Photon and CGC

Kenji Fukushima (Univ. of Tokyo)

The 36th Heavy Ion Cafe

Photon from Early Dynamics

Photon from Saturated Gluons (conventional)

S. Benic, K. Fukushima, O. Garcia-Montero, R. Venugopalan

JHEP171, 115 (2017)
[arXiv:1609.09424 [hep-ph]]

Physics Letters B791, 11-16 (2019)
[arXiv:1807.03806 [hep-ph]]

Photon from Strong Magnetic Field (speculative)

K. Fukushima, X.-G. Huang, M. Ruggieri

We launched a project one year ago…but
we were all quite busy and no result yet…

I — Conventional Part

What we (can) calculate

Prompt Photons

Direct Photons ← **Isolated Photons**

↑

Fragmentation Photons

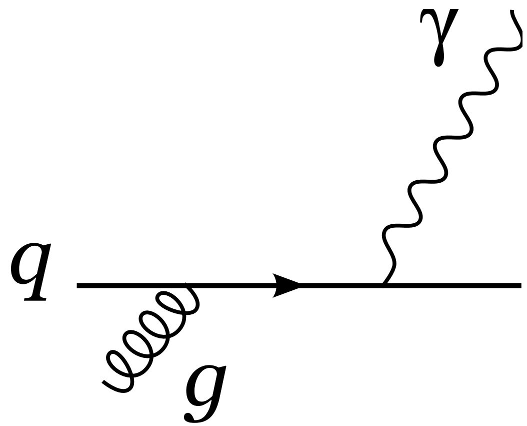
This is measured and calculated.

What we (can) calculate

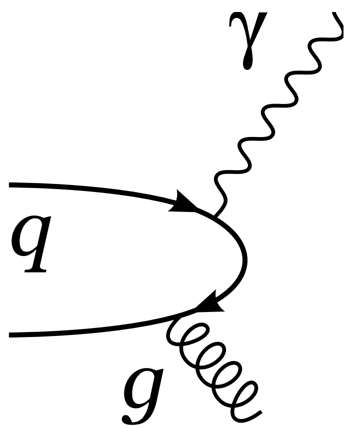
Prompt Photons

Direct Photons

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



Compton



Annihilation

+ crossed

What we (can) calculate

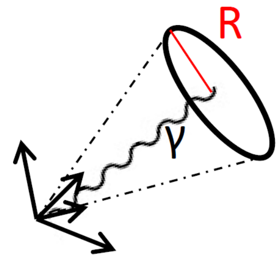
Prompt Photons

Fragmentation Photons

$$q\bar{q} \;\to\; gg \;\to\; \text{jets} \;\to\; \gamma$$

We can perturbatively calculate direct photons and want to drop fragmentation photons (but calculable in principle)

What we (can) calculate



Prompt Photons

+

Isolation Cut $\theta\left(\sqrt{(\eta_\gamma - \eta)^2 + (\phi_\gamma - \phi)^2} - R\right)$

~ 0.4

||

Isolated Photons ← **Experimentally measured**

≀

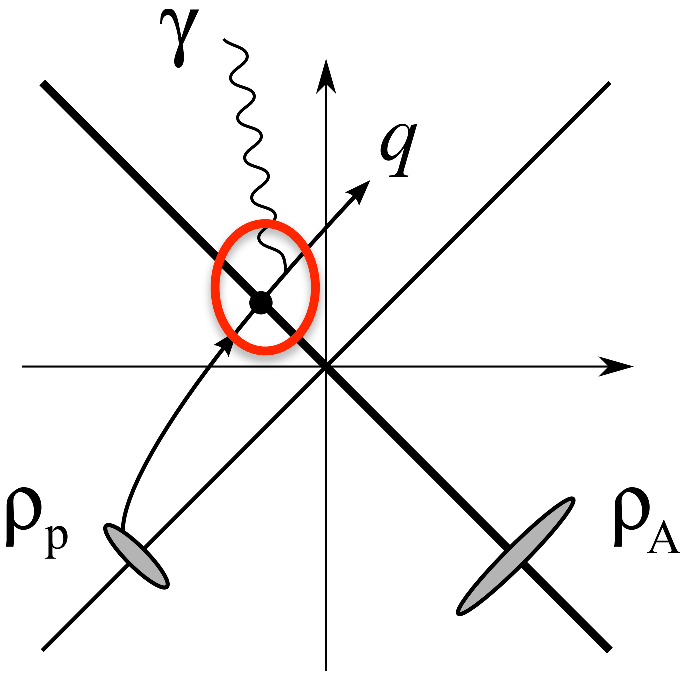
Isolated Direct Photons ← **Theoretically predicted**

Fragmentation photons almost (not perfectly) dropped

LO Photon in pA

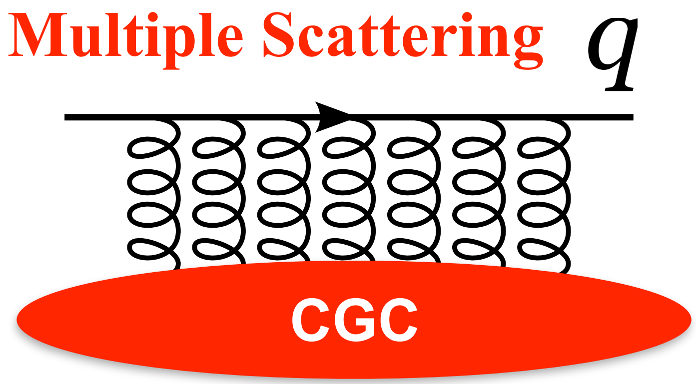
Gauge choice: $A \sim \rho_A \sim \delta(x^+)$ **Gelis-Mehtar-Tani (2006)**

(Coulomb gauge + Light cone gauge)



$$\sim \; \alpha_e n_q \langle \underline{UU^\dagger} \rangle$$

Gelis-Jalilian-Marian (2002)



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

"Leading Twist" → *k_t*-factorized

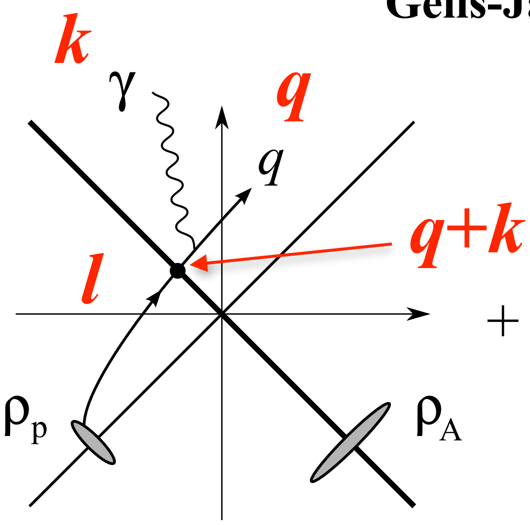
LO Photon in pA

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

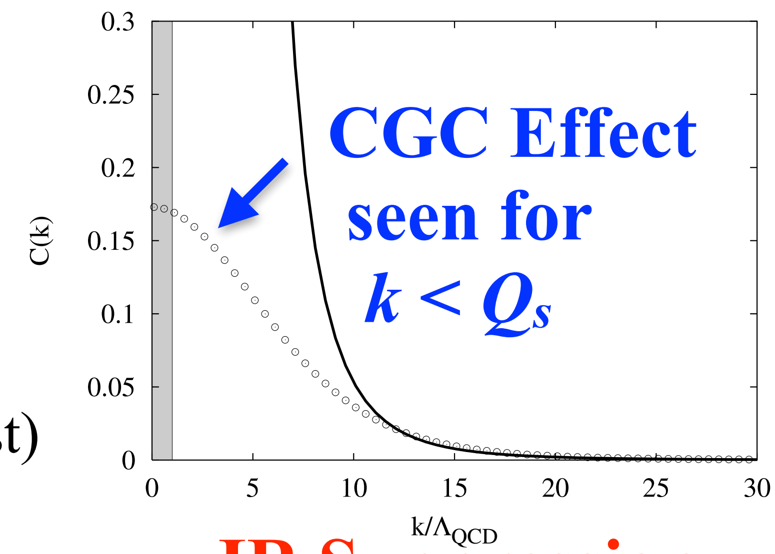
$$C(\boldsymbol{l}_\perp) \equiv \int d^2\boldsymbol{x}_\perp e^{i\boldsymbol{l}_\perp\cdot\boldsymbol{x}_\perp}e^{-B_2(\boldsymbol{x}_\perp)} = \int d^2\boldsymbol{x}_\perp e^{i\boldsymbol{l}_\perp\cdot\boldsymbol{x}_\perp}\left\langle U(0)U^\dagger(\boldsymbol{x}_\perp)\right\rangle_\rho$$

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

Gelis-Jalilian-Marian (2002)



+ crossed diagram
(photon emitted first)

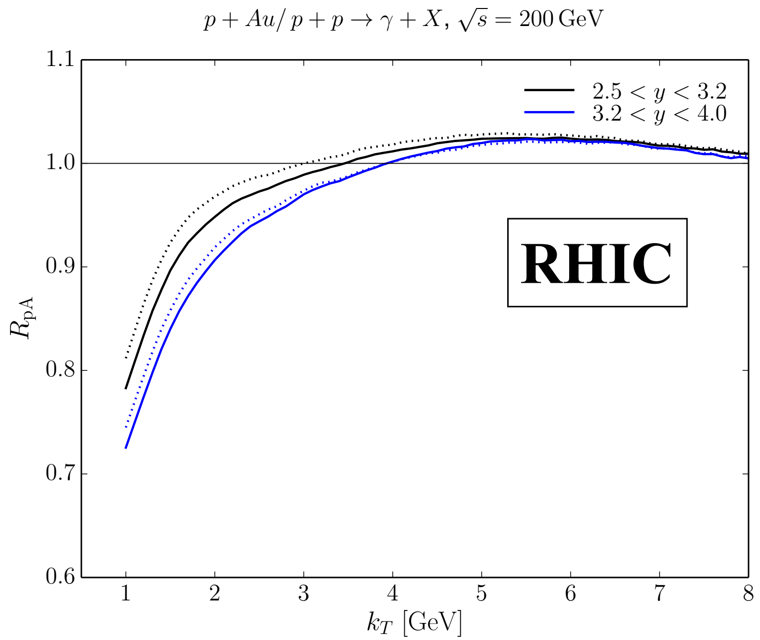


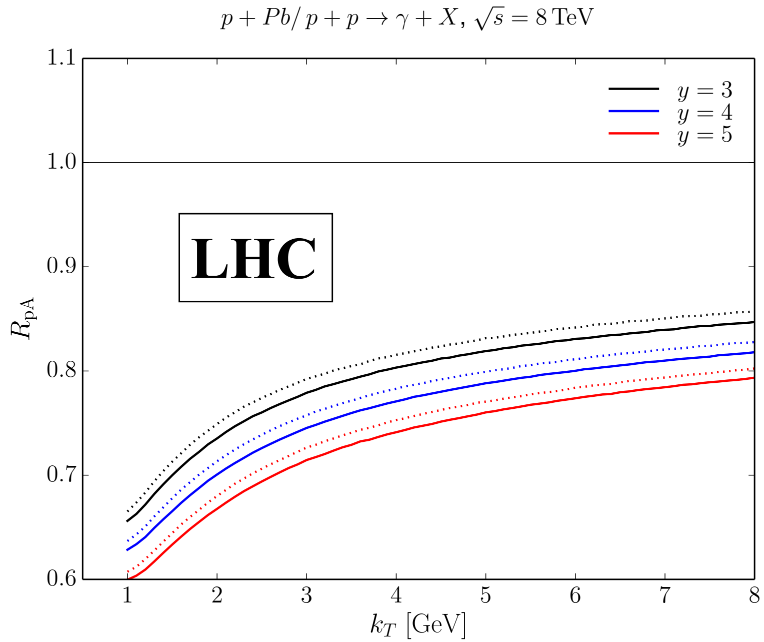
IR Suppression

LO Photon in pA

Ducloue-Lappi-Mantysaari (2017)

$$R_{pA} = \frac{\mathrm{d}N^{pA}}{N_{\mathrm{bin}}\mathrm{d}N^{pp}}$$





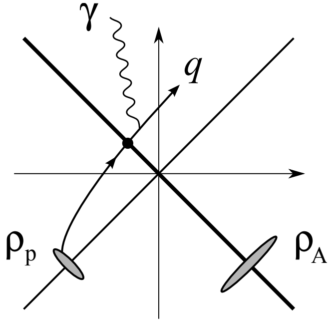
Gelis-Jalilian-Marian formula + isolation cut

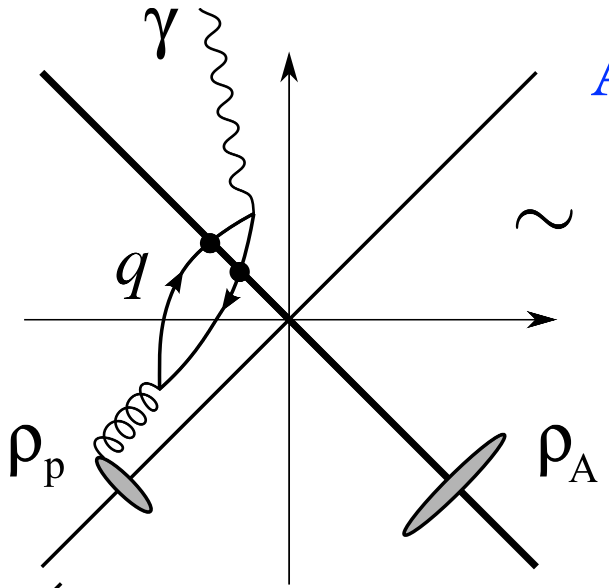
Dense — Wilson lines : MV model + rcBK

Dilute — PDF : CTEQ6

Rapidity Dependence

NLO Photon in pA

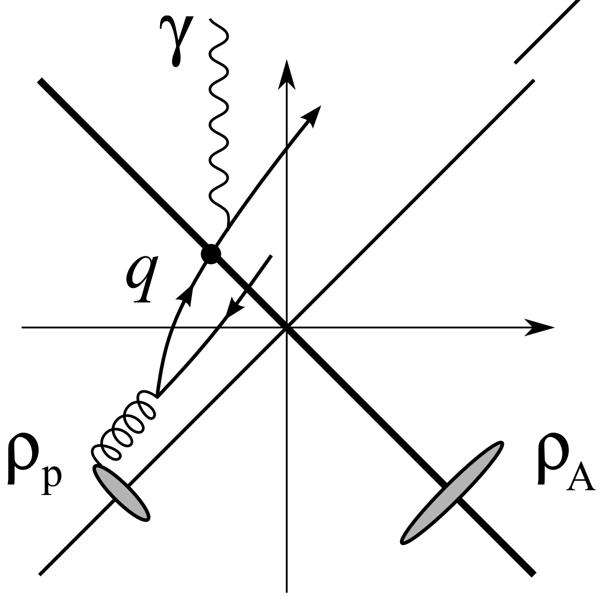




Annihilation

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

Benic-Fukushima (2016)



Bremsstrahlung

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

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

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

LO vs. NLO with CGC

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

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

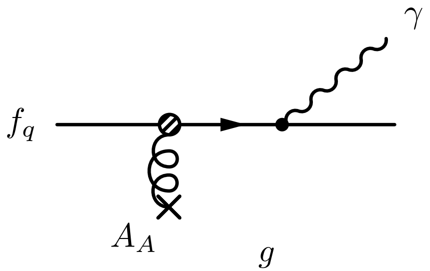
$$(g\rho_p)^4 < n_q < (g\rho_p)^2$$

NLO is overwhelming (i.e., saturation dominant) but the pA (dilute) expansion still works

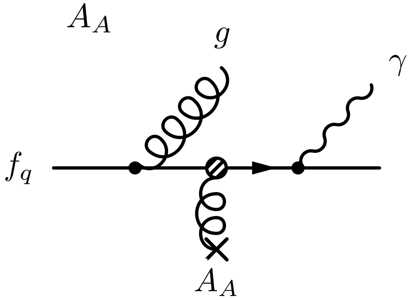
Systematic calculations feasible
Not small corrections but dominant at high energies

Diagrams (schematic)

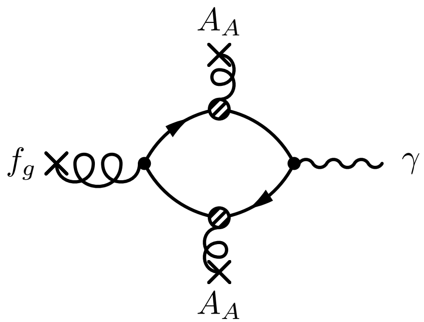
LO



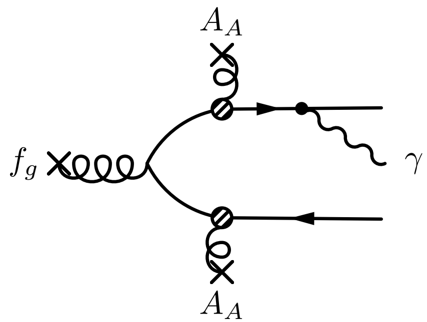
NLO



Included in quark PDF (LO+evolution)



Negligibly small

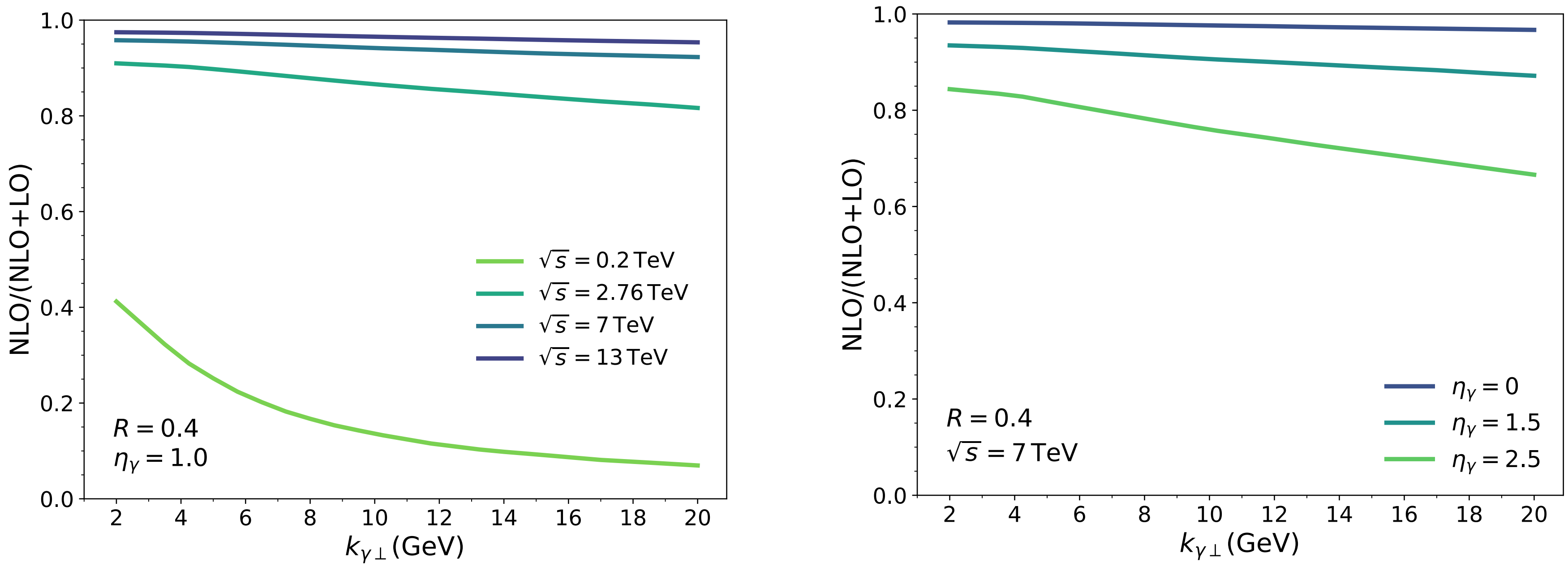


Discussed here!

This is only a schematic picture, and the reality involves many other diagrams

LO vs. NLO with CGC

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

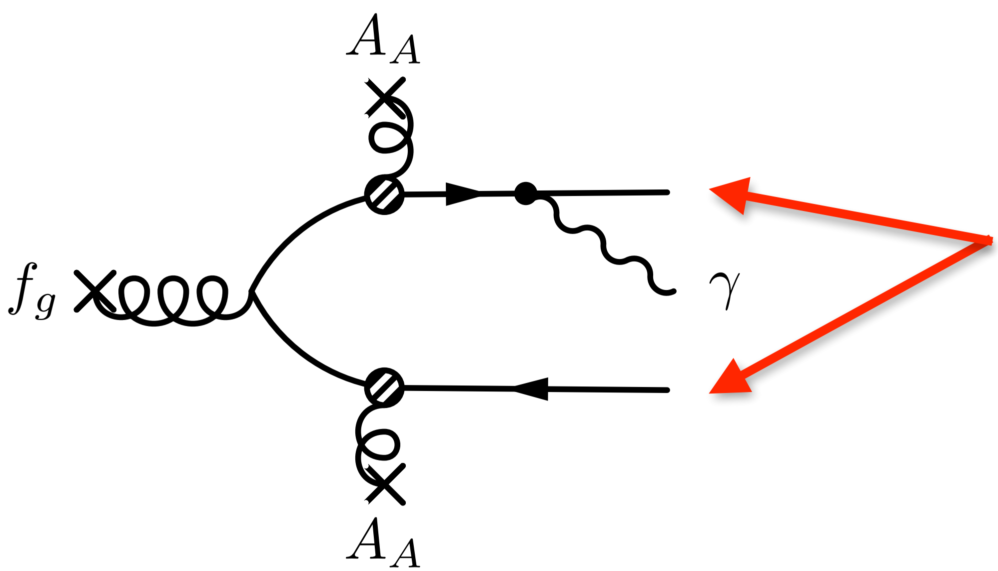


NLO becomes dominant at higher energies and with smaller photon momentum (rapidity)

Kinematics

Hard photons → Hard gluons
(more k_t-factorized)

Soft photons → Soft (and thus saturation) gluons ???

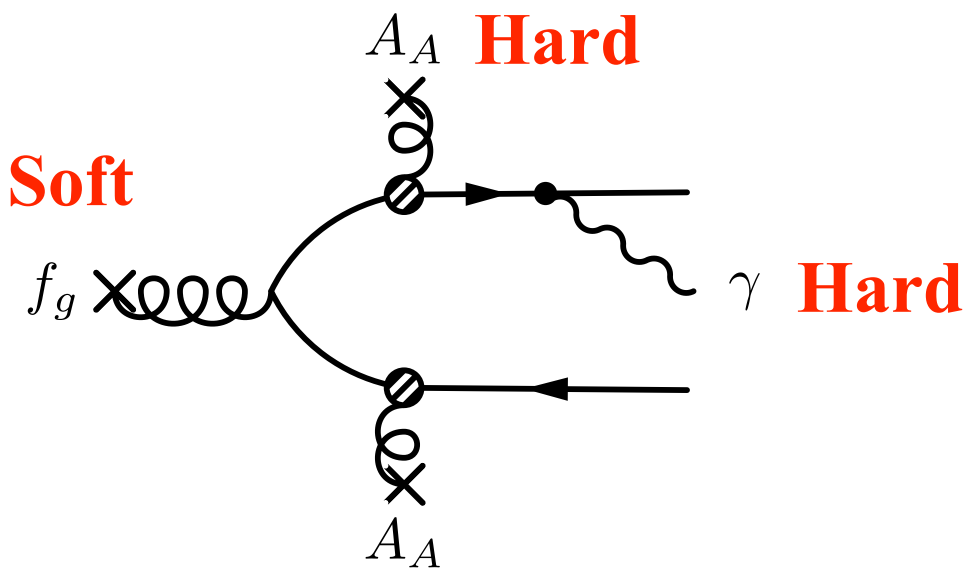


quark-antiquark integrated (“inclusive”)

Kinematics

Hard photons → Hard gluons
(more k_t-factorized)

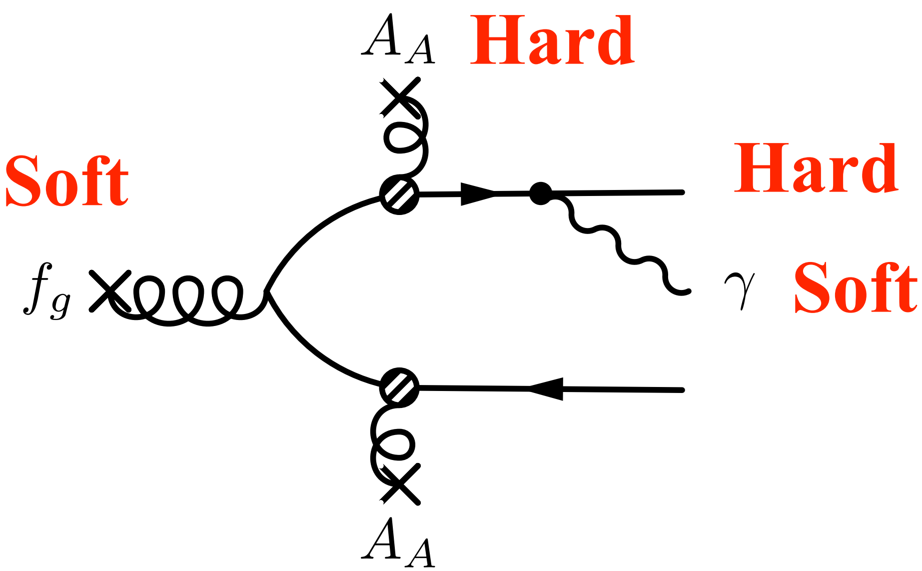
Soft photons → Soft (and thus saturation) gluons ???



Kinematics

Hard photons → Hard gluons
(more k_t-factorized)

Soft photons → Soft (and thus saturation) gluons ???

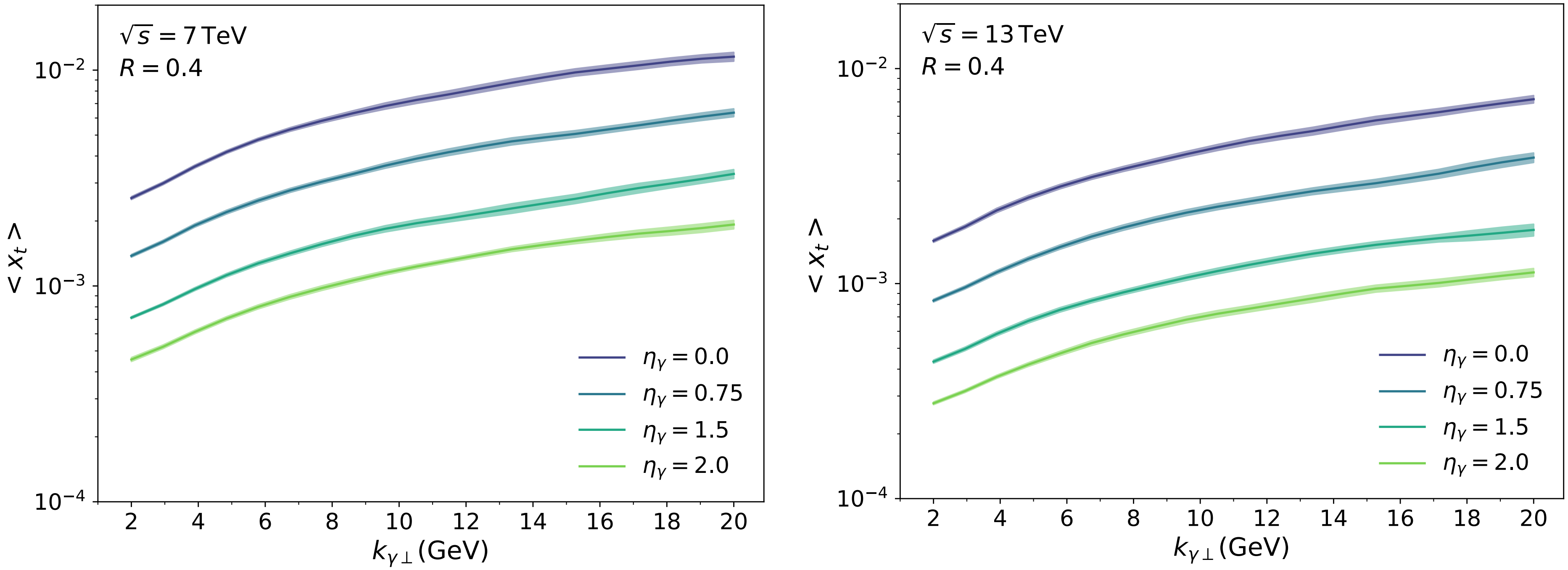


Such processes not prohibited by kinematics…

Relevant x

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

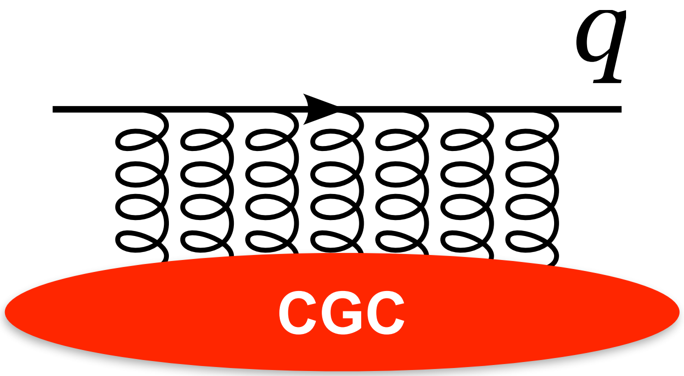
Averaged x over integrand (dominant contributions)



$\log x \sim \log 10^{-3}$ must be resummed → small-x evolution

Comparison w/wo Resummation

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

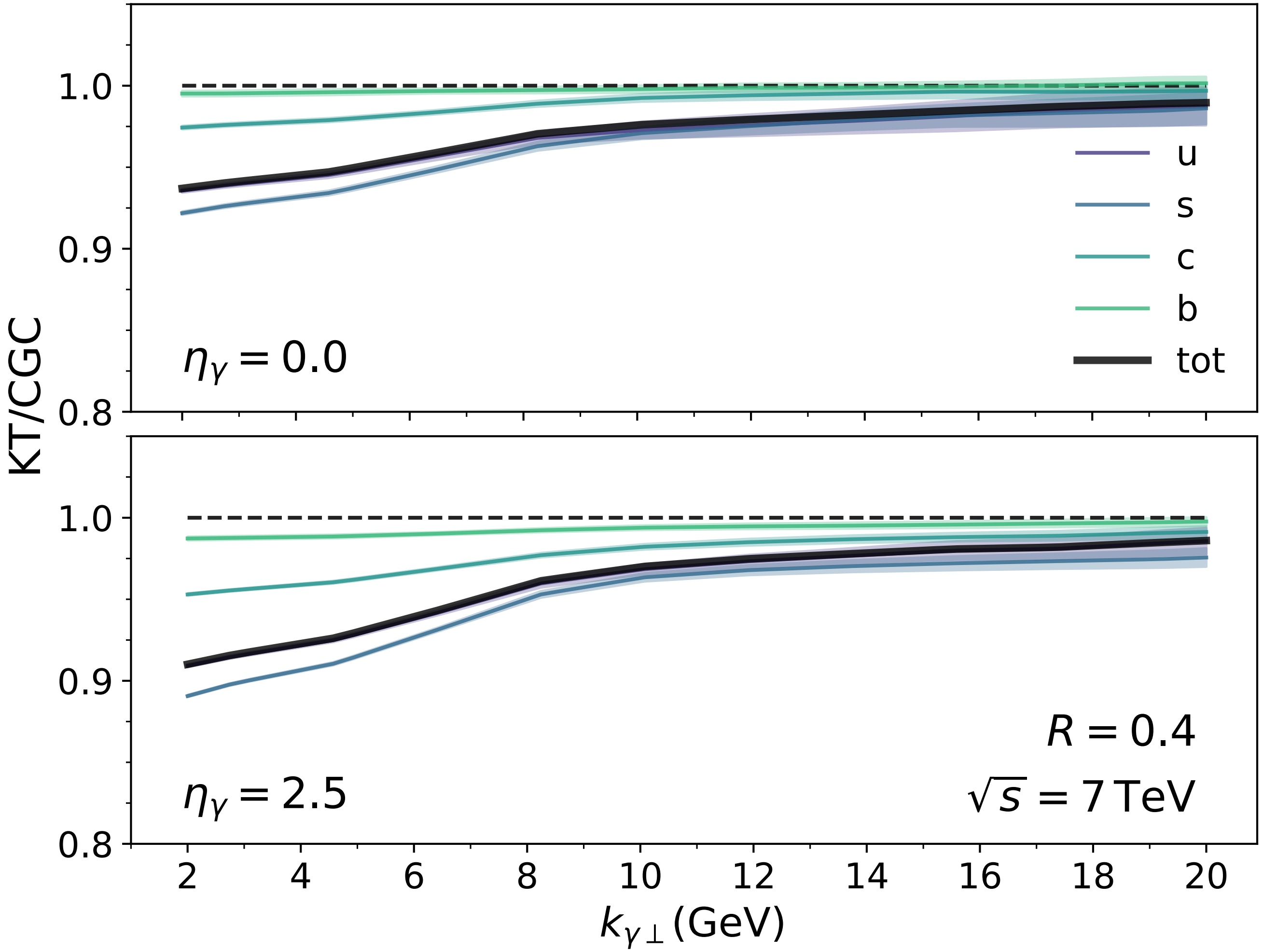


$$U \sim 1 + igA + \frac{1}{2}(igA)^2 + \cdots$$

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

Many complicated PDF reduced to only one

Comparison w/wo Resummation



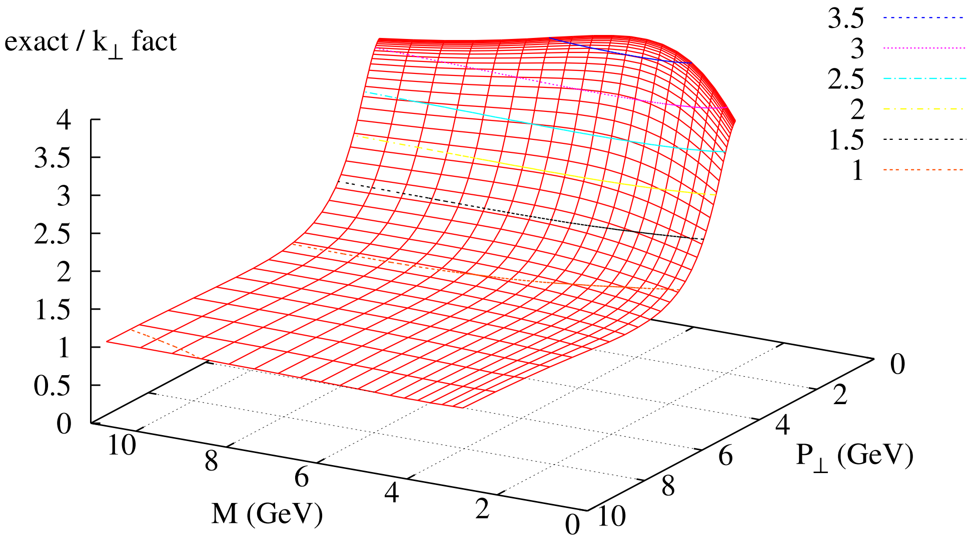
10% difference

10% enhancement by saturation (not suppression!)

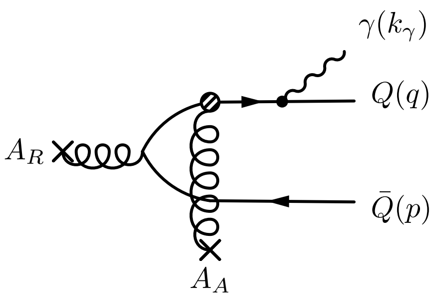
Comparison w/wo Resummation

Similar enhancement also in quark-antiquark

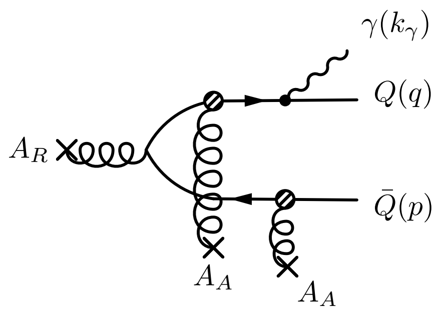
Fujii-Gelis-Venugopalan (2006)



Enhancement attributed to more phase space



Kept



Dropped

Calculation Details

LO + NLO (Bremsstrahlung)

(full-CGC) 10-dimensional numerical integration
(k_T-factorized) 8-dimensional numerical integration

k_T-factorization reduces different PDFs to the same

Quark PDF **CTEQ6M**

Gluon PDF **MV + rcBK matched to CTEQ6M**

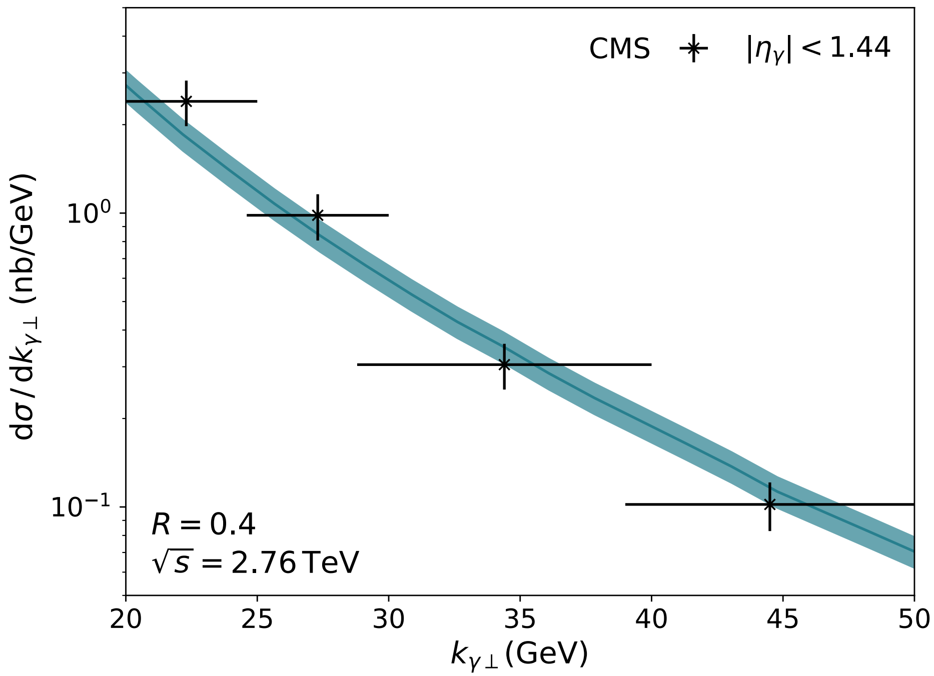
(small-x evol. but DGLAP not considered yet…)

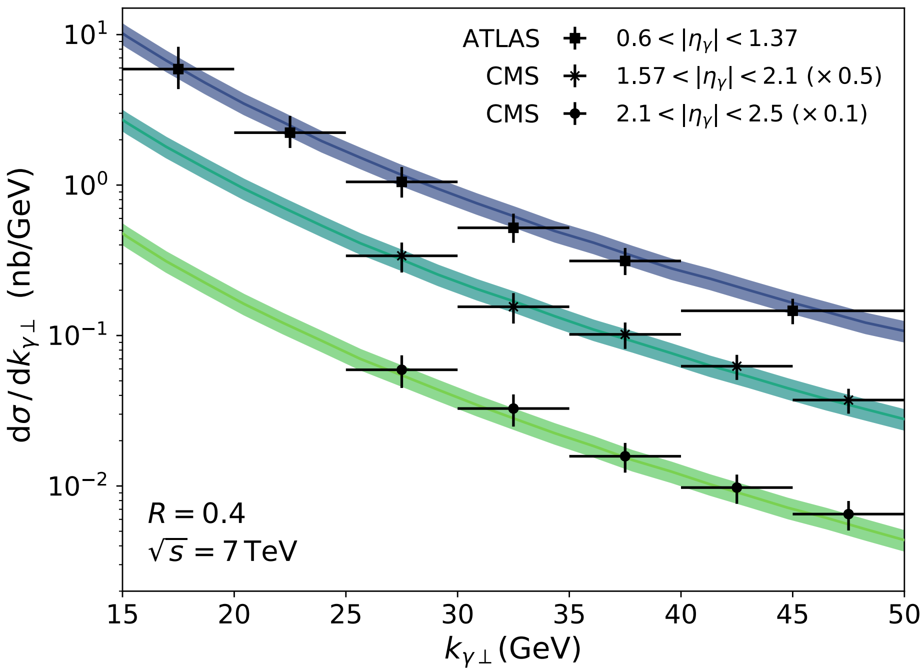
***K*-factor** **$K = 2.4$ (cf. $K = 2.5$ for *D*-meson production)**

Comparison to Available Data

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

Photons in *pp* at LHC



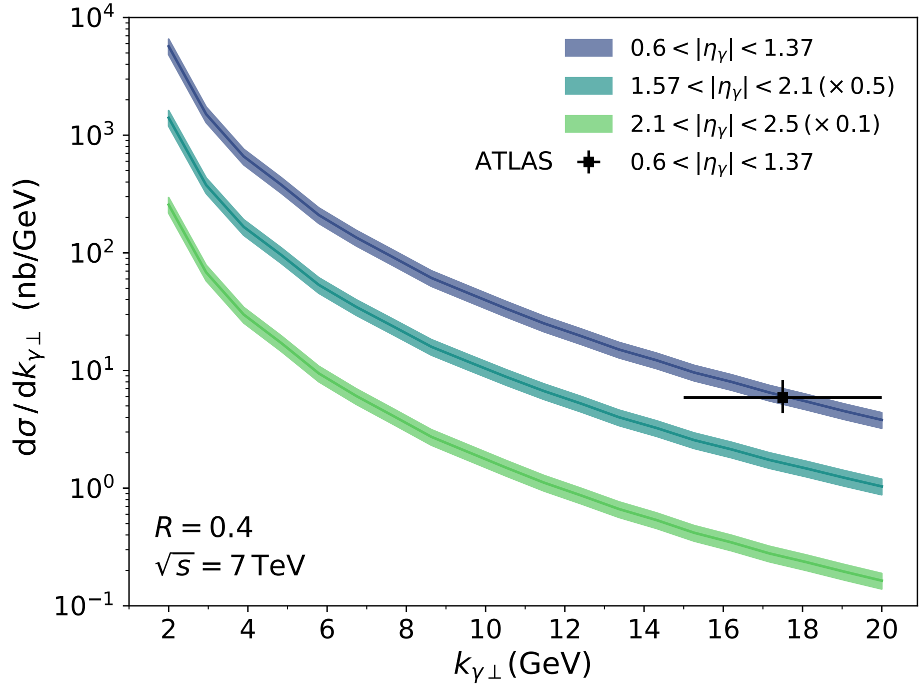


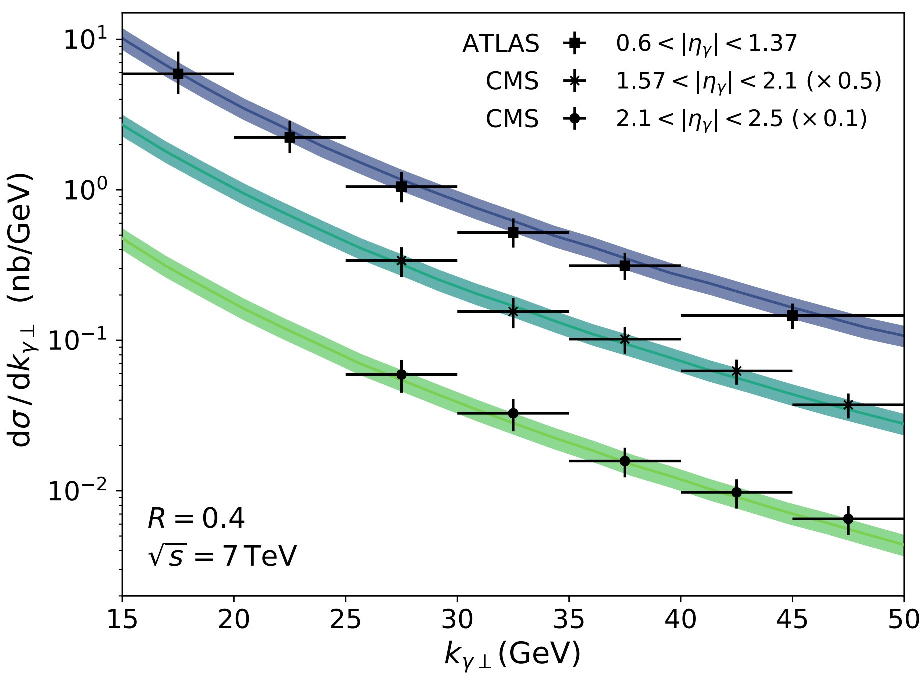
Maybe okay, but maybe DGLAP corrections…

Comparison to Available Data

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

Photons in *pp* at LHC

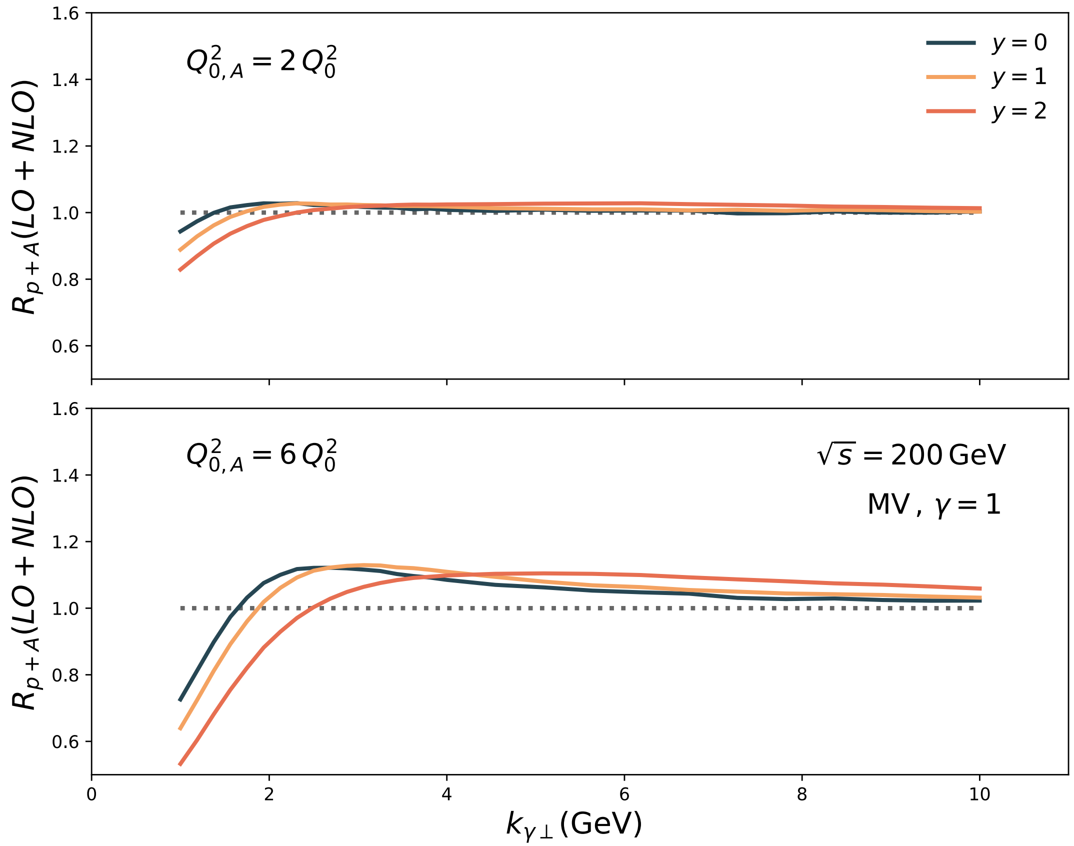




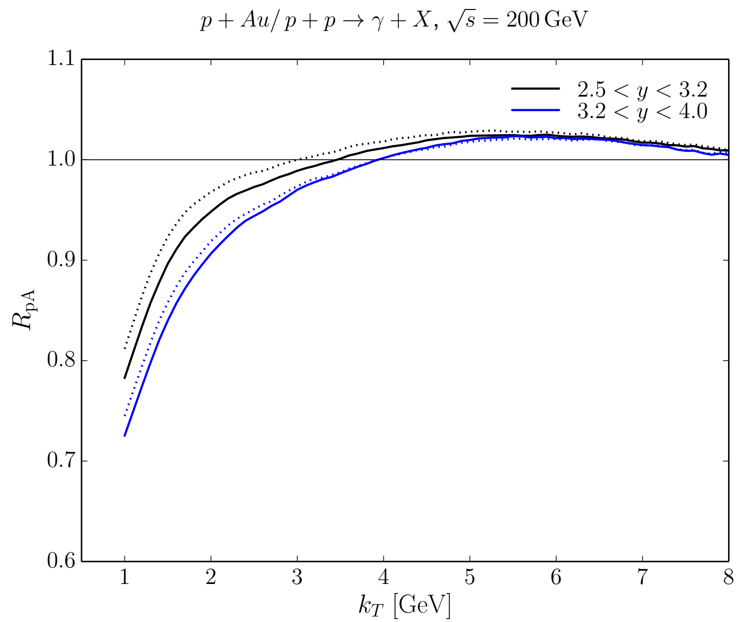
Enhancement here could signal gluon saturation

R_{pA} : Ours and Theirs

Preliminary Results yet…



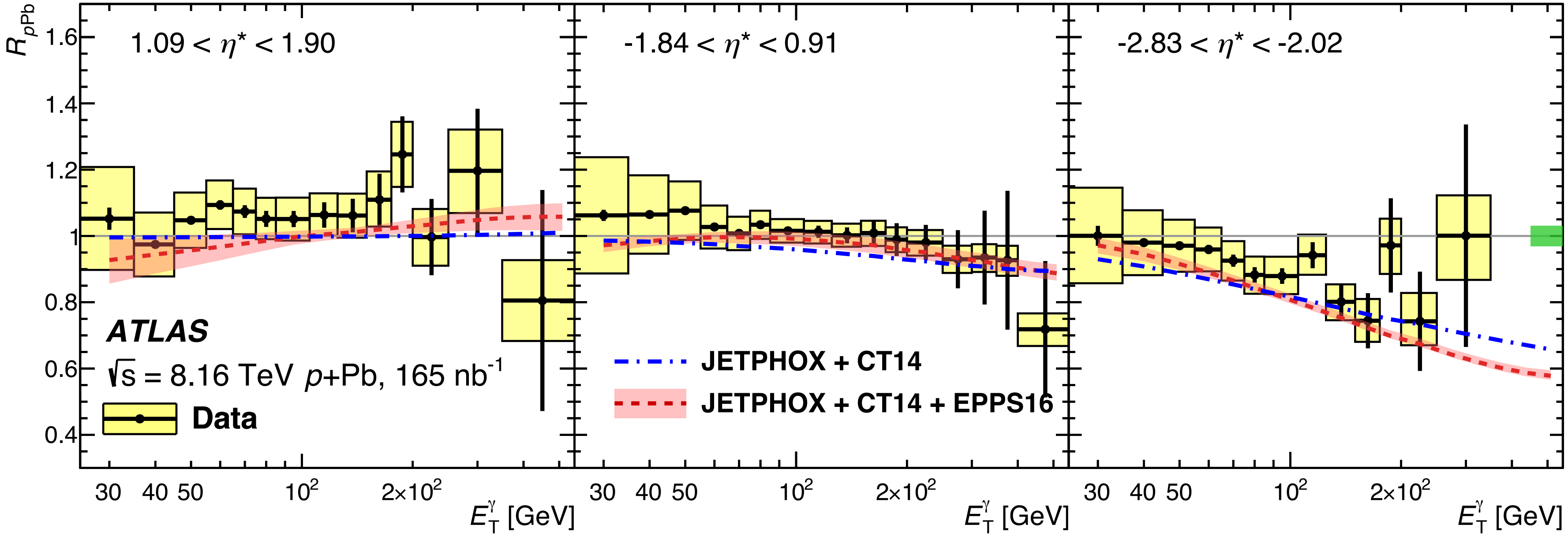
cf. Lappi et al's result

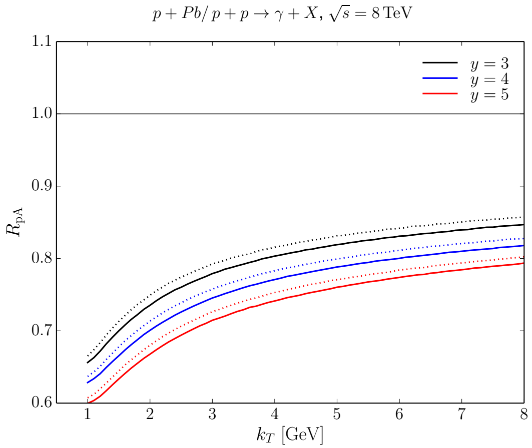


Qualitatively consistent…

R_{pA} : Ours and Theirs

ATLAS 1903.02209



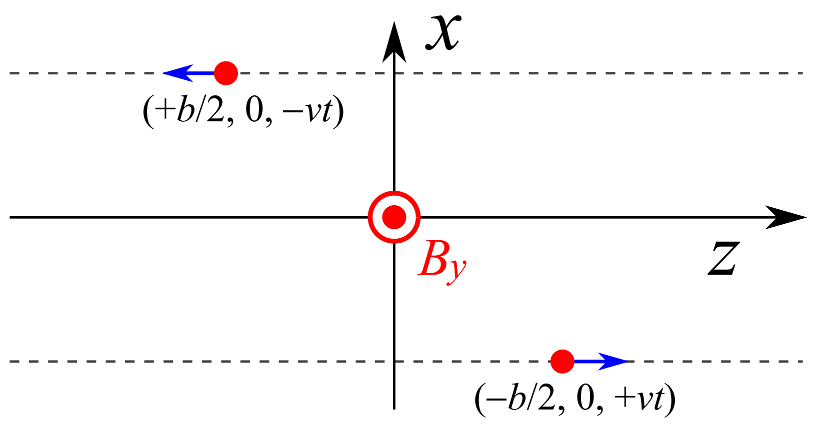


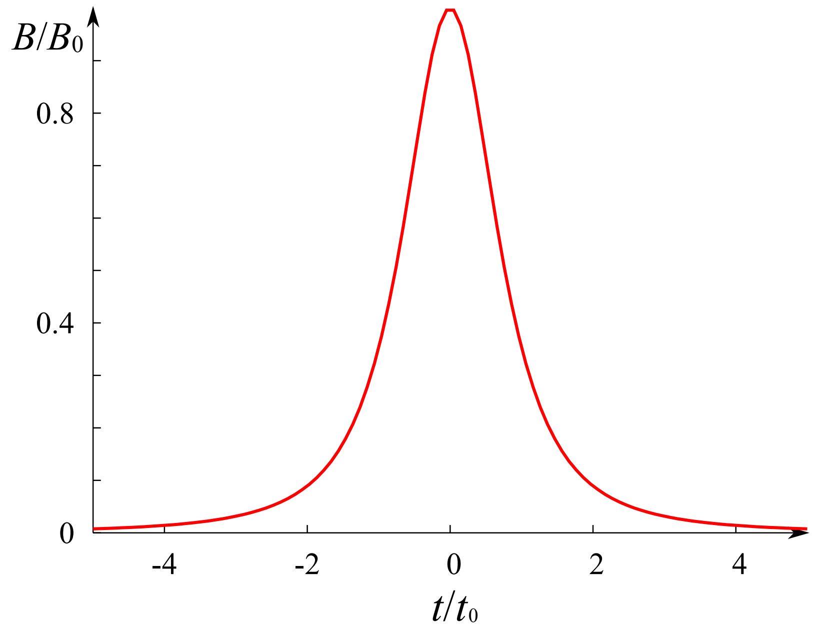
cf. Lappi et al's result

CGC not (yet?) seen…

II — Speculative Part

Time-dependent Magnetic Field

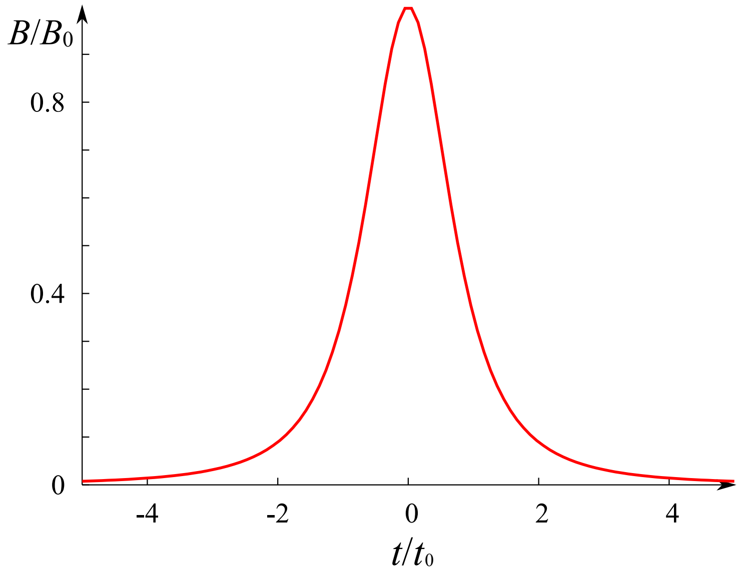




$$eB_0 = \frac{8Z\alpha_e}{b^2}\sinh(Y) = (47.6\ \mathrm{MeV})^2\left(\frac{1\mathrm{fm}}{b}\right)^2 Z\sinh(Y)$$

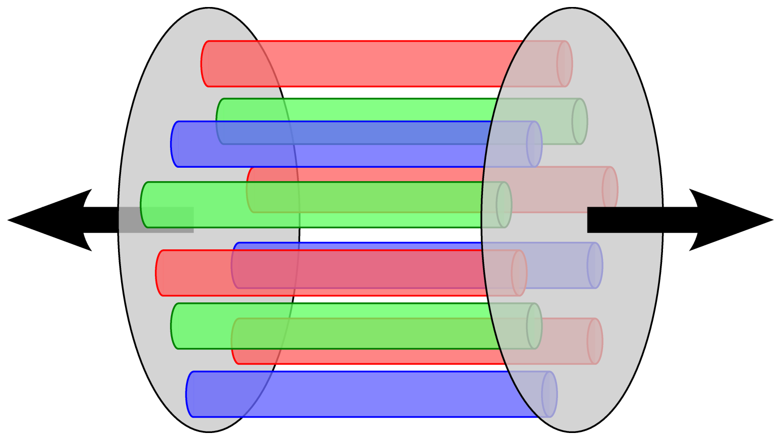
$$t_0 = \frac{b}{2\sinh(Y)}$$ **comparable to 1/*Qs***

Time-dependent Magnetic Field



Spatial uniformity would be a good approximation.
Supplying an energy ~ Qs

CGC Background



Supplying a momentum ~ Qs

Real Photon Emission

Time-dependent Magnetic Field

This should be a very interesting calculation —

People ask: ***what is expected from time-dependent B*** **?**

CGC photon significantly affected by strong *B* !?
(Sizable photon v_2 can be expected…)

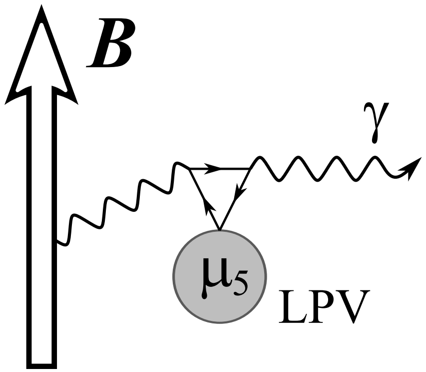
But, needless to say, straightforward calculation would be technically difficult (but feasible…)

Idea

Anomaly induced photon is easily estimated

Fukushima-Mameda (2012)

$$\mathcal{L}_{\mathrm{P}} = \frac{N_{\mathrm{c}}\, e^2\, \mathrm{tr}(Q^2)}{8 N_{\mathrm{f}}\, \pi^2}\, \epsilon^{\mu\nu\rho\sigma} \left[\mathcal{A}_\mu (\partial_\nu \mathcal{A}_\rho) + \mathcal{A}_\mu \bar{F}_{\nu\rho} \right] \partial_\sigma \theta$$



Primakoff effect

Chiral magnetic effect

The form of the WZW action is fixed by the anomaly.

If *B* and *θ* are space-time dependent, *A* can be a real photon.

Idea

Anomaly induced photon is easily estimated

Fukushima-Mameda (2012)

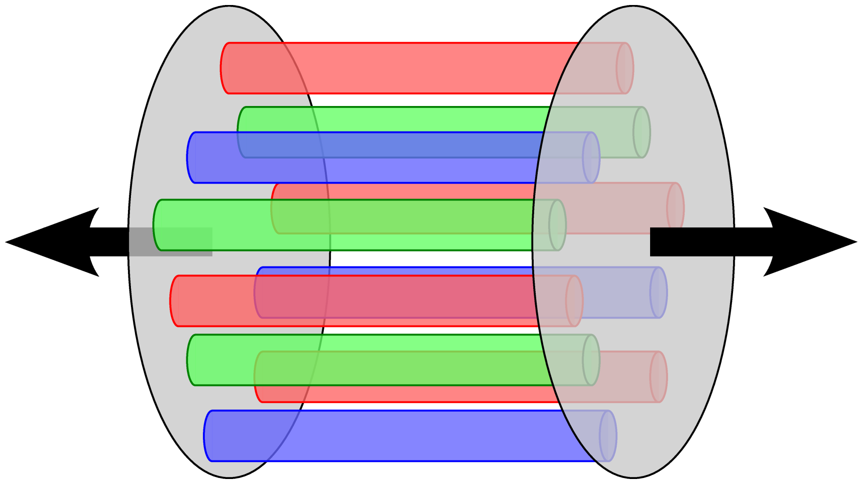
$$q_0 \frac{dN_\gamma}{d^3q} = q_0 \sum_i |\mathcal{M}(i;\boldsymbol{q})|^2$$

$$= \frac{1-(q_y)^2/\boldsymbol{q}^2}{2(2\pi)^3} \left(\frac{N_\mathrm{c}\, e^2\, \mathrm{tr}(Q^2)}{2\pi^2} \int d^4x\, e^{-iq\cdot x} B(x)\mu_5(x) \right)^2$$

Chiral chemical potential represents LPV, which is caused by initial Glasma fluxes.

Idea

Anomaly induced photon is easily estimated



Fukushima-Mameda (2012)

$$\mathcal{E}\cdot\mathcal{B}\neq 0$$

Time-evolution of chiral charge can be given by

$$n_5(t) = N_f \frac{g^2}{16\pi^2}\int_0^t dt\,\mathrm{tr}[\tilde{G}_{\mu\nu}G_{\mu\nu}] \quad \text{for massless quarks}$$

This can be converted to chiral chemical potential.

Idea

LPV : Implemented by the MV model

Magnetic Field : Approximated by Lienard-Wiechert

Photon : Estimated by the WZW coupling

Rapid decay of the magnetic field emits photon catalyzed with the CGC topological background.

Concrete results are coming soon!

Summary

NLO+CGC completed

- □ NLO enhanced over LO by saturated gluons
- □ Technical developments

Applied to *pp* yields and R_{pA}

- □ Enhancement of very soft (< 10GeV) photon
- □ R_{pA} shows sizable suppression

CGC+Magnetic Field as a major photon source

- □ Formulation already available
- □ Just a matter of time…