



# *Inclusive isolated photon in pp collisions up to the next leading order with CGC*



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# **Terminology on Photon**

# *Many Similar Terminologies*



**Prompt Photons**

**Thermal Photons**

**Direct Photons**

**Hadronic Decays**

**Fragmentation Photons**

**Isolated Photons**

**Inclusive Photons**

# *Many Similar Terminologies*



Prompt Photons

Thermal Photons

Direct Photons

Hadronic Decays

Fragment **All photons measured experimentally  
(Theoretically, all others integrated out)**

Isolated Photons

**Inclusive Photons**

# Many Similar Terminologies



Prompt Photon

Coming from something other than  
hadronic decays (fragmentation)  
(interested very much)

**Direct Photons**

**Hadronic Decays**

**Fragmentation Photons**

Isolated Photon

No more information than observed  
hadron spectra (not much interested)

# *Many Similar Terminologies*



## **Prompt Photons**

## **Thermal Photons**

Direct Photo:

**Emitted from thermally equilibrated  
QGP and hadronic matter  
— final state effects —  
(initial temperature inferred in AA)**

Fragmentation Photons

**From pQCD processes  
— initial state effects —  
(parton distribution functions inferred in pp, pA)**

Isol

# *Many Similar Terminologies*



**Prompt Photons**

**Direct Photons**

**← Isolated Photons**

**Fragmentation Photons**

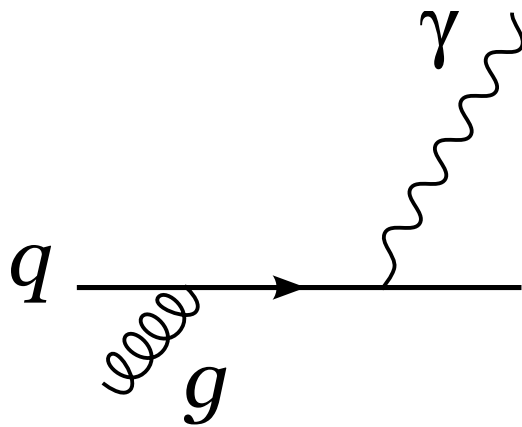
**In pp and pA where thermal matter not created**

# Many Similar Terminologies

**Prompt Photons**

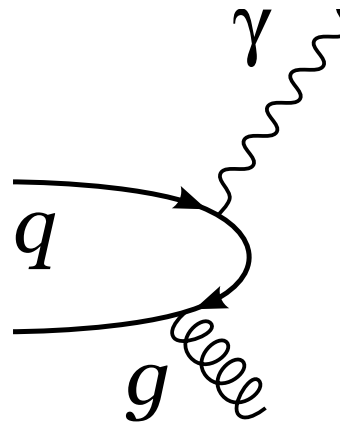
**Direct Photons**

$$gq \rightarrow \gamma q$$



**Compton**

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



+ crossed

**Annihilation**



# *Many Similar Terminologies*



**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...**

# Many Similar Terminologies



**Prompt Photons**

+

**Isolation Cut**

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

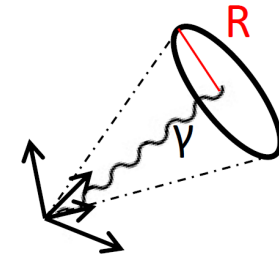
||

**Isolated Photons** ← Experimentally measured

}

**Isolated Direct Photons** ← Theoretically predicted

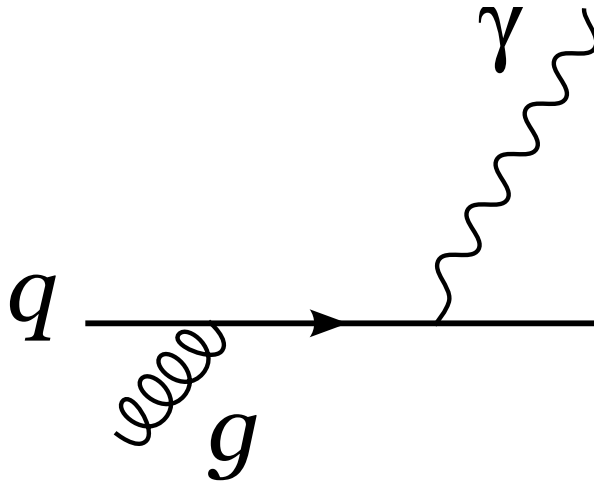
**Fragmentation photons almost (not perfectly) dropped**



# CGC Calculus

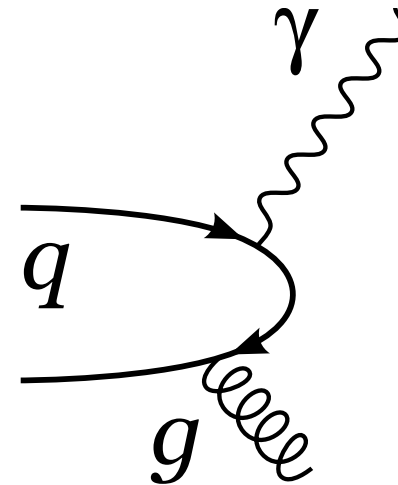
# Why CGC ?

## Compton Scattering



$$\propto \alpha_e \alpha_s n_q (1 - n_q) n_g$$
$$(qg \rightarrow q\gamma)$$

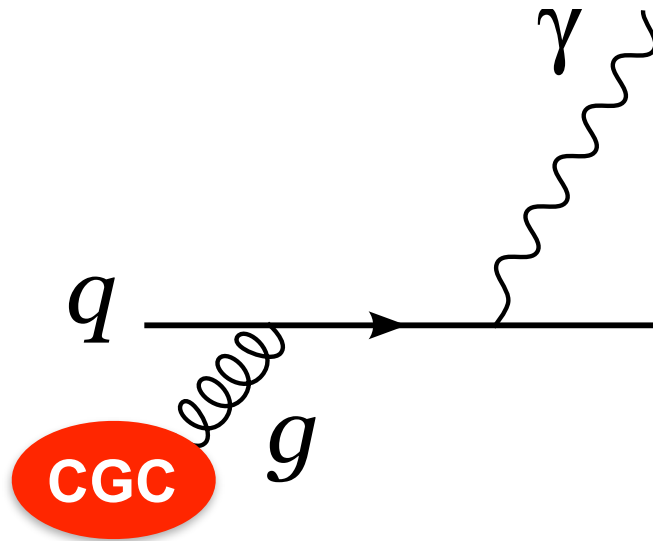
## Annihilation



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

# Why CGC ?

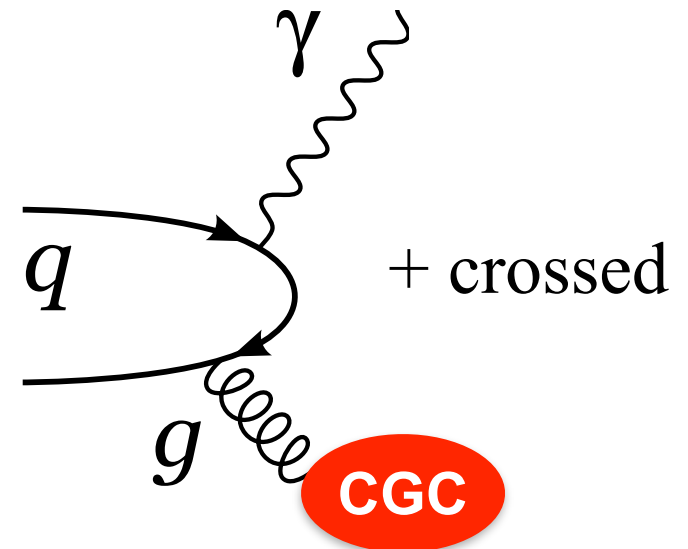
## Compton Scattering



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

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

## Annihilation



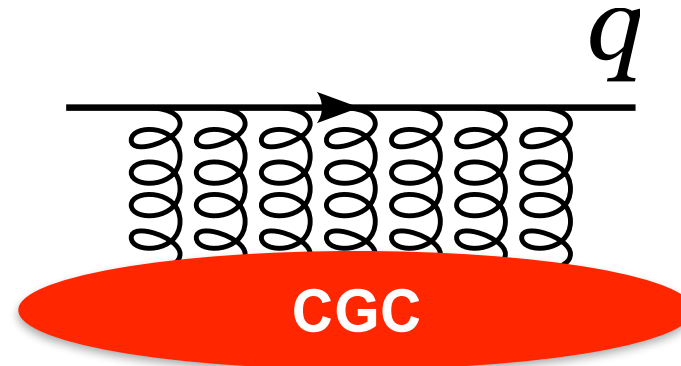
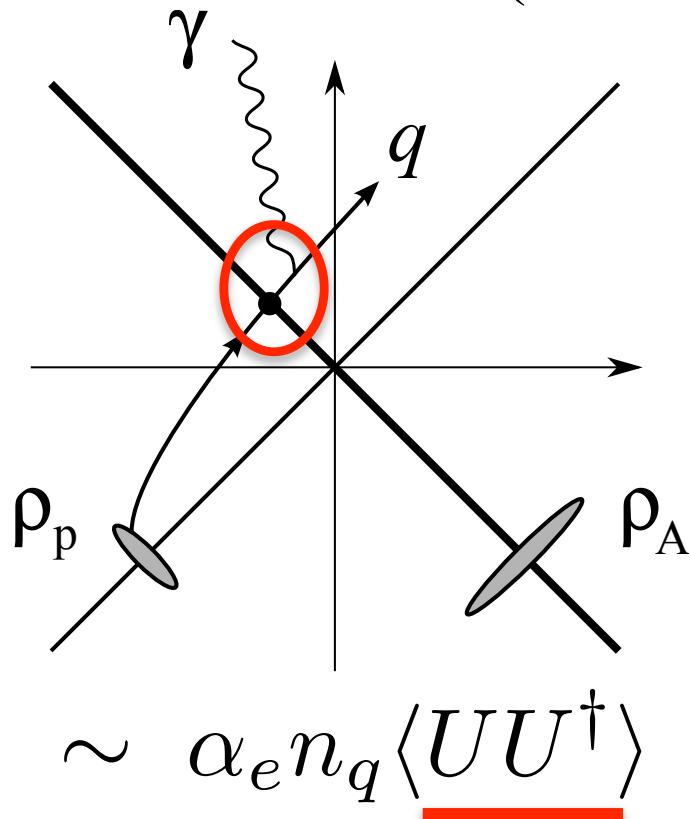
$$\propto \alpha_e \alpha_s n_q n_{\bar{q}} \alpha_s^{-1}$$

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

# CGC Calculation for Photon

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

(Coulomb gauge + Light cone gauge)



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

**Multiple Scattering with CGC**

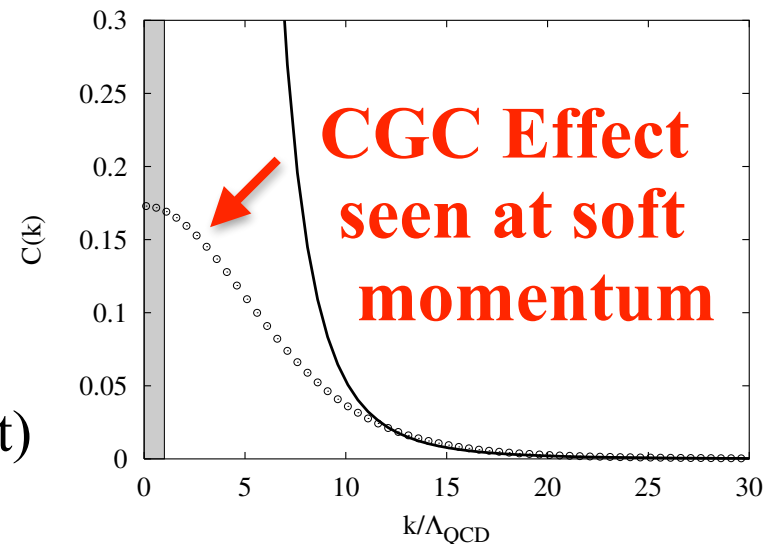
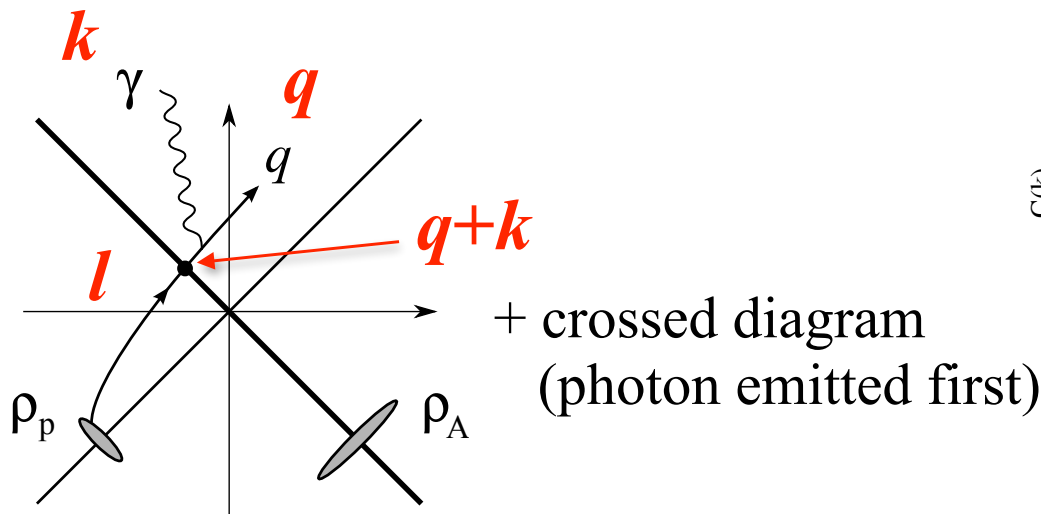
Gelis-Jalilian-Marian (2002)

# CGC Calculation for Photon

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

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

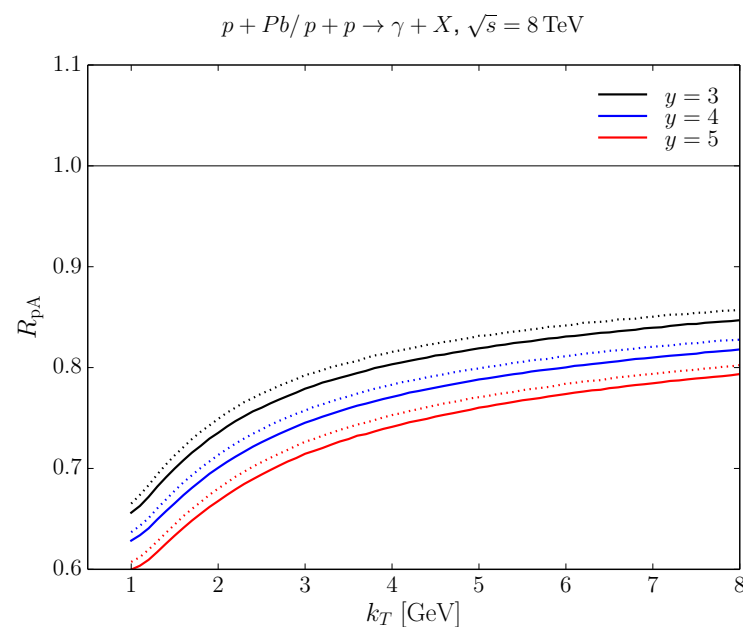
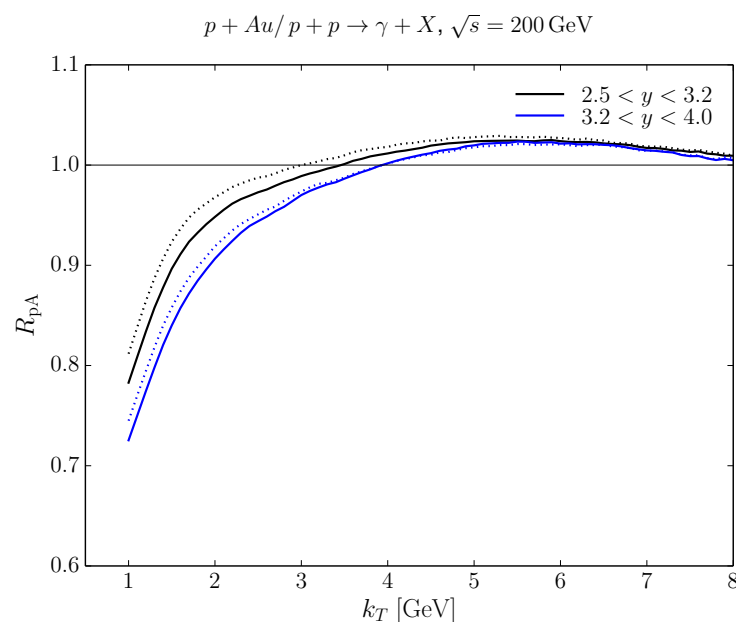
$$B_2(\mathbf{x}_{\perp} - \mathbf{y}_{\perp}) \equiv Q_s^2 \int d^2\mathbf{z}_{\perp} [G_0(\mathbf{x}_{\perp} - \mathbf{z}_{\perp}) - G_0(\mathbf{y}_{\perp} - \mathbf{z}_{\perp})]^2$$



Gelis-Jalilian-Marian (2002)

# Some Updates

## Ducloue-Lappi-Mantysaari (2017)



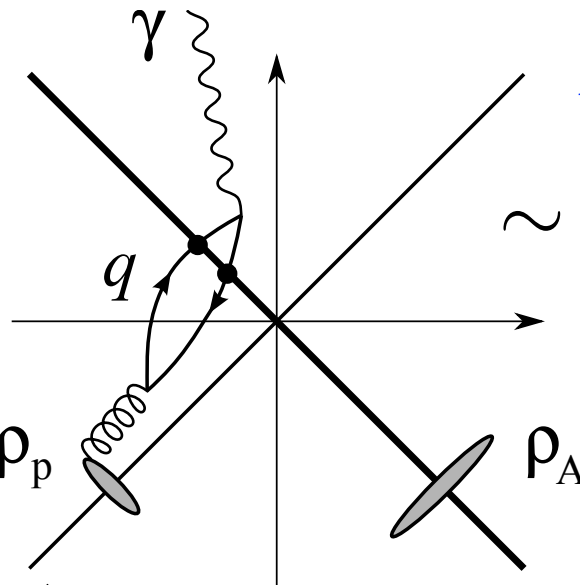
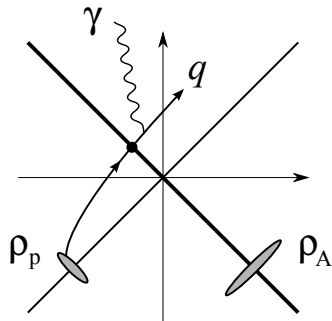
**Gelis-Jalilian-Marian formula + isolation cut**

**Dense : MV model + rcBK**

**Dilute : Quark PDF (CTEQ6)**



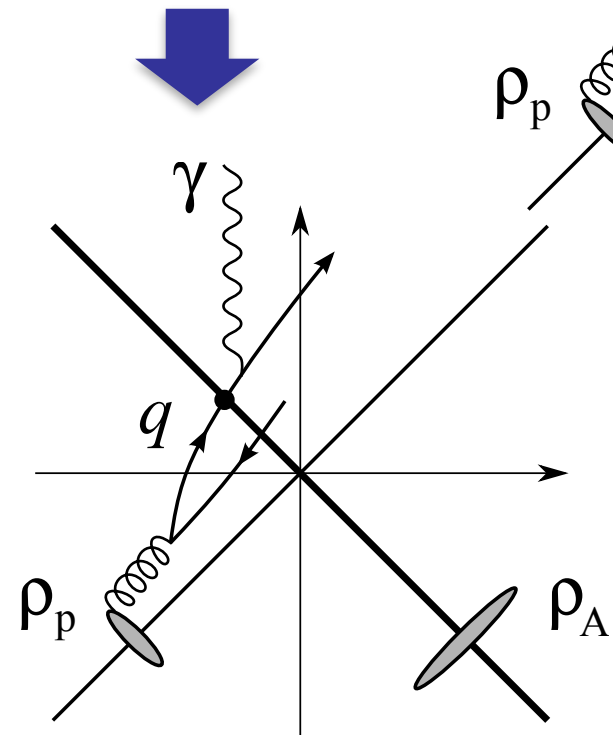
# CGC Calculation for Photon



**Annihilation**

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

**Benic-Fukushima (2016)**



**Bremsstrahlung**

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

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

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

# CGC Calculation for Photon



$$\mathbf{LO:} \quad \sim \alpha_e n_q \langle UU^\dagger \rangle$$

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

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

**NLO is overwhelming but the pA expansion still works**

**Systematic calculations feasible**

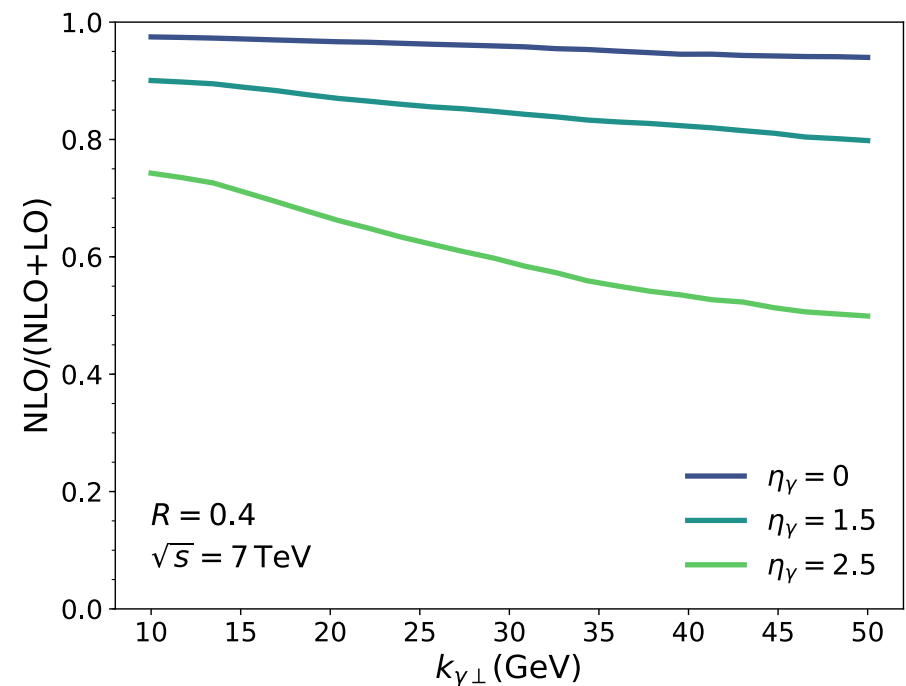
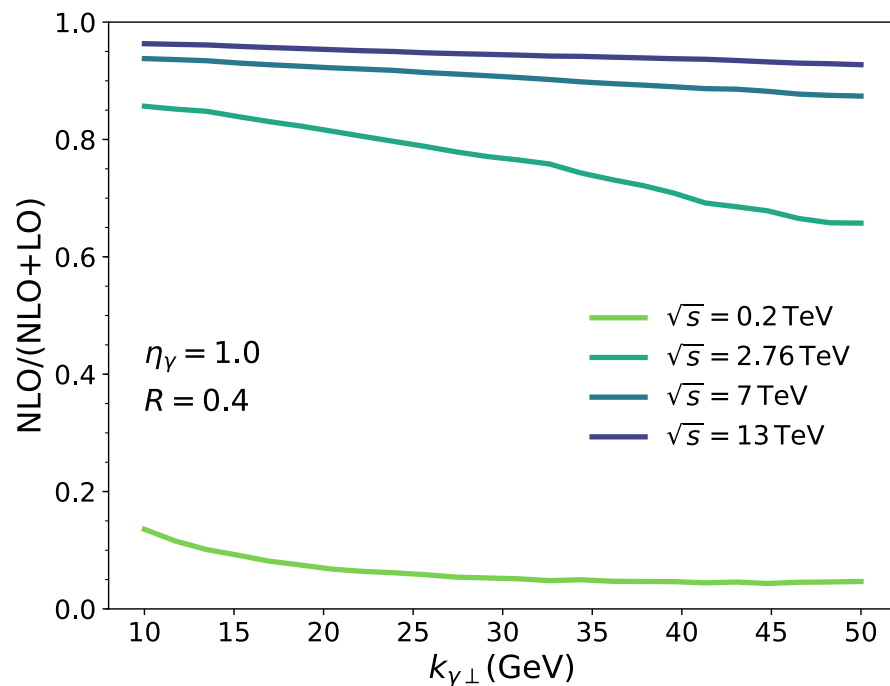
**Not small corrections but dominant at high energies**

**pA photon data (hopefully) coming very soon**

# CGC Calculation for Photon



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

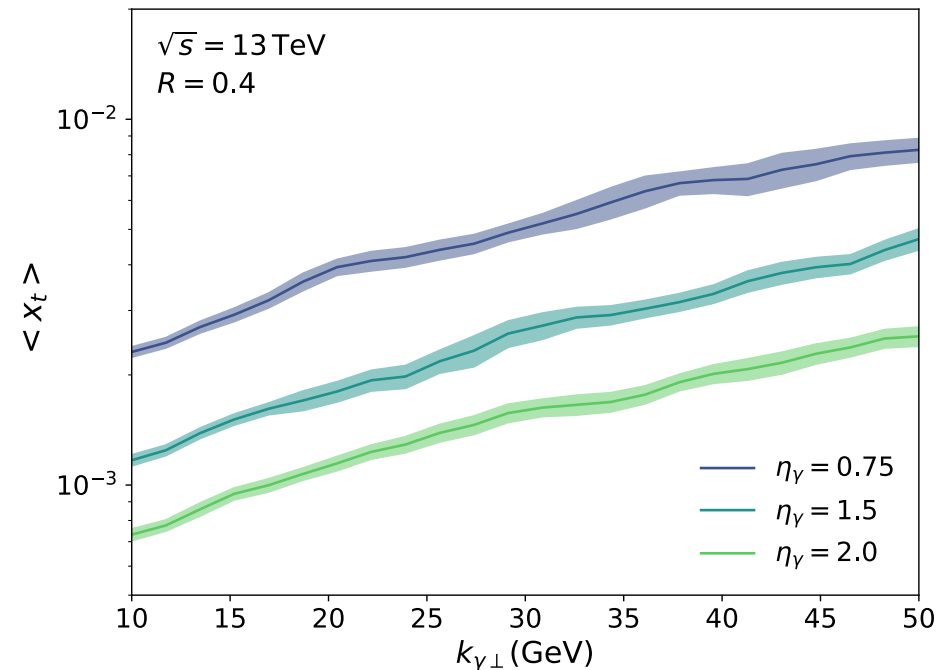
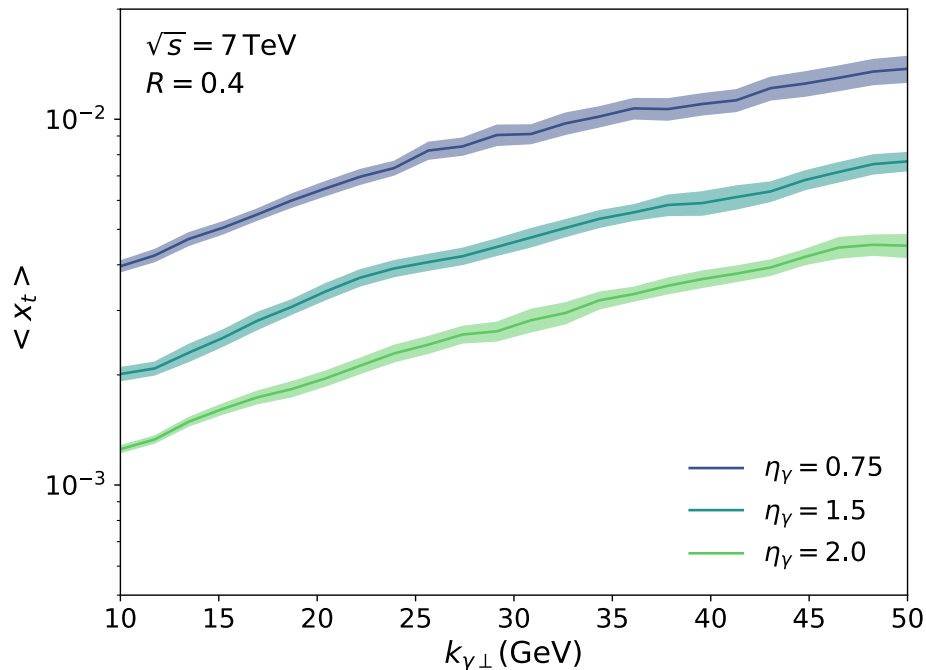


**NLO becomes dominant at higher energies  
and with smaller photon momentum, as expected**

# CGC Calculation for Photon



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

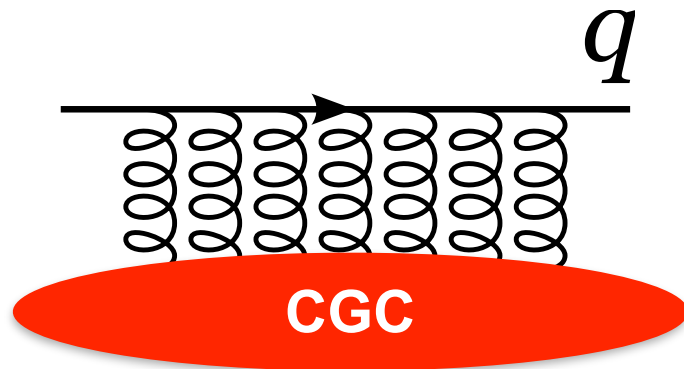


**NLO becomes more important  
where relevant  $x$  is smaller**

# CGC Calculation for Photon



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

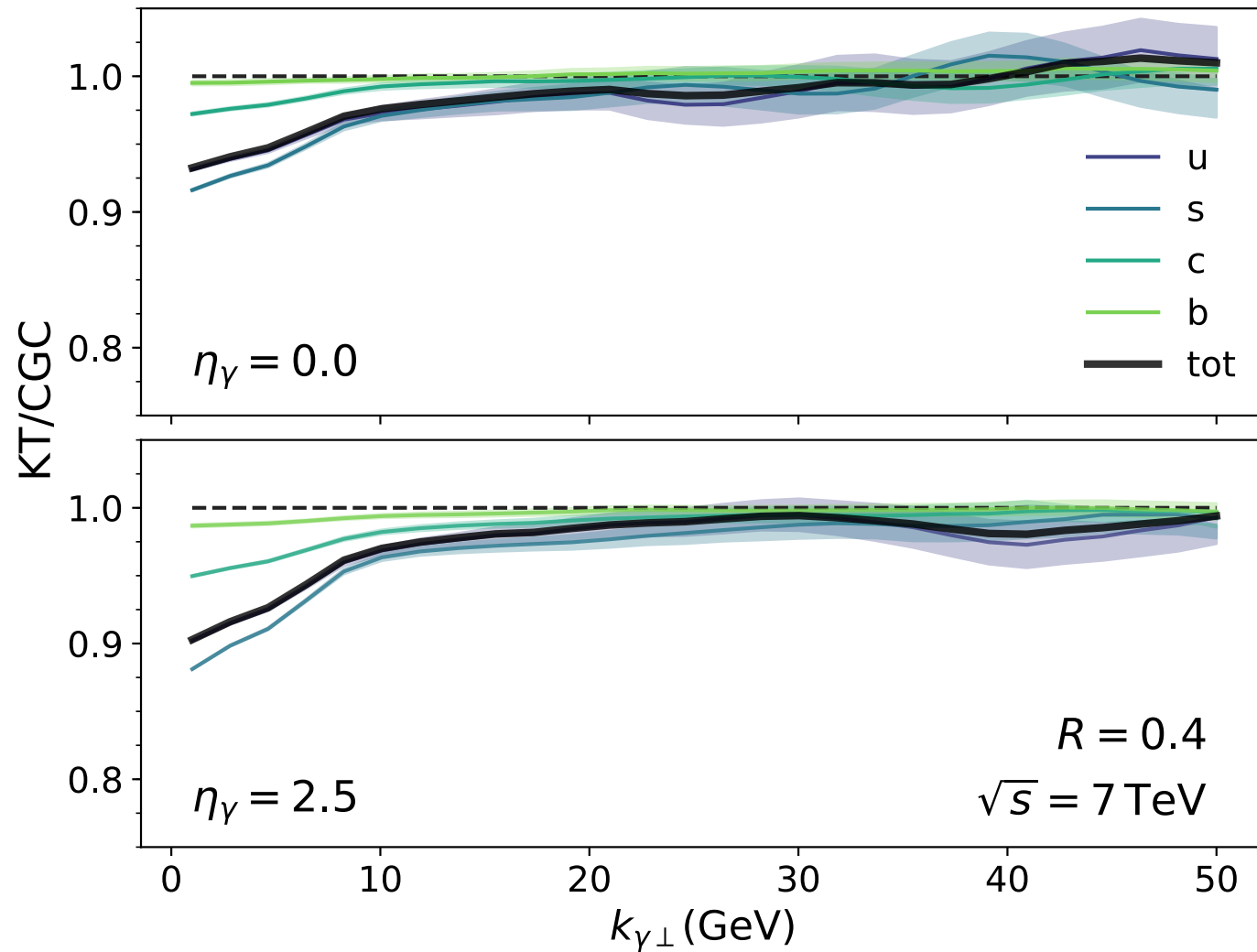


replaced by a perturbative vertex

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**

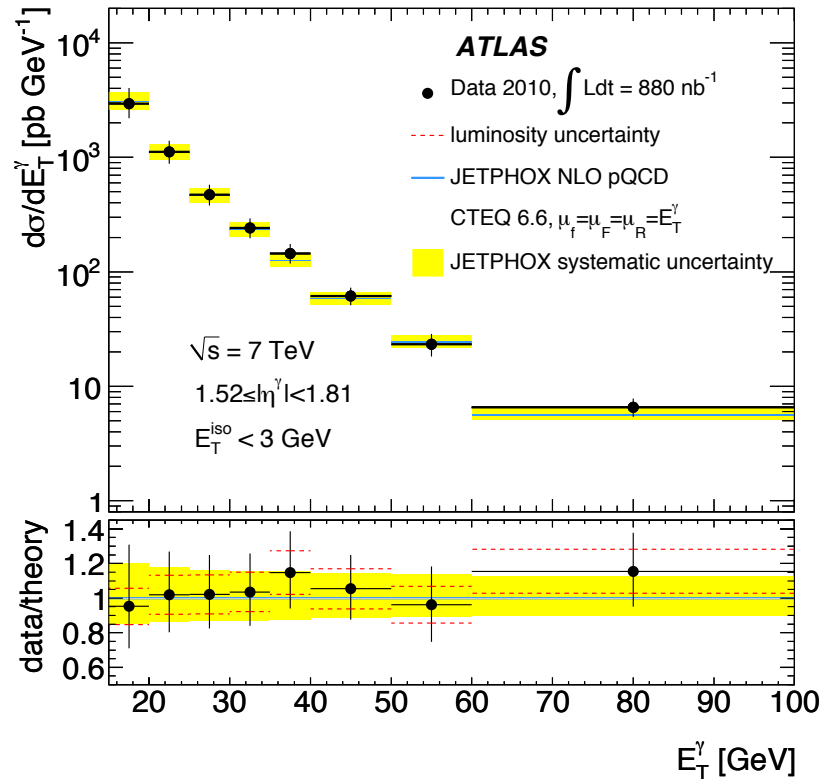
# CGC Calculation for Photon



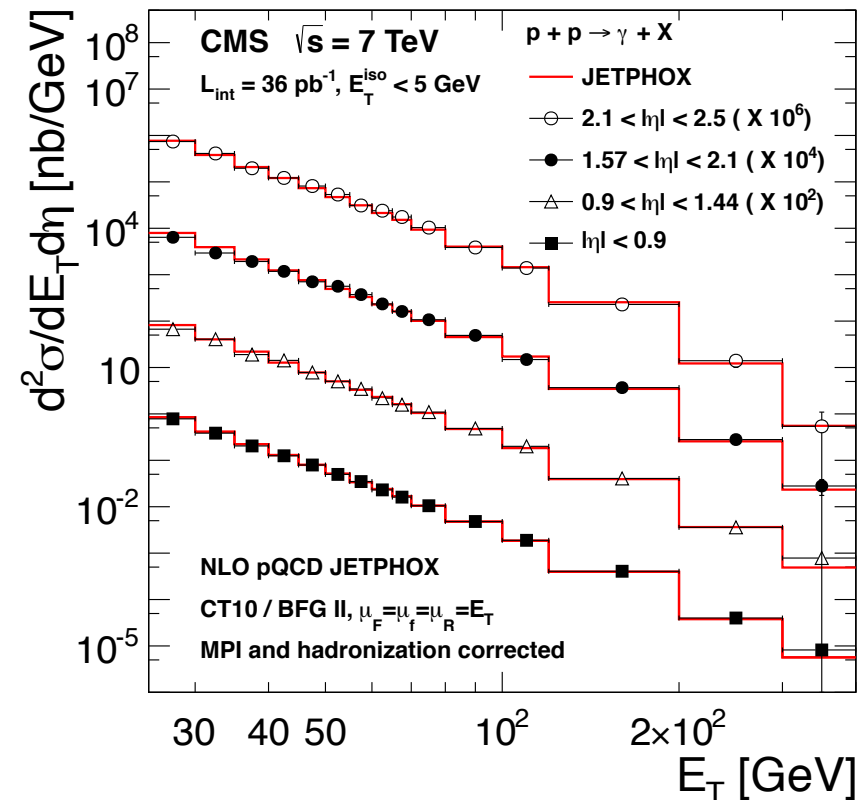
# Consistency Check

# Available Data

1012.4389 [hep-ex]



1108.2044 [hep-ex]

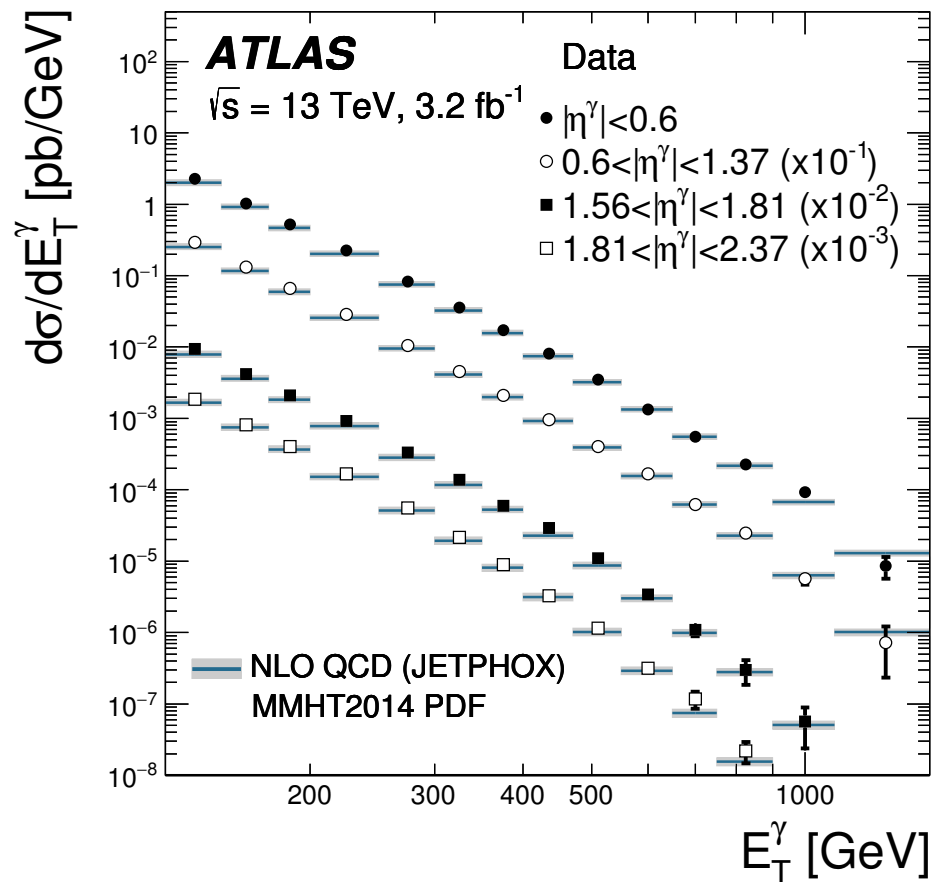


For “saturation physics” *soft* photons needed



# Available Data

1701.06882 [hep-ex]



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**

**$\eta$  dependence from rcBK**

**$K$ -factor**

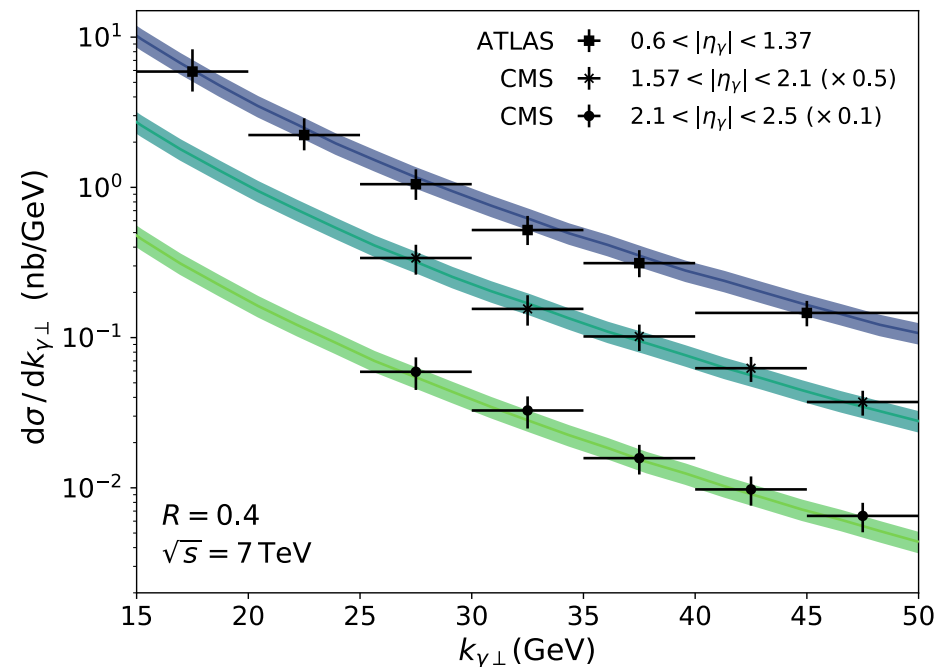
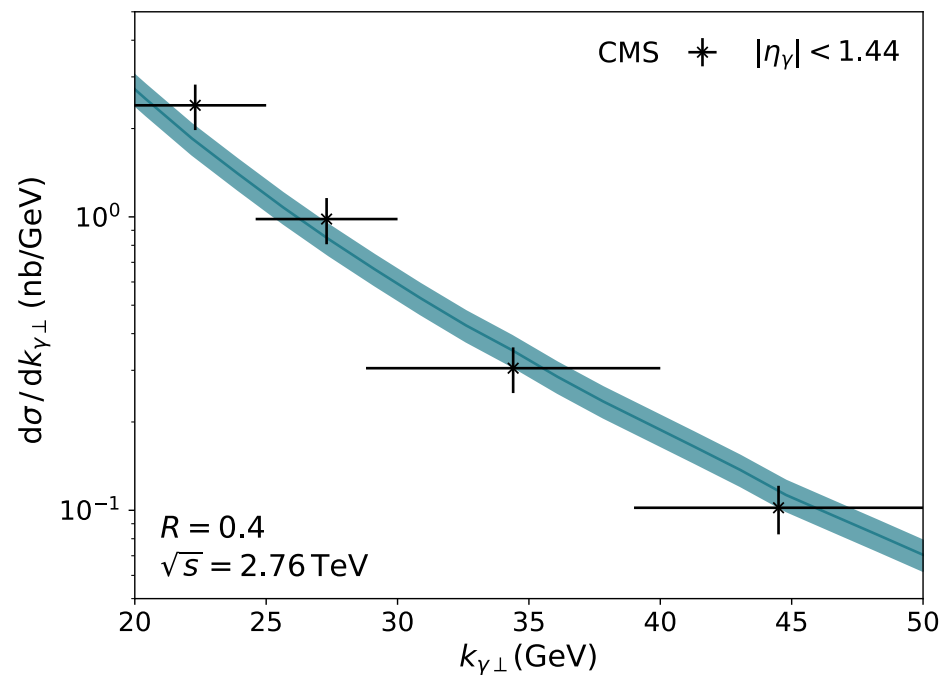
**$K = 2.4$  (cf.  $K = 2.5$  for  $D$ -meson production)**

# Comparison to “Available” Data



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

## Photons in pp at LHC



**Consistency check : CGC effects not seen yet!**  
**More experimental data at small momenta needed**

# Outlooks



**Our framework is intended for pA or pp in forward**

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

**CGC accessible by soft direct photons  $\sim$  a few GeV**

**In pA the nuclear PDF could be probed directly**

**CGC effects would enhance soft direct photons ?**