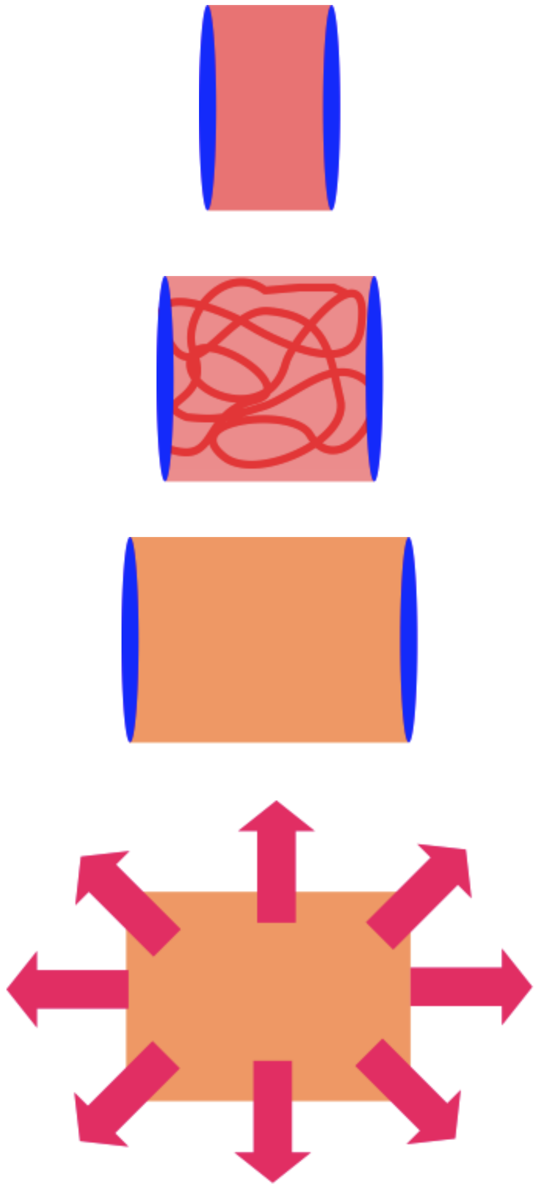
初期の物理 (CGC, Glasma, 流体化や熱化) と課題について

福嶋健二（東京大学）

高度化後のALICE実験での物理の可能性

Q1 : What is "Early Thermalization" ?

What is "Early Thermalization"



Color Glass Condensate (CGC)

$$\tau \lesssim 1/Q_s \sim 0.1\mathrm{fm/c}$$

Color Glass + Plasma = Glasma

$$\tau \lesssim \tau_0 \sim \Lambda_{\mathrm{QCD}}^{-1}$$

(s) Quark-Gluon Plasma

$$\tau \lesssim \tau_f \sim 10\mathrm{fm/c}$$

Hadronization (quarks → hadrons)

What is “Early Thermalization”

Can Thermalization in Heavy Ion Collisions be

Described by QCD Diagrams?

Yuri V. Kovchegov*

Department of Physics, The Ohio State University
Columbus, OH 43210

March, 2005

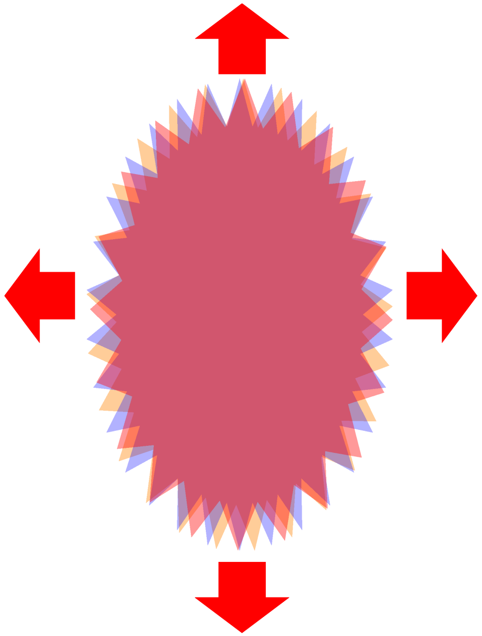
pQCD expert and pioneer of AdS/CFT for HIC

CGC : $1/\tau$ → Bjorken : $1/\tau^{4/3}$

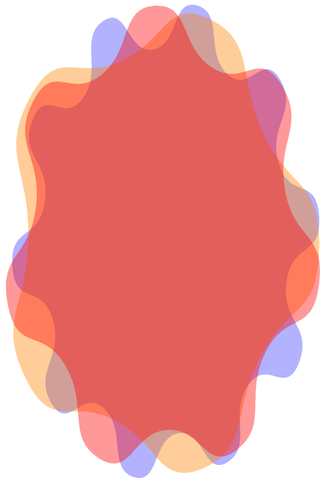
How? Impossible?

What is "Early Thermalization"

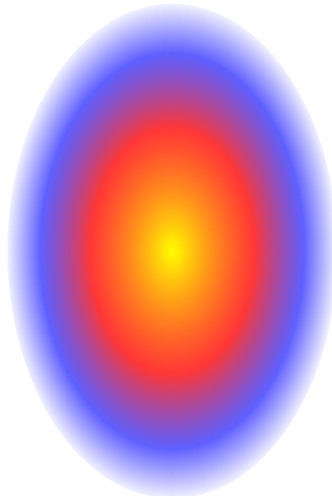
Fukushima, RoPP (2016)



Isotropization



hydrodynamization



(Pre-) Thermalization

Three concepts clearly distinguished since Chesler-Yaffe (2010)

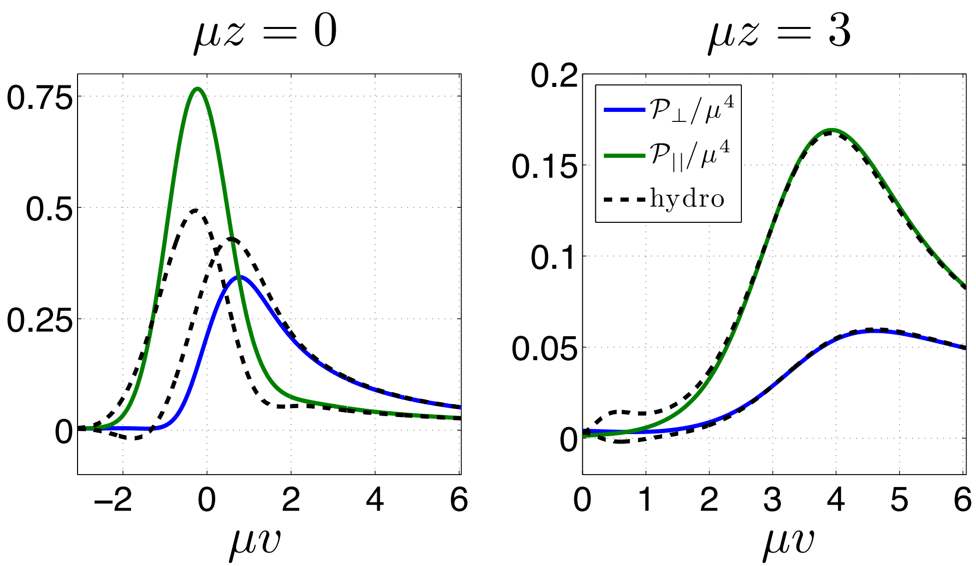
What is "Early Thermalization"

Holography and colliding gravitational shock waves in asymptotically AdS_5 spacetime

Paul M. Chesler
*Department of Physics, MIT, Cambridge, MA 02139, USA**

Laurence G. Yaffe
Department of Physics, University of Washington, Seattle, WA 98195, USA†
(Dated: November 17, 2010)

One of the most important holographic papers



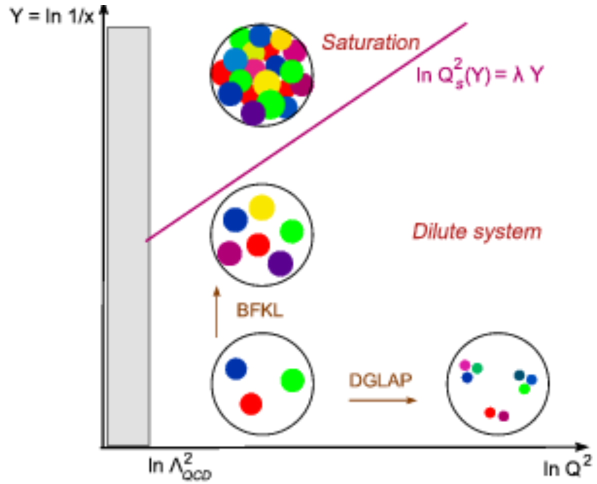
Validity of hydro does not require thermalization nor isotropization!

Not known in other fields

Q2 : Physics of isotropization?

Color Glass Condensate (CGC)

Not **a new state of matter**
Phase diagram?
→ A chart of approx. schemes

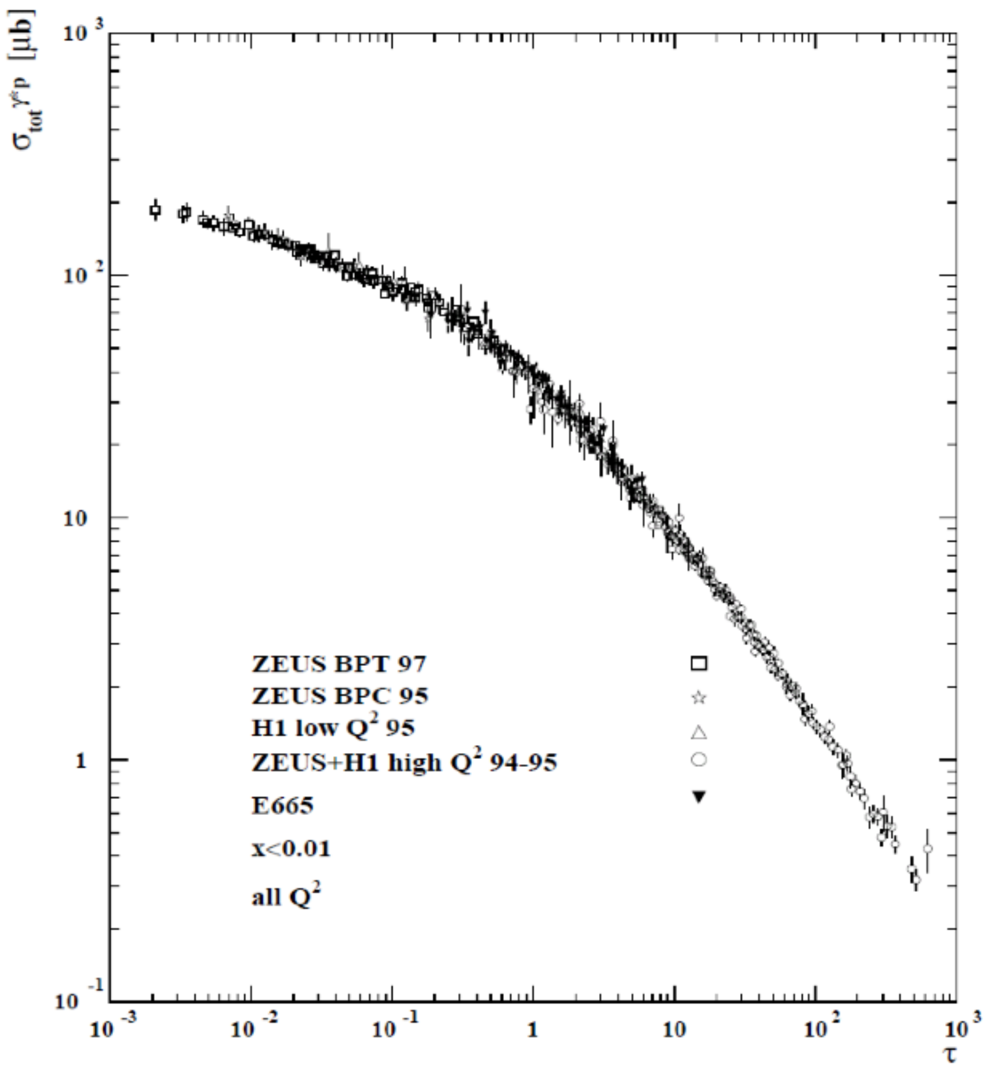


A new regime of perturbative and nonlinear theory

Small coupling constant
Resummation (BFKL / DGLAP)

Large amplitude
Resummation (classical EoM)

Color Glass Condensate (CGC)



Stasto-Golec-Biernat-Kwiecinski Plot

Geometric Scaling

Scaling variable

$$Q_s^2(x) = Q_0^2(x/x_0)^{-\lambda}$$

CGC already seen?
Extended geometric scaling

Color Glass Condensate (CGC)

Finding CGC =

Finding Scaling Properties (with Q_s)

Possible in *ep*, *pA*, etc, but not so clear in *AA*

Color Glass Condensate (CGC)

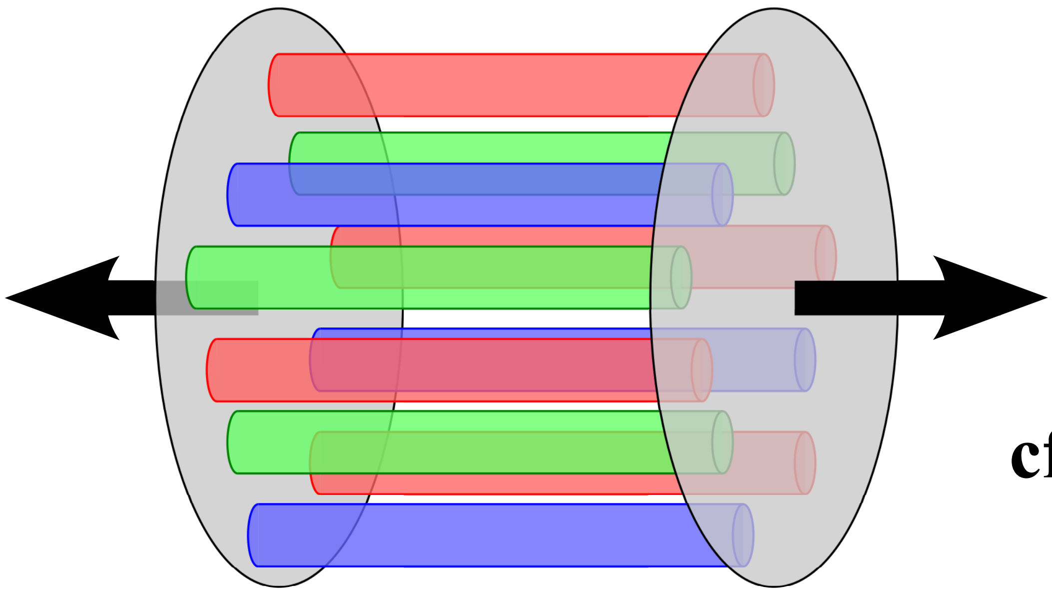
Finding CGC =

Finding necessity of special class of resummation (Wilson lines)

Will be discussed later

Glasma

Early-time dynamics of heavy-ion collision described in the CGC approximation



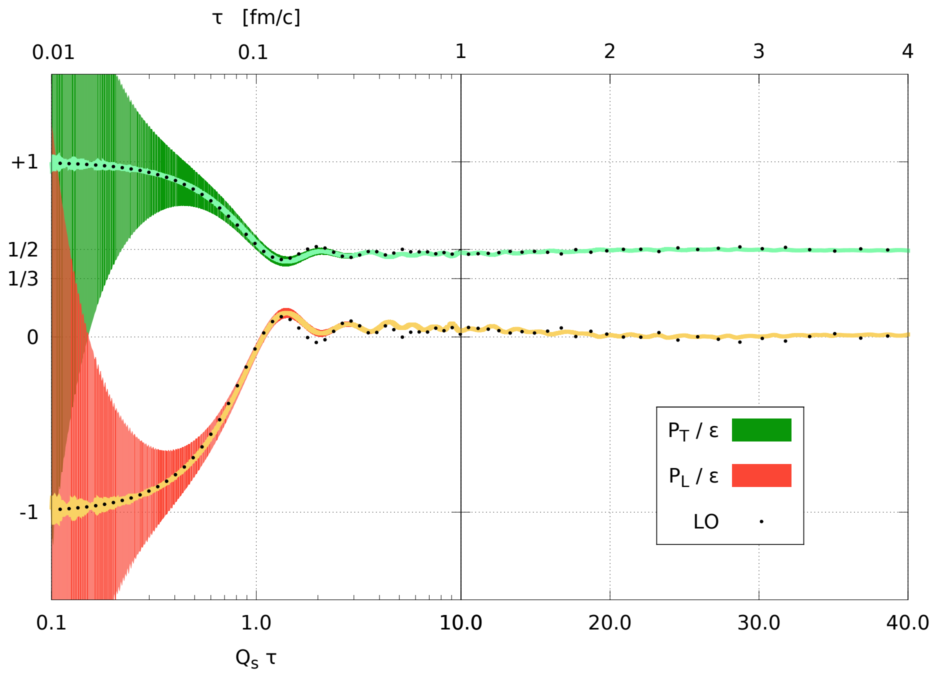
cf. ridge

Initial longitudinal pressure is negative

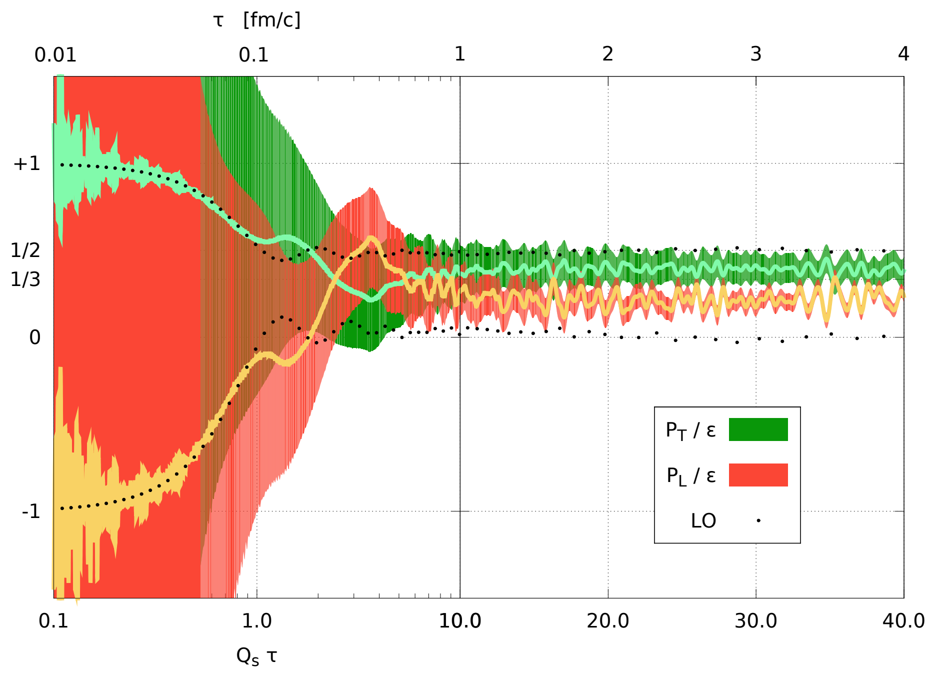
Isotropic plasma has positive pressure

Glasma

Gelis-Epelbaum, PRL (2013), see also a plenary talk @ QM2013



weak coupling



strong coupling

However, UV contamination unavoidable

Glasma

Maybe P_L / $P_T \sim 0.6$ or smaller (free streaming?)

Q **: Why not very small ?**
A**: Very viscous ! → aHydro**

Please tell me what can be measured to probe it ?

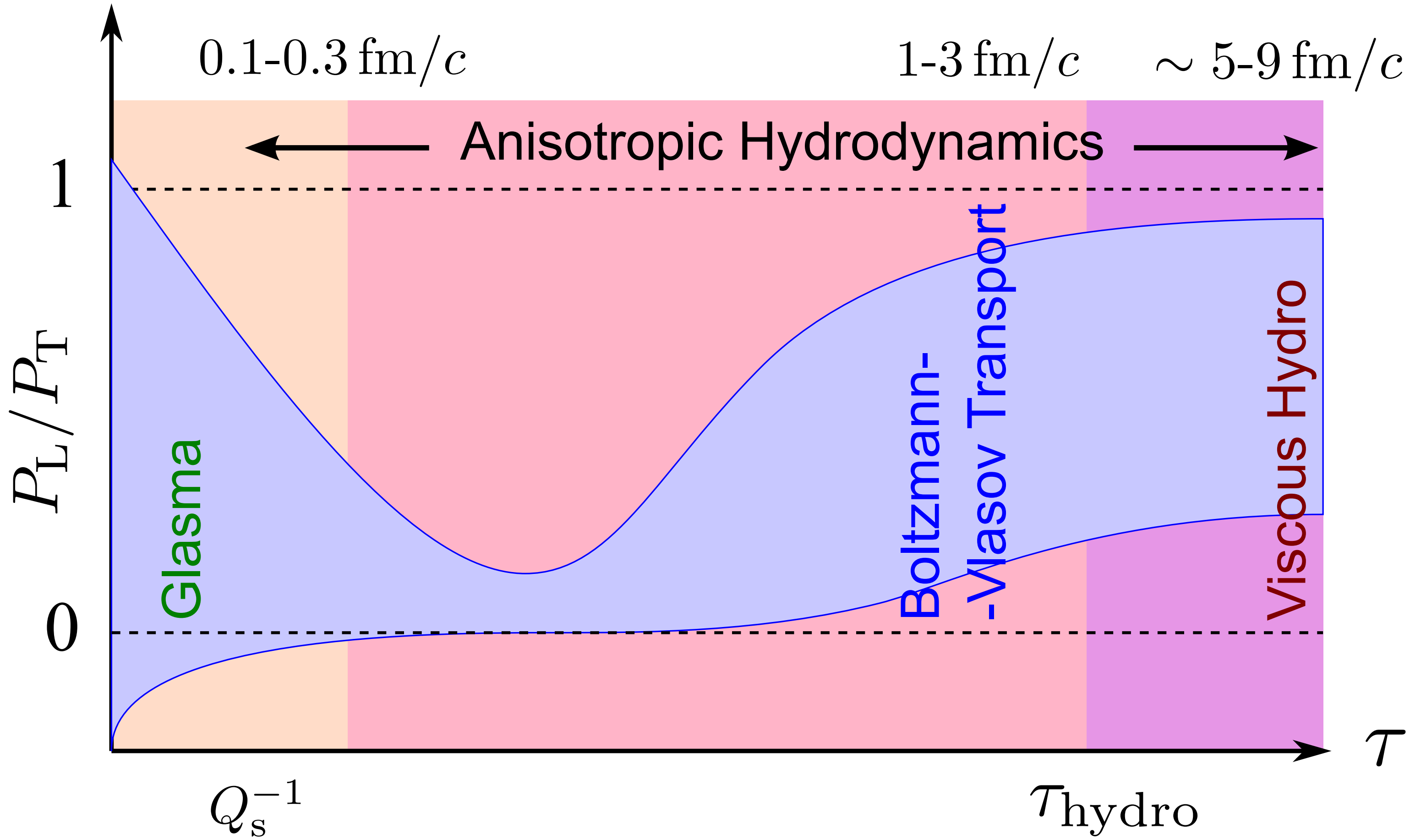
I asked this question to Berndt 4 years ago,
and his answer was "balance function."

Any observable to quantify anisotoropization ?
Anything sensitive to initial negative P_L ?

Q3 : Physics of hydrodynamization?

Hydrodynamization

Fukushima, RoPP (2016) based on Strickland



Hydrodynamization

$$P_{\mathrm{T}} - P_{\mathrm{L}} = \frac{2\eta}{\tau}$$

or equivalently

$$\frac{P_{\mathrm{L}}}{P_{\mathrm{T}}} = \frac{3\tau T - 16(\eta/s)}{3\tau T + 8(\eta/s)}$$

$P_{\mathrm{L}}/P_{\mathrm{T}} \approx 0.5$ for initial $\tau_0 \sim 0.5\,\mathrm{fm}/c$ and $T_0 \sim 0.4\,\mathrm{GeV}$, if $\eta/s \sim 1/(4\pi)$

Hydrodynamization

Definition of "Hydrodynamization" is unclear

Hydrodynamization occurs for viscous hydro far earlier than ideal hydro…

Hydrodynamization is a theoretical concept
I do not think there is any observable for this…

For more details please ask Hirano-san, Nonaka-san

Q4 : Physics of thermalization?

Thermalization

Distribution function of gluons

Local thermal eq. : $f(p) \sim \dfrac{1}{e^{p\cdot u(x)/T(x)}-1}$

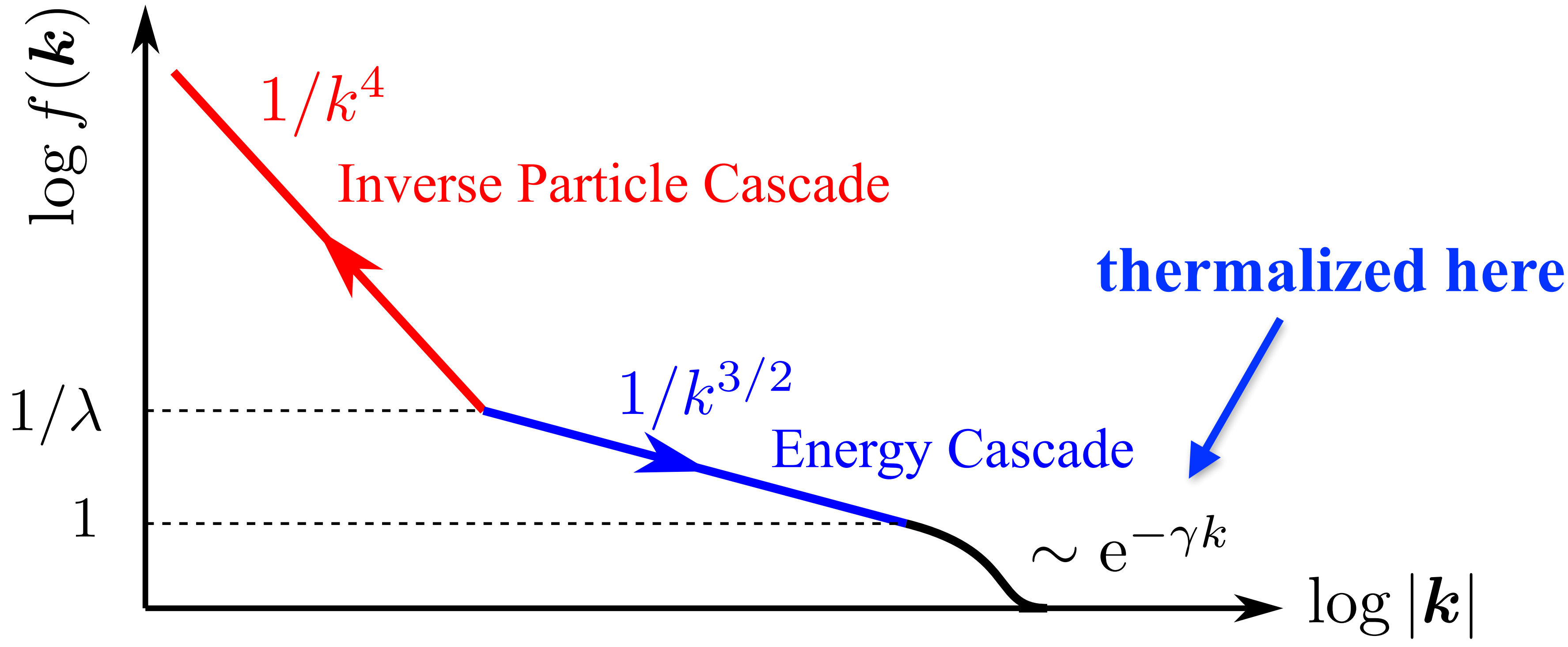
Time evolution ?

CGC initial condition : $f(p) \sim p^{-\nu}$

perturbative tail

Thermalization

Fukushima, RoPP (2016) based on Berges



Fixed-points of the Boltzmann equations ~ Power law
(Kolmogorov-Zakharov spectrum)

Thermalization

Initial-time numerical simulation is reliably done as long as the spectrum is power-law.

UV divergence if the spectrum is power-law.

No simulation valid over the whole momentum region

small-*p*

Dense gluon

Classical statistical sim.

large-*p*

Dilute gluon

Boltzmann equations

Thermalization

KZ Spectrum
~ (Wave) Turbulence ~ Non-thermal Fixed-Point

Overpopulation (2011)

Bose–Einstein Condensation and Thermalization of the Quark Gluon Plasma

Jean-Paul Blaizot[1], François Gelis[1],
Jinfeng Liao[2], Larry McLerran[2,3], Raju Venugopalan[2]

Observable ? Some value of ν

Thermalization

Is “turbulence” observable?

In principle yes :

Early-time gluons with power-law spectrum may affect hadron spectrum and correlation

Caveats :

*** Perturbative calculations → Power-law**

*** Hard to tell power-law from exponential**

CGC in pA (or forward AA)

Flow Observables

n-th harmonics of m-particles (nucl-th/0105040)

$$\kappa_n\{m\} := \prod_{i=1}^{m} \int \frac{\mathrm{d}^2 \boldsymbol{p}_{\perp i}}{(2\pi)^2}\, \mathrm{e}^{\mathrm{i}n(-1)^{i+1}\phi_i}\, \frac{\mathrm{d}^m N}{\mathrm{d}^2 \boldsymbol{p}_{\perp 1} \cdots \boldsymbol{p}_{\perp m}}$$

In the dipole model

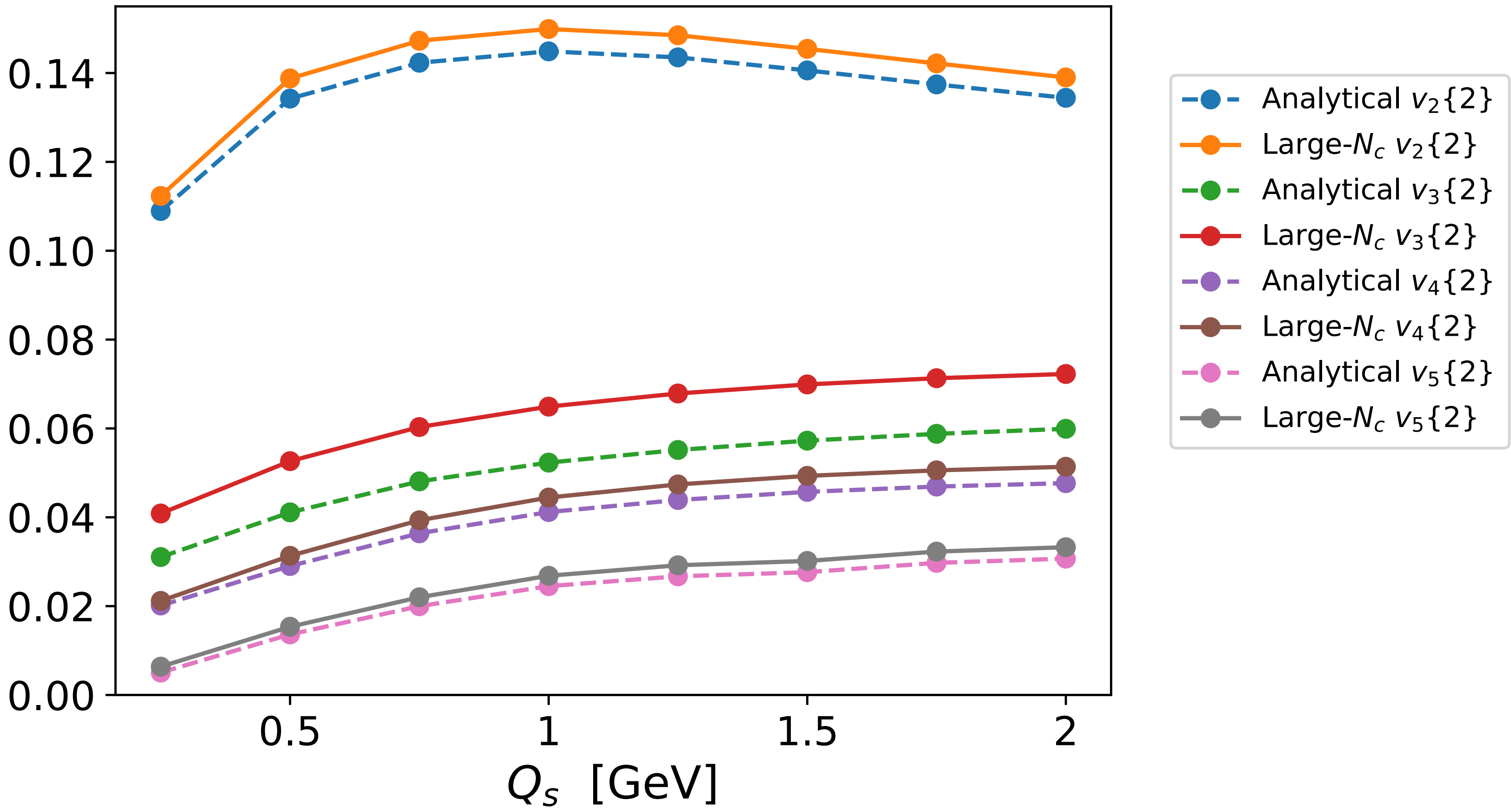
$$\sqrt{B} = 2\mathrm{GeV}^{-1} \sim \text{nucleon size}$$

$$\frac{\mathrm{d}^m N}{\mathrm{d}^2 \boldsymbol{p}_{\perp 1} \cdots \mathrm{d}^2 \boldsymbol{p}_{\perp m}} = \left(\frac{B}{\pi}\right)^m \prod_{i=1}^{m} \int \mathrm{d}^2 \boldsymbol{x}_{\perp i}\, \mathrm{d}^2 \boldsymbol{y}_{\perp i}\, \underline{\mathrm{e}^{-\frac{\boldsymbol{x}_{\perp i}^2 + \boldsymbol{y}_{\perp i}^2}{2B} + \mathrm{i}(\boldsymbol{x}_{\perp i} - \boldsymbol{y}_{\perp i}) \cdot \boldsymbol{p}_{\perp i}}} \left\langle \prod_{j=1}^{m} D(\boldsymbol{x}_{\perp j}, \boldsymbol{y}_{\perp j}) \right\rangle$$

Dipole distribution inside of a proton

Flow Observables

Fukushima-Hidaka (2017) motivated by Dusling-Mace-Venugopalan (2017)



Flow Observables

Recent developments along the same lines

Mace-Skokov-Tribedy-Venugopalan (2018)

$$v_{2n}^2\{2\} \propto N_{\rm ch}^0 \qquad v_{2n+1}^2\{2\} \propto N_{\rm ch}$$

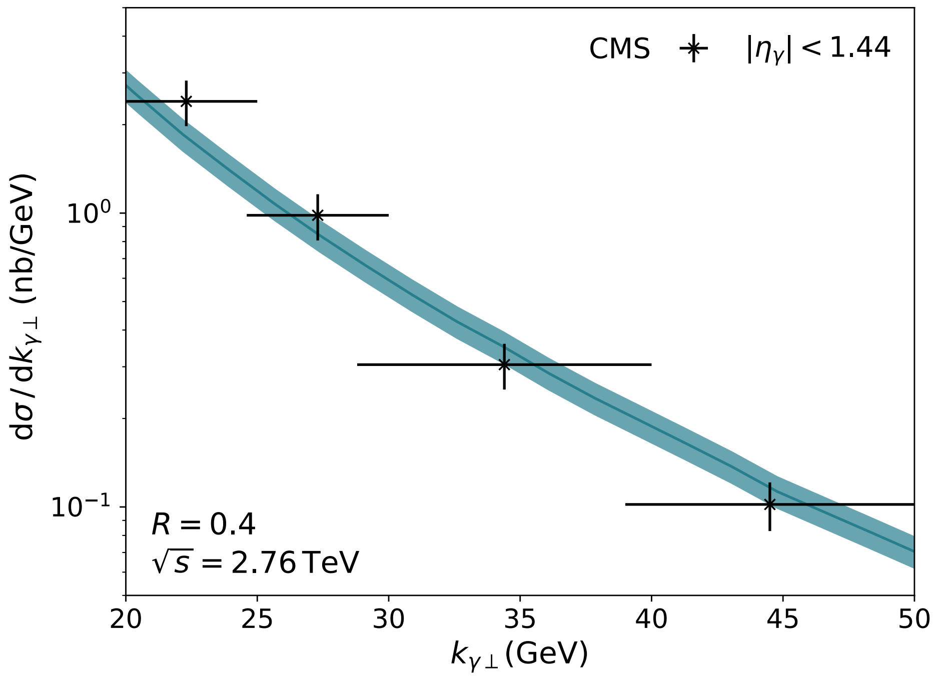
CGC-based prediction not depending on a dipole model

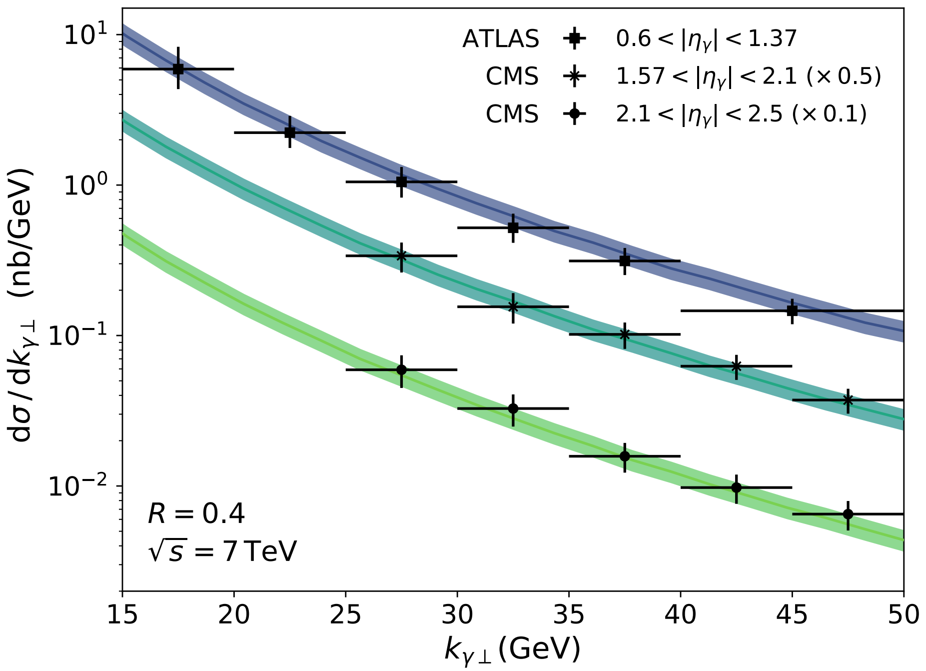
Systematics can tell the CGC-type correlation from hydro

CGC Calculation for Photon

Benic-Fukushima-Garcia-Montero-Venugopalan (2018)

Photon in pp at LHC



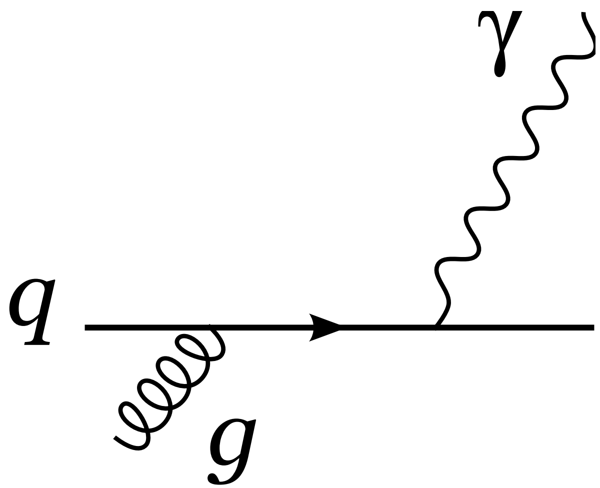


Good agreement! More soft photons needed!

Many "CGC" calculations assume the k_T factorization

CGC Calculation for Photon

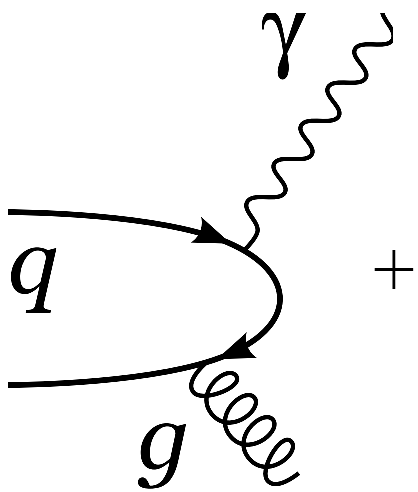
Compton Scattering



$$\propto \ \alpha_e \alpha_s n_q (1 - n_q) n_g$$

$$(qg \ \to \ q\gamma)$$

Annihilation



+ crossed

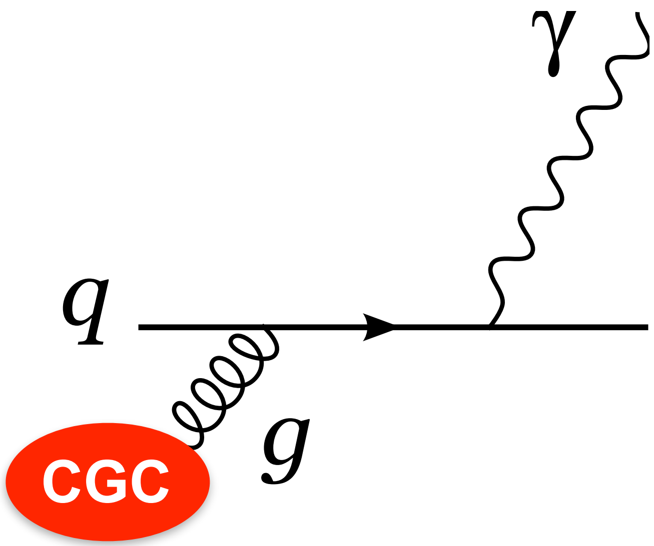
+ ~~LPM~~ large N_c

$$\propto \ \alpha_e \alpha_s n_q n_{\bar{q}} (1 + n_g)$$

$$(q\bar{q} \ \to \ g\gamma)$$

CGC Calculation for Photon

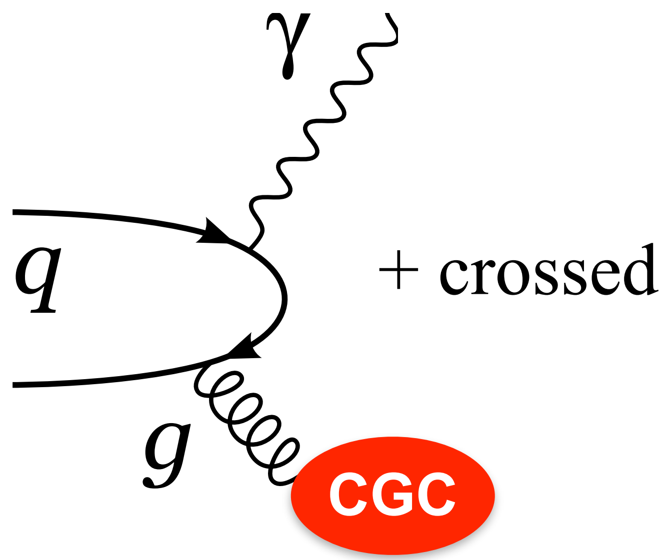
Compton Scattering



$$\propto \alpha_e \alpha_s n_q (1 - n_q) \alpha_s^{-1}$$

$$\sim \alpha_e n_q (1 - n_q)$$

Annihilation



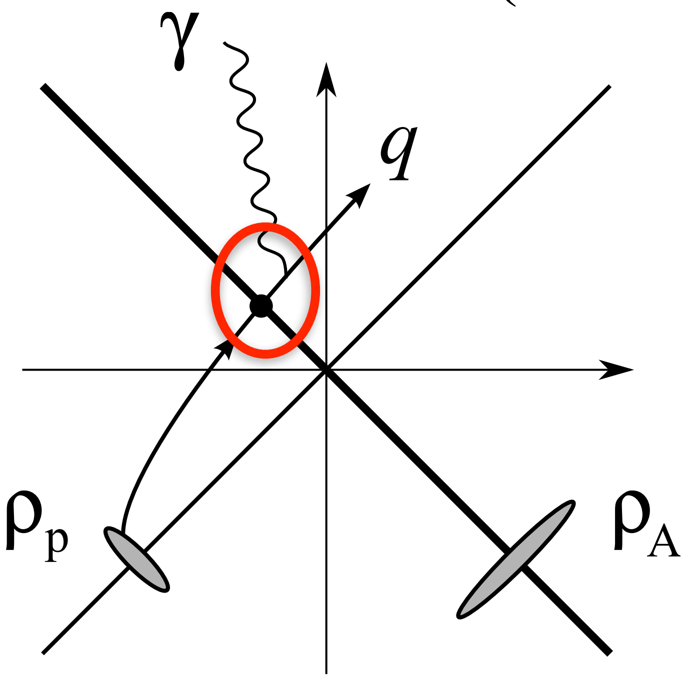
$$\propto \alpha_e \alpha_s n_q n_{\bar{q}} \alpha_s^{-1}$$

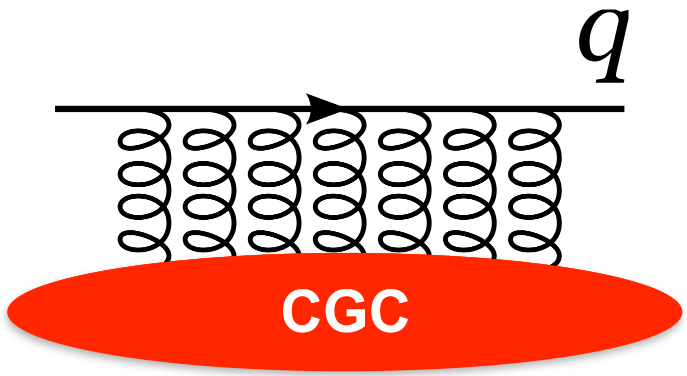
$$\sim \alpha_e n_q n_{\bar{q}}$$

CGC Calculation for Photon

Gauge choice: $A \sim \rho_A \sim \delta(x^+)$ **Gelis-Mehtar-Tani (2006)**

(Coulomb gauge + Light cone gauge)

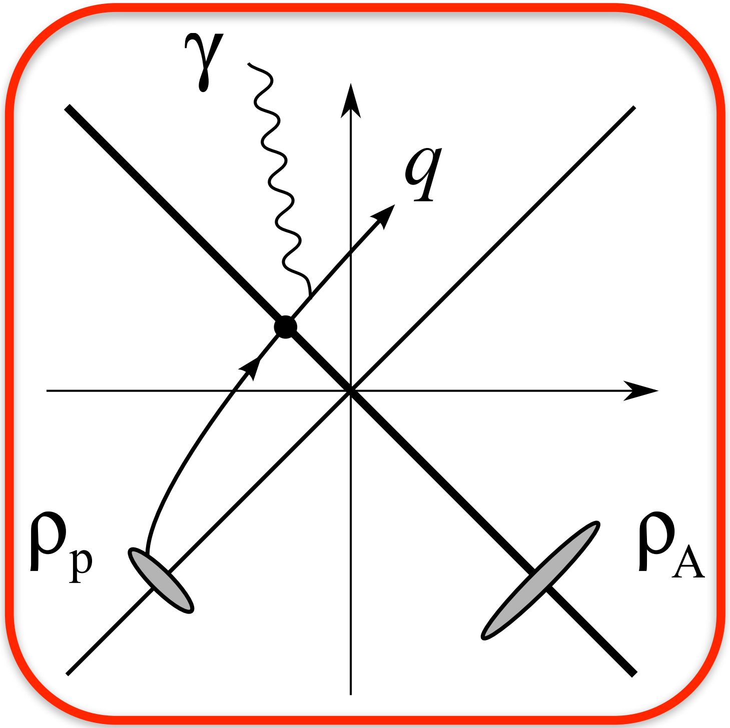




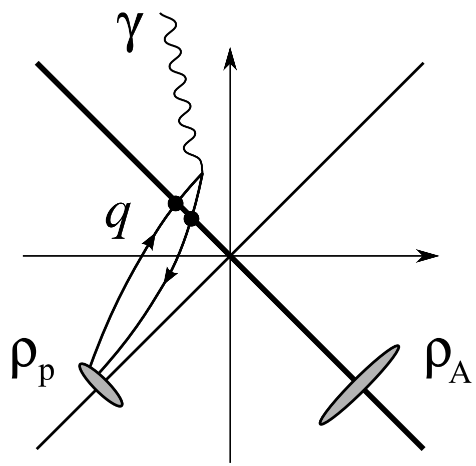
$$U \sim 1 + igA + \frac{1}{2}(igA)^2 + \cdots$$

CGC Calculation for Photon

Gelis-Jalilian-Marian (2002)



$$\sim \; \alpha_e n_q \langle UU^\dagger \rangle$$



$$\sim \; \alpha_e n_q n_{\bar{q}} \langle UU^\dagger UU^\dagger \rangle$$

Annihilation process suppressed by quark distribution

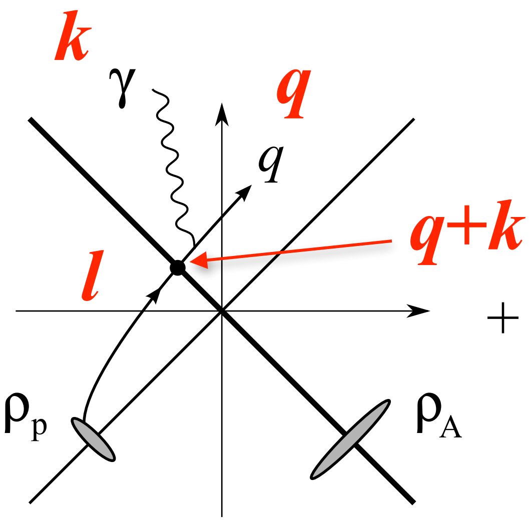
Multiple Scattering with CGC

CGC Calculation for Photon

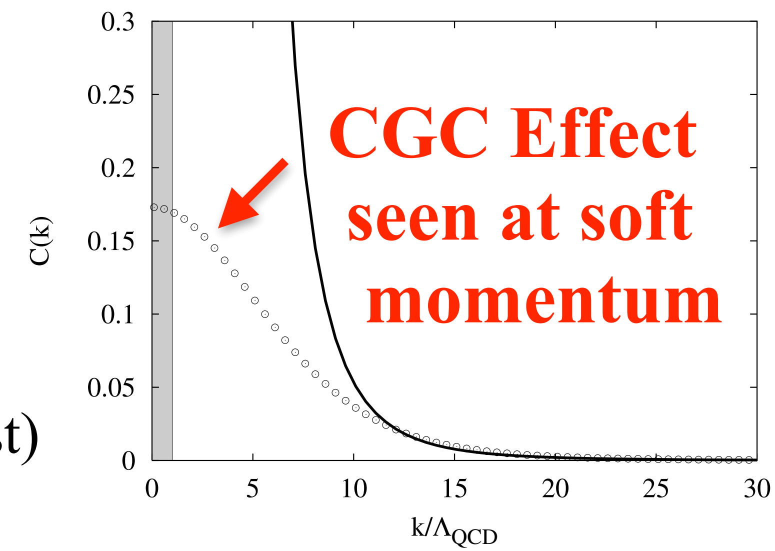
$$\frac{1}{A_\perp}\frac{d\sigma^{q\to q\gamma}}{d^2\boldsymbol{k}_\perp} = \frac{2\alpha_e}{(2\pi)^4\boldsymbol{k}_\perp^2}\int_0^1 dz\frac{1+(1-z)^2}{z}\int d^2\boldsymbol{l}_\perp\,\frac{\boldsymbol{l}_\perp^2 C(\boldsymbol{l}_\perp)}{(\boldsymbol{l}_\perp-\boldsymbol{k}_\perp/z)^2}$$

$$C(\boldsymbol{l}_\perp) \equiv \int d^2\boldsymbol{x}_\perp e^{i\boldsymbol{l}_\perp\cdot\boldsymbol{x}_\perp} e^{-B_2(\boldsymbol{x}_\perp)} = \int d^2\boldsymbol{x}_\perp e^{i\boldsymbol{l}_\perp\cdot\boldsymbol{x}_\perp}\left\langle U(0)U^\dagger(\boldsymbol{x}_\perp)\right\rangle_\rho$$

$$B_2(\boldsymbol{x}_\perp-\boldsymbol{y}_\perp) \equiv Q_s^2\int d^2\boldsymbol{z}_\perp[G_0(\boldsymbol{x}_\perp-\boldsymbol{z}_\perp)-G_0(\boldsymbol{y}_\perp-\boldsymbol{z}_\perp)]^2$$

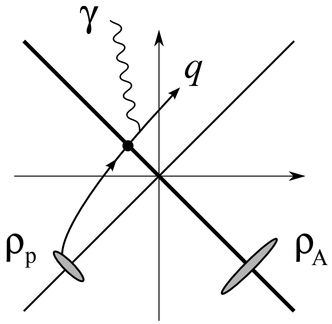


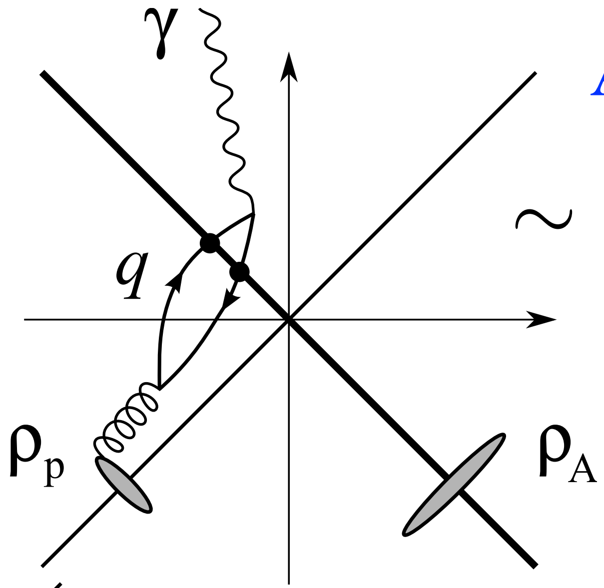
+ crossed diagram
(photon emitted first)



Gelis-Jalilian-Marian (2002)

CGC Calculation for Photon



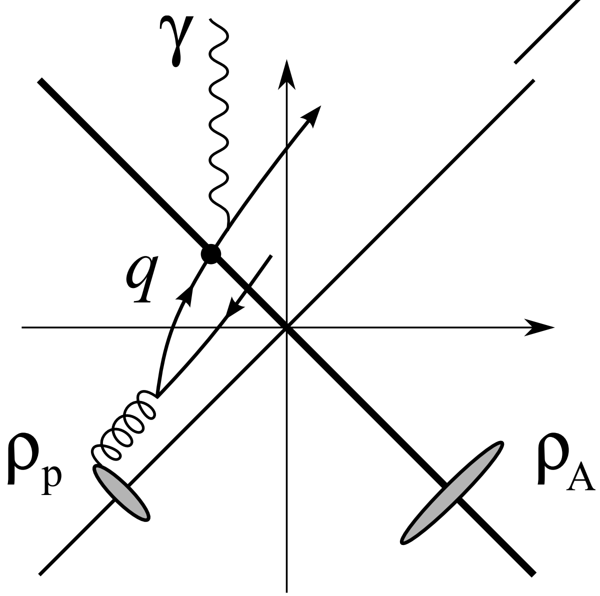


Annihilation

$$\sim \ \alpha_e \langle (g\rho_p)^2 \rangle \langle U U^\dagger U U^\dagger \rangle$$

Benic-Fukushima (2016)

Not important (suppressed)



Bremsstrahlung

$$\sim \ \alpha_e \delta n_q \langle U U^\dagger \rangle$$

$$\sim \ \alpha_e \langle (g\rho_p)^2 \rangle \langle U U^\dagger U U^\dagger \rangle$$

CGC Calculation for Photon

LO: $\sim \alpha_e n_q \langle UU^\dagger \rangle$

NLO: $\sim \alpha_e \langle (g\rho_p)^2 \rangle \langle UU^\dagger UU^\dagger \rangle$

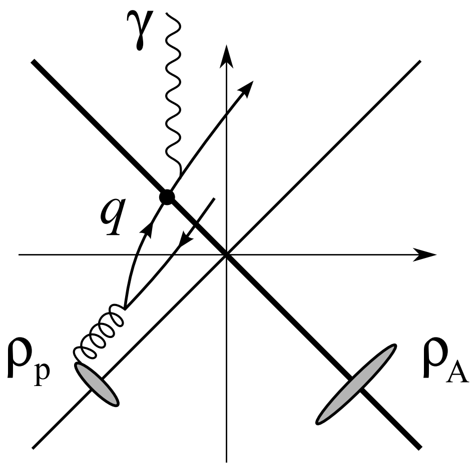
$$(g\rho_p)^2 < n_q \leq g\rho_p$$

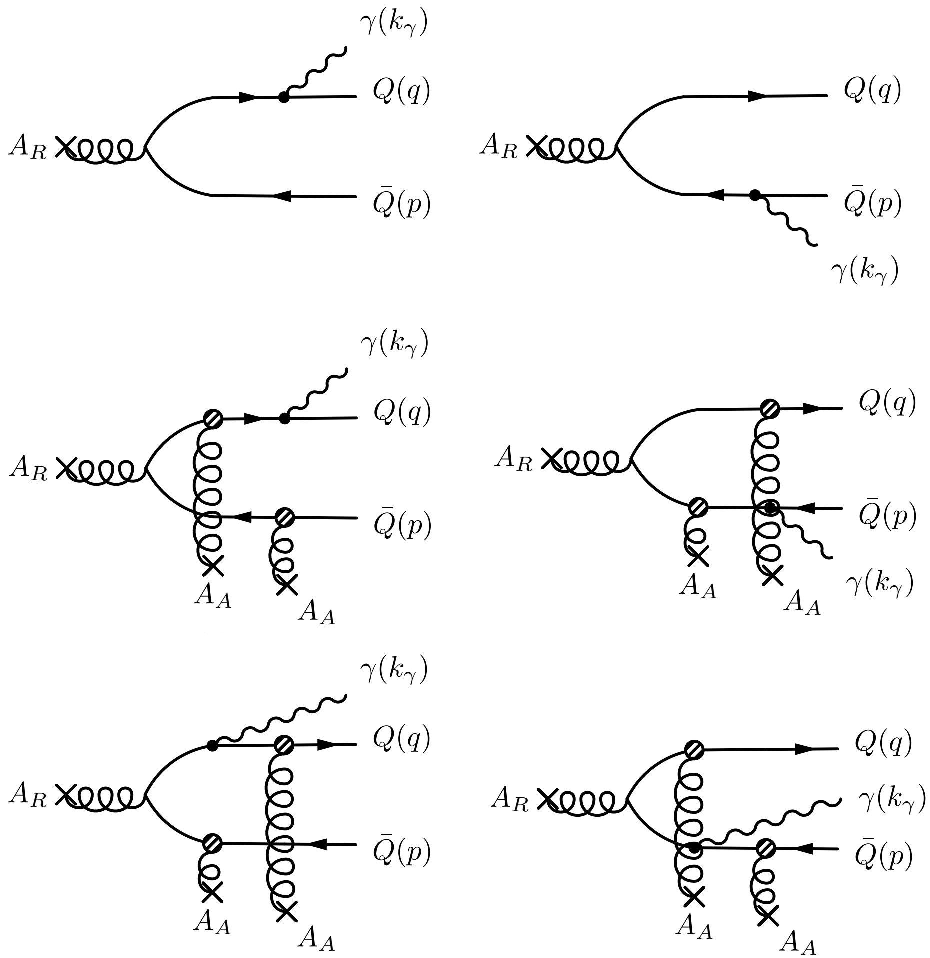
NLO is overwhelming but the pA expansion still works

Systematic calculations feasible
Not small corrections but dominant at high energies
pA photon data (hopefully) coming very soon

CGC Calculation for Photon

Benic-Fukushima-Garcia-Montero-Venugopalan (2016)



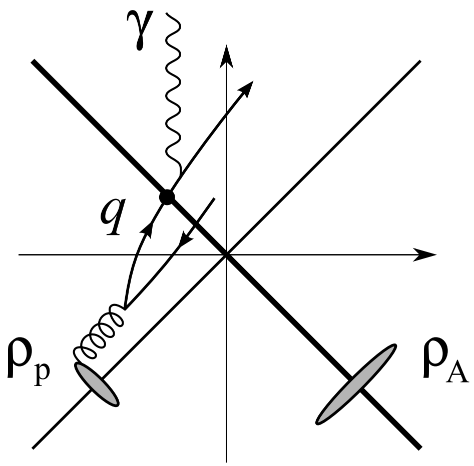


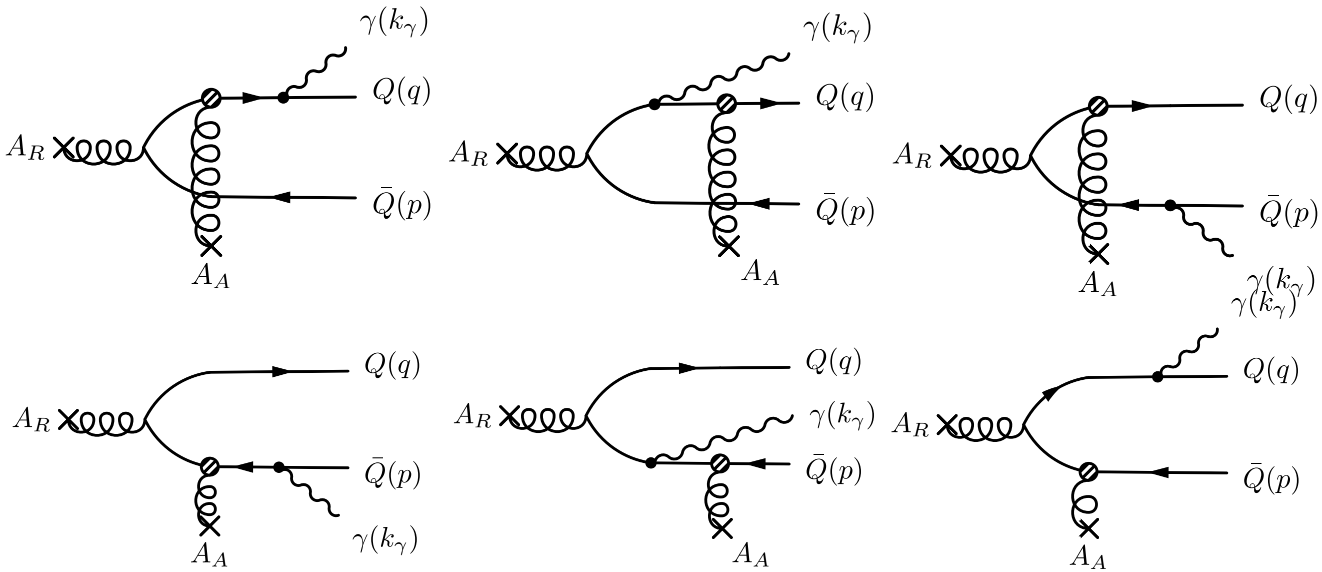
$$\sim \; U_{ad}$$

$$\sim \; U t^a U^\dagger$$

CGC Calculation for Photon

Benic-Fukushima-Garcia-Montero-Venugopalan (2016)

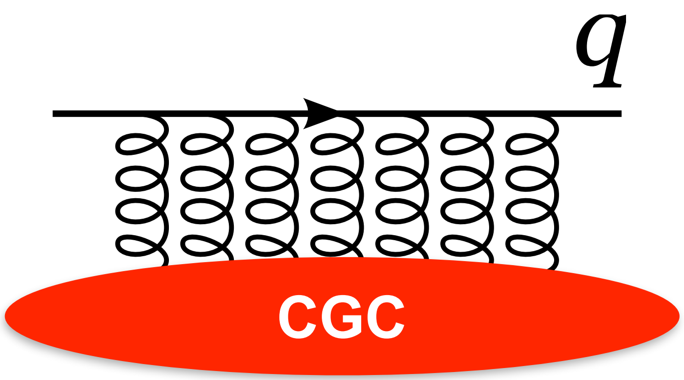




$$\sim \; U, \; U^{\dagger}$$

CGC Calculation for Photon

k_T factorized approximation from the expansion of the Wilson line (no CGC resummation !?)

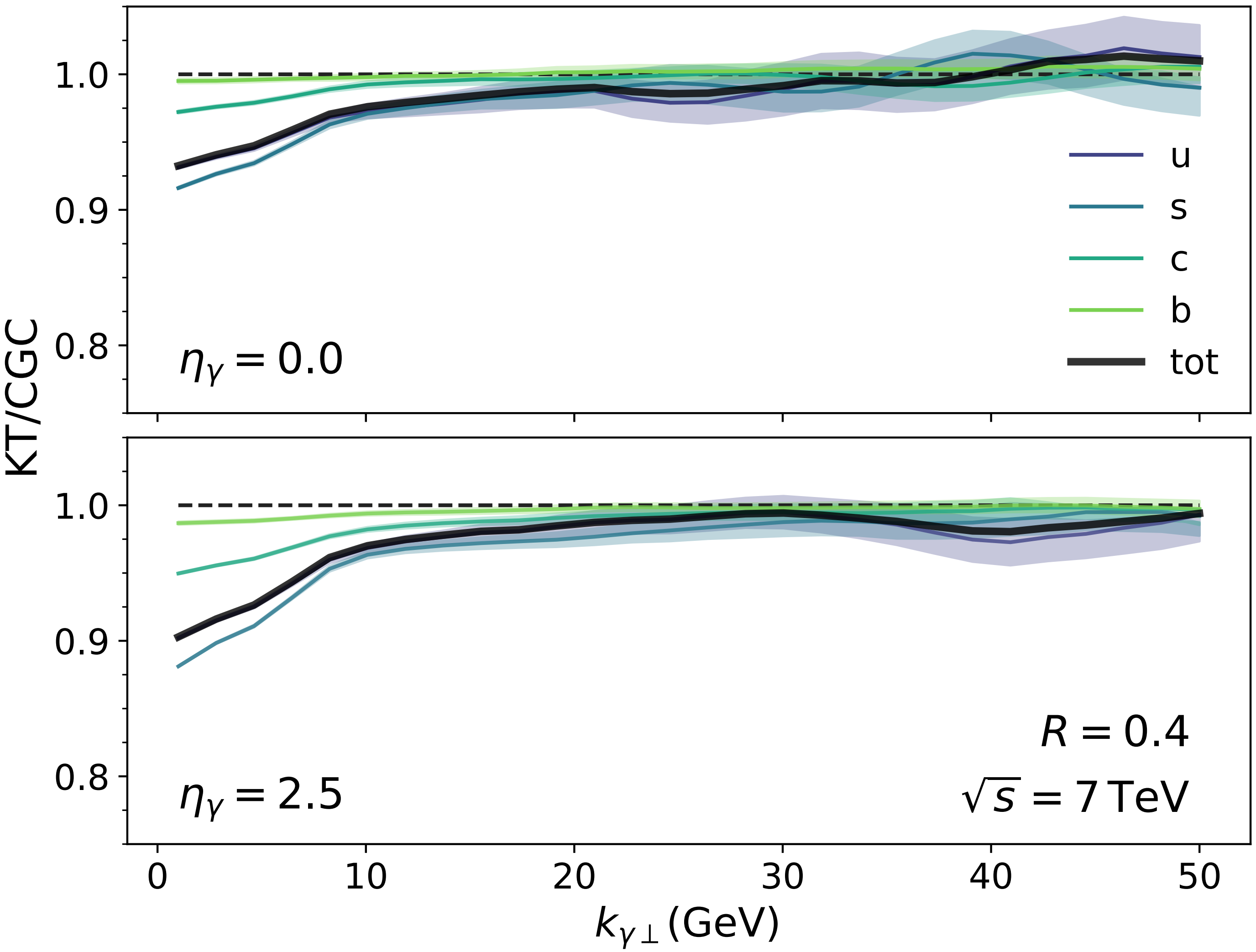


replaced by a perturbative vertex

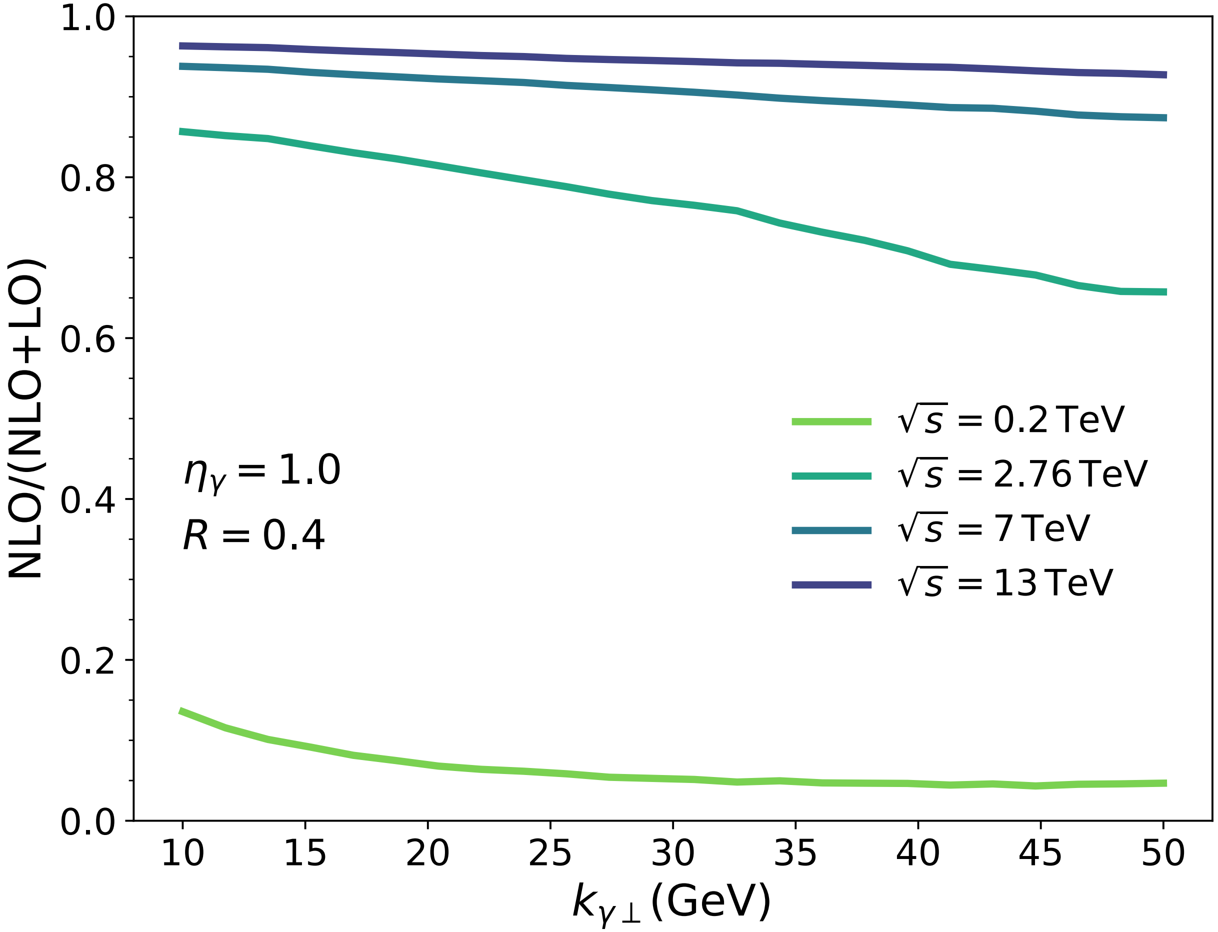
This approximation makes sense when a large momentum (or quark mass) is involved in the considered process

Then, the distribution function is introduced, in which a part of resummation is taken into account

CGC Calculation for Photon



CGC Calculation for Photon



Gluons are surely dominant degrees of freedom

CGC Calculation for Photon

Heavy flavor is hard to see the true CGC effect

To see the true CGC effect, direct photons ~ a few GeV

Is this possible? How far?

In pA the nuclear PDF could be probed directly

Photons ~ a few GeV is interesting also as a probe to detect strong magnetic fields and induced phenomena