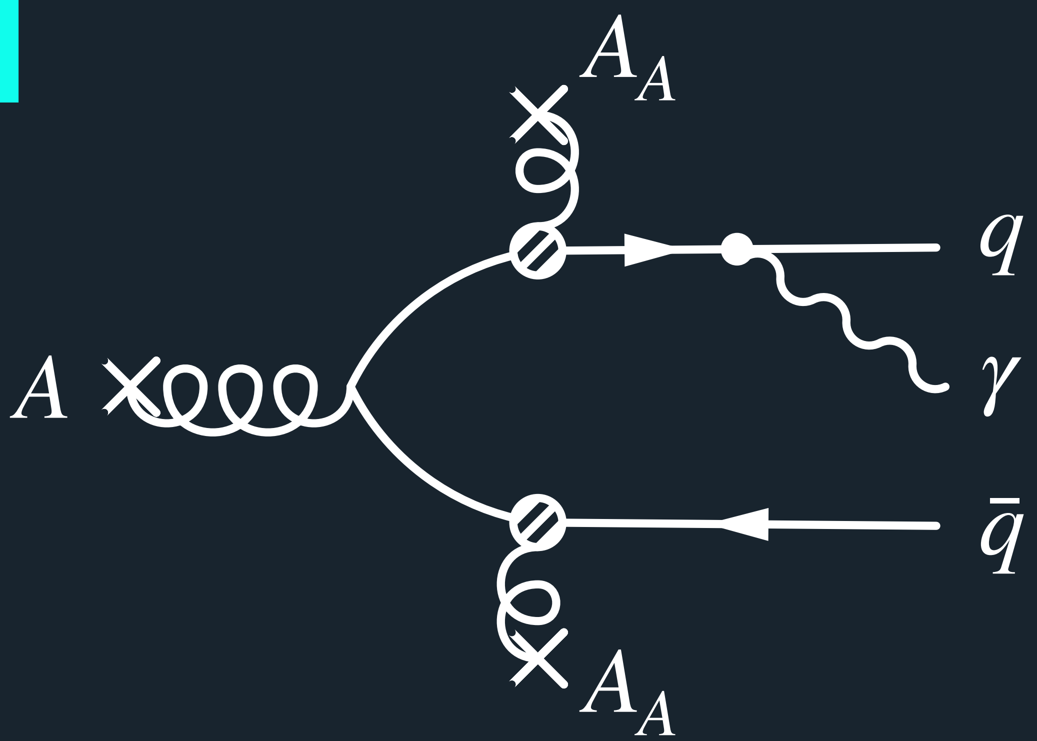
JHEP 1701 (**2017**) 115
arXiv:1807.03806

NLO III[$\mathcal{O}(\alpha_s\alpha_e)$]

$x \sim 10^{-2}$

Enhanced by

$\alpha_s f_g \geq f_q$



$$\frac{\mathrm{d}\sigma}{\mathrm{d}^2\boldsymbol{k}_{\gamma_\perp}\mathrm{d}\eta_\gamma} = \frac{\alpha\alpha_S^2\, q_f^2}{(2\pi)^8 C_F}\int_{\eta_q,\eta_p}\int_{\boldsymbol{q}_\perp,\boldsymbol{p}_\perp,\boldsymbol{k}_{1\perp},\boldsymbol{k}_{2\perp}} \delta^{(2)}(\boldsymbol{P}_\perp - \boldsymbol{k}_{1\perp} - \boldsymbol{k}_{2\perp})\ \frac{\varphi_p(\boldsymbol{k}_{1\perp})}{k_{1\perp}^2}$$

$$\times\theta_{LT}(\boldsymbol{k}_{1\perp}, \boldsymbol{k}'_\perp)\,\tilde{N}(x_0, \boldsymbol{k}_{2\perp})$$

AT LT

EVOLUTION

$$\frac{\partial \mathcal{N}(\boldsymbol{r}, x)}{\partial \log(x_0/x)} = \int \mathrm{d}^2\boldsymbol{r}_1 \, K^{run}(\boldsymbol{r}, \boldsymbol{r}_1, \boldsymbol{r}_2)\left[\mathcal{N}(\boldsymbol{r}_1, x) + \mathcal{N}(\boldsymbol{r}_1, x) - \mathcal{N}(\boldsymbol{r}, x) - \mathcal{N}(\boldsymbol{r}_1, x)\,\mathcal{N}(\boldsymbol{r}_2, x)\right]$$

EVOLUTION

$$\frac{\partial \mathcal{N}(\boldsymbol{r}, x)}{\partial \log(x_0/x)} = \int \mathrm{d}^2\boldsymbol{r}_1\, K^{run}(\boldsymbol{r}, \boldsymbol{r}_1, \boldsymbol{r}_2)\left[\mathcal{N}(\boldsymbol{r}_1, x) + \mathcal{N}(\boldsymbol{r}_1, x) - \mathcal{N}(\boldsymbol{r}, x) - \mathcal{N}(\boldsymbol{r}_1, x)\,\mathcal{N}(\boldsymbol{r}_2, x)\right]$$

↑

KERNEL

EVOLUTION

$$\frac{\partial \mathcal{N}(\boldsymbol{r}, x)}{\partial \log(x_0/x)} = \int \mathrm{d}^2\boldsymbol{r}_1\, K^{run}(\boldsymbol{r}, \boldsymbol{r}_1, \boldsymbol{r}_2)\left[\mathcal{N}(\boldsymbol{r}_1, x) + \mathcal{N}(\boldsymbol{r}_1, x) - \mathcal{N}(\boldsymbol{r}, x) - \mathcal{N}(\boldsymbol{r}_1, x)\,\mathcal{N}(\boldsymbol{r}_2, x)\right]$$

↑ KERNEL

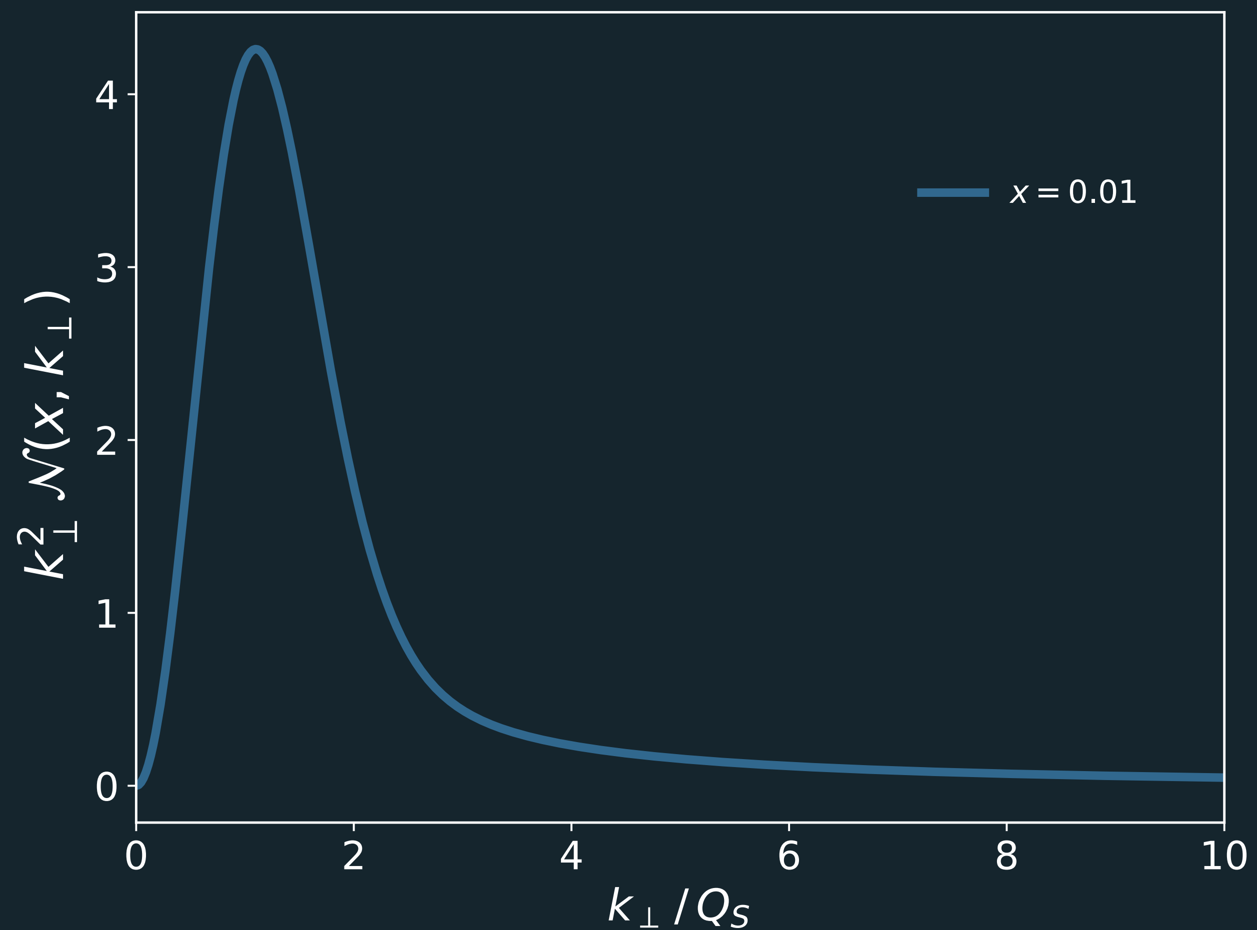
↑ NON LINEAR

EVOLUTION

$$\frac{\partial \mathcal{N}(\boldsymbol{r},x)}{\partial \log(x_0/x)} = \int \mathrm{d}^2\boldsymbol{r}_1\, K^{run}(\boldsymbol{r},\boldsymbol{r}_1,\boldsymbol{r}_2)\big[\mathcal{N}(\boldsymbol{r}_1,x)+\mathcal{N}(\boldsymbol{r}_1,x)-\mathcal{N}(\boldsymbol{r},x)-\mathcal{N}(\boldsymbol{r}_1,x)\,\mathcal{N}(\boldsymbol{r}_2,x)\big]$$

KERNEL

NON LINEAR



Initial condition:

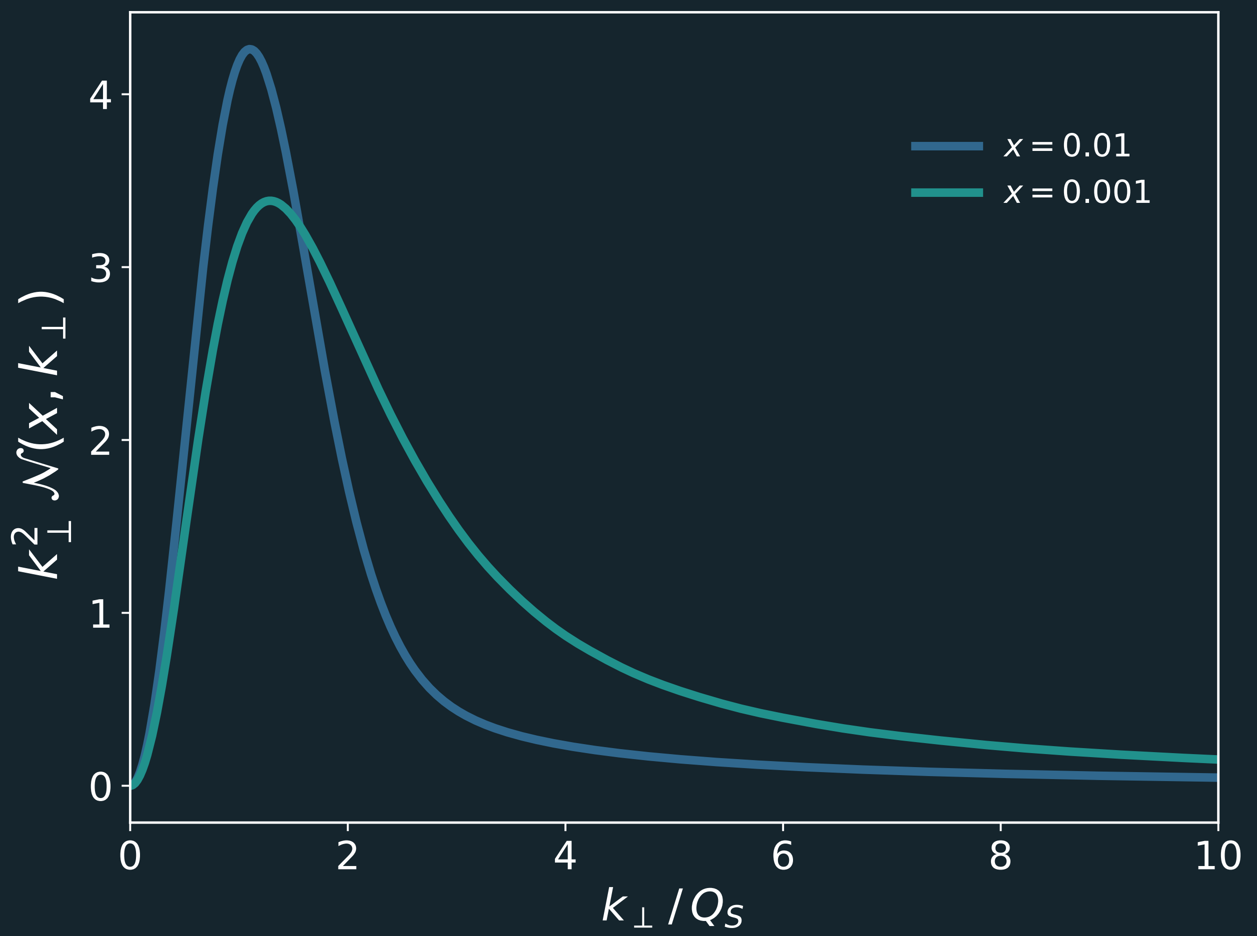
MV MODEL

EVOLUTION

$$\frac{\partial \mathcal{N}(\boldsymbol{r}, x)}{\partial \log(x_0/x)} = \int \mathrm{d}^2\boldsymbol{r}_1\, K^{run}(\boldsymbol{r}, \boldsymbol{r}_1, \boldsymbol{r}_2)\left[\mathcal{N}(\boldsymbol{r}_1, x) + \mathcal{N}(\boldsymbol{r}_1, x) - \mathcal{N}(\boldsymbol{r}, x) - \mathcal{N}(\boldsymbol{r}_1, x)\,\mathcal{N}(\boldsymbol{r}_2, x)\right]$$

KERNEL

NON LINEAR



Initial condition:

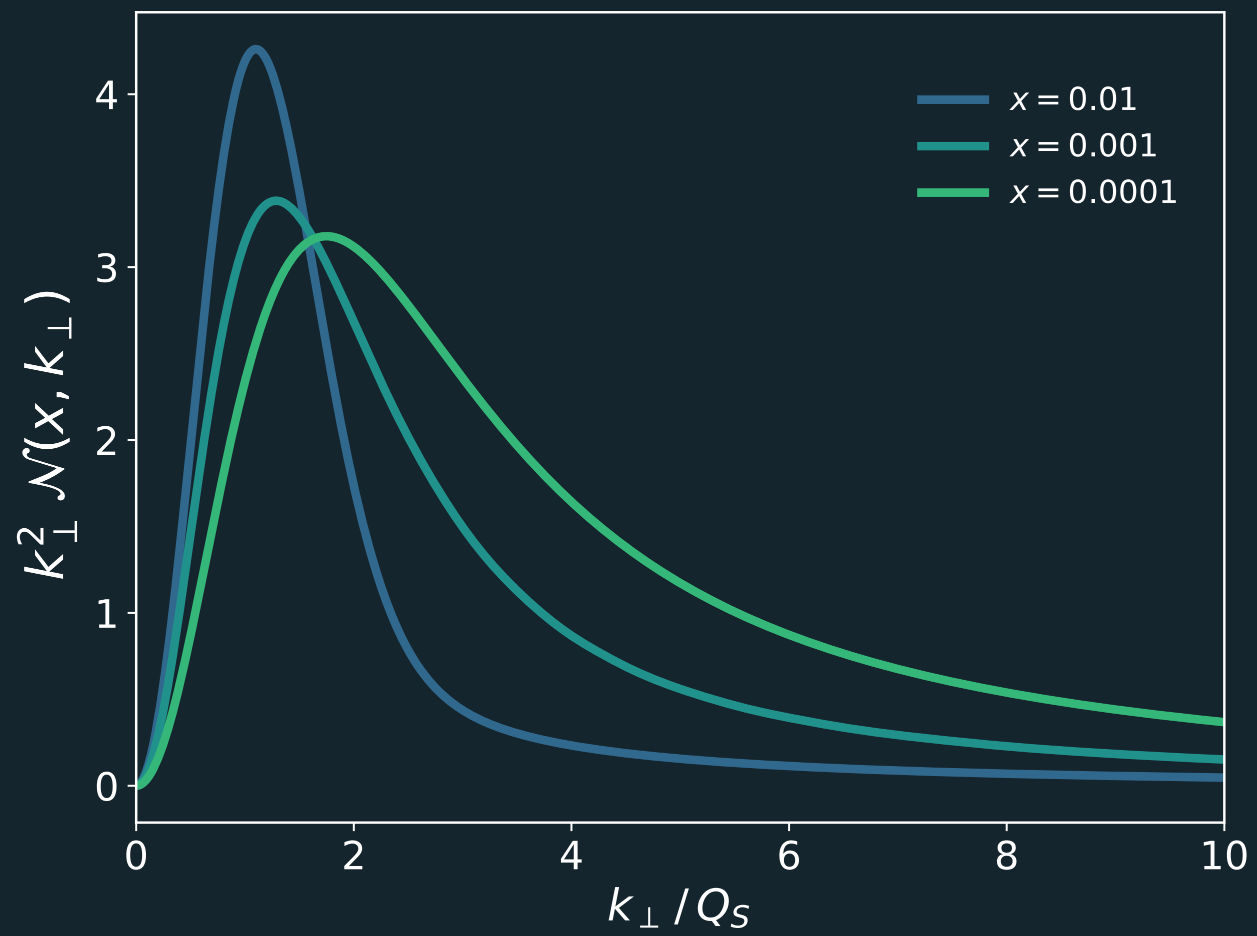
MV MODEL

EVOLUTION

$$\frac{\partial \mathcal{N}(\boldsymbol{r},x)}{\partial \log(x_0/x)} = \int \mathrm{d}^2\boldsymbol{r}_1\, K^{run}(\boldsymbol{r},\boldsymbol{r}_1,\boldsymbol{r}_2)\left[\mathcal{N}(\boldsymbol{r}_1,x)+\mathcal{N}(\boldsymbol{r}_1,x)-\mathcal{N}(\boldsymbol{r},x)-\mathcal{N}(\boldsymbol{r}_1,x)\,\mathcal{N}(\boldsymbol{r}_2,x)\right]$$

KERNEL

NON LINEAR



Initial condition:

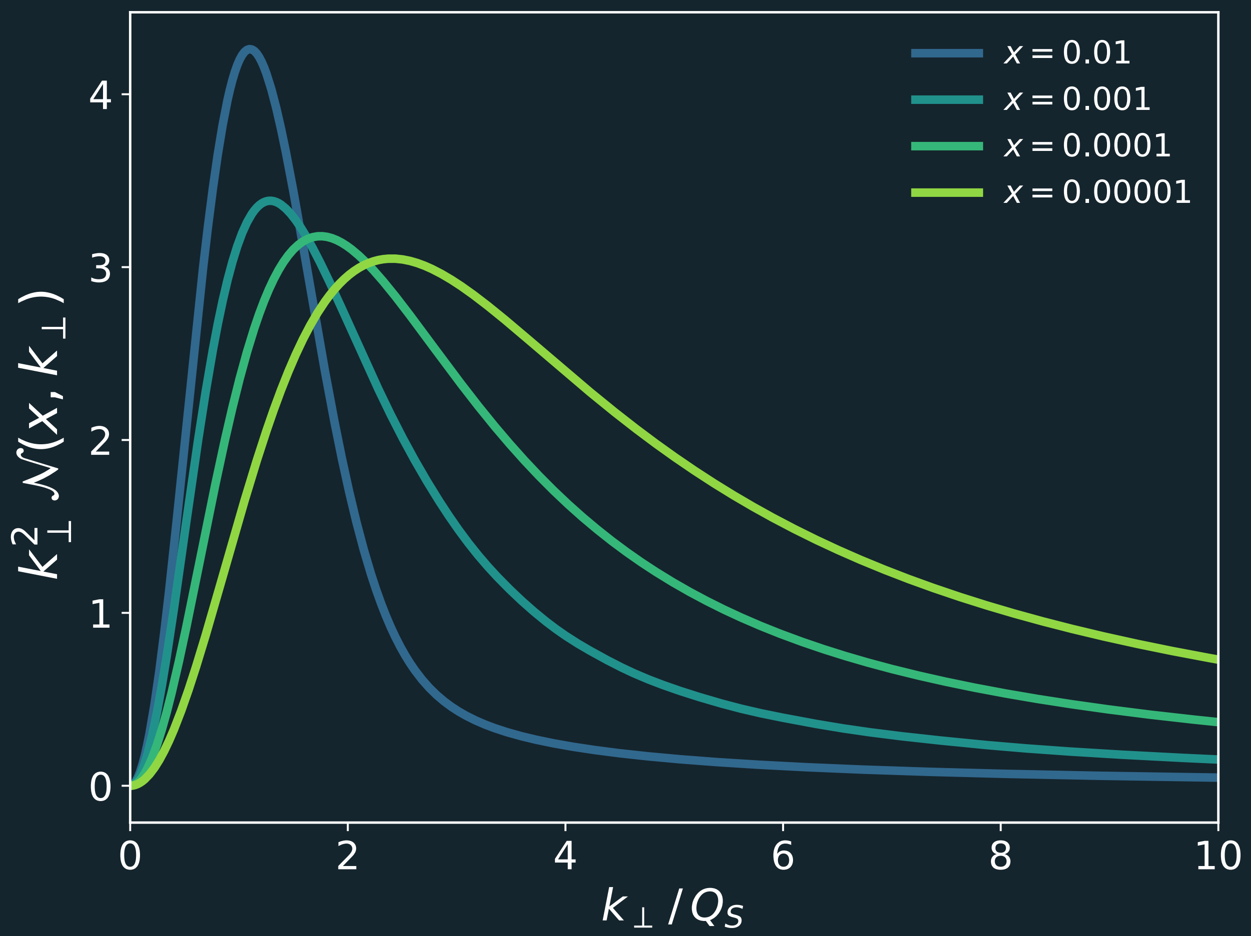
MV MODEL

EVOLUTION

$$\frac{\partial \mathcal{N}(\boldsymbol{r},x)}{\partial \log(x_0/x)} = \int \mathrm{d}^2\boldsymbol{r}_1\, K^{run}(\boldsymbol{r},\boldsymbol{r}_1,\boldsymbol{r}_2)\left[\mathcal{N}(\boldsymbol{r}_1,x) + \mathcal{N}(\boldsymbol{r}_1,x) - \mathcal{N}(\boldsymbol{r},x) - \mathcal{N}(\boldsymbol{r}_1,x)\,\mathcal{N}(\boldsymbol{r}_2,x)\right]$$

KERNEL

NON LINEAR



Initial condition:

MV MODEL

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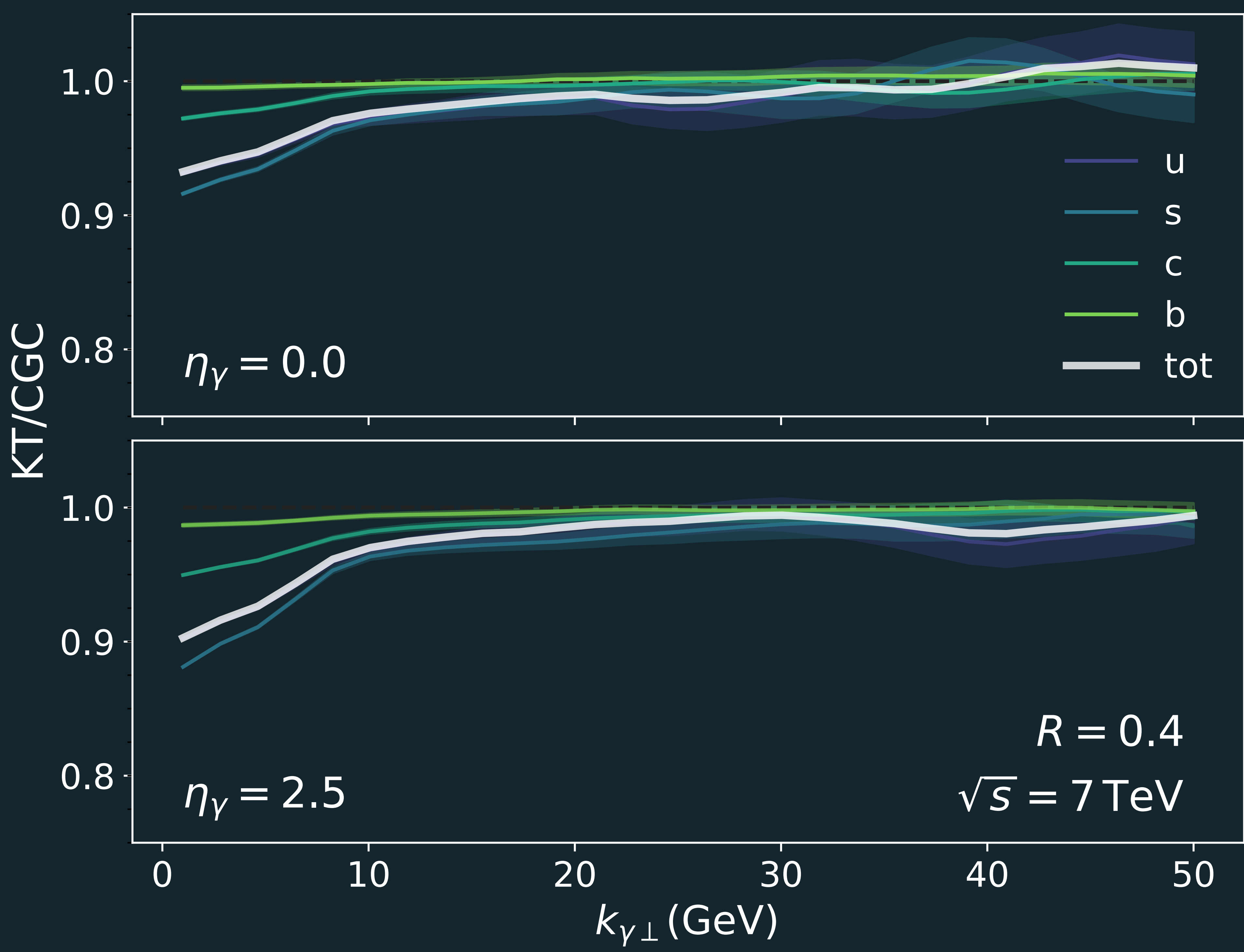
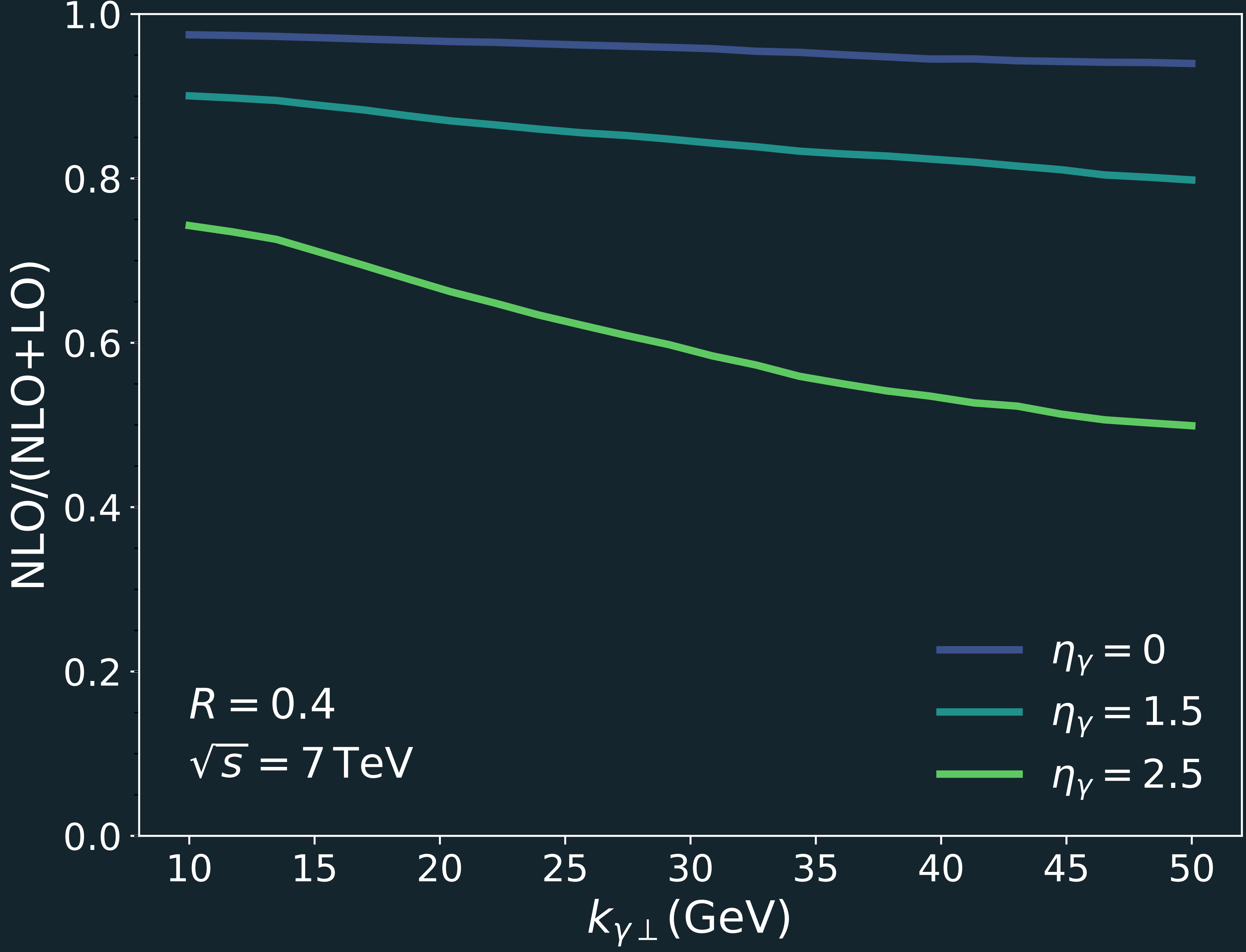
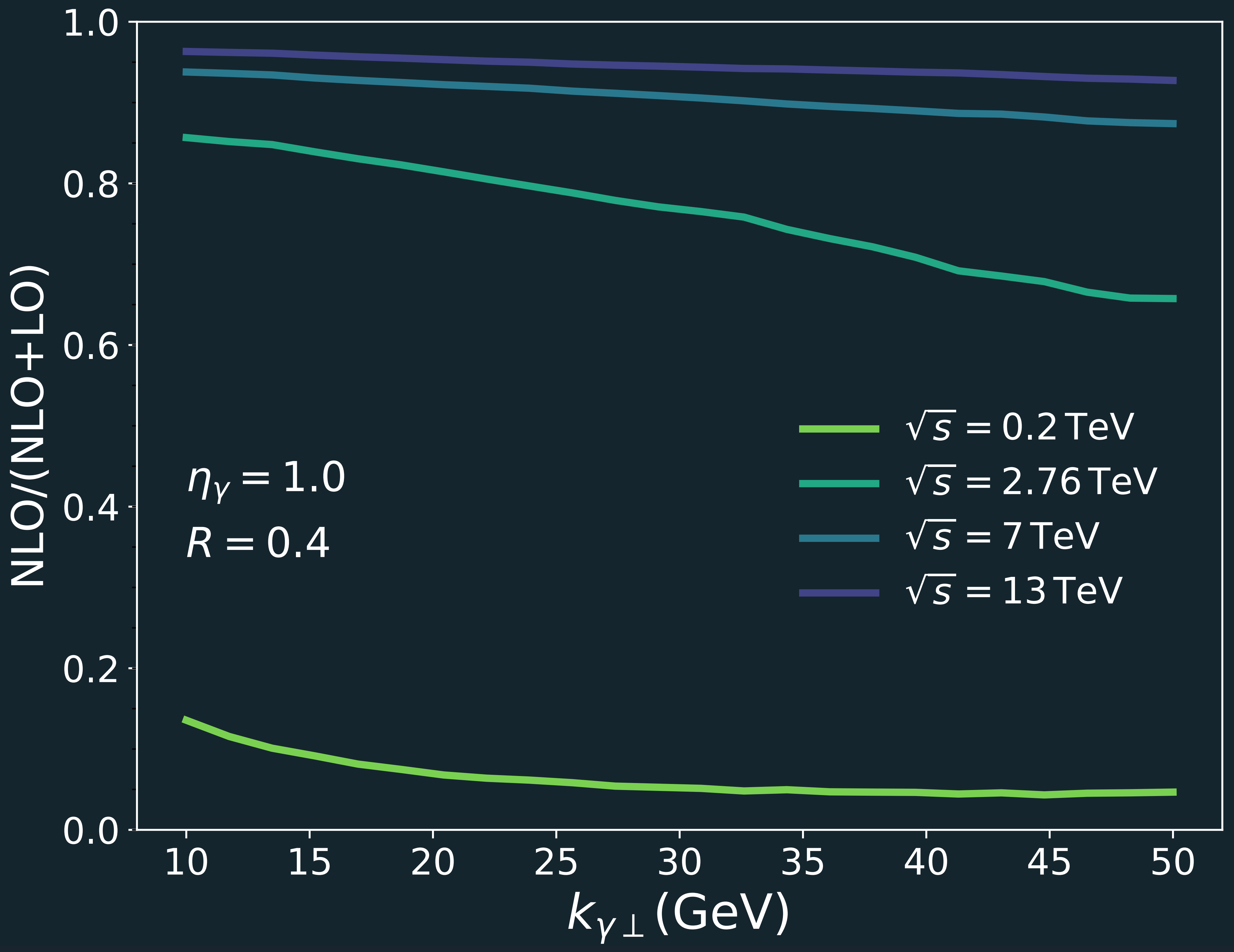
APPROXIMATION



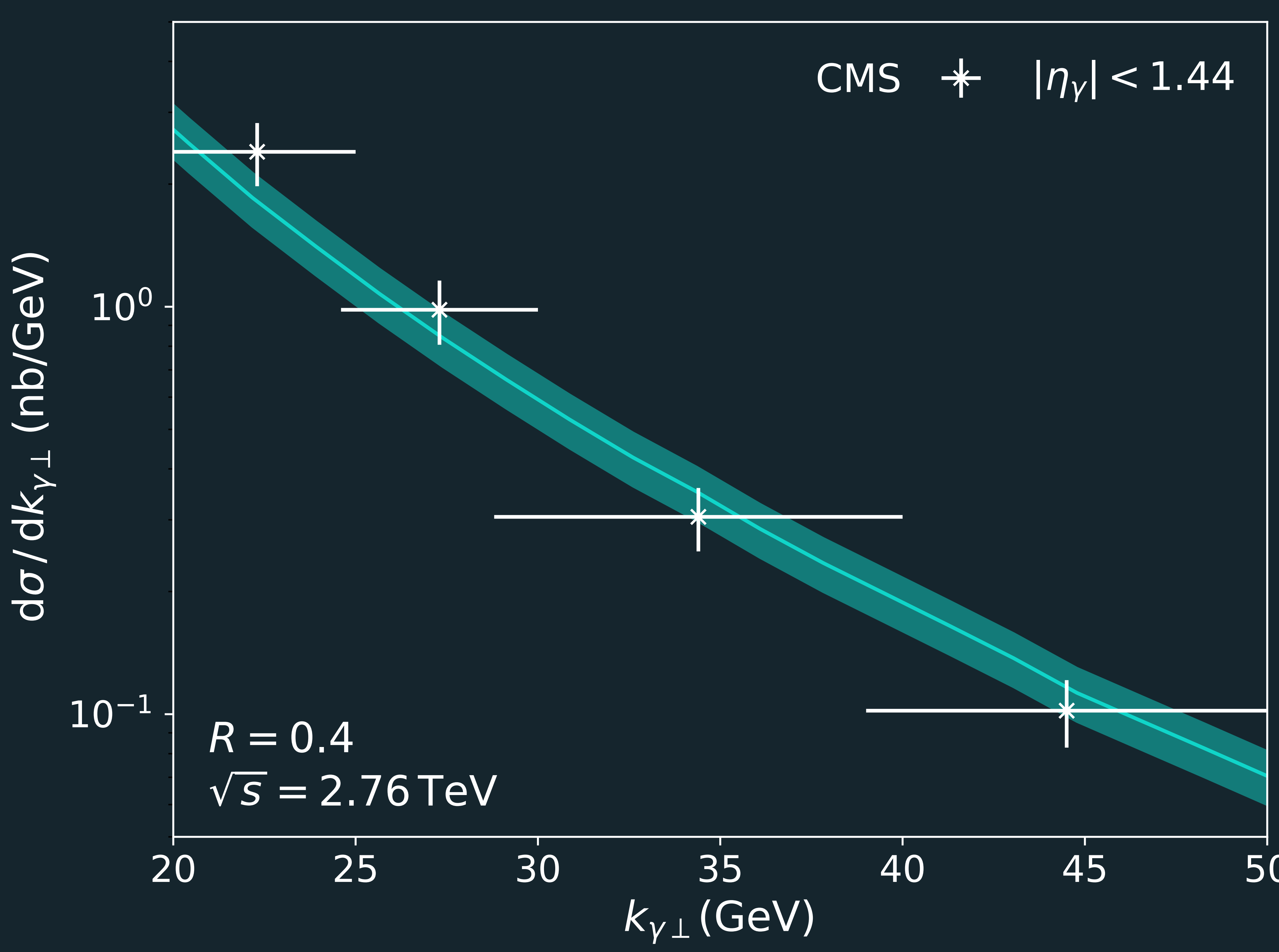
LO VS NLO: RAPIDITY



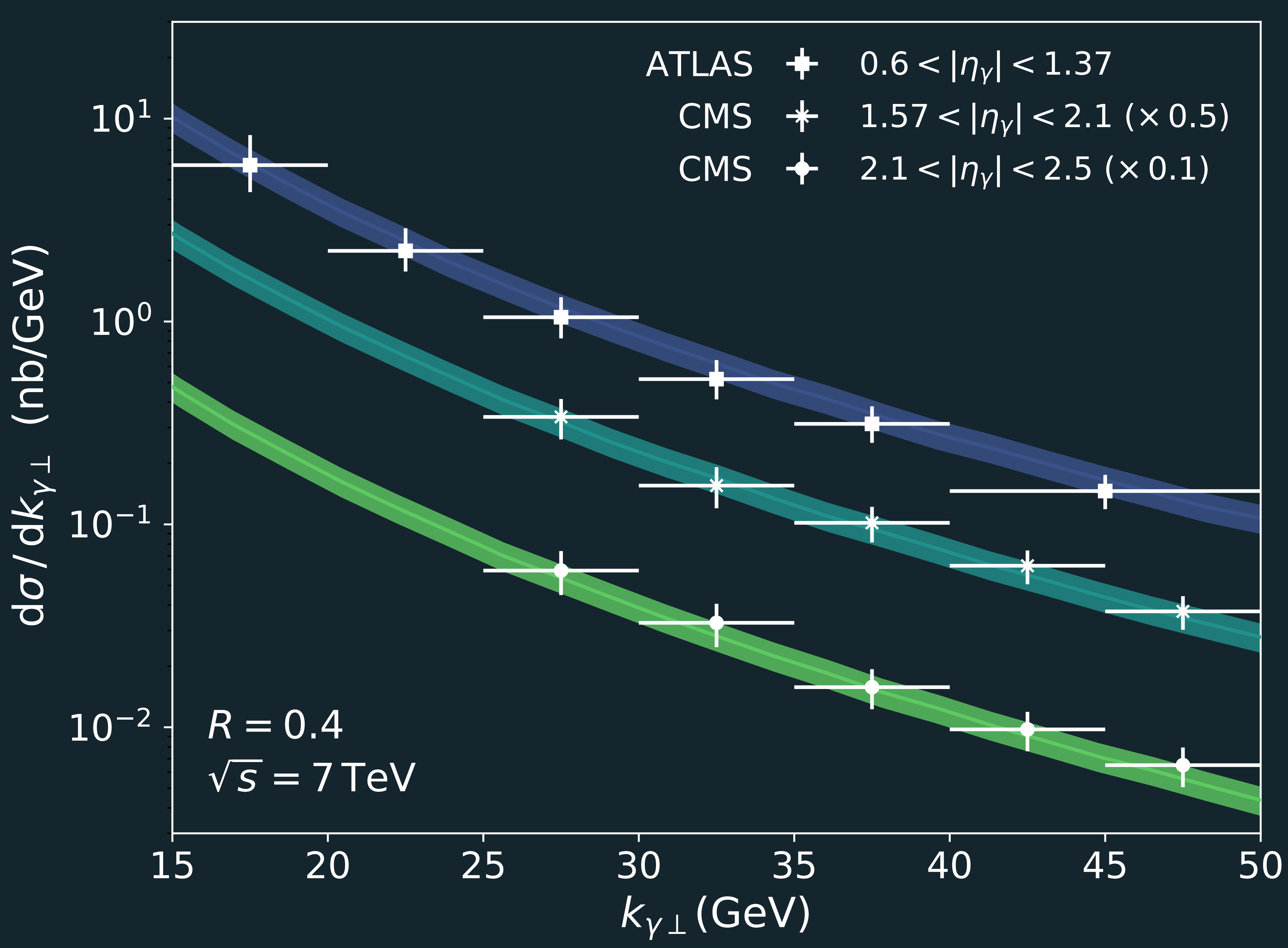
LO VS NLO: ENERGY



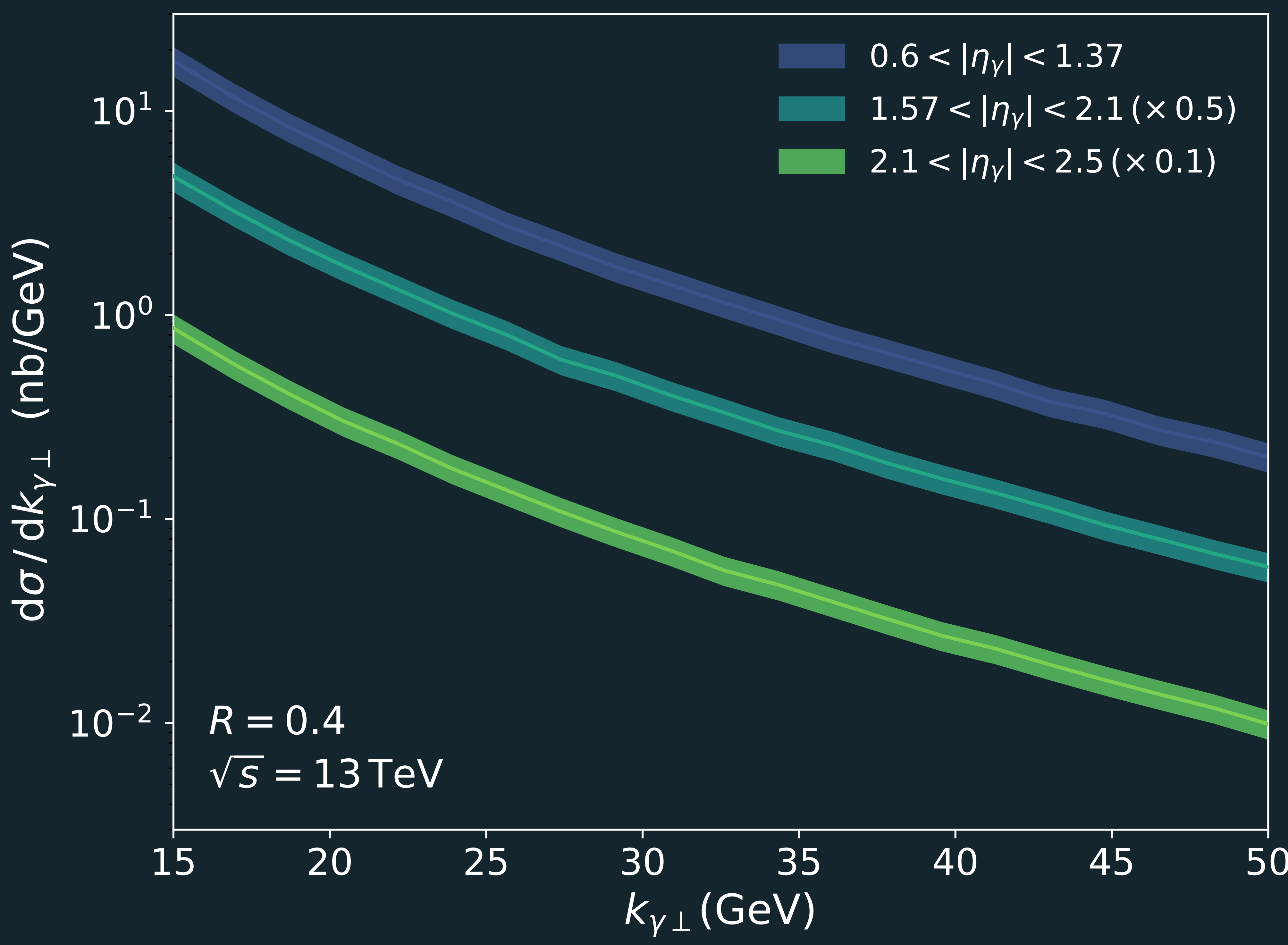
THEORY VS EXPERIMENT



THEORY VS EXPERIMENT



PREDICTION



$0.6 < |\eta_\gamma| < 1.37$
$1.57 < |\eta_\gamma| < 2.1\,(\times 0.5)$
$2.1 < |\eta_\gamma| < 2.5\,(\times 0.1)$
$R = 0.4$
$\sqrt{s} = 13\,\mathrm{TeV}$
$\mathrm{d}\sigma/\mathrm{d}k_{\gamma\perp}$ (nb/GeV)
$k_{\gamma\perp}$ (GeV)
10^{1}
10^{0}
10^{-1}
10^{-2}
15
20
25
30
35
40
45
50

1 MOTIVATION

2 FRAMEWORK: CGC

3 POWER COUNTING?

4 SOME RESULTS

5 SUMMARY AND OUTLOOK

SUMMARY

- **A** Saturation modifies the emission process thanks to multi-particle scatterings
- **B** Complete analytical result at NLO, that is $\mathcal{O}(\alpha_s \alpha_e)$
- **C** CGC formalism yields correct limits to the pQCD results
- **D** CGC $k_\perp$-factorized yields good agreement with the experimental data

OUTLOOK

A. Comparison to current and future p+A experimental data

B. Photon hadron correlations are sensitive to saturation

C. More exciting studies

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


THANK YOU
GARCIA@THPHYS.UNI-HEIDELBERG.DE