Small-x physics probed by forward photons

Kenji Fukushima (Univ. of Tokyo)

International Workshop on
Forward Physics and Forward Calorimeter Upgrade in ALICE

The title might have been confusing… my talk is about:

Small-x physics probed by photons in forward collisions

I will address *soft* photons, but not hard photons that are literally *forward* photons…

"Forward" ⟷ Dense-Dilute Systems

Based on Brookhaven-Heidelberg-Tokyo (Kyoto) Collab.

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

Probing gluon saturation with next-to-leading order photon production at central rapidities in proton-nucleus collisions

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

Formalism

Constraining unintegrated gluon distributions from inclusive photon production in proton-proton collisions at the LHC

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

Numerics

Photon as a probe

Advantages

Clean probe — (almost) no uncertainty of hadronization

Systematic calculations feasible

Directly sensitive to nuclear PDF (for pA)

Disadvantages

Parton kinematics integrated for *inclusive* photon

Need to measure *very* soft photons

Suggestions from the experimental side welcome!

What we (can) calculate

Prompt Photons

Direct Photons ← **Isolated Photons**

↑

Fragmentation Photons

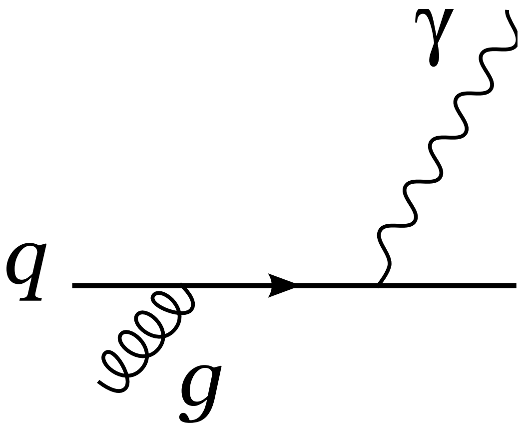
This is measured and calculated.

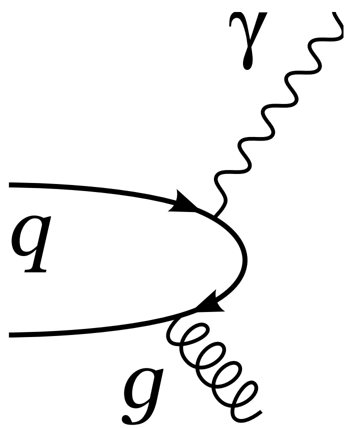
What we (can) calculate

Prompt Photons

Direct Photons

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





+ crossed

Compton **Annihilation**

What we (can) calculate

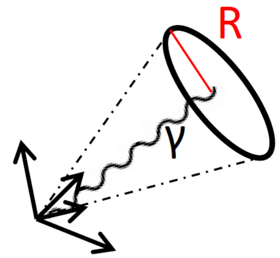
Prompt Photons

Fragmentation Photons

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

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**

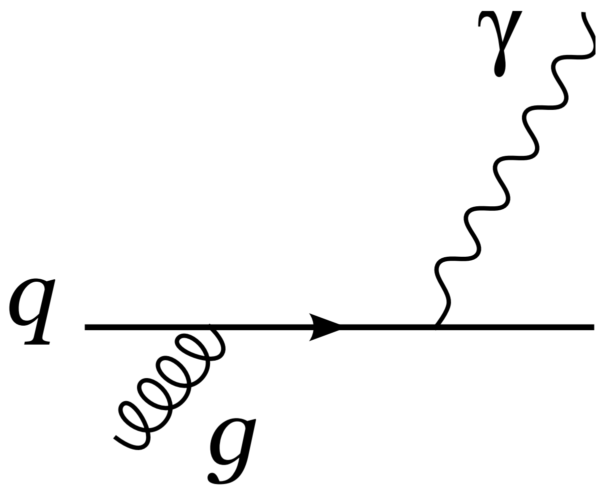
≀

Isolated Direct Photons ← **Theoretically predicted**

Fragmentation photons almost (not perfectly) dropped

Order Counting with Saturation

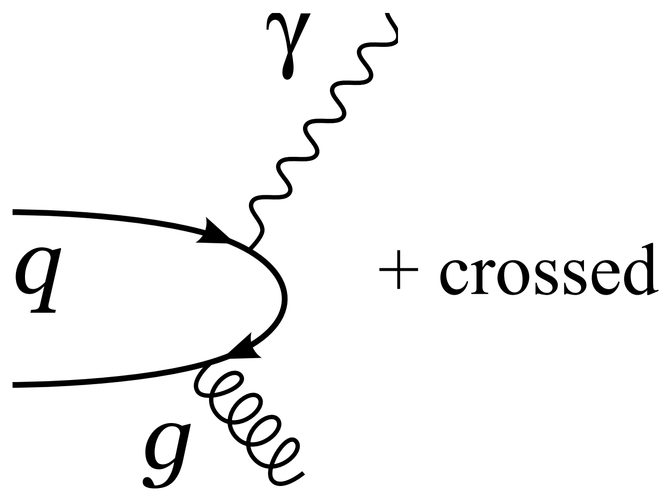
Compton Scattering



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

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

Annihilation

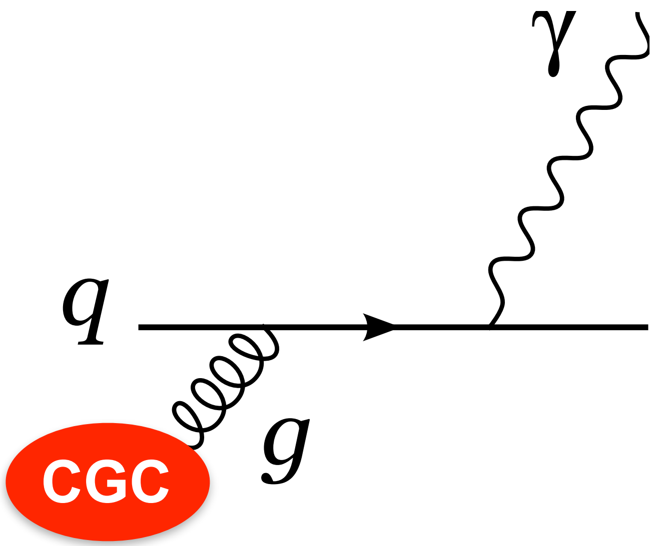


$$\propto \alpha_e \alpha_s n_q n_{\bar{q}} (1 + n_g)$$

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

Order Counting with Saturation

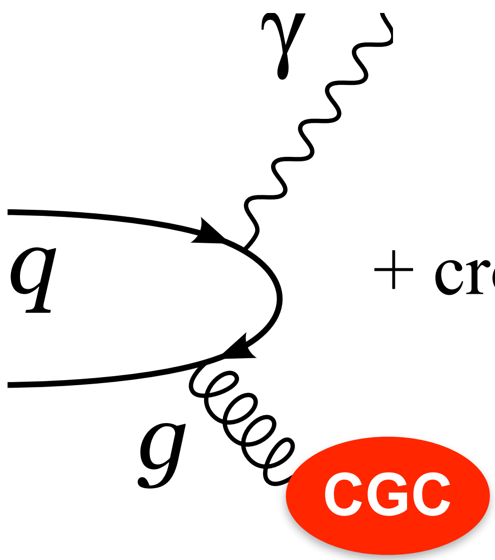
Compton Scattering



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

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

Annihilation



+ crossed

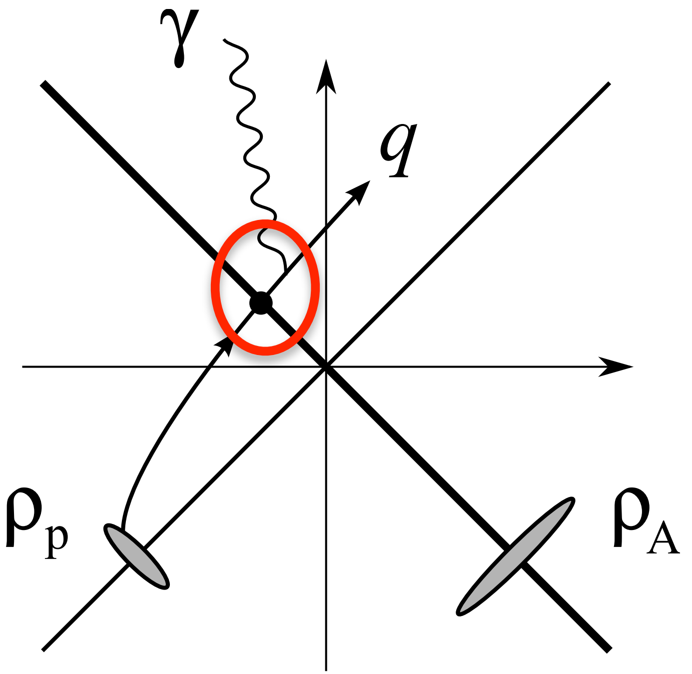
$$\propto \ \alpha_e \alpha_s n_q n_{\bar{q}} \alpha_s^{-1}$$

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

LO Photon in pA

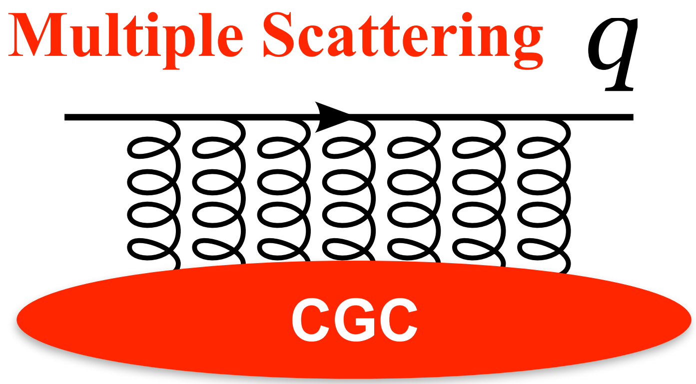
Gauge choice: $A \sim \rho_A \sim \delta(x^+)$ **Gelis-Mehtar-Tani (2006)**

(Coulomb gauge + Light cone gauge)



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

Gelis-Jalilian-Marian (2002)



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

"Leading Twist" → k_t-factorized

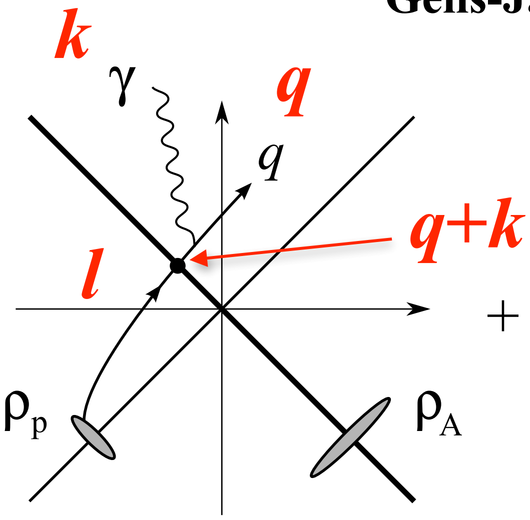
LO Photon in pA

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

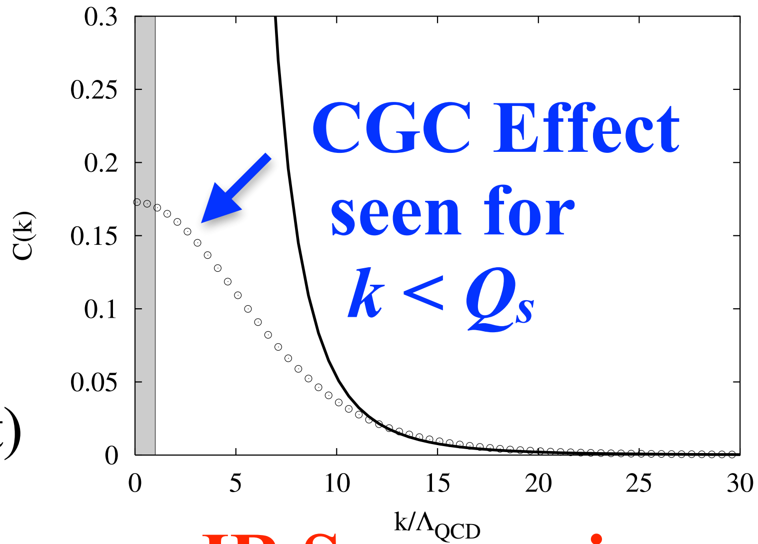
$$C(\boldsymbol{l}_\perp) \equiv \int d^2\boldsymbol{x}_\perp e^{i\boldsymbol{l}_\perp\cdot\boldsymbol{x}_\perp} e^{-B_2(\boldsymbol{x}_\perp)} = \int d^2\boldsymbol{x}_\perp e^{i\boldsymbol{l}_\perp\cdot\boldsymbol{x}_\perp}\left\langle U(0)U^\dagger(\boldsymbol{x}_\perp)\right\rangle_\rho$$

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

Gelis-Jalilian-Marian (2002)



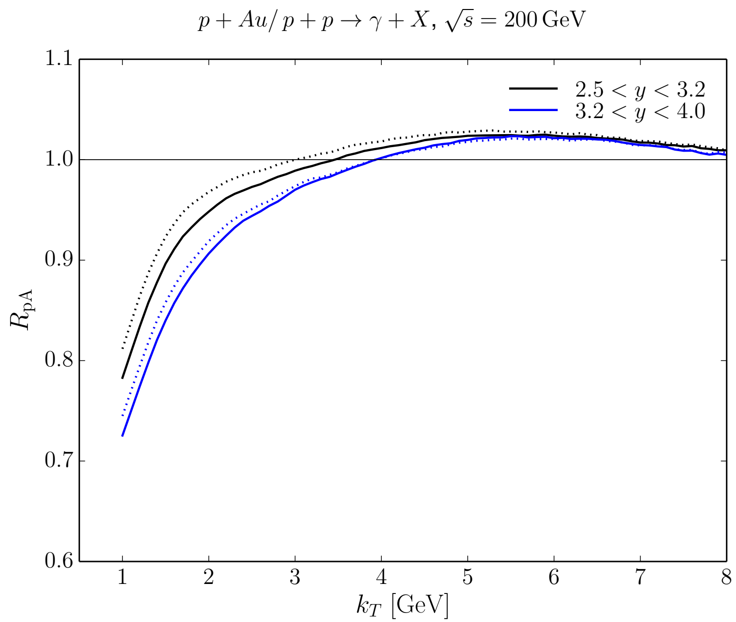
+ crossed diagram
(photon emitted first)

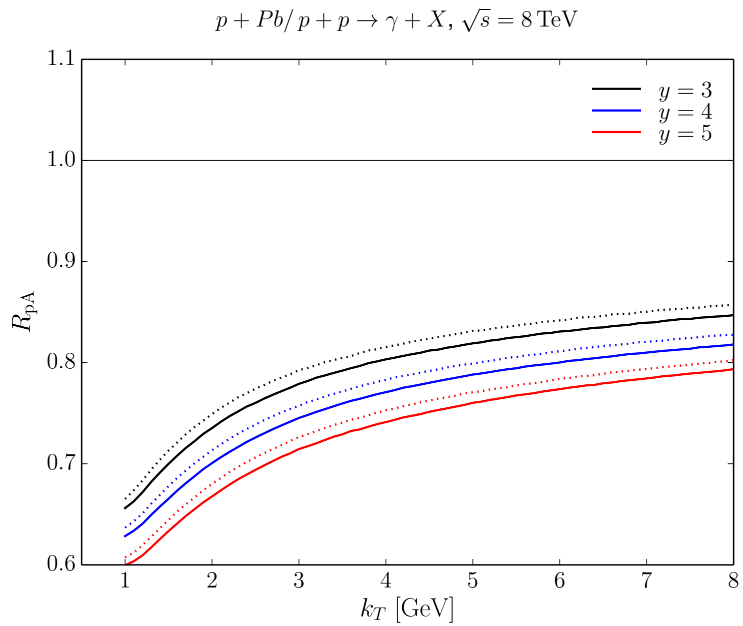


IR Suppression

LO Photon in pA

Ducloue-Lappi-Mantysaari (2017)





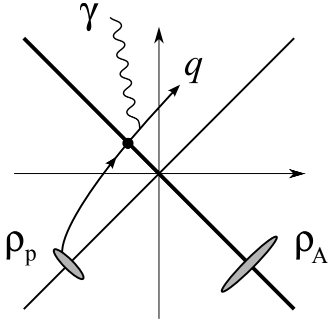
Gelis-Jalilian-Marian formula + isolation cut

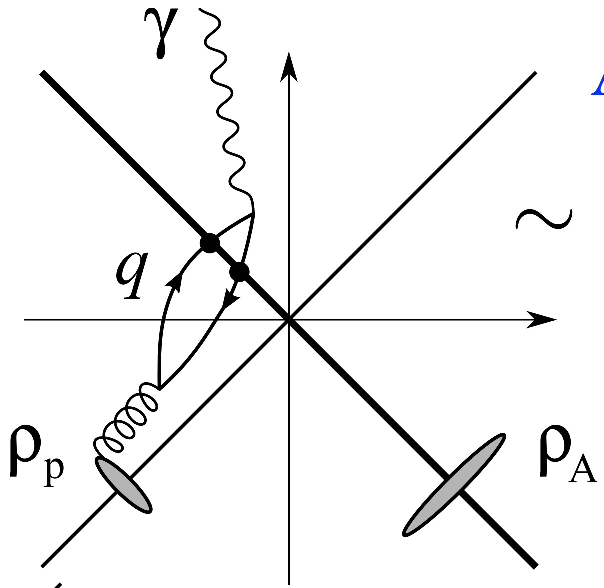
Dense — Wilson lines : MV model + rcBK

Dilute — PDF : CTEQ6

Rapidity Dependence

NLO Photon in pA

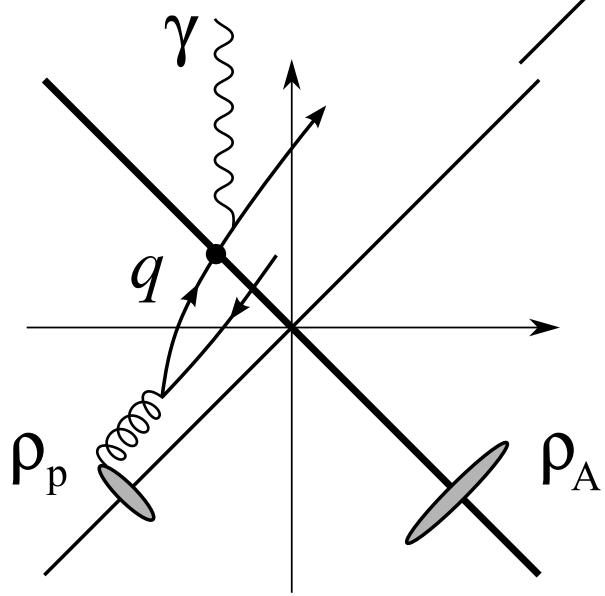




Annihilation

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

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

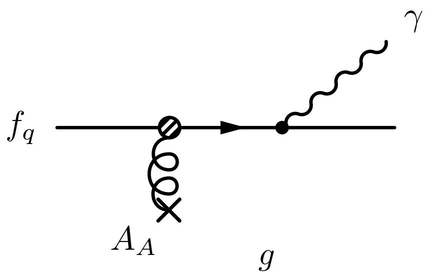
$$(g\rho_p)^2 < n_q \leq g\rho_p$$

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

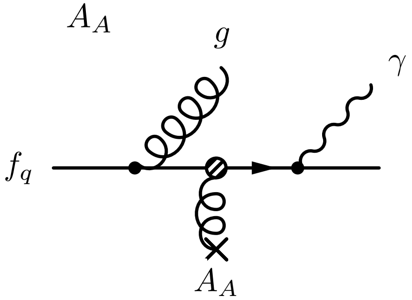
Systematic calculations feasible
Not small corrections but dominant at high energies

Diagrams (schematic)

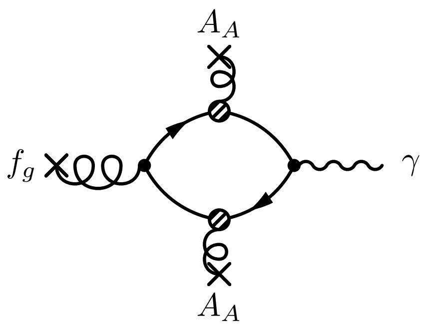
LO



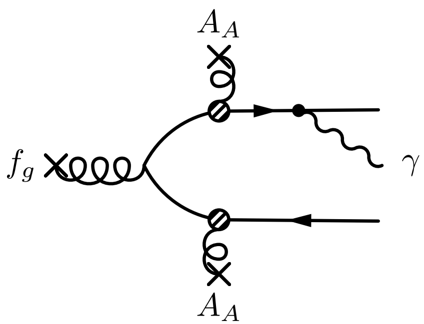
NLO



Included in
quark PDF
(LO+evolution)



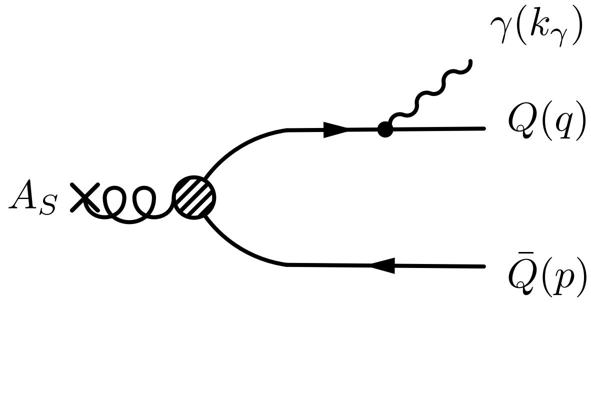
Negligibly
small



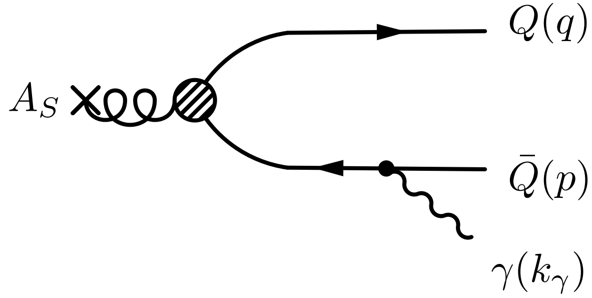
Discussed here!

This is only a schematic picture,
and the reality is as complicated as…

Diagrams (I)

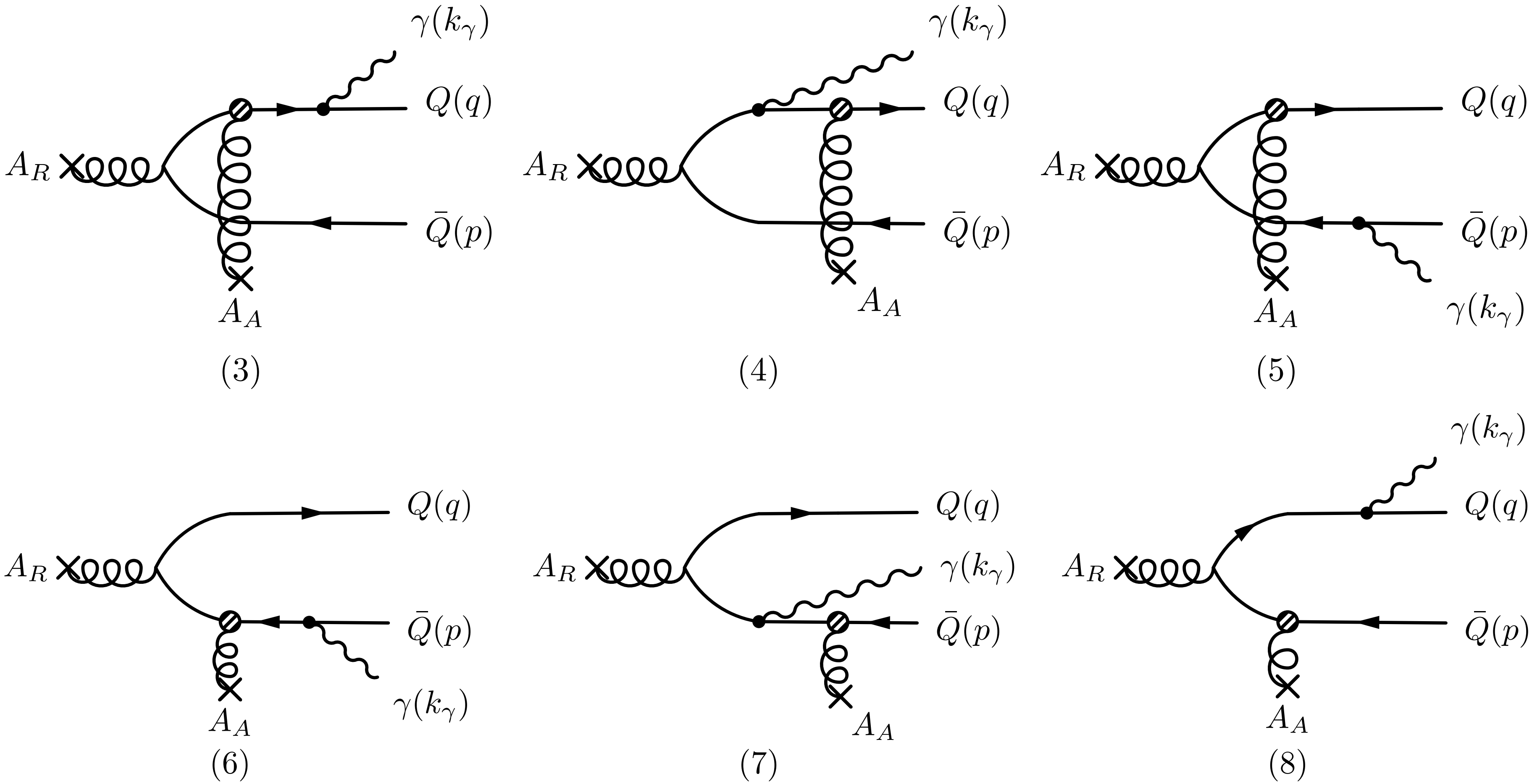


(S1)

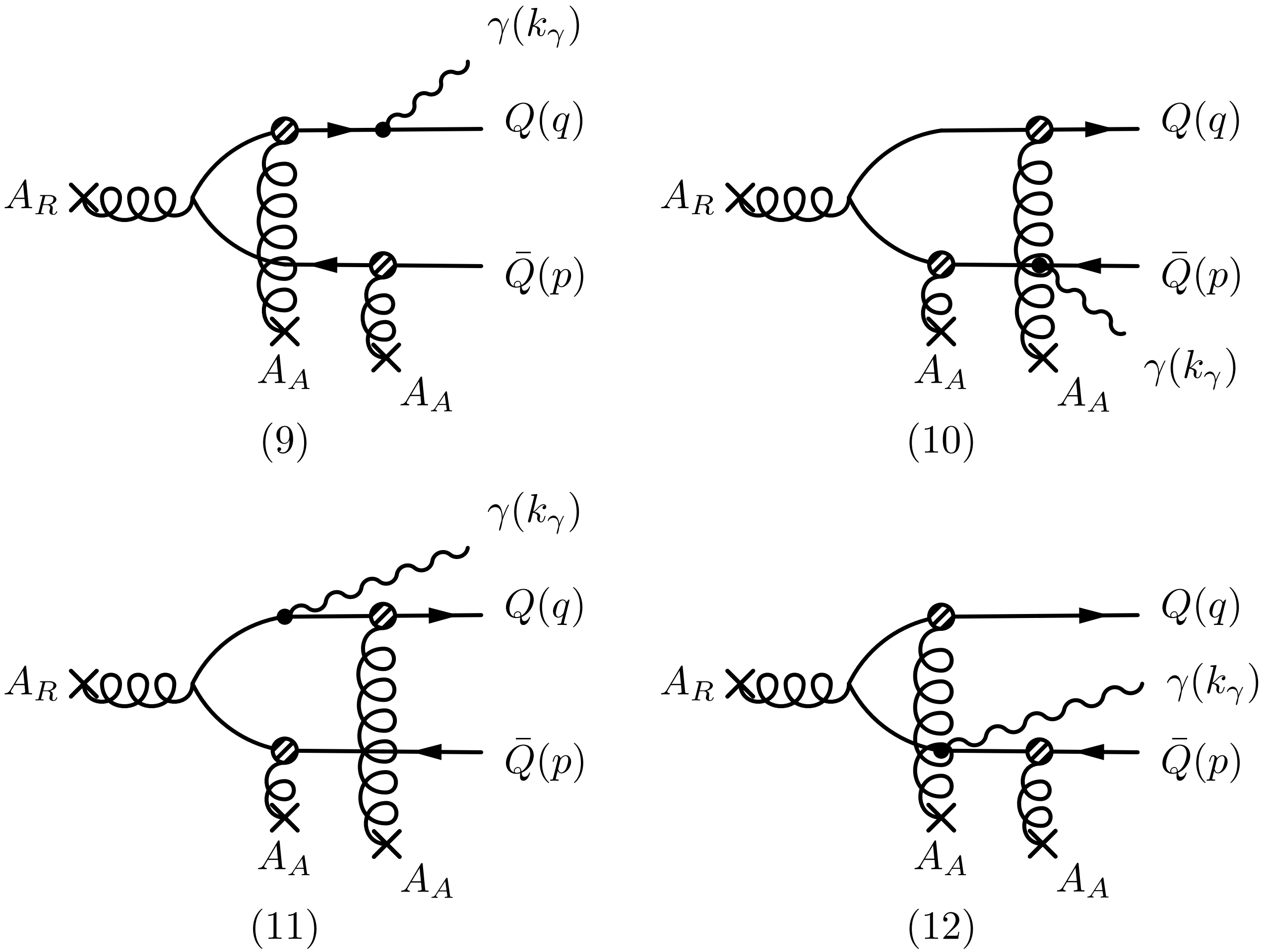


(S2)

Diagrams (II)


$\gamma(k_\gamma)$
$Q(q)$
A_R
$\bar{Q}(p)$
A_A
(3)
$\gamma(k_\gamma)$
$Q(q)$
A_R
$\bar{Q}(p)$
A_A
(4)
$Q(q)$
A_R
$\bar{Q}(p)$
A_A
$\gamma(k_\gamma)$
(5)
$Q(q)$
A_R
$\bar{Q}(p)$
A_A
$\gamma(k_\gamma)$
(6)
$Q(q)$
A_R
$\gamma(k_\gamma)$
$\bar{Q}(p)$
A_A
(7)
$\gamma(k_\gamma)$
$Q(q)$
A_R
$\bar{Q}(p)$
A_A
(8)

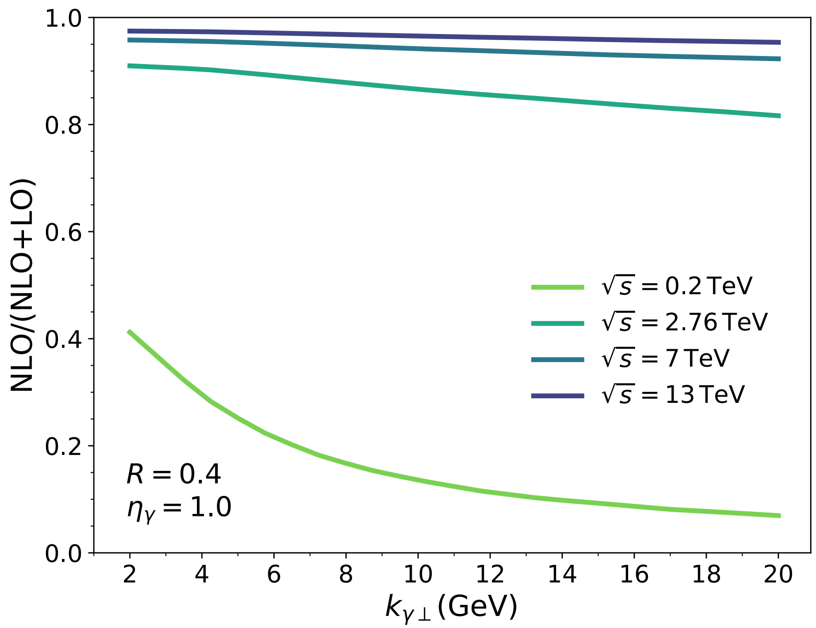
Diagrams (III)

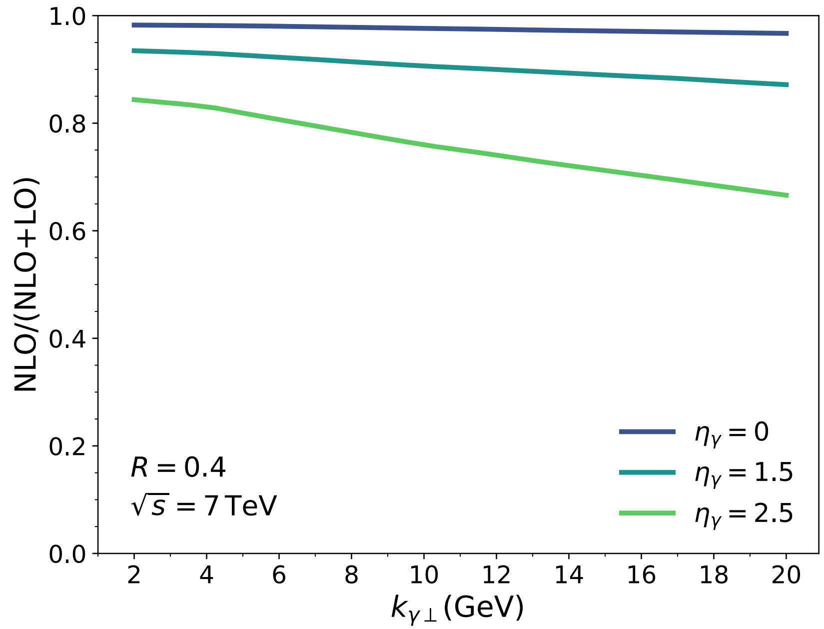


10-dimensional numerical integration needed!

LO vs. NLO with CGC

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



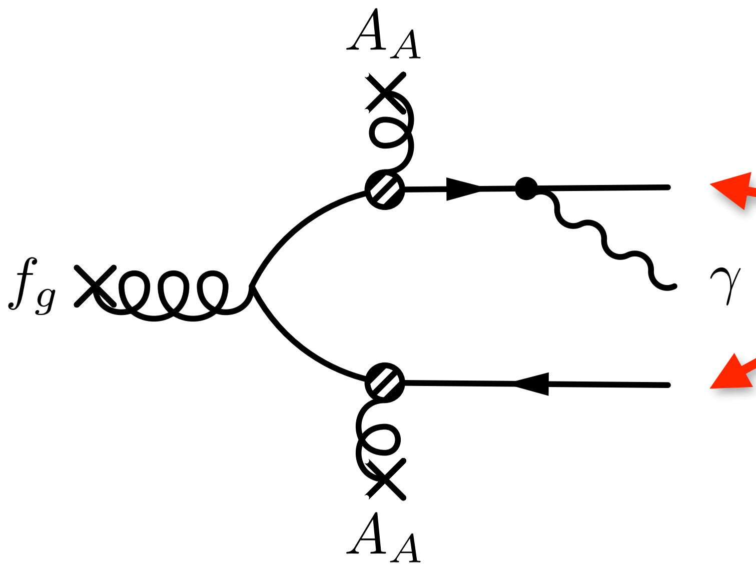


NLO becomes dominant at higher energies and with smaller photon momentum (rapidity)

Analysis on kinematics

Hard photons → Hard gluons
(more k_t-factorized)

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

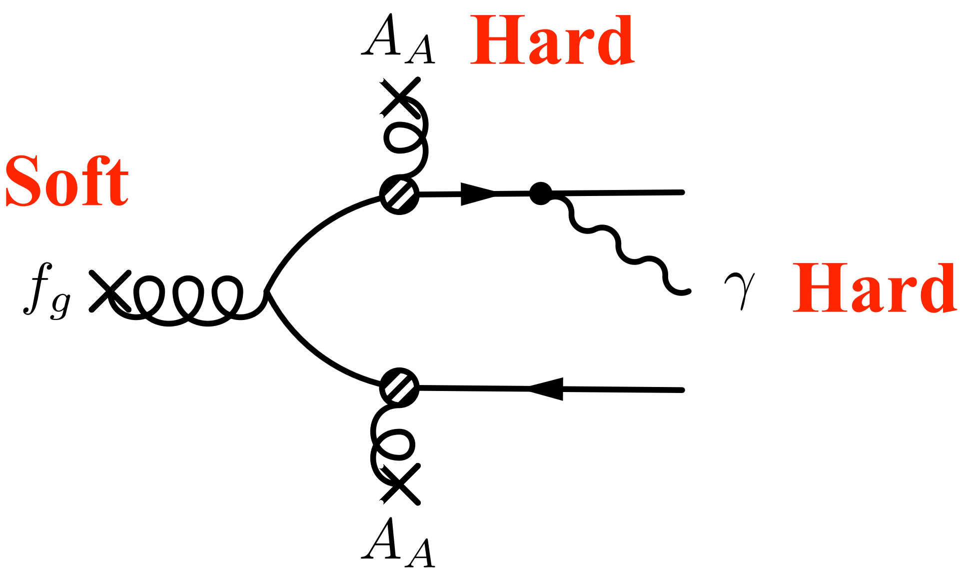


quark-antiquark integrated ("inclusive")

Analysis on kinematics

Hard photons → Hard gluons
(more k_t-factorized)

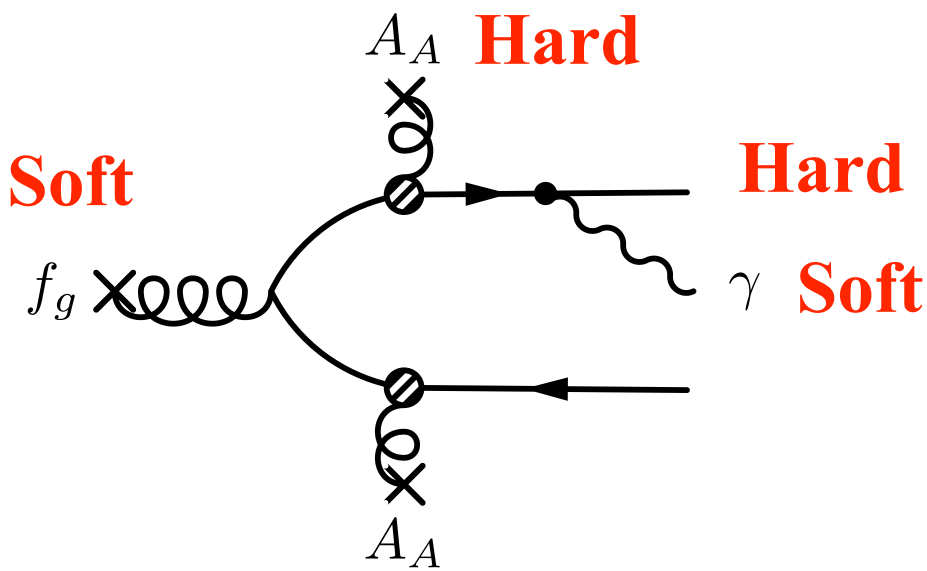
Soft photons → Soft (and thus saturation) gluons ???



Analysis on kinematics

Hard photons → Hard gluons
(more k_t-factorized)

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

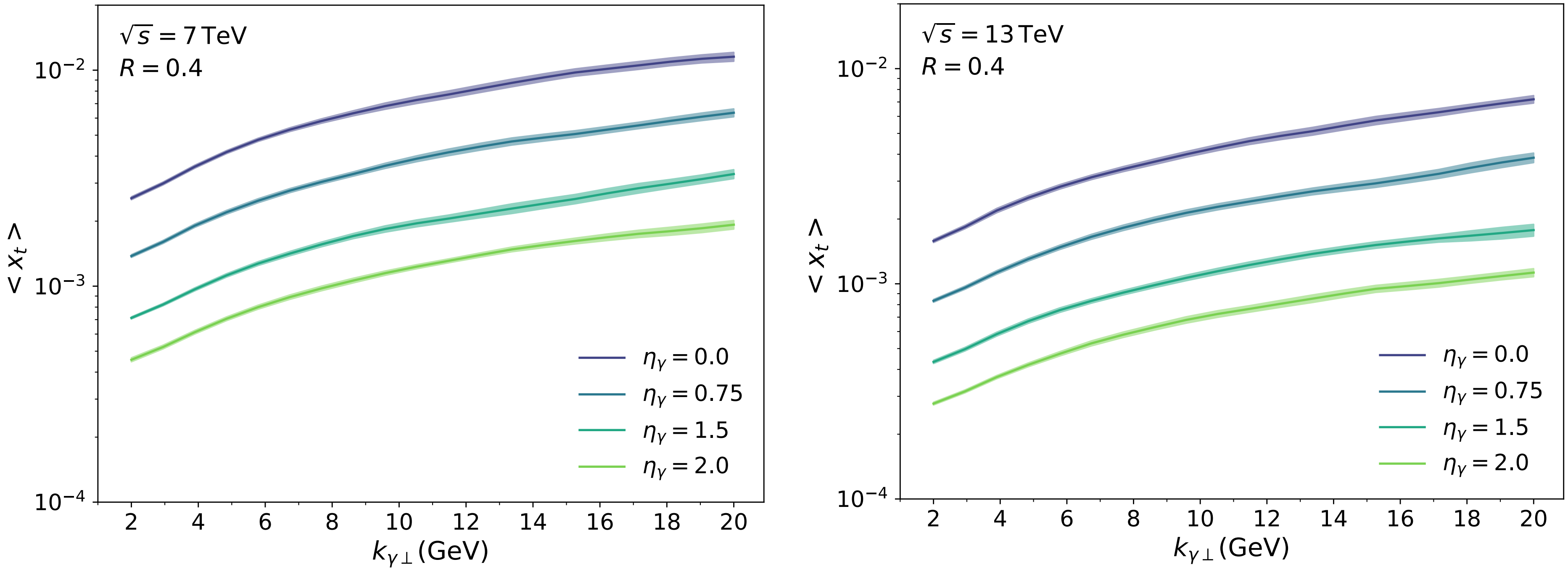


Such processes not prohibited by kinematics…

Relevant x

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

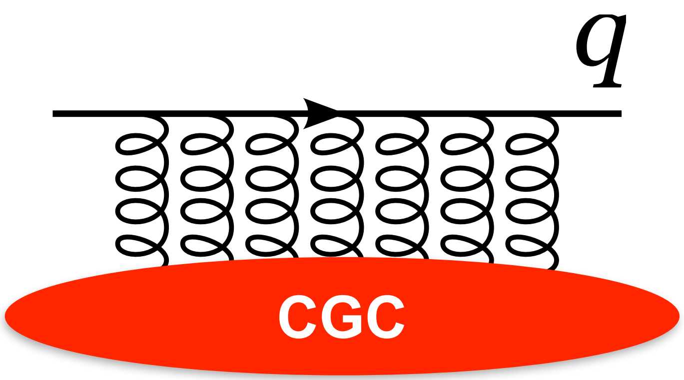
Averaged x over integrand (dominant contributions)



$\log x \sim \log 10^{-3}$ 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

Many complicated PDF reduced to only one **(one example)**

gluon-gluon

$$\int_{\boldsymbol{k}_\perp \boldsymbol{k}'_\perp} \int_{\boldsymbol{x}_\perp \boldsymbol{x}'_\perp \boldsymbol{y}_\perp \boldsymbol{y}'_\perp} \mathrm{e}^{\mathrm{i}(\boldsymbol{k}_\perp \cdot \boldsymbol{x}_\perp - \boldsymbol{k}'_\perp \cdot \boldsymbol{x}'_\perp) + \mathrm{i}(\boldsymbol{k}_{2\perp} - \boldsymbol{k}_\perp)\cdot \boldsymbol{y}_\perp - \mathrm{i}(\boldsymbol{k}_{2\perp} - \boldsymbol{k}'_\perp)\cdot \boldsymbol{y}'_\perp} \, \delta^{aa'} \, \mathrm{tr}_c \underline{\langle t^b U^{ba}(\boldsymbol{x}_\perp) t^{b'} U^{\dagger a'b'}(\boldsymbol{x}'_\perp) \rangle}$$

$$\equiv \frac{2N_c \alpha_S}{\boldsymbol{k}_{2\perp}^2} \, \phi_A^{g,g}(\boldsymbol{k}_{2\perp}) \, .$$

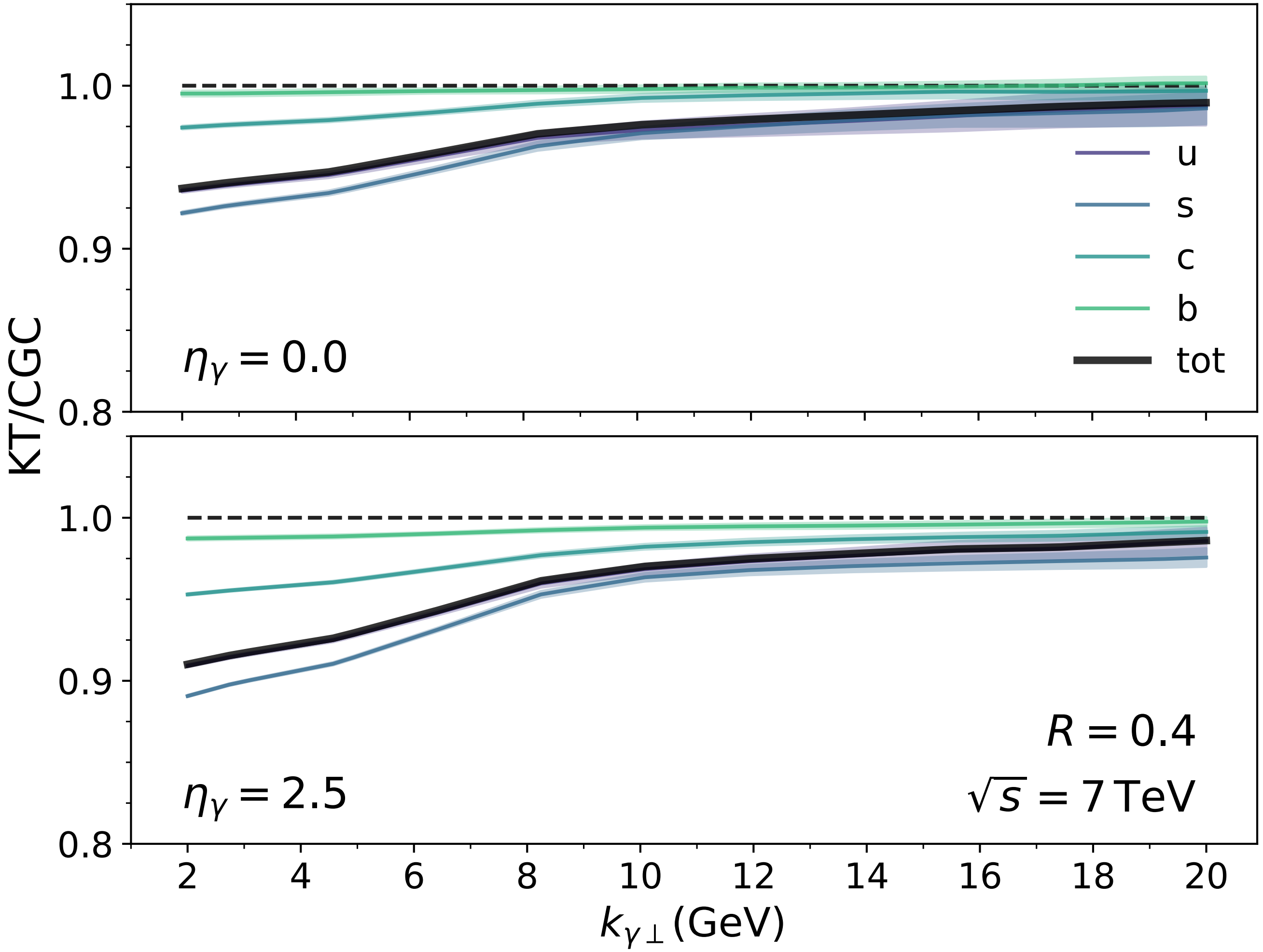
quark-antiquark-gluon

$$\int_{\boldsymbol{k}'_\perp} \int_{\boldsymbol{x}_\perp \boldsymbol{x}'_\perp \boldsymbol{y}_\perp \boldsymbol{y}'_\perp} \mathrm{e}^{\mathrm{i}(\boldsymbol{k}_\perp \cdot \boldsymbol{x}_\perp - \boldsymbol{k}'_\perp \cdot \boldsymbol{x}'_\perp) + \mathrm{i}(\boldsymbol{k}_{2\perp} - \boldsymbol{k}_\perp)\cdot \boldsymbol{y}_\perp - \mathrm{i}(\boldsymbol{k}_{2\perp} - \boldsymbol{k}'_\perp)\cdot \boldsymbol{y}'_\perp} \, \delta^{aa'} \, \mathrm{tr}_c \underline{\langle \tilde{U}(\boldsymbol{x}_\perp) t^a \tilde{U}^\dagger(\boldsymbol{y}_\perp) t^{b'} U^{\dagger a'b'}(\boldsymbol{x}'_\perp) \rangle}$$

$$\equiv \frac{2N_c \alpha_S}{\boldsymbol{k}_{2\perp}^2} \, \phi_A^{q\bar{q},g}(\boldsymbol{k}_\perp, \boldsymbol{k}_{2\perp} - \boldsymbol{k}_\perp; \boldsymbol{k}_{2\perp}) \, ,$$

LT-limit $\phi_A^{q\bar{q},g}(Y_A, \boldsymbol{k}_\perp, \boldsymbol{k}_{2\perp} - \boldsymbol{k}_\perp; \boldsymbol{k}_{2\perp}) = \frac{1}{2}(2\pi)^2 \varphi_A(Y_A, \boldsymbol{k}_{2\perp}) \left[\delta^{(2)}(\boldsymbol{k}_\perp) + \delta^{(2)}(\boldsymbol{k}_{2\perp} - \boldsymbol{k}_\perp)\right]$

Comparison w/wo Resummation



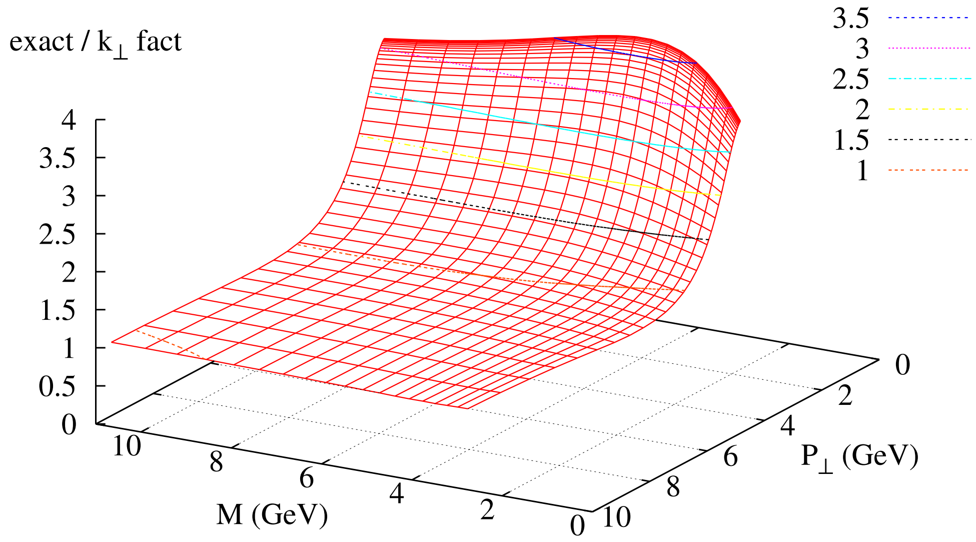
10% difference

10% enhancement by saturation (not suppression!)

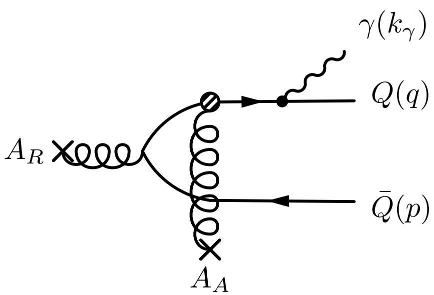
Comparison w/wo Resummation

Similar enhancement also in quark-antiquark

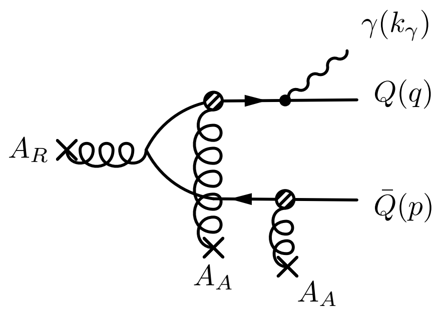
Fujii-Gelis-Venugopalan (2006)



Enhancement attributed to more phase space



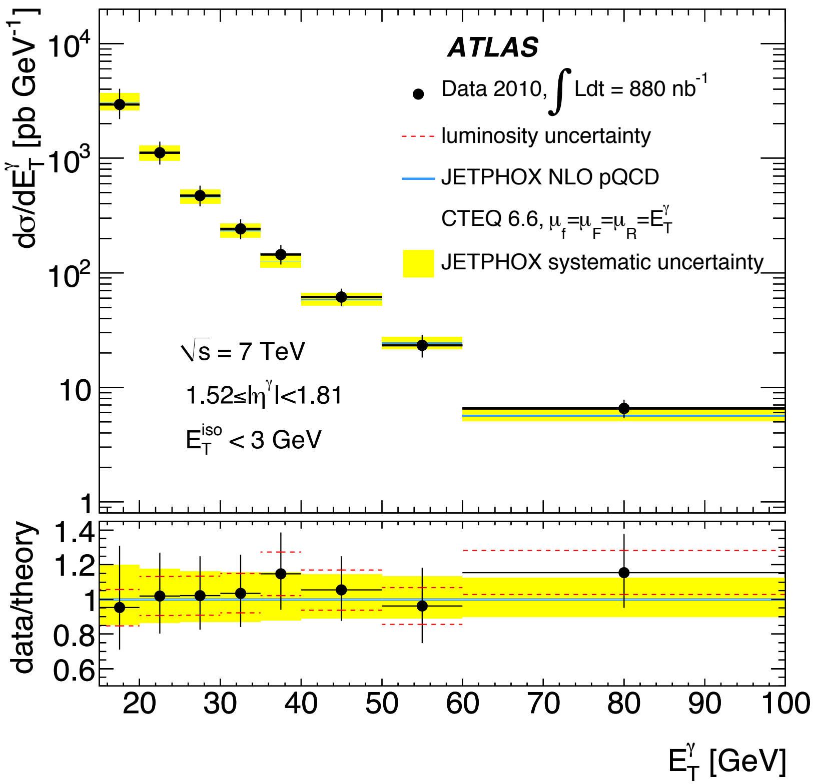
Kept



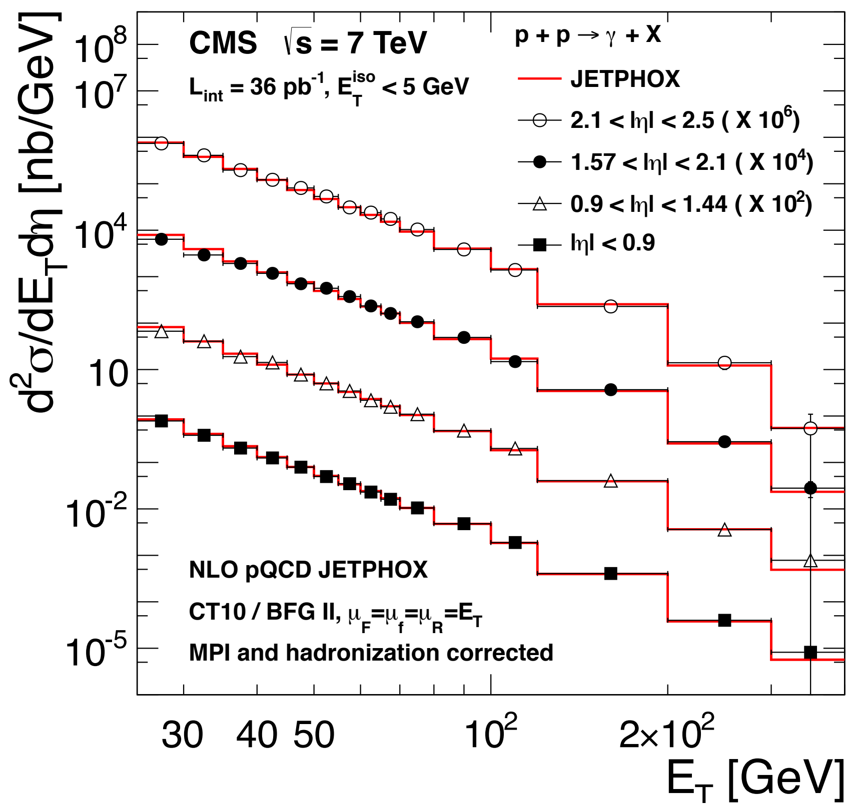
Left

Data

1012.4389 [hep-ex]



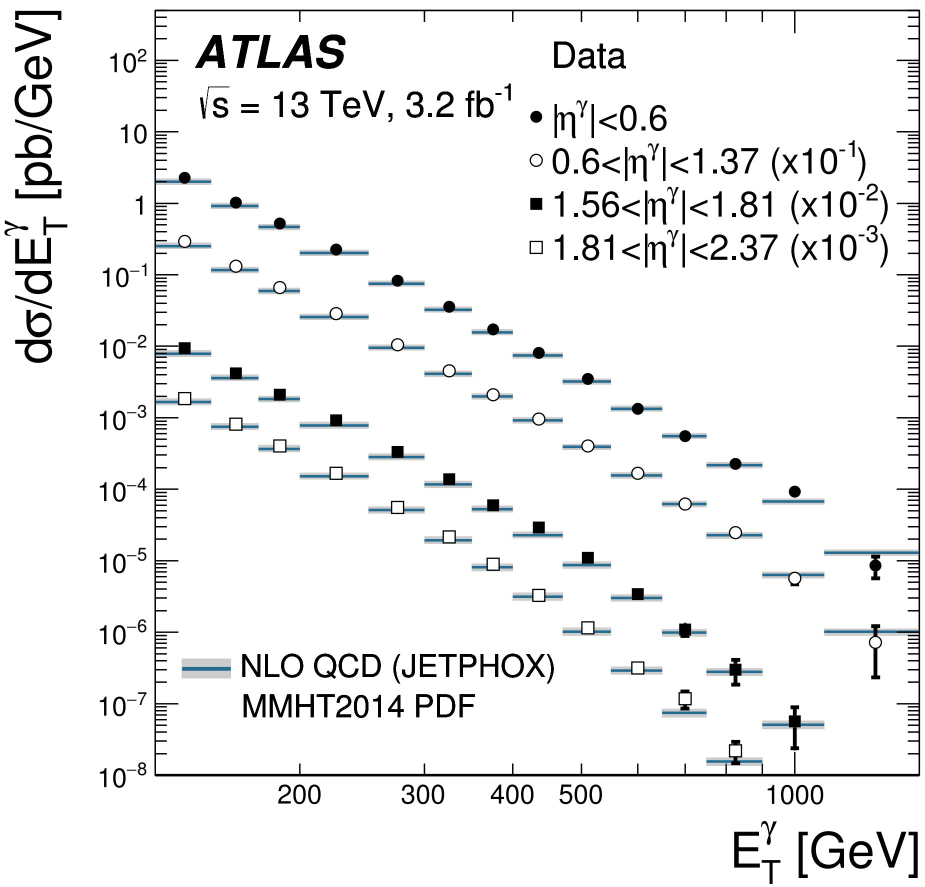
1108.2044 [hep-ex]



For "saturation physics" *soft* photons needed

Data

1701.06882 [hep-ex]



$$\log(Q/\Lambda_{\rm QCD}) \lesssim |\log x| \sim \log 10^3$$

For small-x being dominant, *Q* must be smaller than 100GeV scales (or at most tens GeV)

Good for pQCD, but too hard for CGC

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**

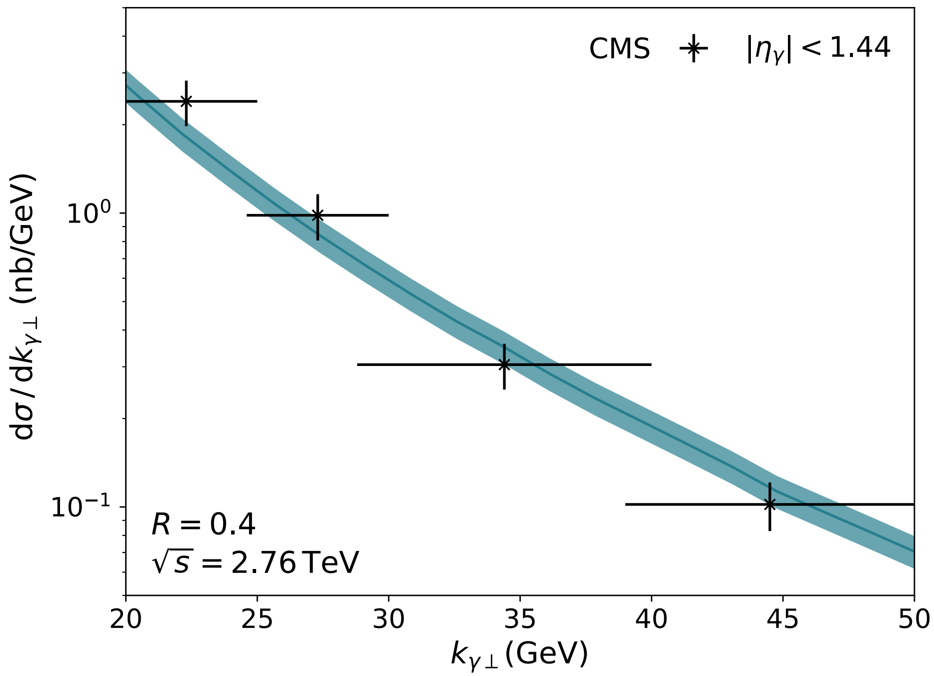
(small-x evol. but DGLAP not considered yet…)

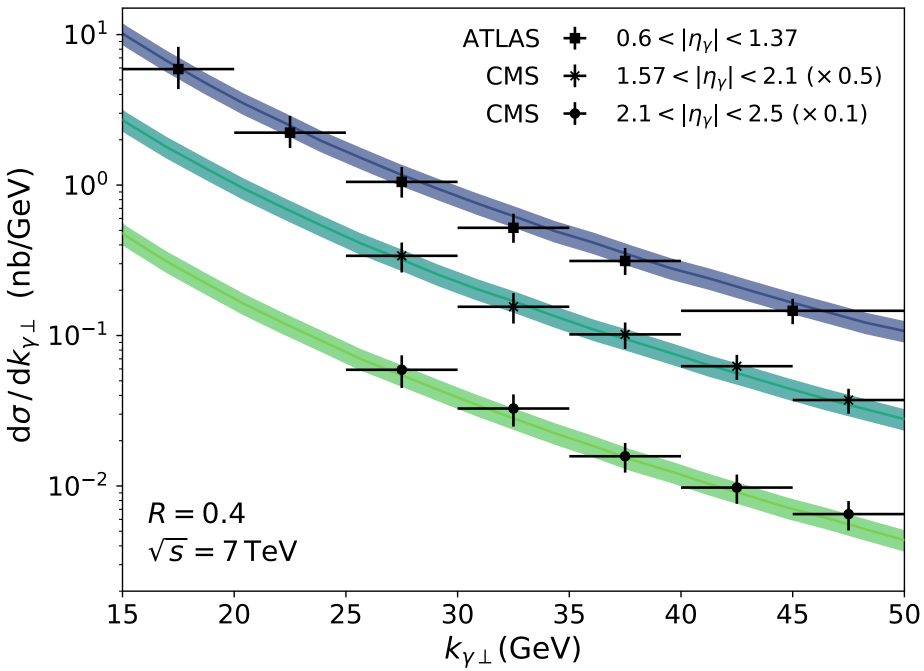
***K*-factor** **$K = 2.4$ (cf. $K = 2.5$ for *D*-meson production)**

Comparison to "Available" Data

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

Photons in pp at LHC



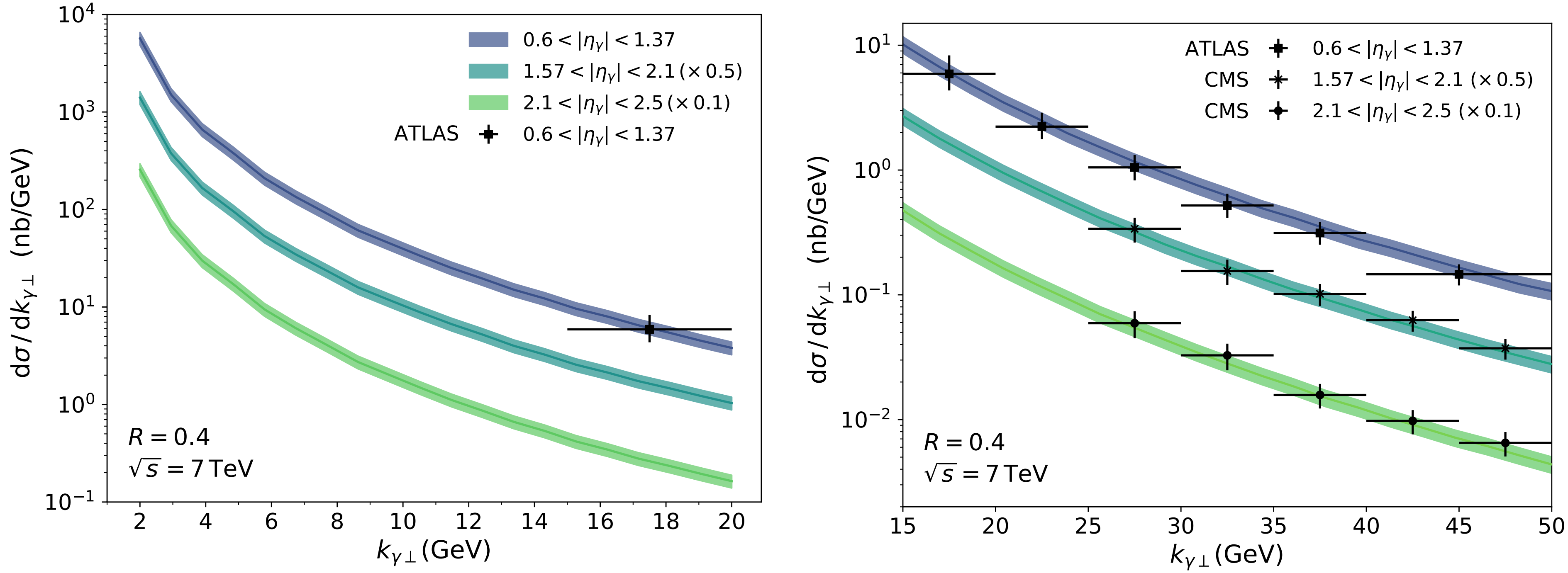


Maybe okay, but maybe DGLAP corrections…

Comparison to "Available" Data

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

Photons in pp at LHC



Enhancement here could signal gluon saturation

Summary

NLO+CGC completed

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

Applied to pp (at nonzero rapidity)

- □ Enhancement of very soft (<10GeV) photon
- □ DGLAP not yet considered but could be

pA would be far more interesting

- □ Calculation only straightforward (the same)
- □ Data ?

Outlooks

Our framework is intended for pA or pp in forward

For the moment no experimental date in kinetic region relevant for the CGC effects

CGC accessible by soft direct photons ~ a few GeV

In pA the nuclear PDF could be probed directly

CGC effects would enhance soft direct photons ?