INCLUSIVE PROMPT PHOTON PRODUCTION FROM THE CGC

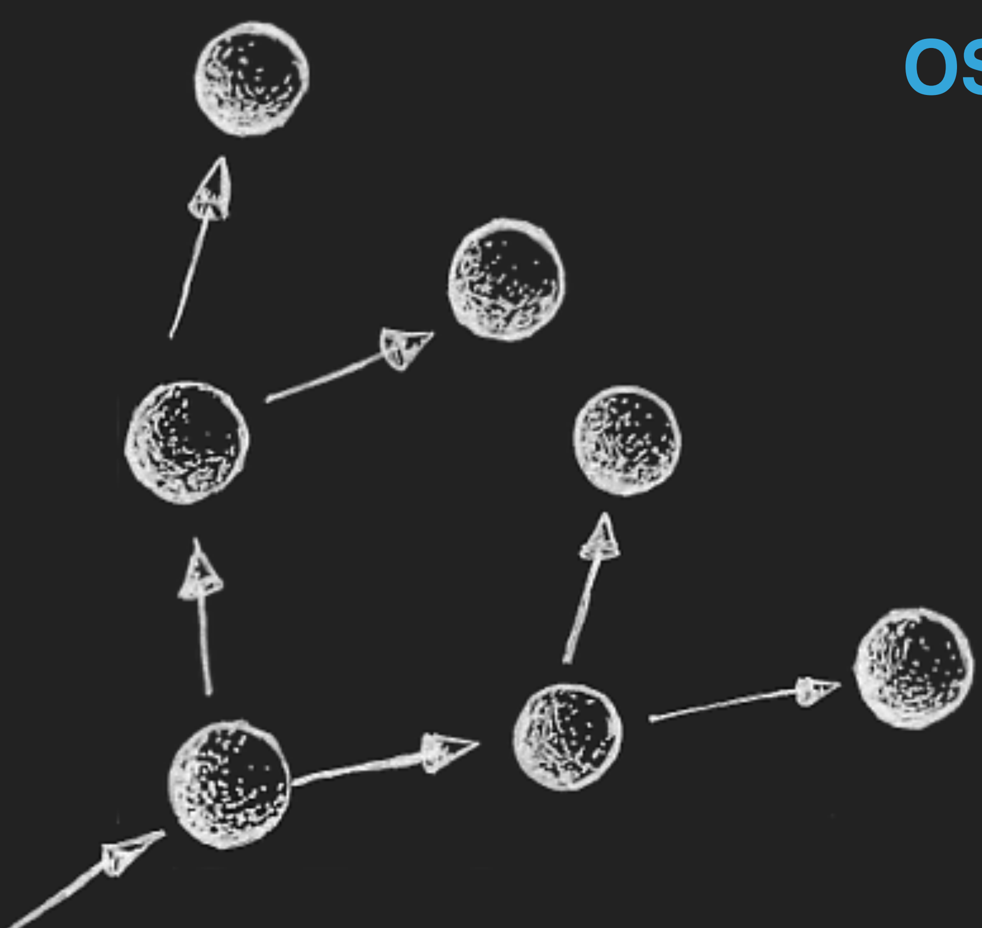
OSCAR GARCIA-MONTERO

In collaboration with

Sanjin Benic

Kenji Fukushima

Raju Venugopalan

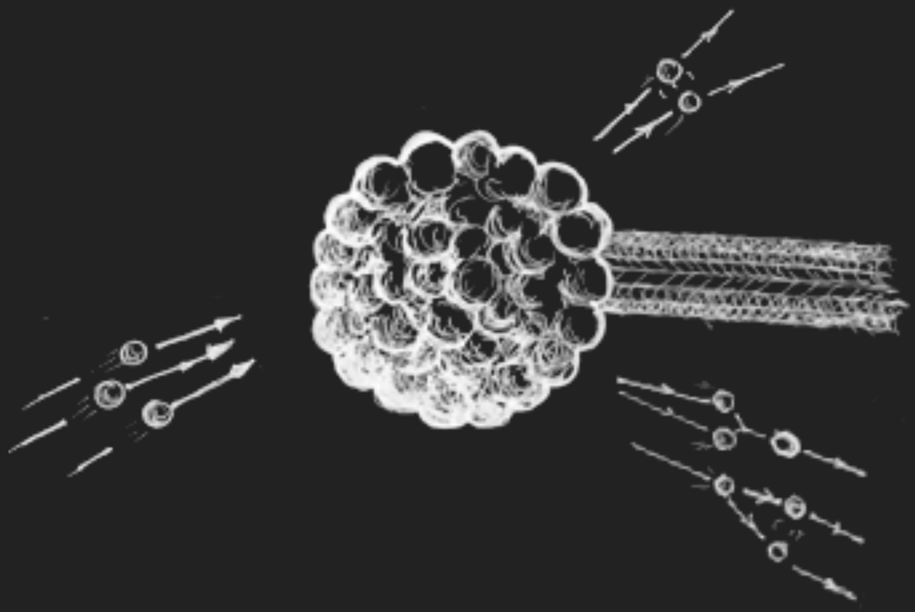


Based on JHEP 1701 (**2017**) 115

CONTENTS

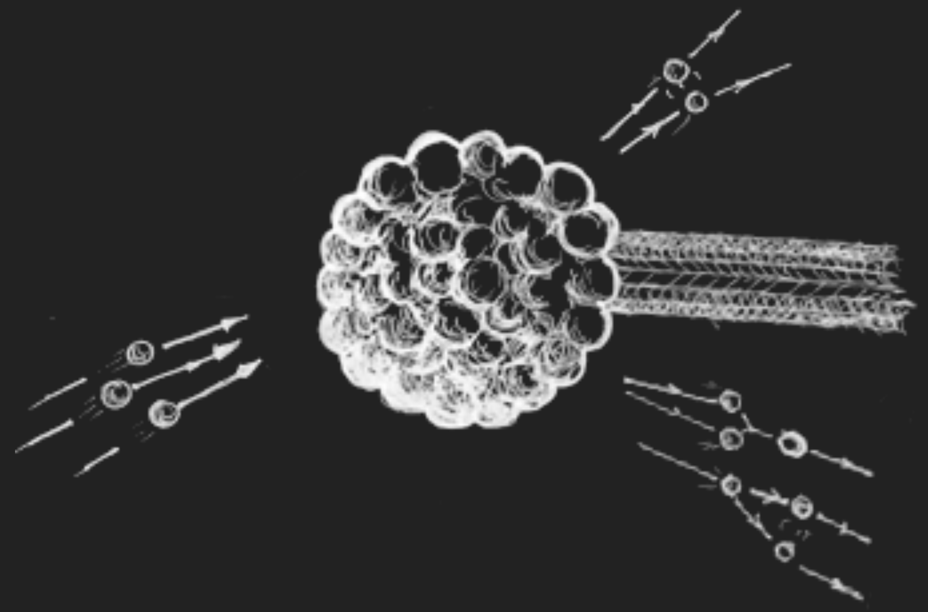
GLOBAL GOAL

Understand nuclear matter under extreme conditions



LOCAL GOAL

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



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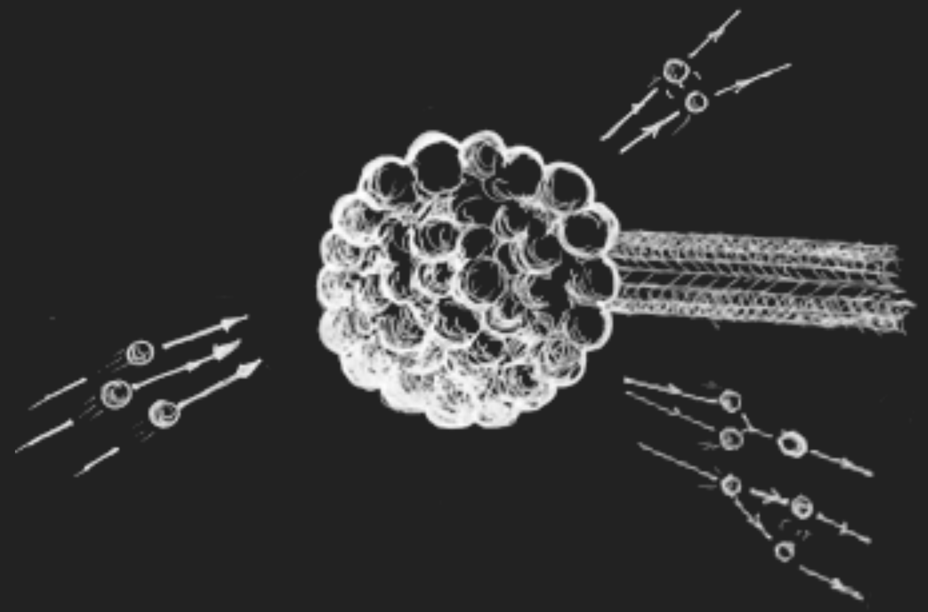
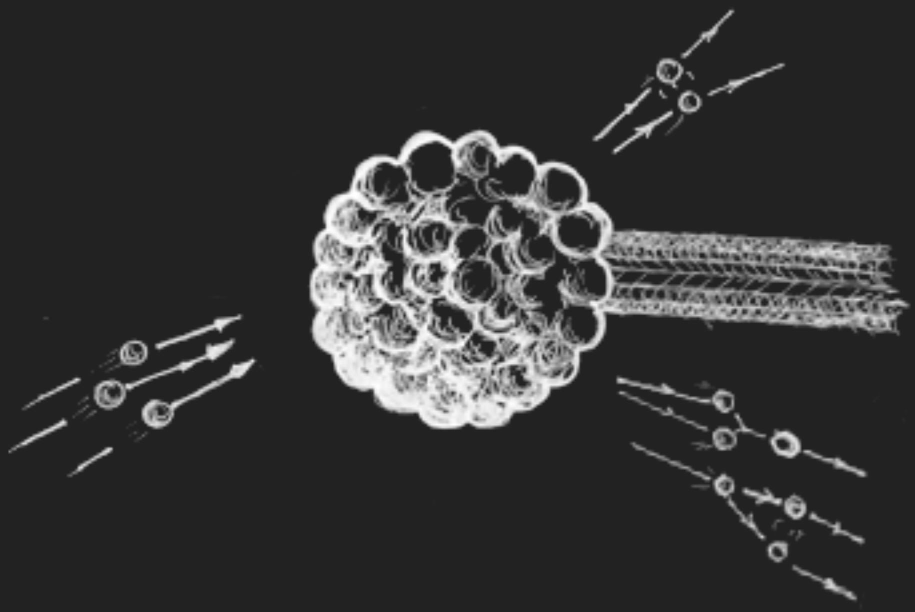


WHY PHOTONS?

No strong interaction

LOCAL GOAL



Use photons as probes for saturation
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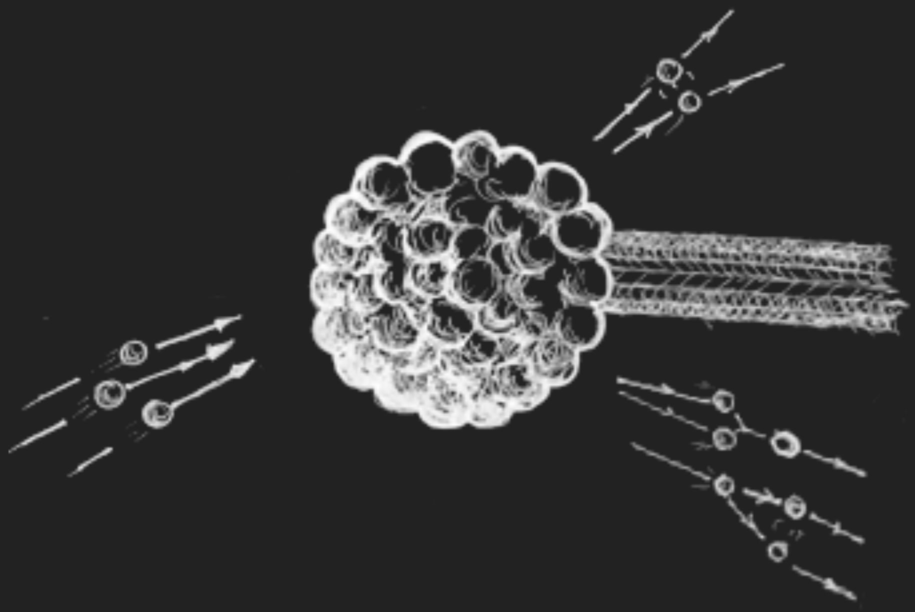
WHY PHOTONS?

No strong interaction → Clean probes.

LOCAL GOAL



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

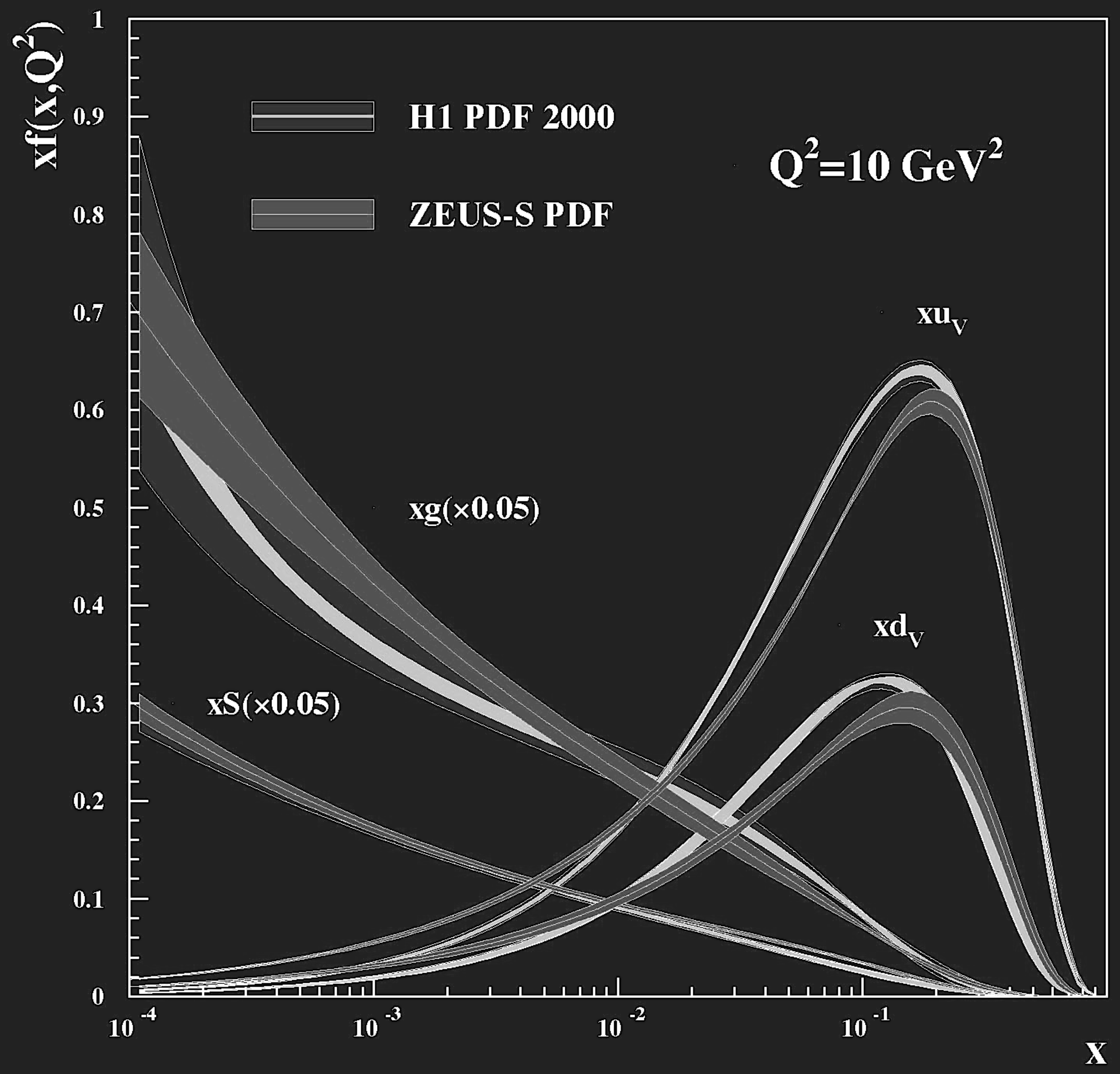
WHY PHOTONS?

No strong interaction → Clean probes.

WHY P+A?

Use known probes to probe the "unknown"

PARTON DISTRIBUTION FUNCTIONS



HOW TO CATCH A GLUON SOUP?

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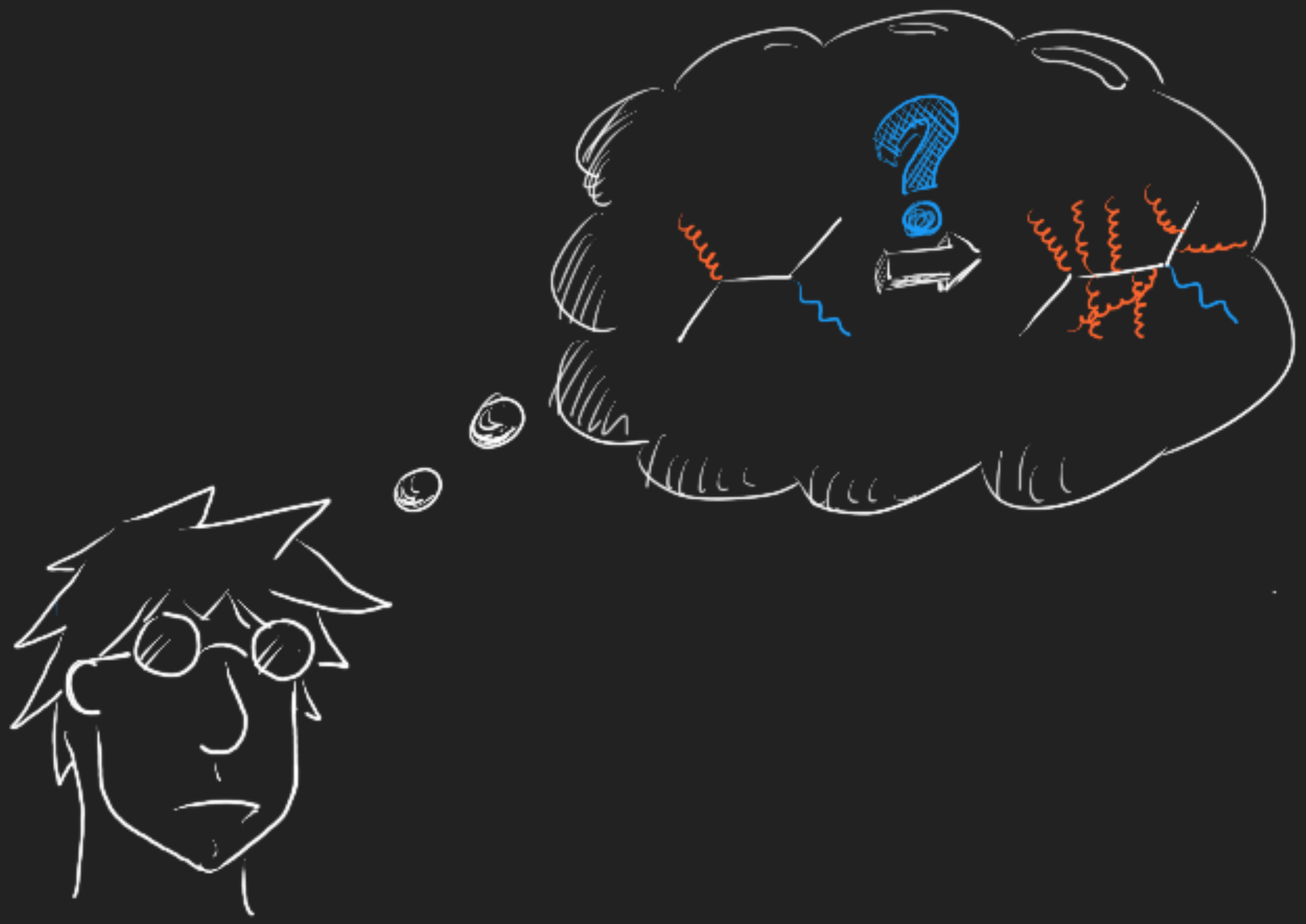
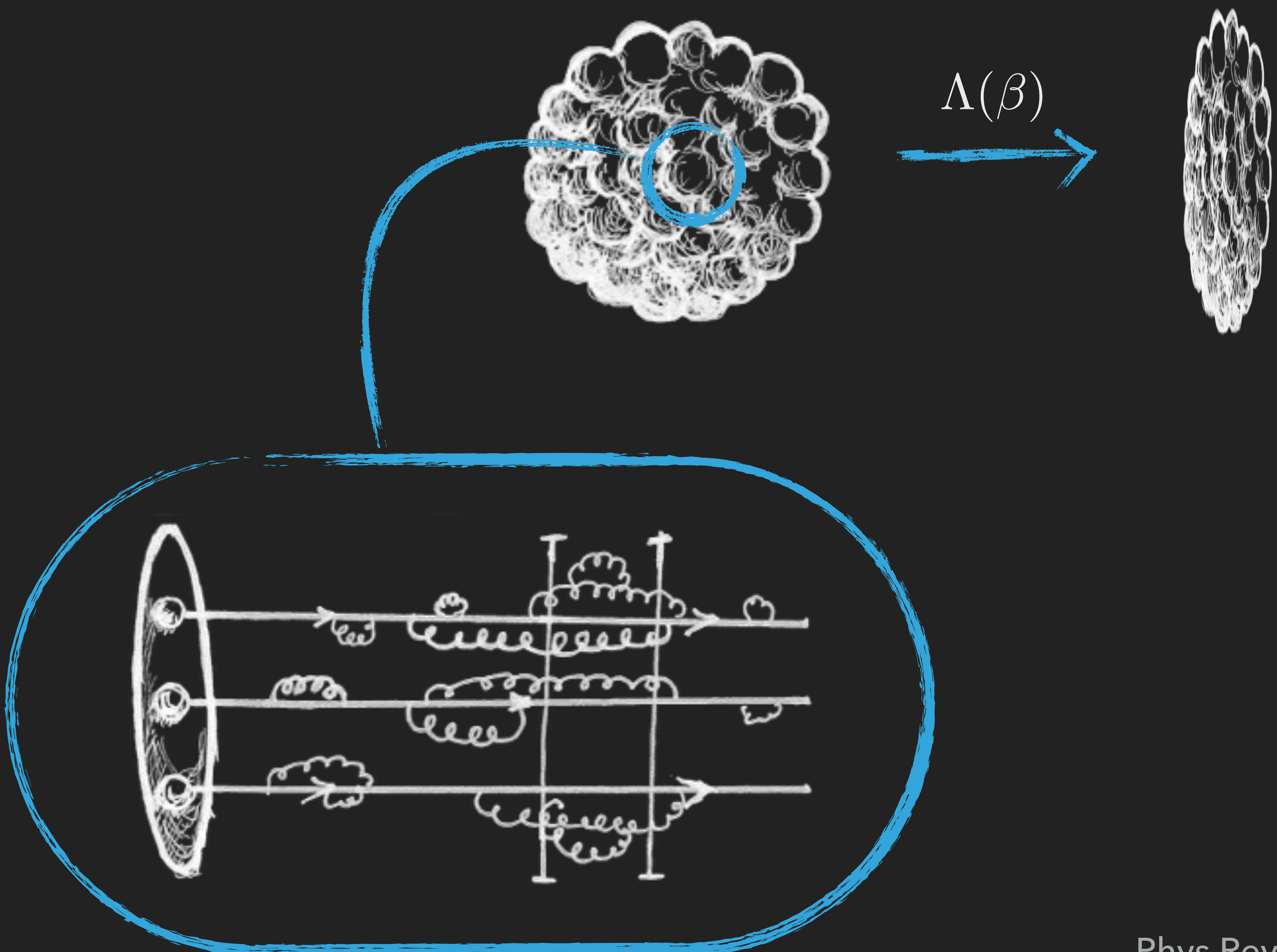


COLOR GLASS CONDENSATE



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

COLOR GLASS CONDENSATE

Glue

Soft Partons

Macroscopic Field

$\mathcal{A}(x)$

$Q_S(x)$

Hard Partons

Static Color Sources

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

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

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

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Soft Partons

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Static Color Sources

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

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

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

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

COLOR GLASS CONDENSATE

Glue

Soft Partons

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$\mathcal{A}(x)$

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

$$\mathcal{A}(x)$$

Hard Partons

Static Color Sources

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

SPECIAL CASE

McLerran-Venugopalan Model

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

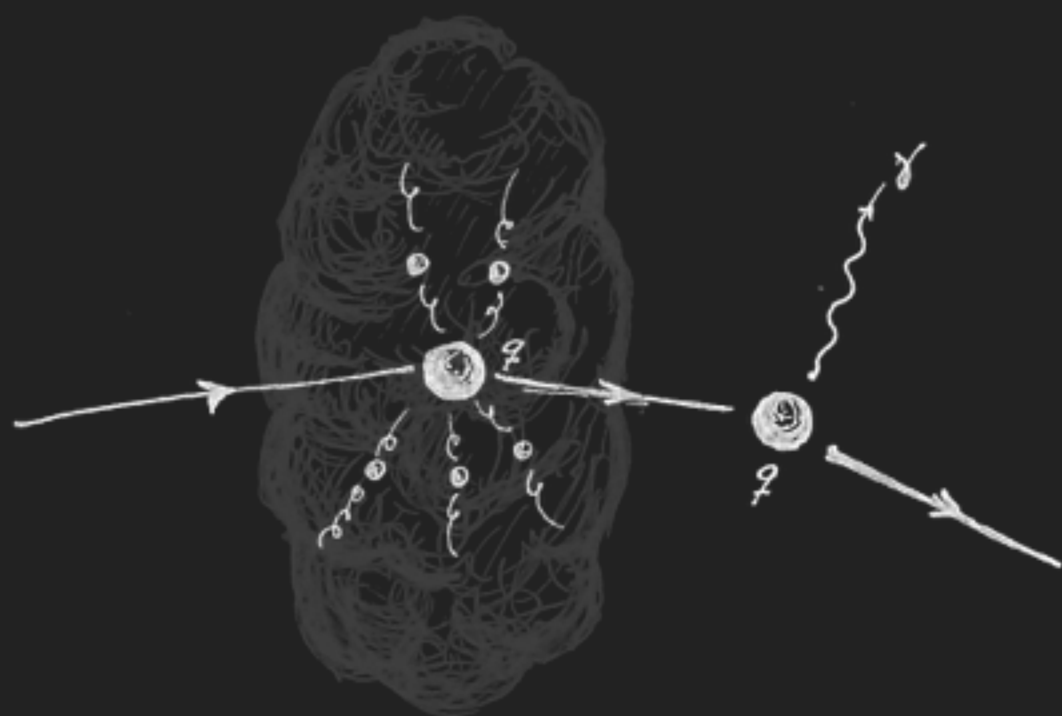
GLUON PROPAGATOR

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

Multiple Scatterings

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

QUARK PROPAGATOR



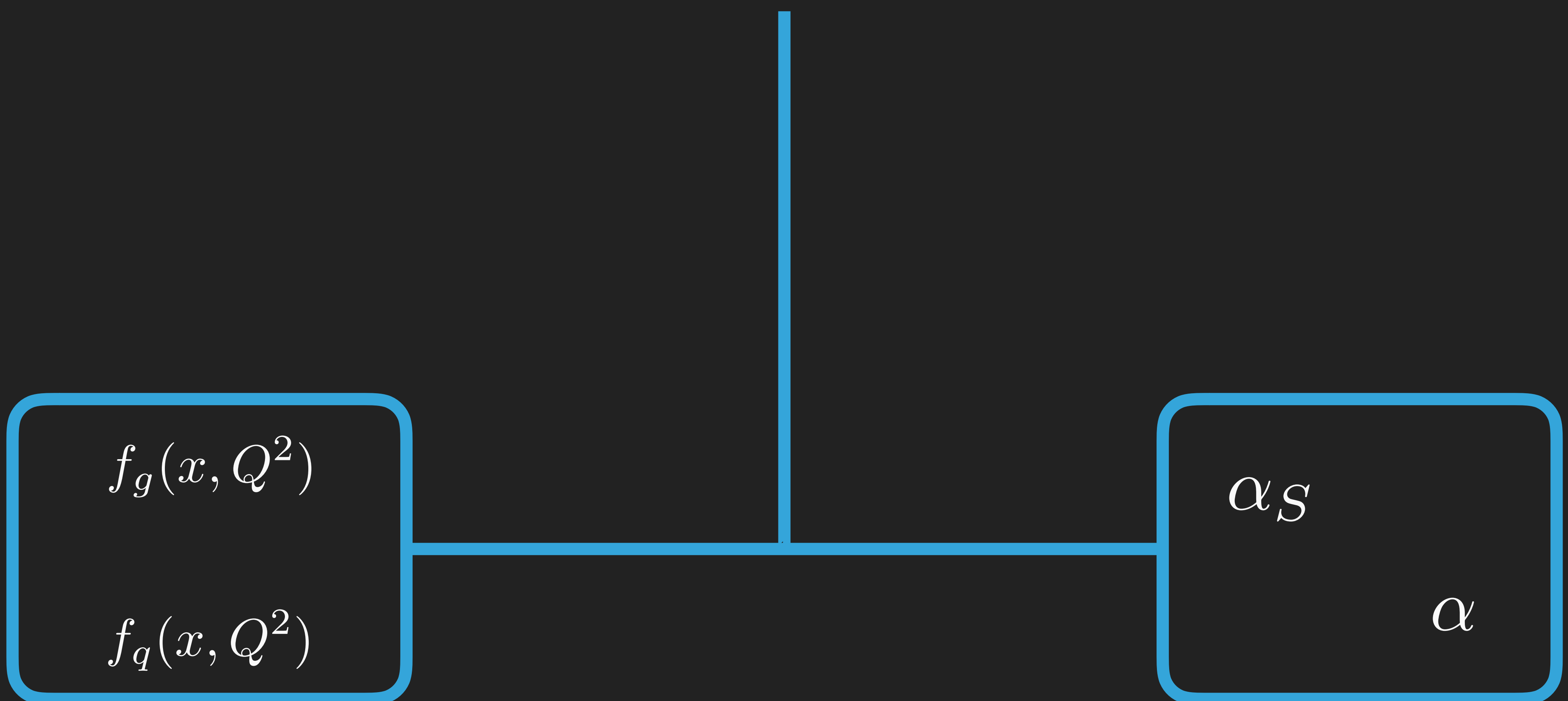
How do quarks behave through the CGC?

Multiple Scatterings

Dressed propagator

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

POWER COUNTING



POWER COUNTING

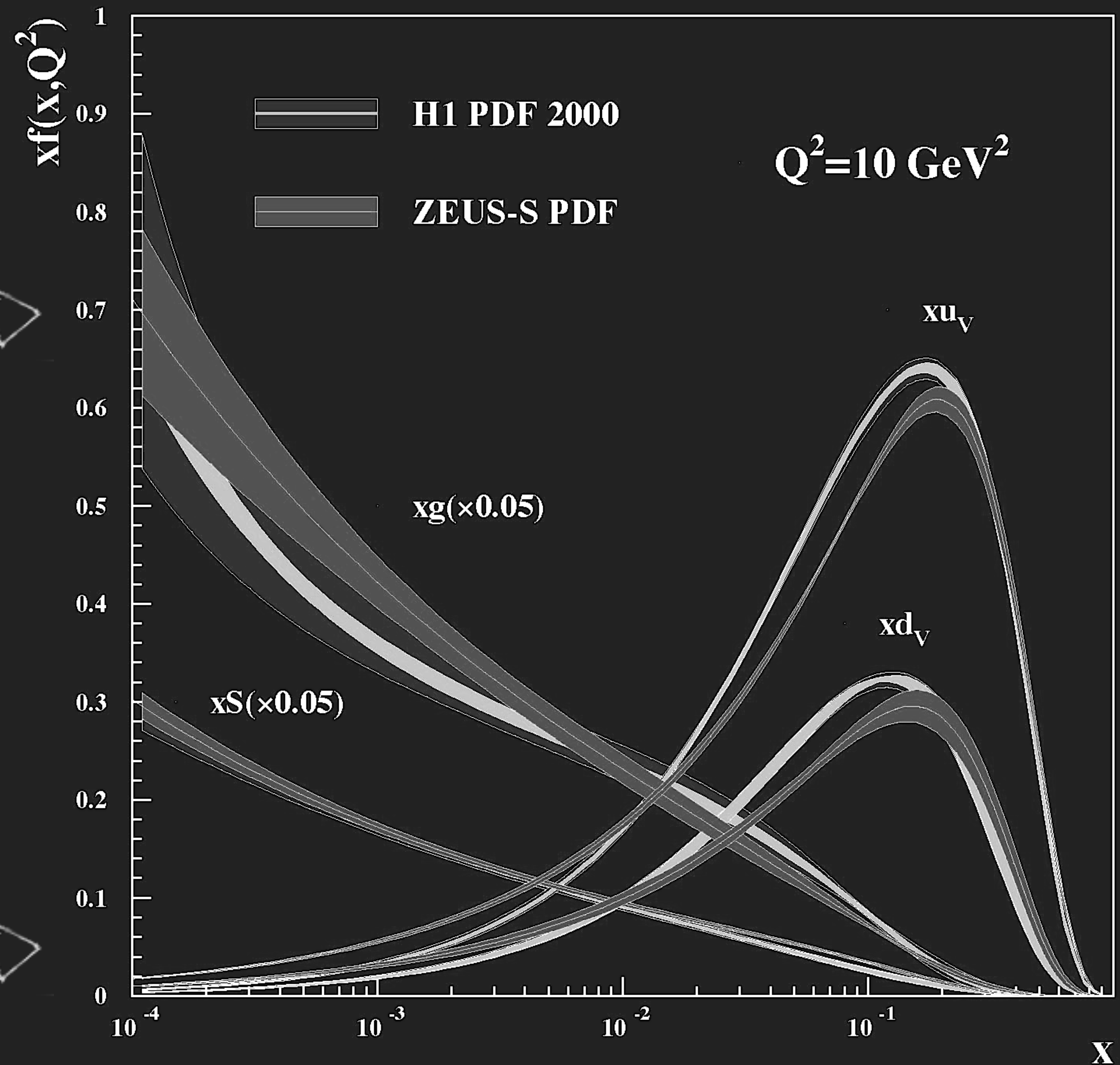
$f_g(x, Q^2)$

$f_q(x, Q^2)$

$\alpha_S > \alpha$

$f_g(x, Q^2)$ ⇨

$f_q(x, Q^2)$ ⇨



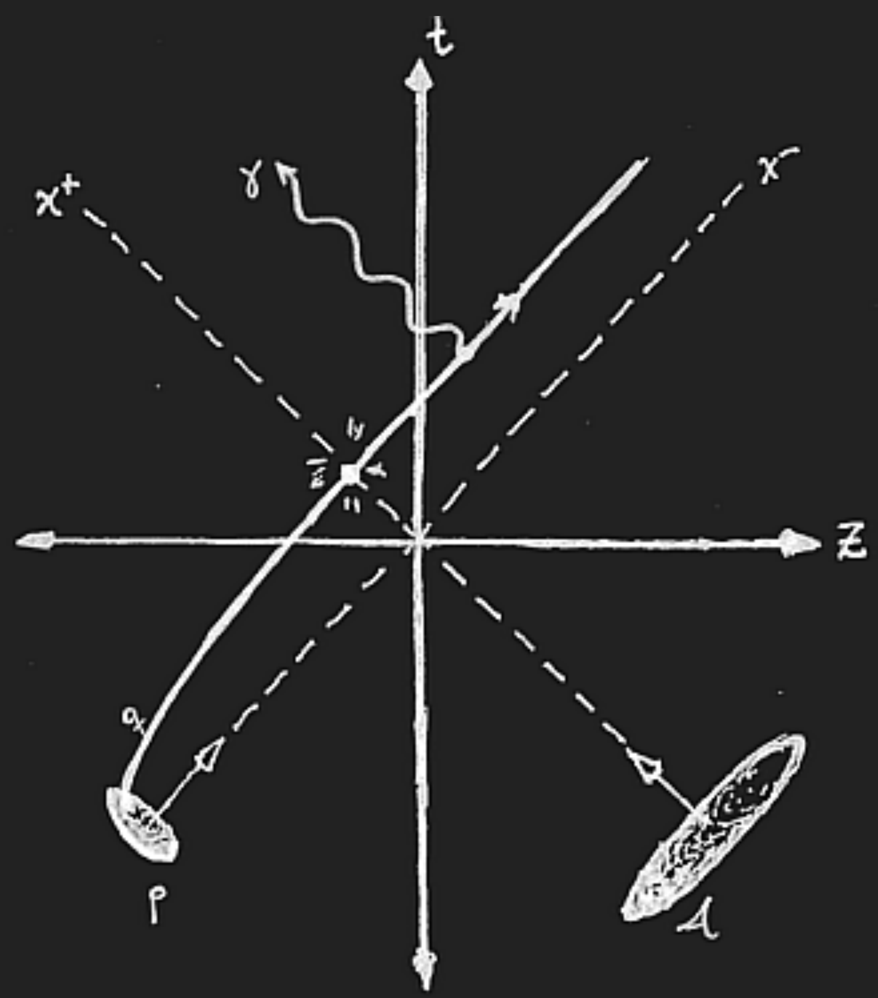
xf(x,Q^2)
H1 PDF 2000
ZEUS-S PDF
Q^2=10 GeV^2
xu_V
xd_V
xg(×0.05)
xS(×0.05)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10^-4
10^-3
10^-2
10^-1
x

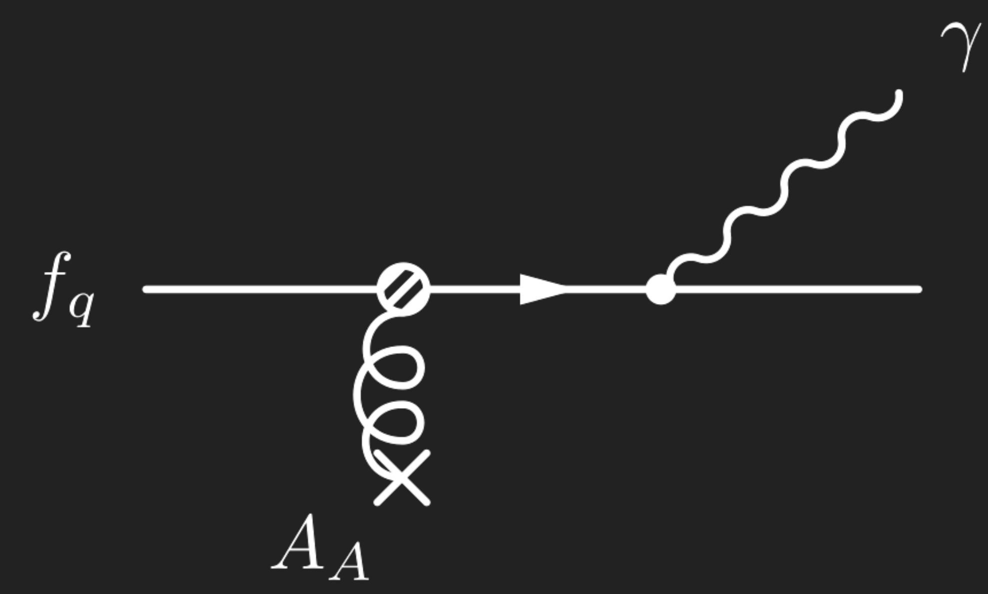
POWER COUNTING

$f_g(x, Q^2)$ > $f_q(x, Q^2)$

α_S > α

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





$$x \sim 10^{-2}$$

⇩

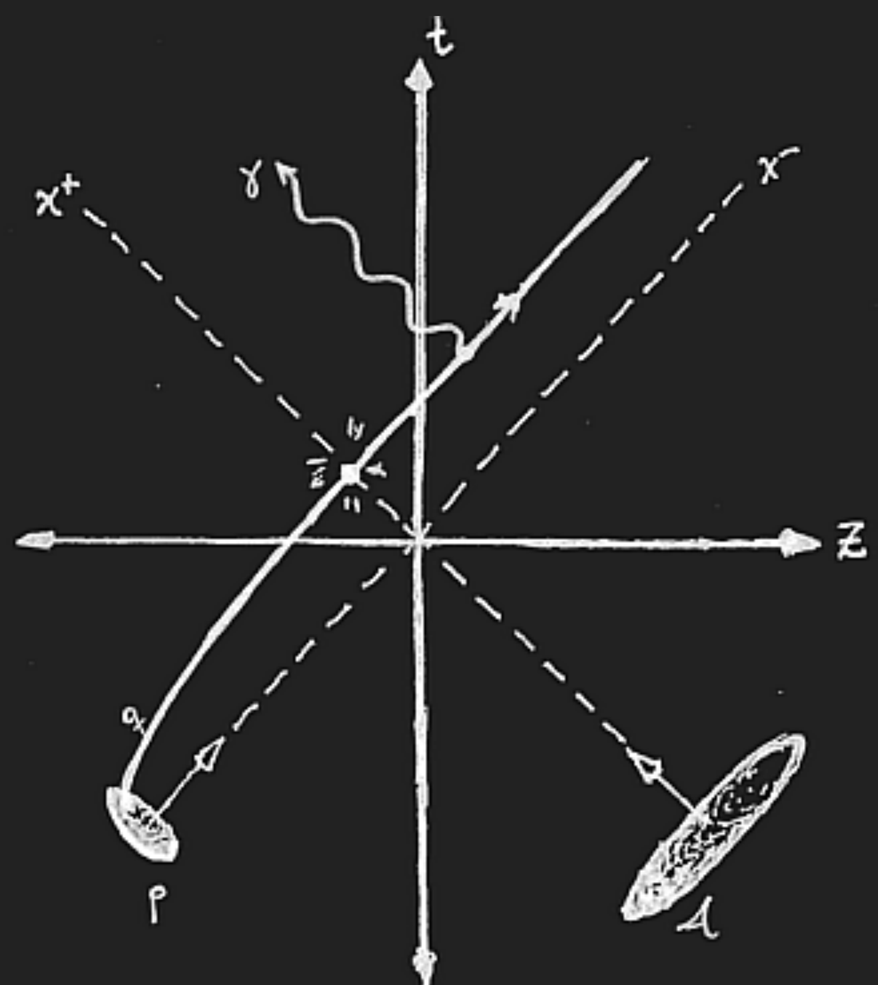
$$f_g(x, Q^2) \gg f_q(x, Q^2)$$

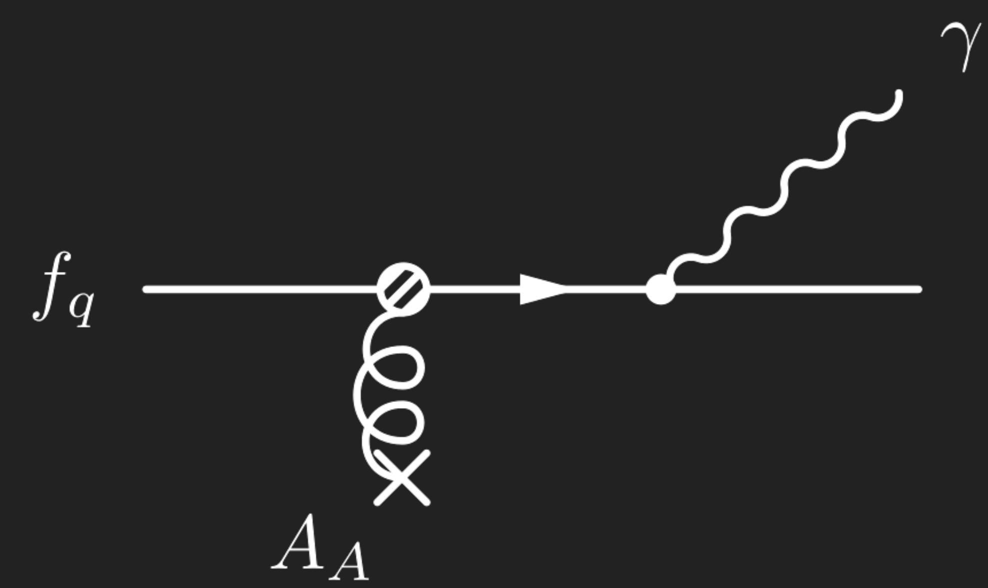
Kopeliovich, Tarasov, Schaefer, Phys. Rev. C 59 (1999) 1609

Gelis, Jalilian-Marian, Phys. Rev. D 66 (2002) 014021

Baier, Mueller, Schi, Nucl. Phys. A 741 (2004) 358

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





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

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

Kopeliovich, Tarasov, Schaefer, Phys. Rev. C 59 (1999) 1609
Gelis, Jalilian-Marian, Phys. Rev. D 66 (2002) 014021
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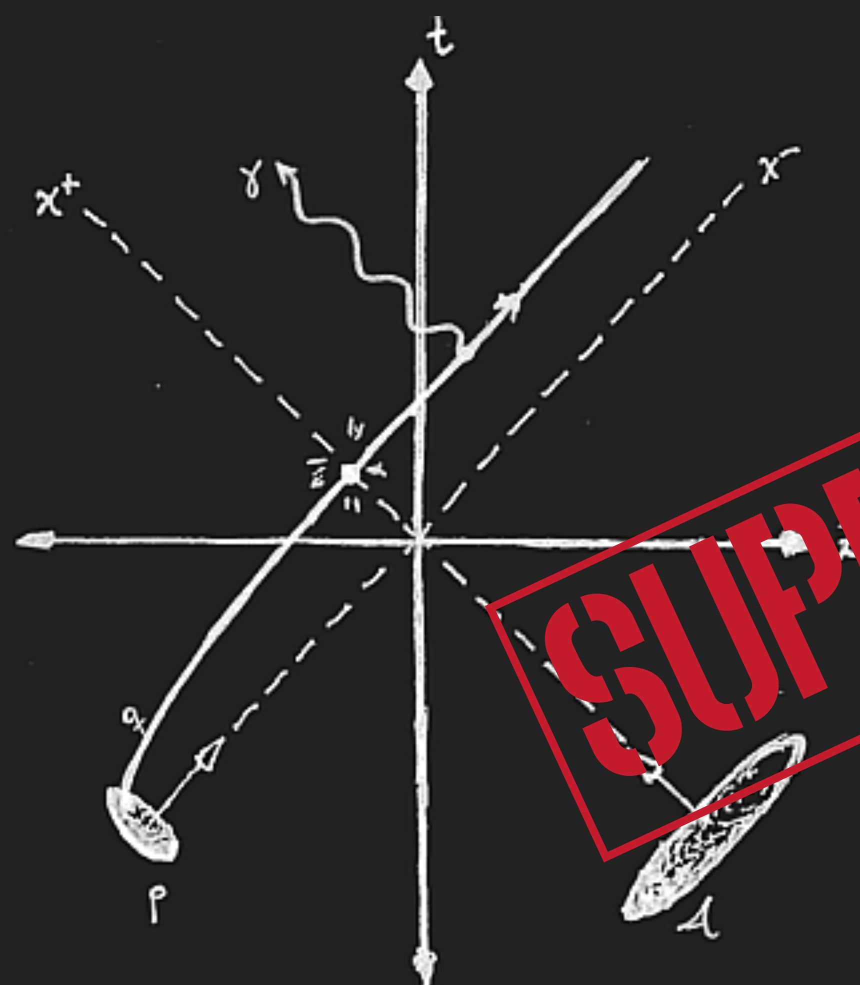
LO [$\mathcal{O}(\alpha)$]



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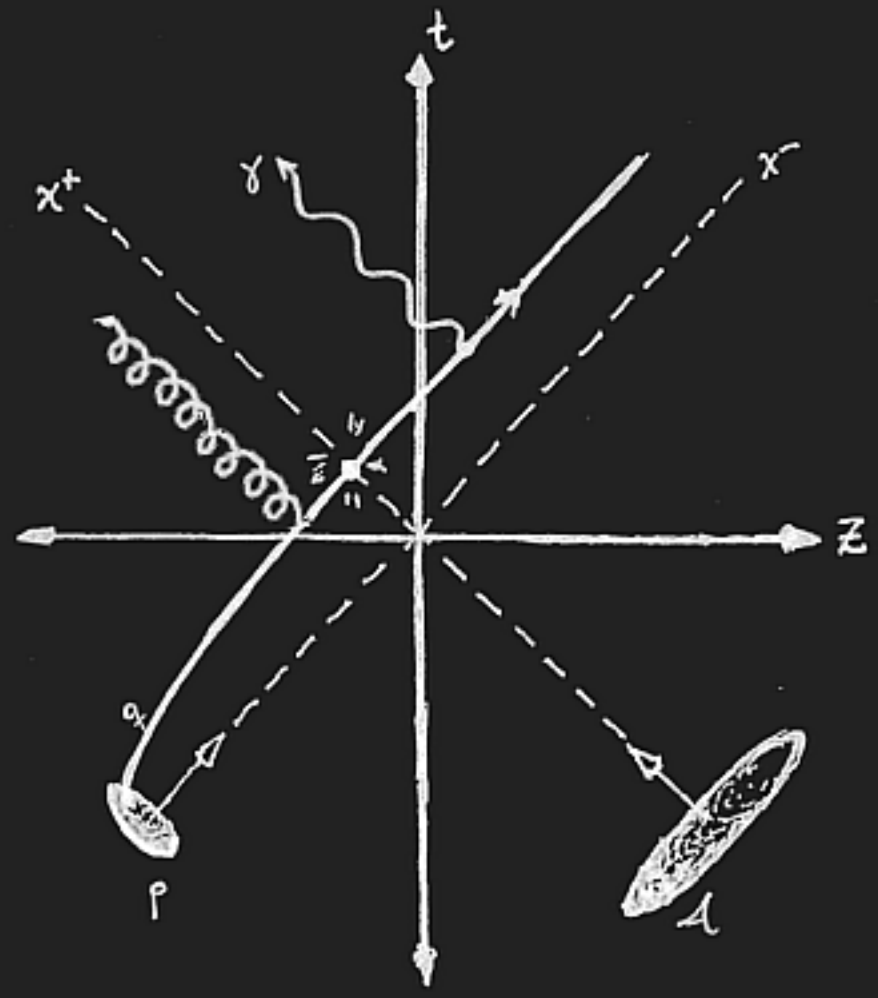
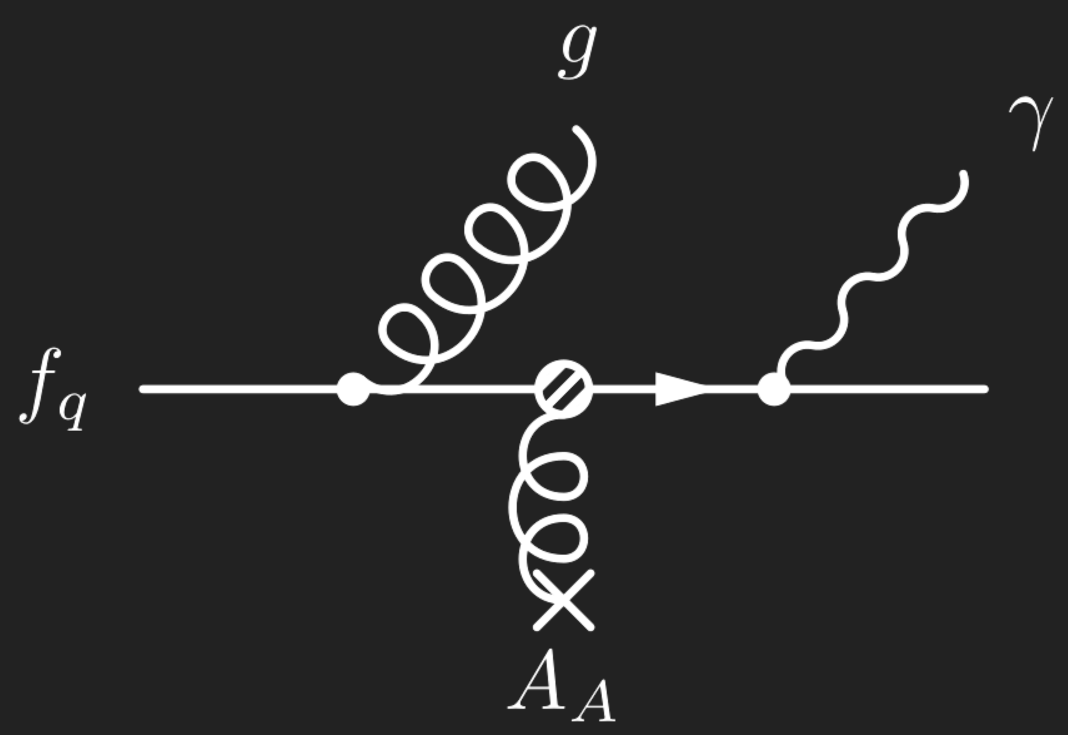
NLO: GLUON BREMSSTRAHLUNG





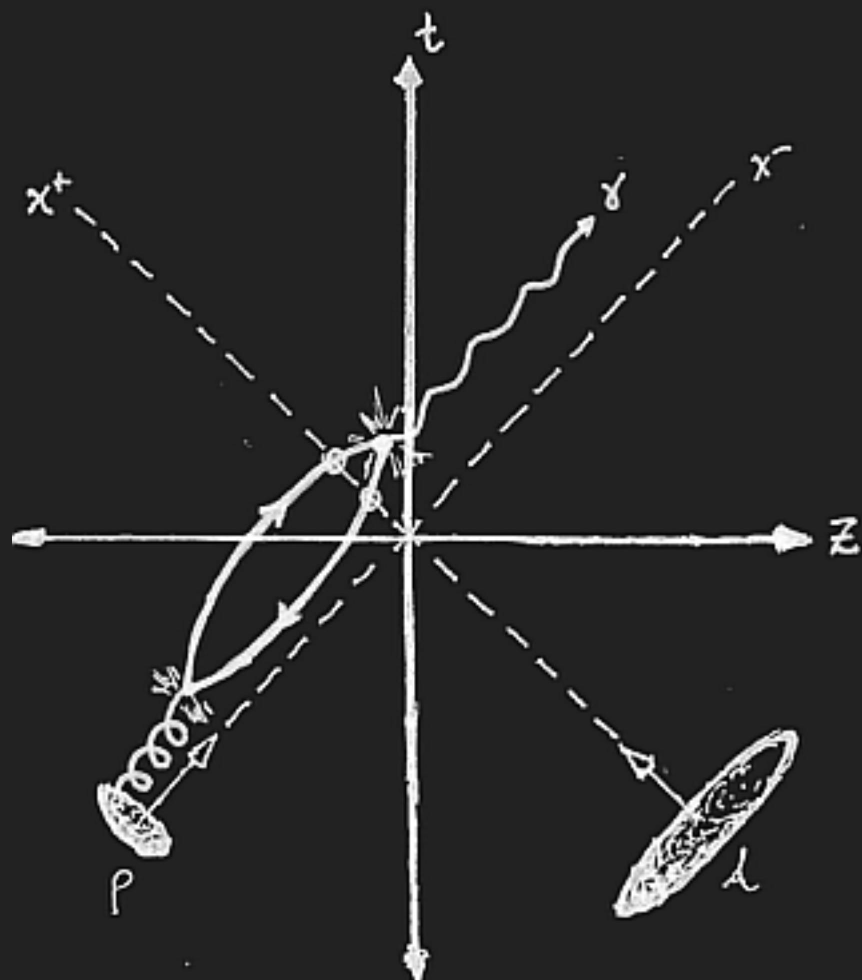
$x \sim 10^{-2}$

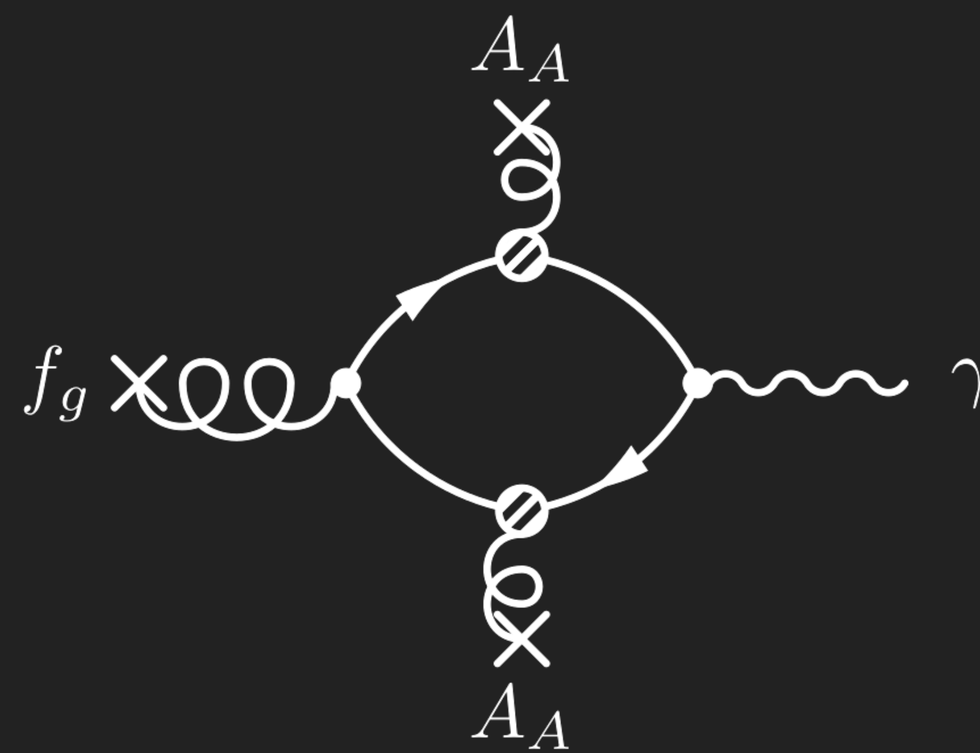
⇩

$f_g(x,Q^2) \gg f_q(x,Q^2)$

- Can be reabsorbed as renormalisation of $f_q(x,Q^2)$

NLO: ANNIHILATION





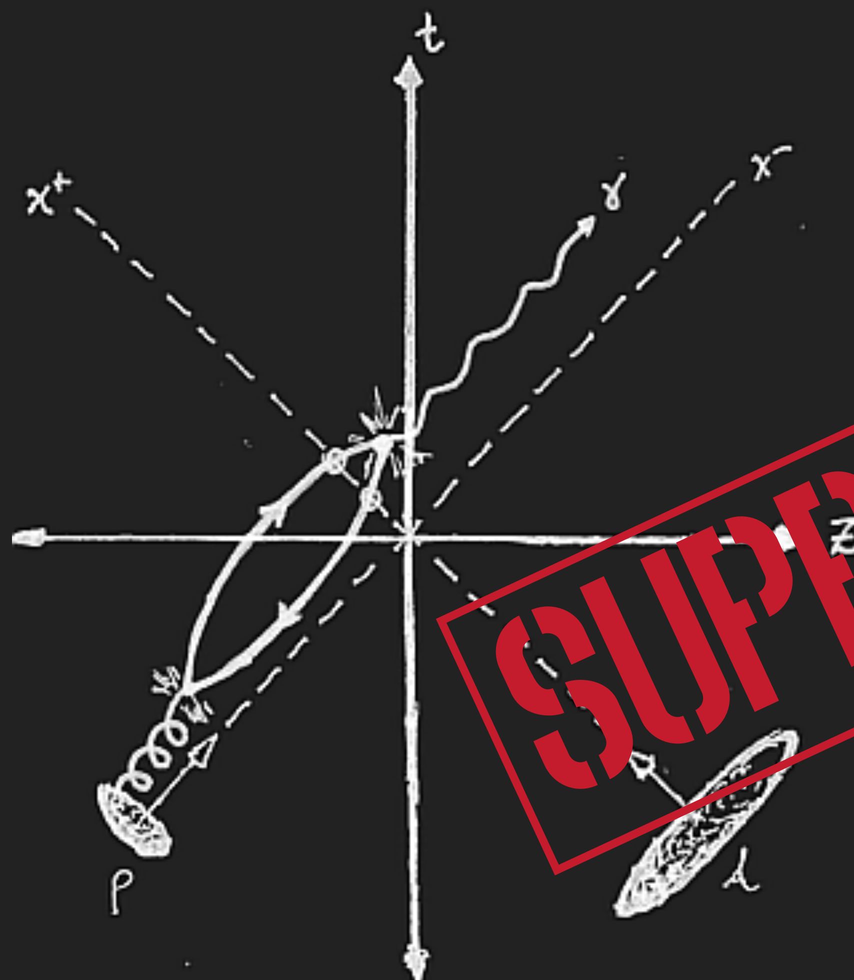
Enhanced by $f_g(x, Q^2)$

Kinematically constrained

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

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

NLO: ANNIHILATION

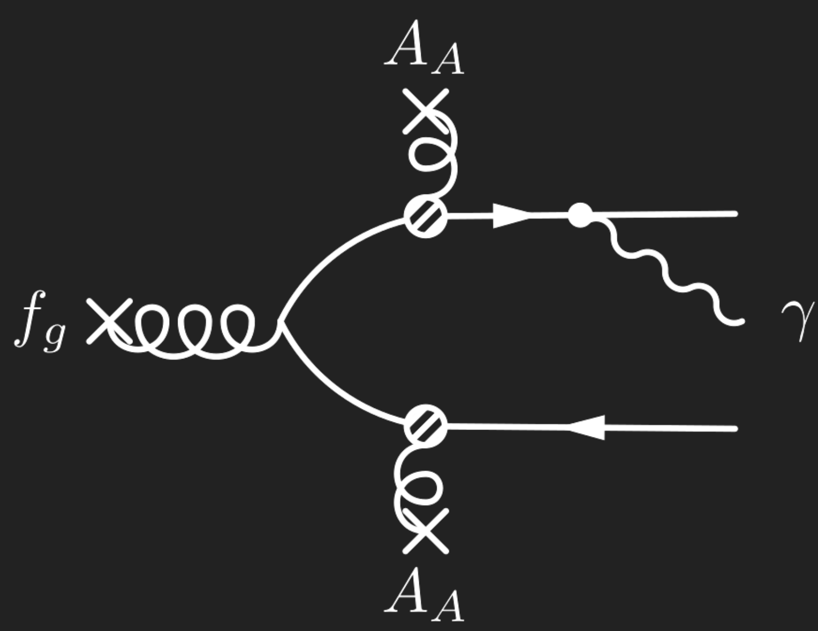


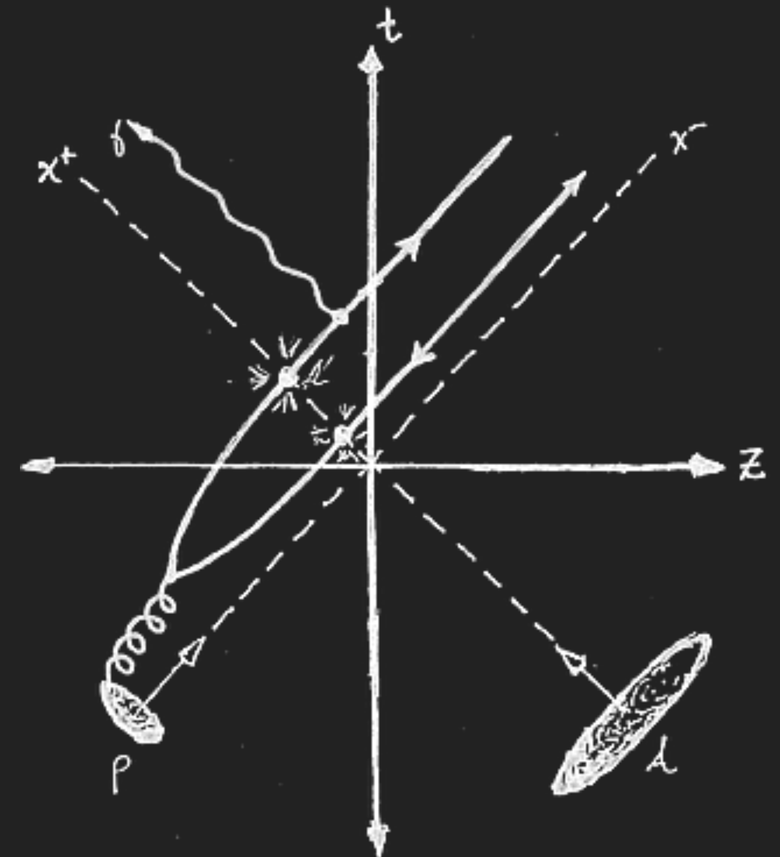
Enhanced by $f_g(x, Q^2)$

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

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

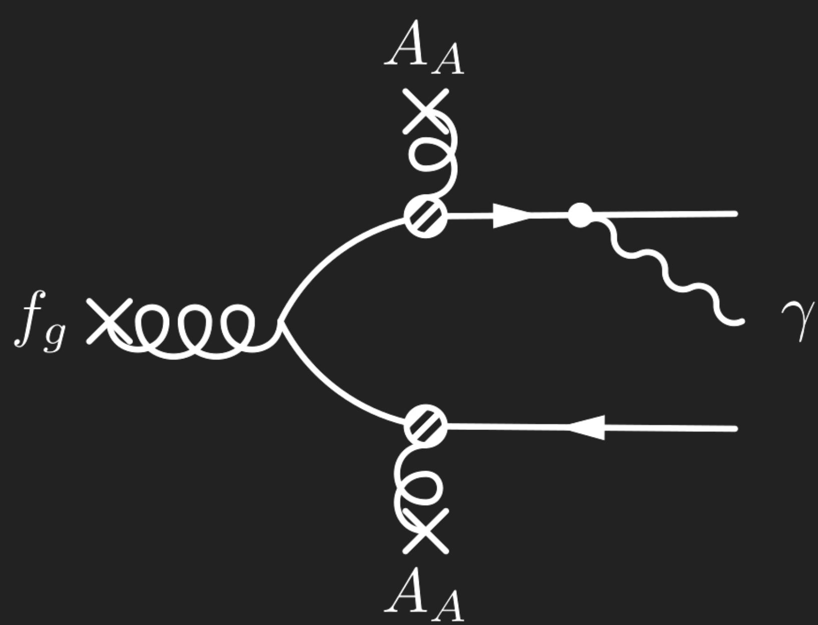
NLO: Q$\bar{\text{Q}}$ PAIR + PHOTON

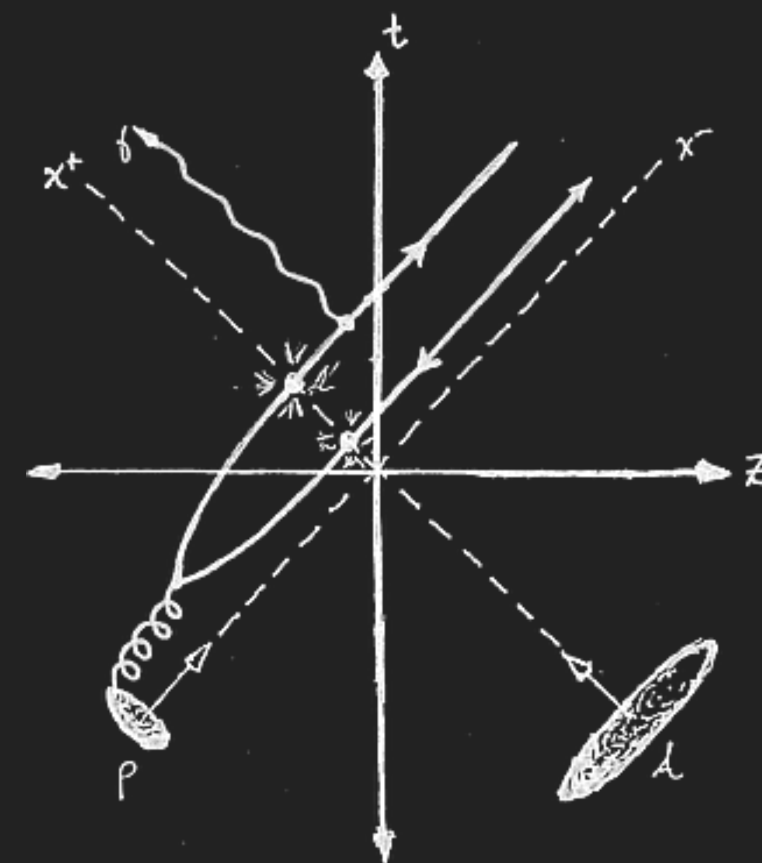




JHEP 1701 (**2017**) 115

NLO: $Q\bar{Q}$ PAIR + PHOTON



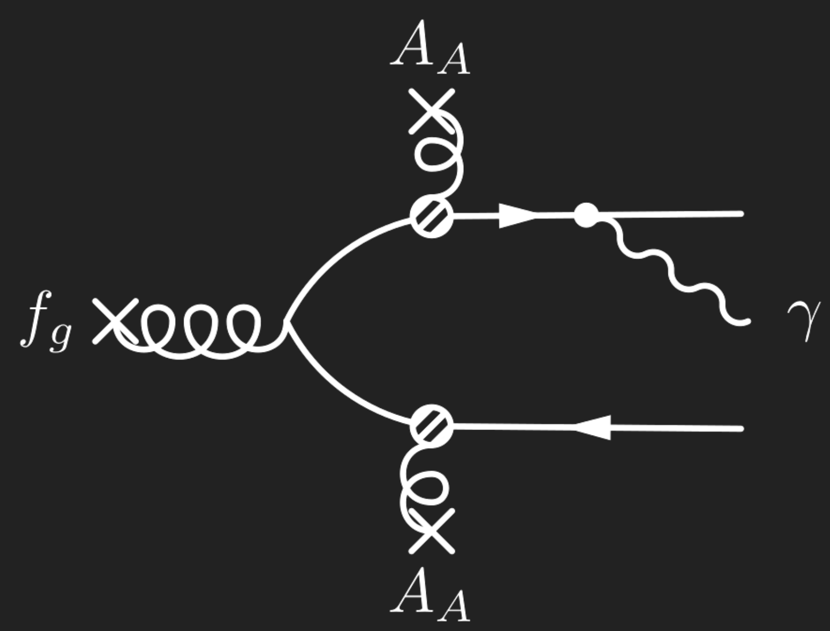


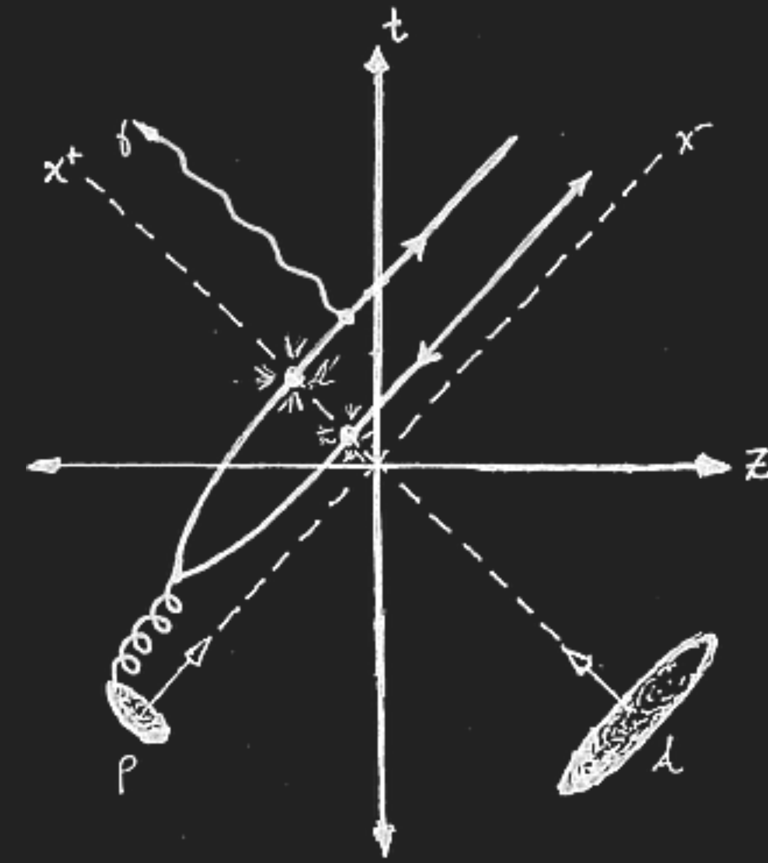
$$\frac{\mathrm{d}\sigma}{\mathrm{d}^2\boldsymbol{k}_{\gamma\perp}\mathrm{d}\eta_\gamma} = \frac{\alpha\alpha_S^2\, q_f^2}{(2\pi)^8 C_F}\int_{\eta_q,\eta_p}\int_{\boldsymbol{q}_\perp,\boldsymbol{p}_\perp,\boldsymbol{k}_\perp,\boldsymbol{k}_{1\perp},\boldsymbol{k}_{2\perp}} \delta^{(2)}(\boldsymbol{P}_\perp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

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

JHEP 1701 (**2017**) 115

NLO: Q$\bar{\text{Q}}$ PAIR + PHOTON





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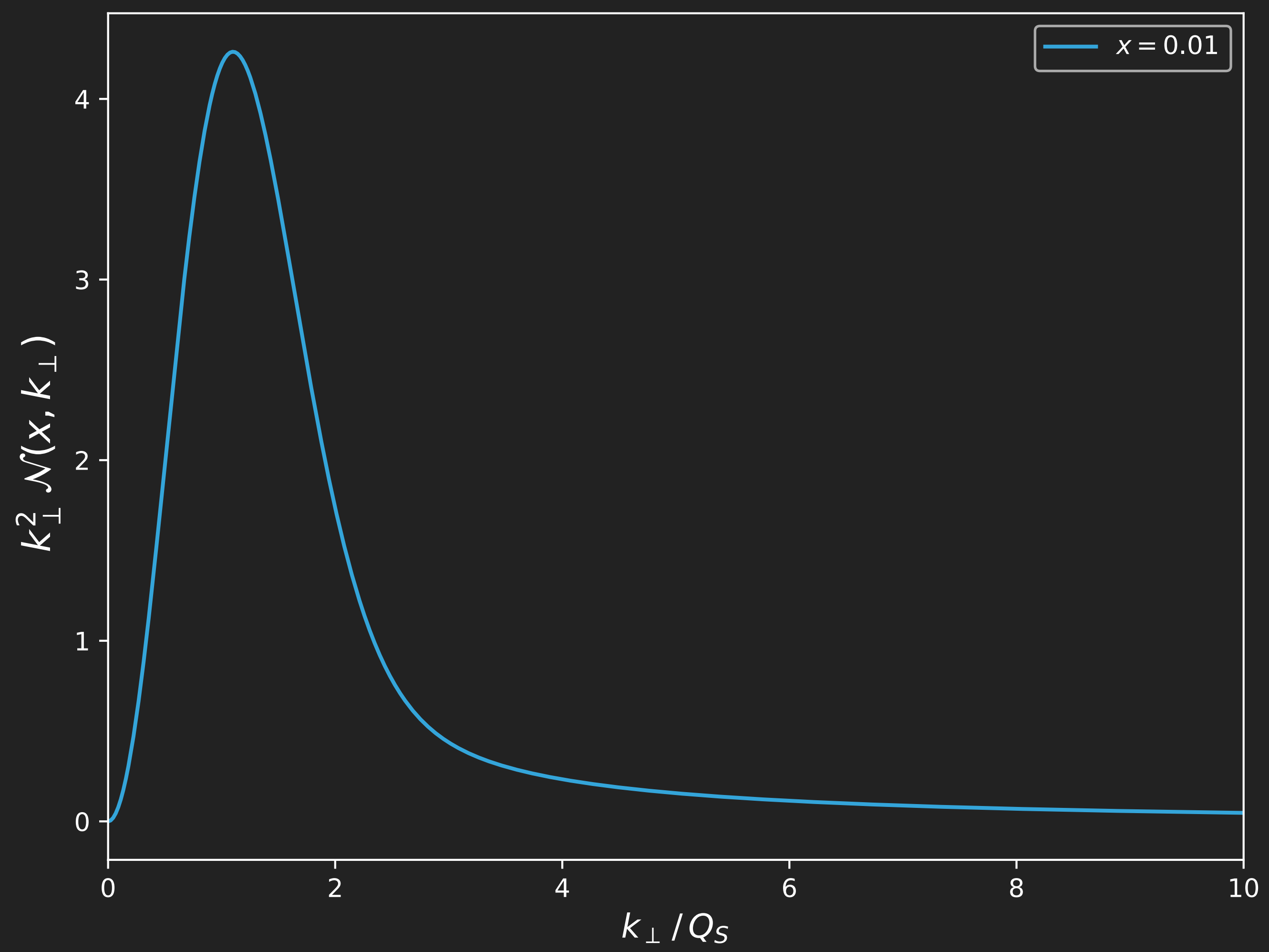
$$\times\theta(\boldsymbol{k}_{1\perp},\boldsymbol{k}_\perp,\boldsymbol{k}'_\perp)\,\mathcal{N}(x_0,\boldsymbol{k}_{2\perp})\,\mathcal{N}(x_0,\boldsymbol{k}_\perp - \boldsymbol{k}_{2\perp})$$

JHEP 1701 (**2017**) 115

DIPOLE

@ MV-model

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



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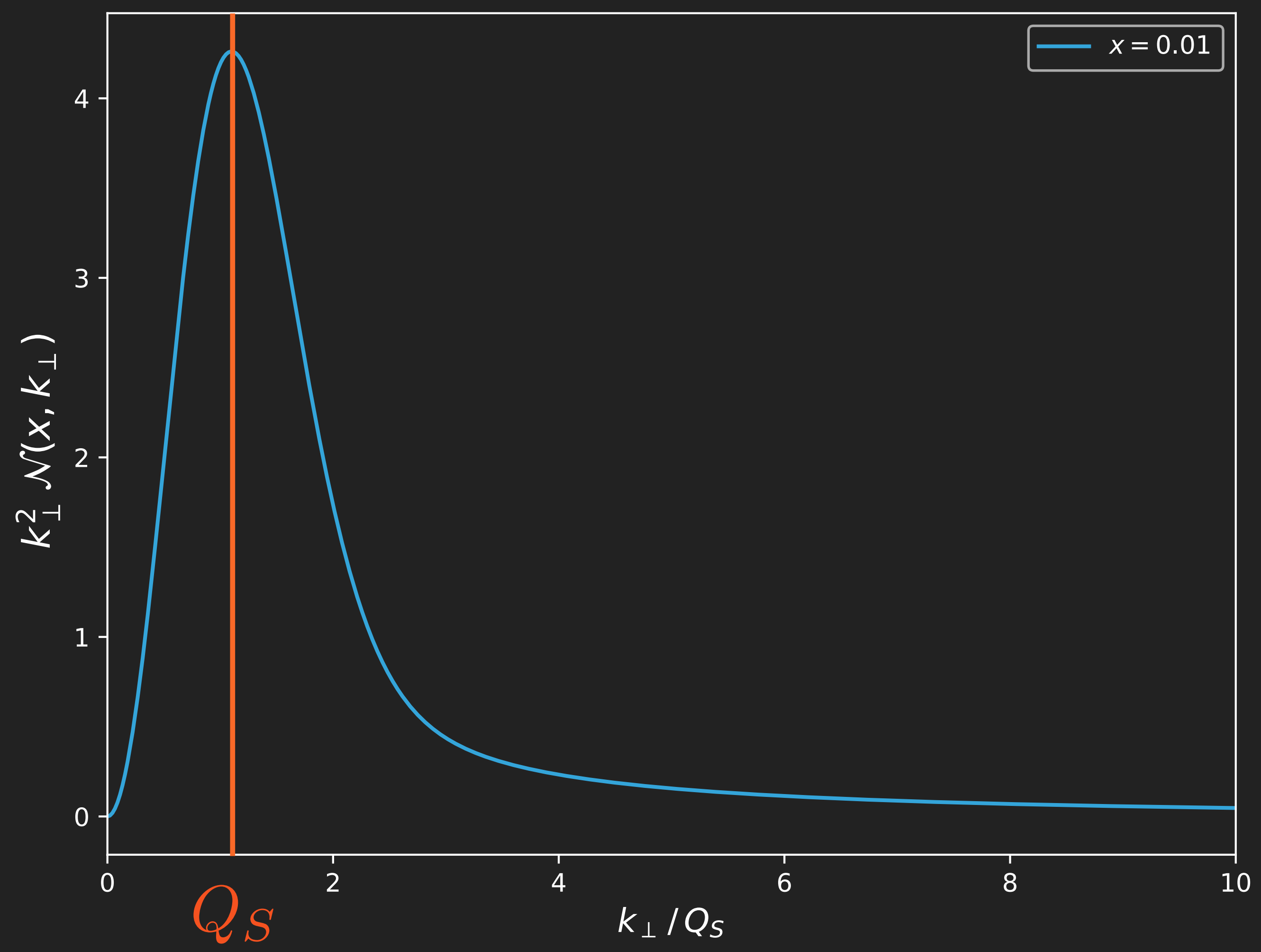


EVOLUTION

↓

rcBK on the dipole

EVOLUTION

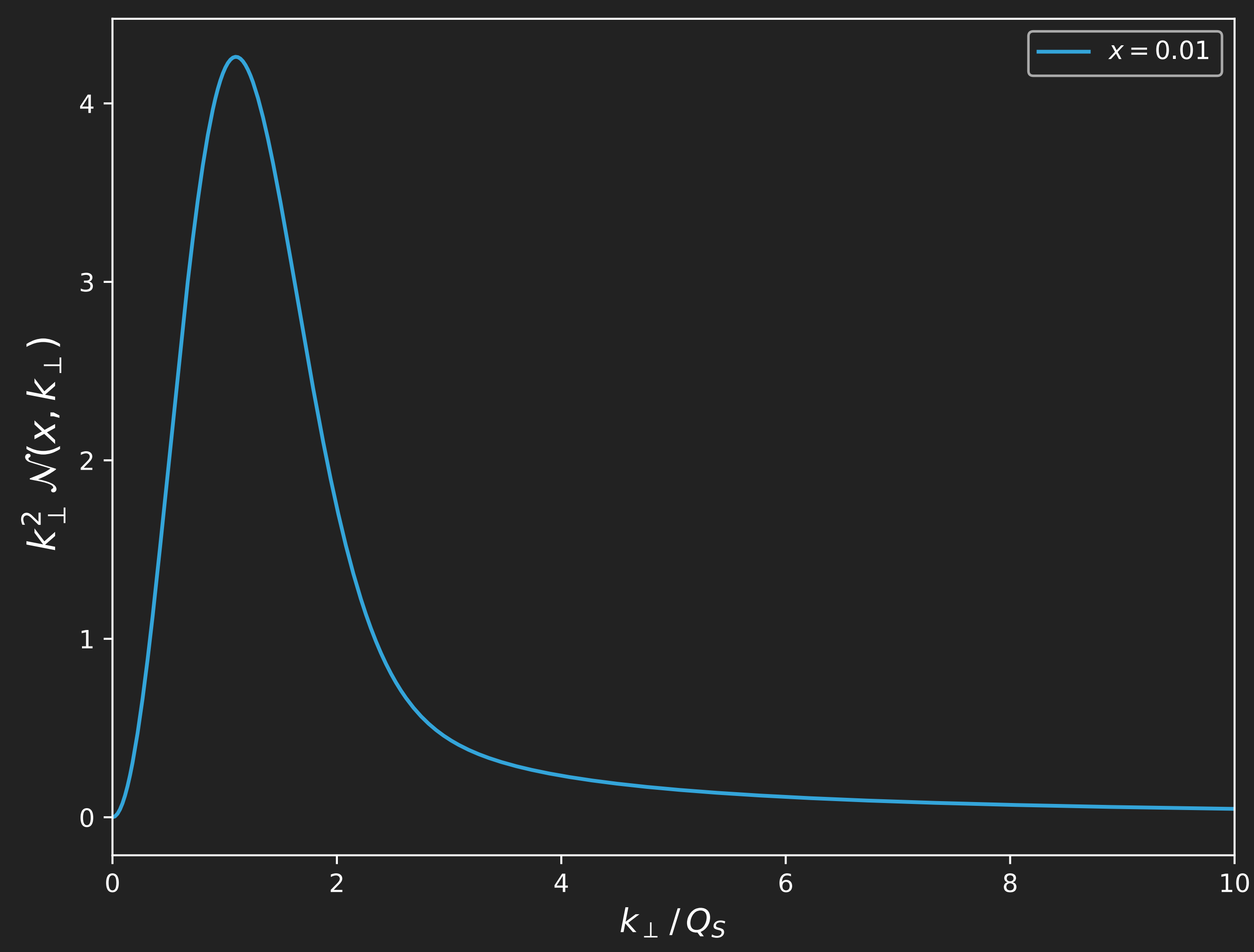
↓

rcBK on the dipole

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

EVOLUTION

rcBK on the dipole



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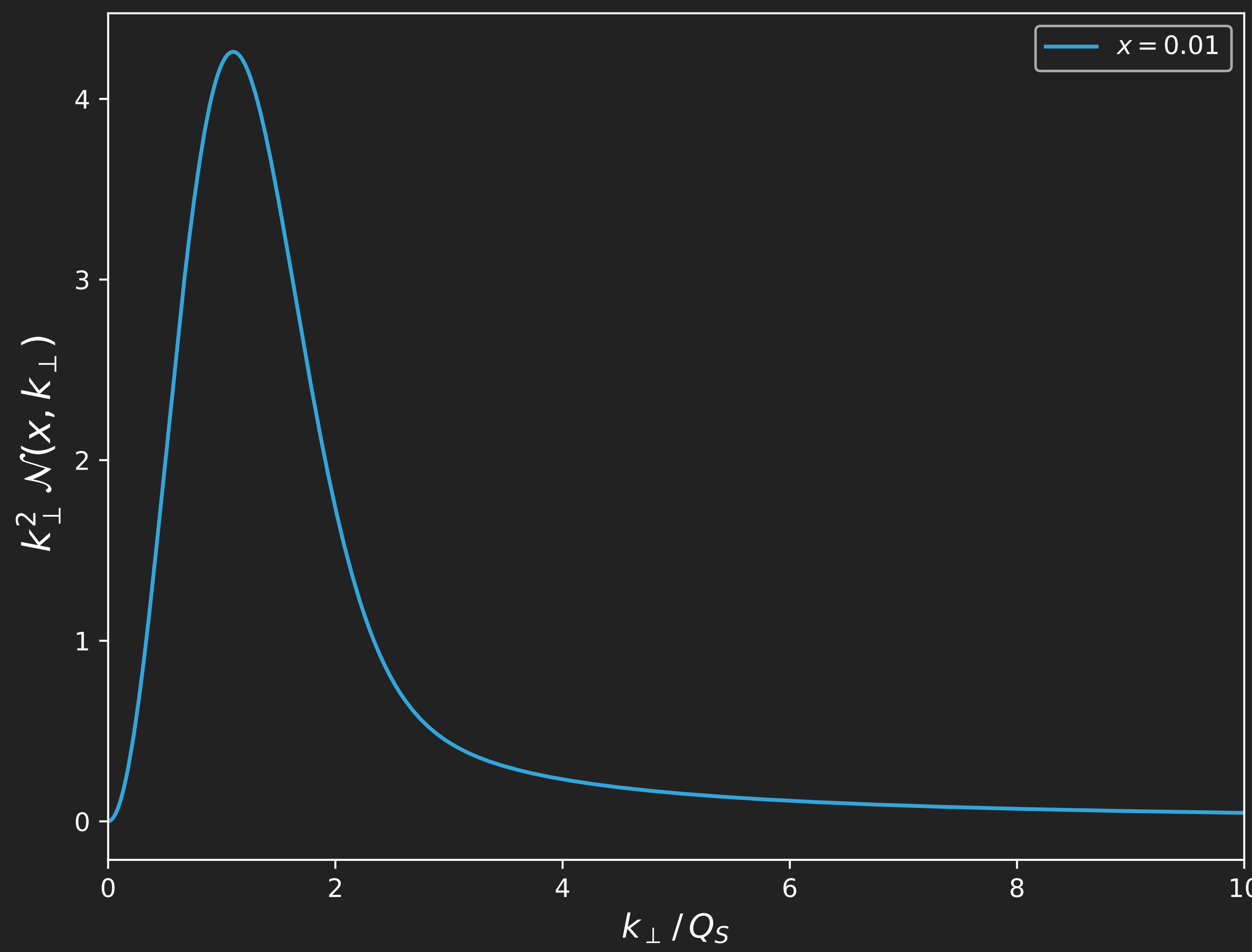
Kernel

EVOLUTION

↓

rcBK on the dipole



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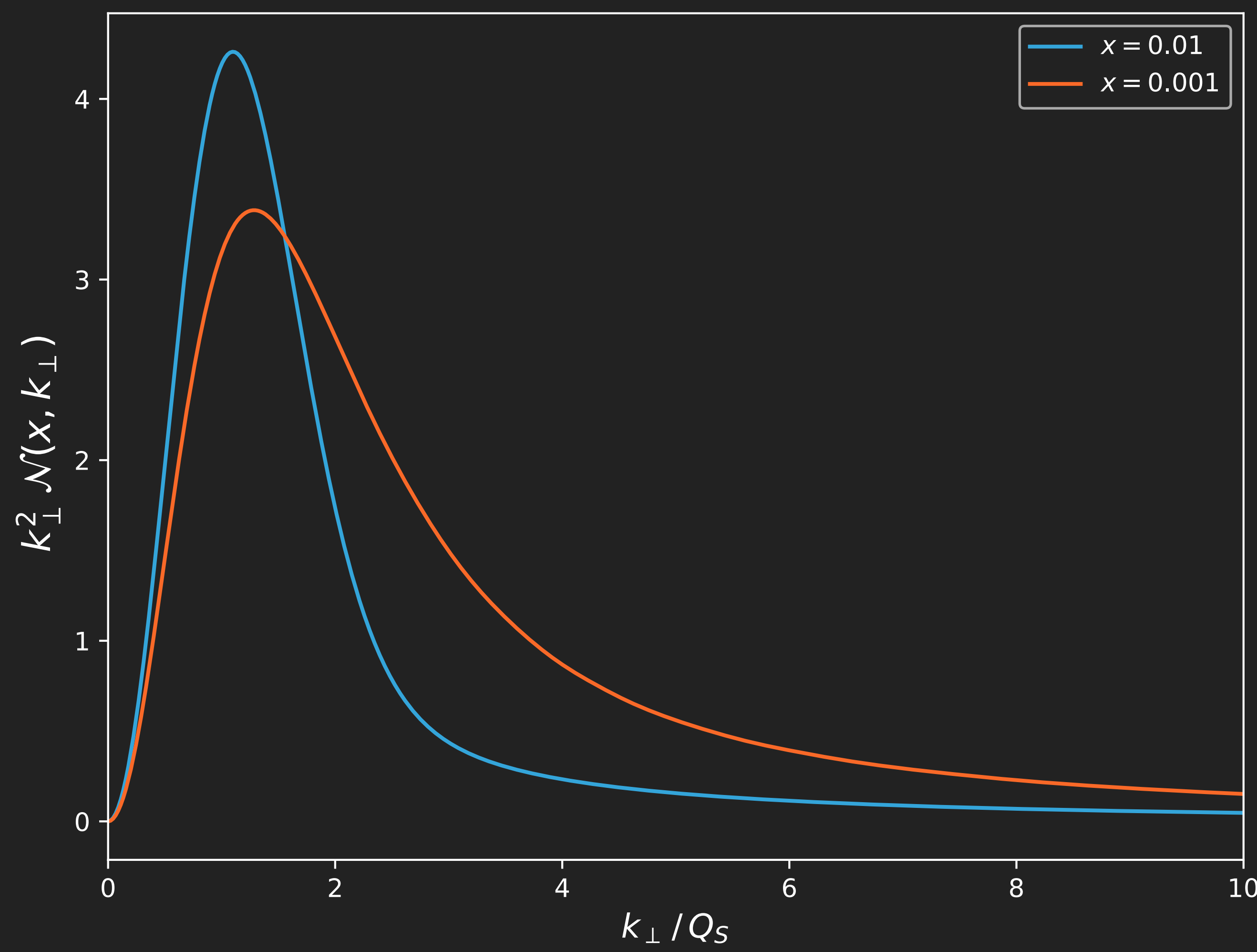
Kernel

Non-linear terms

EVOLUTION

rcBK on the dipole



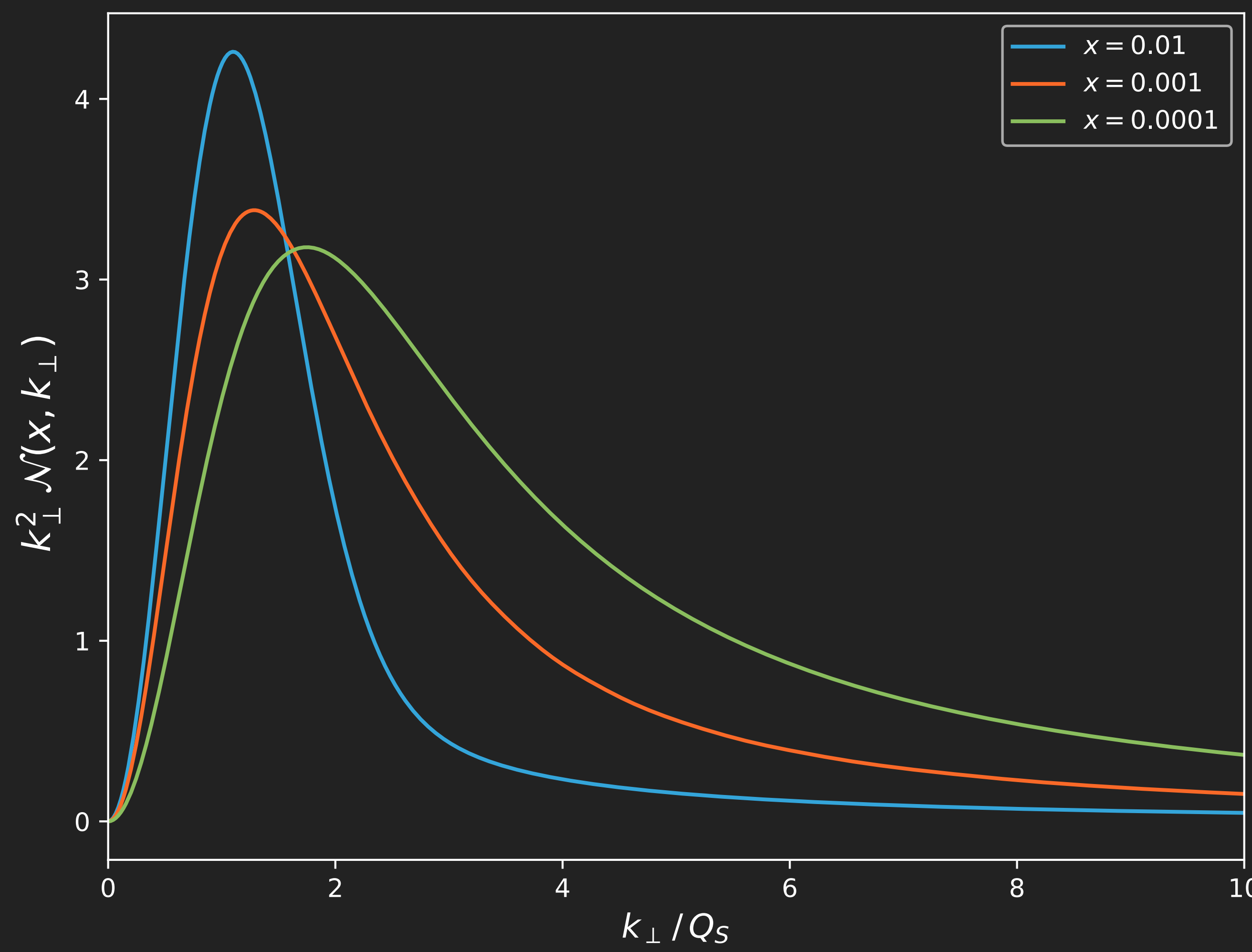
$$\frac{\partial \mathcal{N}(\boldsymbol{r}, x)}{\partial \log(x_0/x)} = \int \mathrm{d}\boldsymbol{r}_1 K^{\mathrm{run}}(\boldsymbol{r}, \boldsymbol{r}_1, \boldsymbol{r}_2) \left[\mathcal{N}(\boldsymbol{r}_1, x) + \mathcal{N}(\boldsymbol{r}_2, x) - \mathcal{N}(\boldsymbol{r}, x) - \mathcal{N}(\boldsymbol{r}_1,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

Kernel

Non-linear terms

EVOLUTION

rcBK on the dipole



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Kernel

Non-linear terms

EVOLUTION

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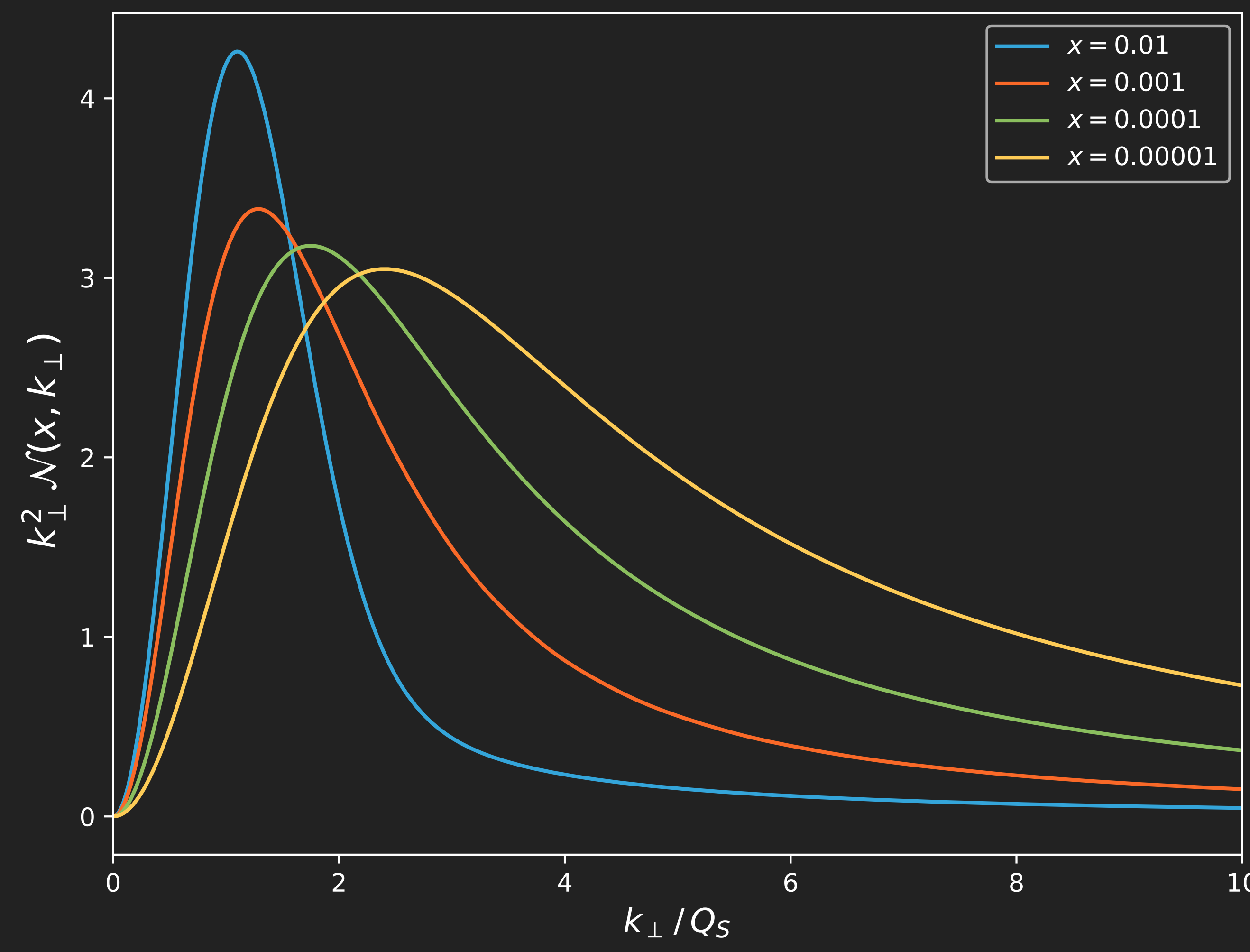
rcBK on the dipole



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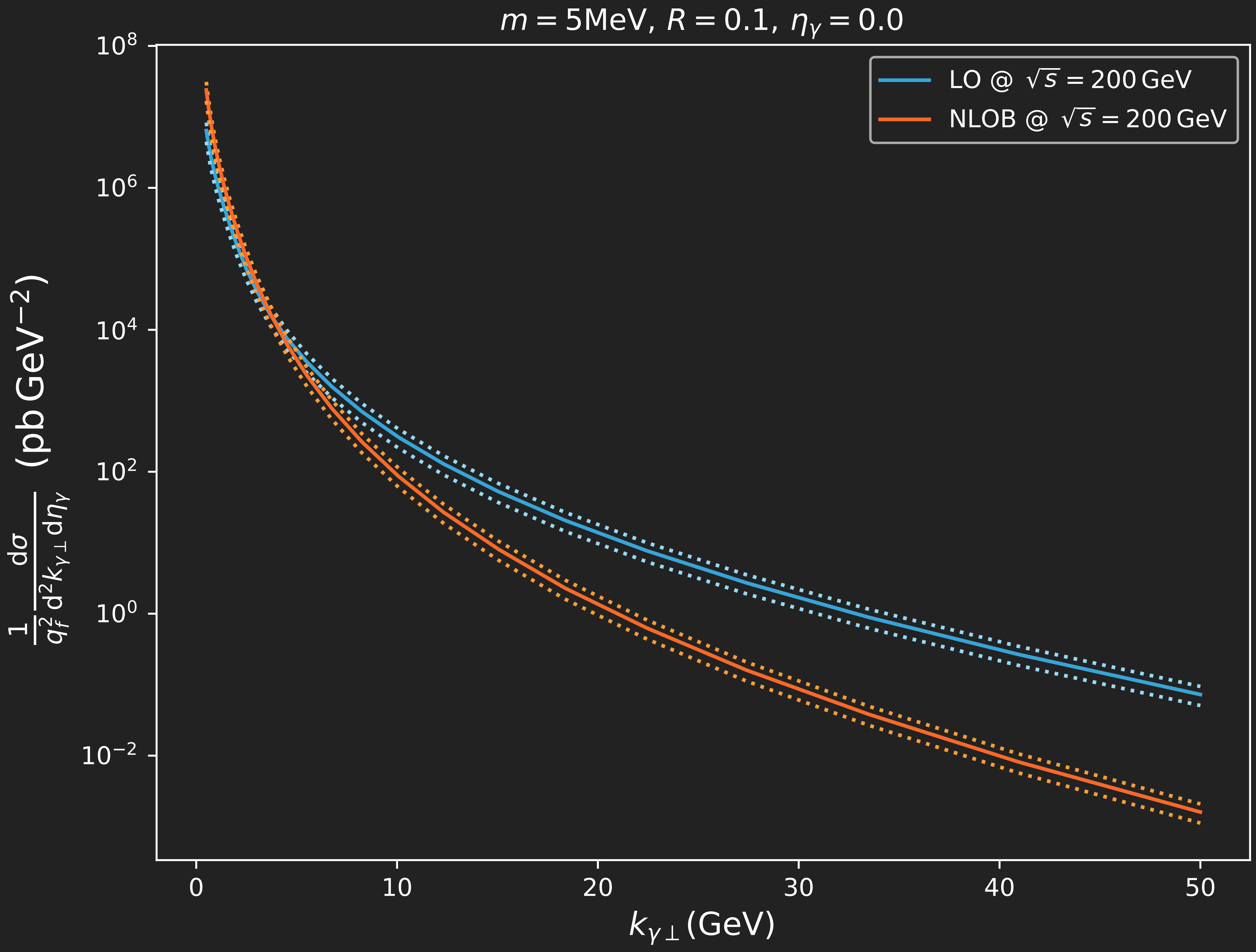
Kernel

Non-linear terms

RESULTS

CROSS SECTION



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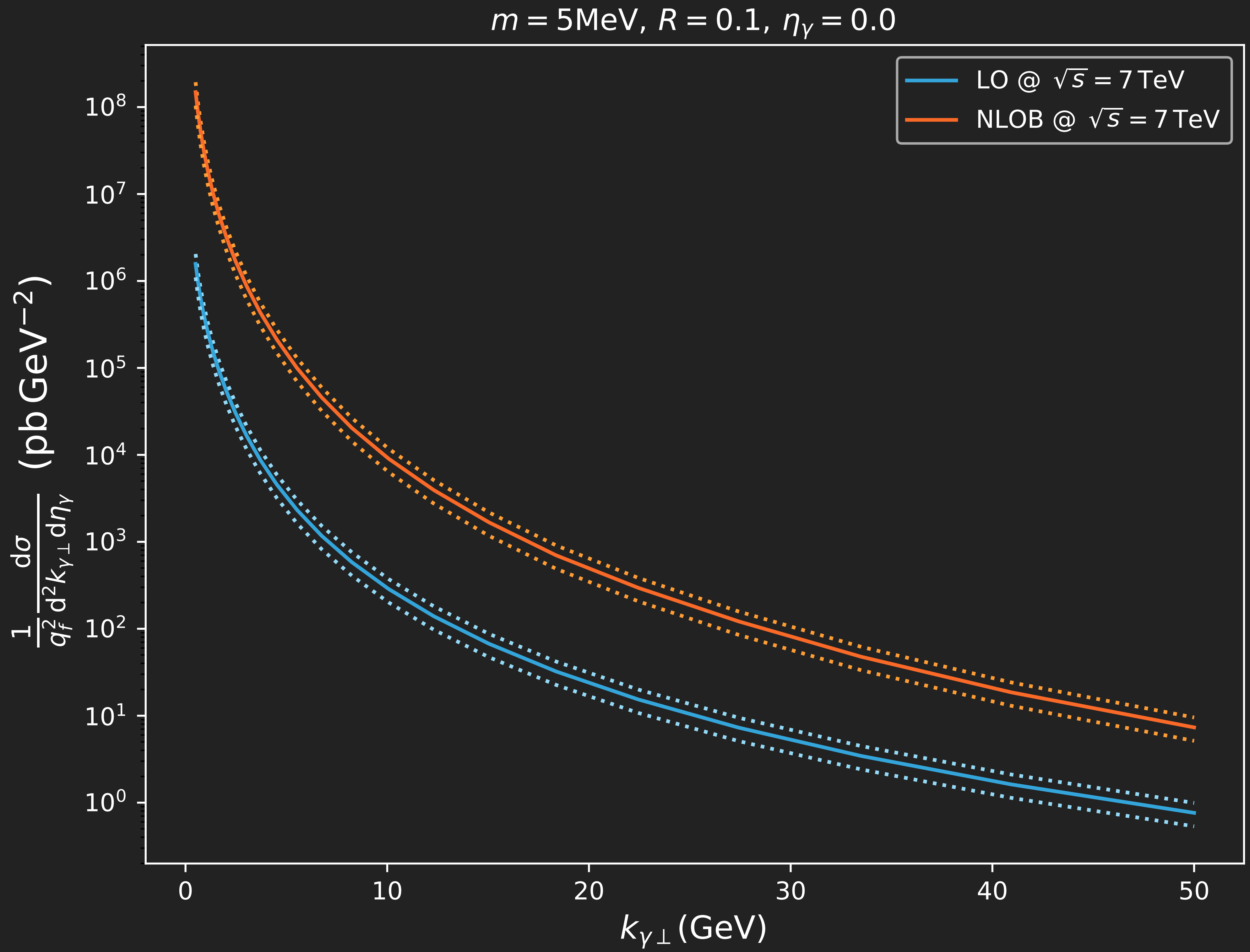

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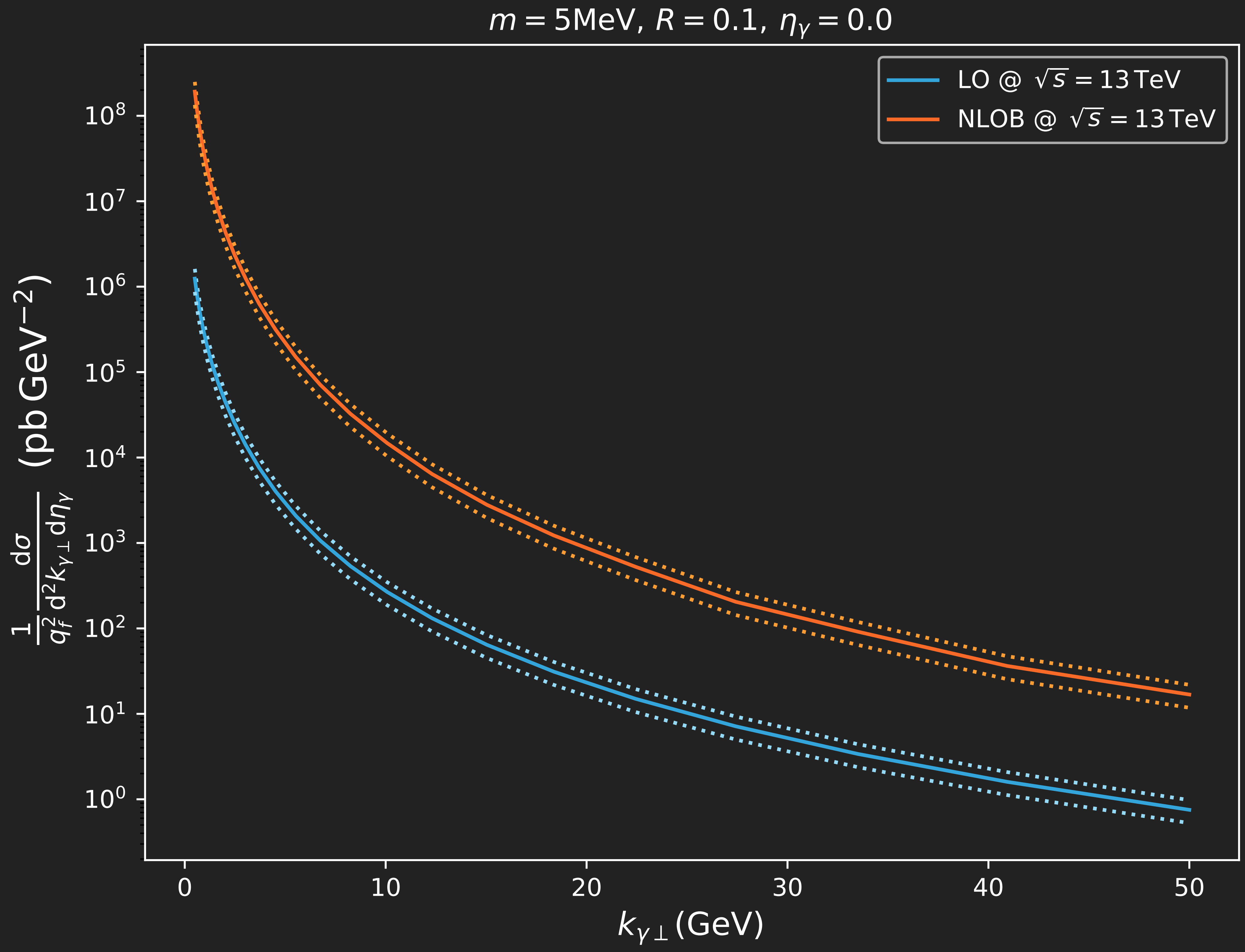
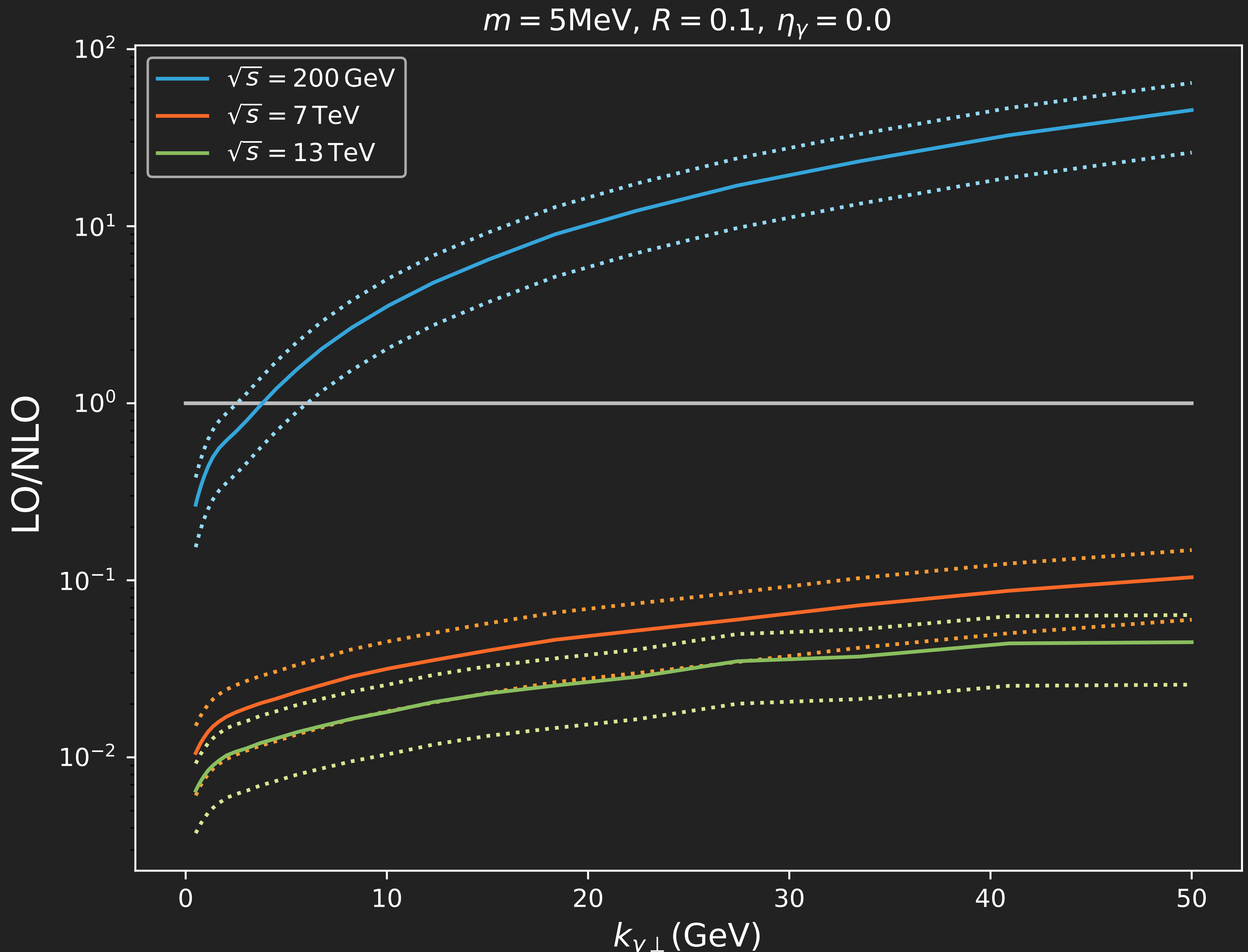
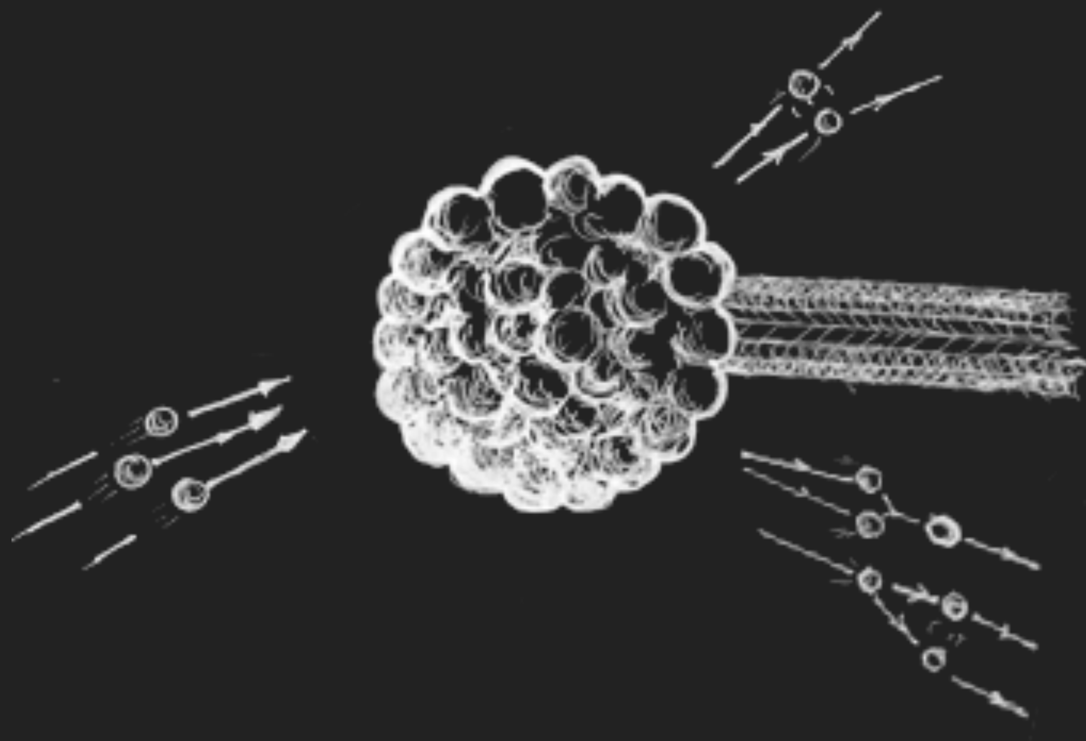


RATIOS



$m = 5\text{MeV},\ R = 0.1,\ \eta_\gamma = 0.0$
$\sqrt{s} = 200\,\text{GeV}$
$\sqrt{s} = 7\,\text{TeV}$
$\sqrt{s} = 13\,\text{TeV}$
LO/NLO
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
0
10
20
30
40
50
$k_{\gamma\perp}\,(\text{GeV})$

SUMMARY



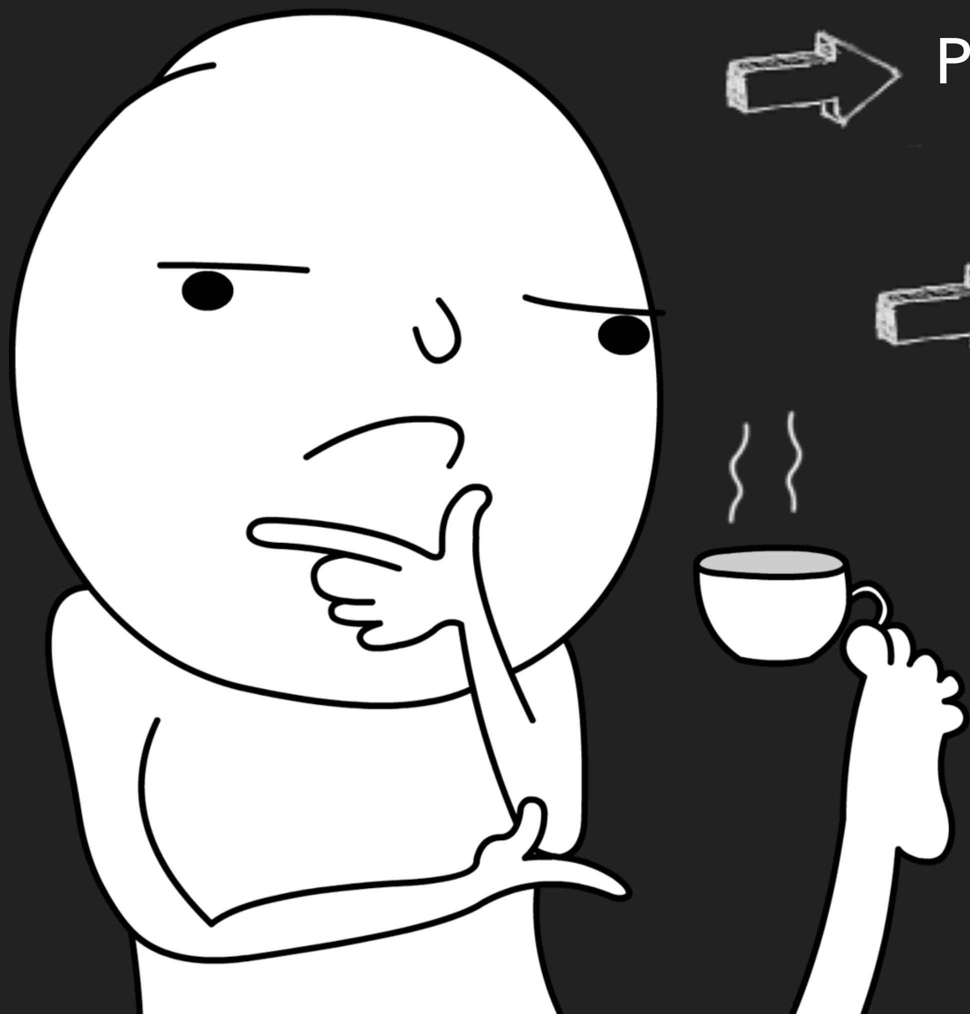
- Saturation modifies the emission process thanks to multi-particle scatterings
- Complete analytical result at NLO, $\mathcal{O}(\alpha\,\alpha_s)$
- CGC formalism yields correct limits to the pQCD results

OUTLOOK

- Comparison to current pp and pA experimental data, as well as prediction for new runs.

- Photon-hadron correlations are sensitive to saturation.

- More exciting studies:
  - NNLO?
  - Higher particle correlations?
  - Saturation and Anomalies?



THANK YOU