Investigating the high energy QCD approaches for prompt photon production at the LHC*

Magno V.T. Machado

UNIPAMPA - Bagé

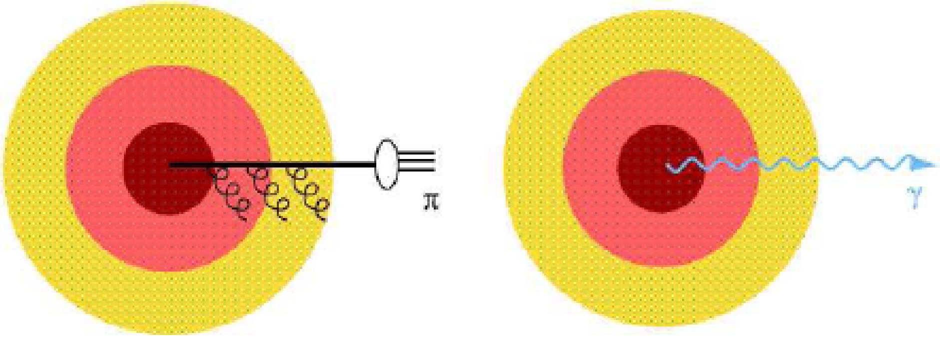
* M.V.T. Machado, C. Brenner Mariotto, Eur. Phys. J. C61, 871 (2009)

Outline

- Motivation - Hard Probes
- Motivation - Prompt Photons
- Prompt photons in NLO QCD in pp collisions
- Prompt photons within the color dipole approach
- Few comments on the Color Glass Condensate (CGC) calculations
- Summary

Motivation – hard probes

- Hard probes are useful because in this case pQCD works, we have low background and there are constraints from more elementary reactions.
- Hard as compared to soft medium, $Q \gg gT, T$, and to non-perturbatice scale, $Q \gg \Lambda_{QCD}$.
- Coloured probes (jets, heavy quarkonia) interact with a dense medium (energy loss, Debye screening).
- Blind probes (DY, $W^{\pm}/Z^{0}$, prompt photons) allow to study nuclear effects (shadowing, saturation physics, Cronin).



Motivation – prompt photons

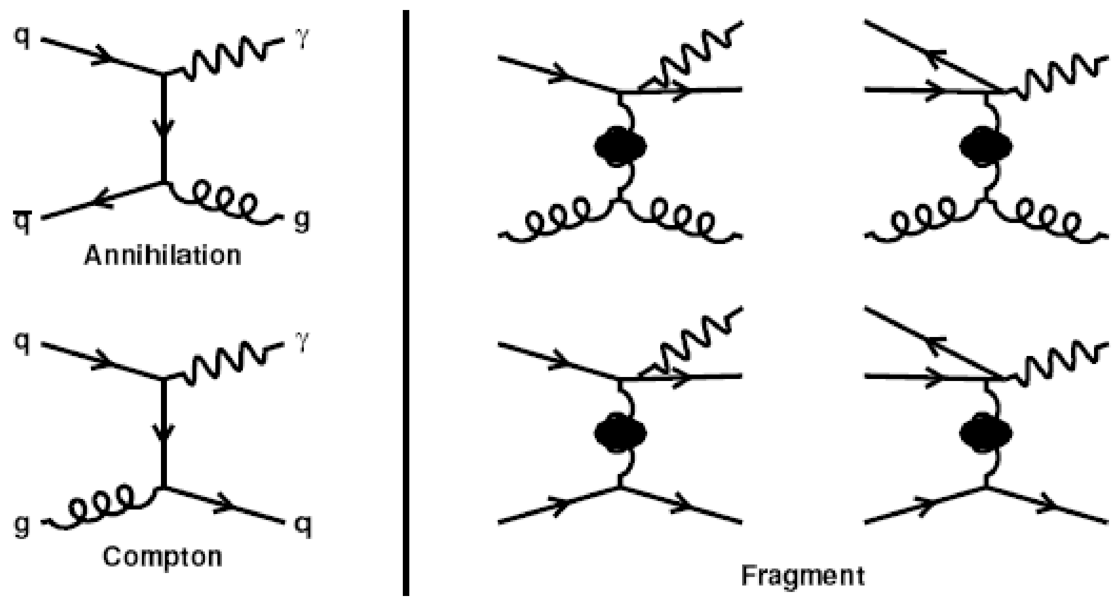
- Primary motivation to study prompt photons (not from hadronic decay) is to extract information about the gluon density inside proton in conjunction with DIS data.
- Provide powerful probe for initial state of matter created in HIC because interact with medium only electromagnetically.
- Therefore, direct photons provide a baseline for the interpretation of jet-quenching models.
- They are reasonably well understood for pp collisions in pQCD (pA: uncertainty on the nuclear gluon PDF).
- Recently, results using color dipole approach have appeared (unified framework for DY dilepton and inclusive direct-γ production). It is suitable for very small-p_T and allow introduction of nuclear effects.

Prompt photons – pQCD approach

- We focus on prompt photons ($p_T \gg \Lambda_{QCD}$).
- In pQCD we have Direct contribution ("Drell-Yan like") and Fragmentation contribution ("jet like").

$$d\sigma_{\rm dir} \propto f_i^{p,A}(x_1,Q) \otimes f_j^{p,A}(x_2,Q) \otimes \hat{\sigma}$$

$$d\sigma_{\rm frag} \propto f_i^{p,A}(x_1) \otimes f_j^{p,A}(x_2) \otimes \hat{\sigma} \otimes D_{\gamma/k}$$



Leading Order (LO)

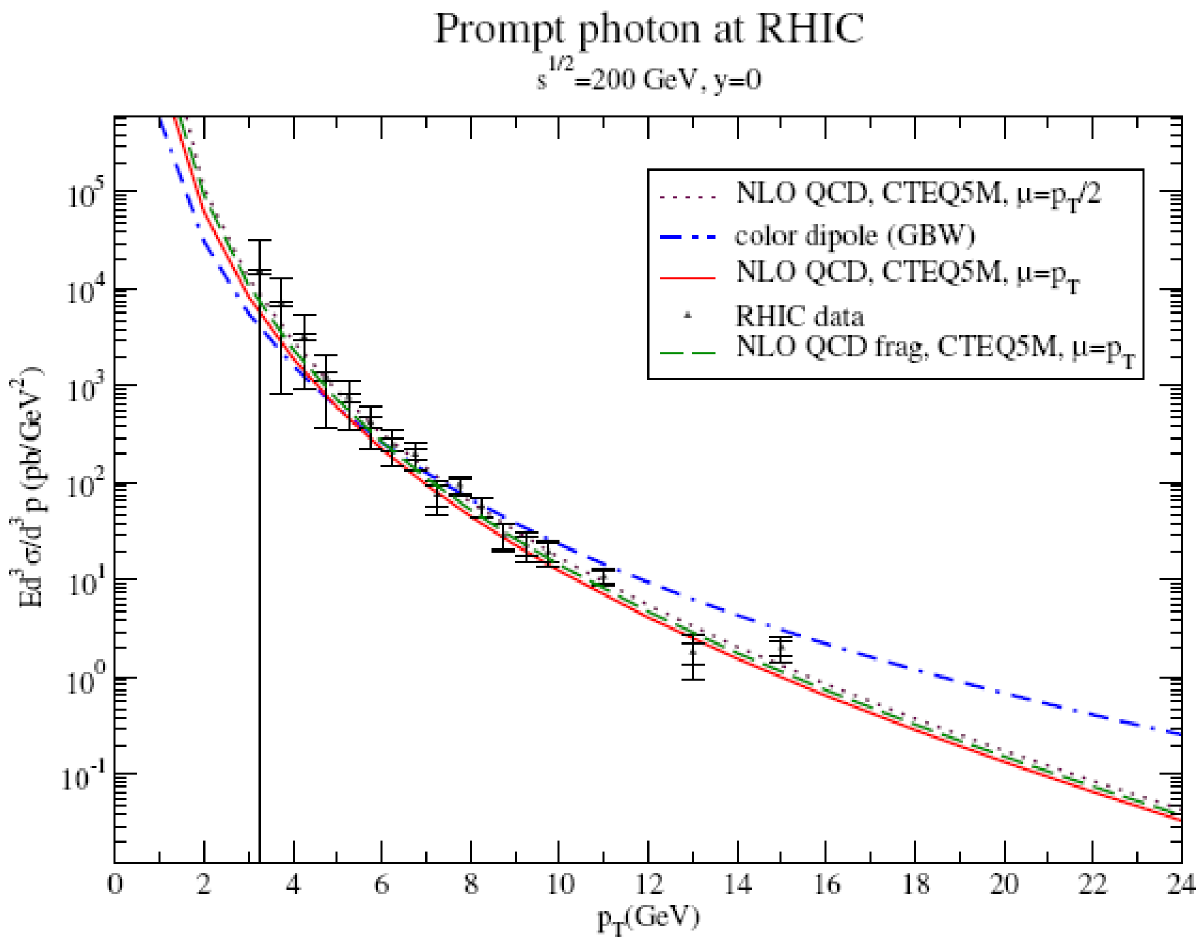
Next Leading Order (NLO)

Prompt photons – pQCD approach

- Direct photons allow for precision test of pQCD (few clean sub-processes).
- LO: Compton scattering process, $q + q \rightarrow \bar{q} + \gamma$, and annihilations process, $q + \bar{q} \rightarrow g + \gamma$.
- NLO: bremsstrahlung.
- NNLO: jet fragmentation.
- Typically 20–30 % theoretical uncertainty due to various choice of scale.
- Intrinsic uncertainties of NLO: the renormalization, factorization and fragmentation scale.

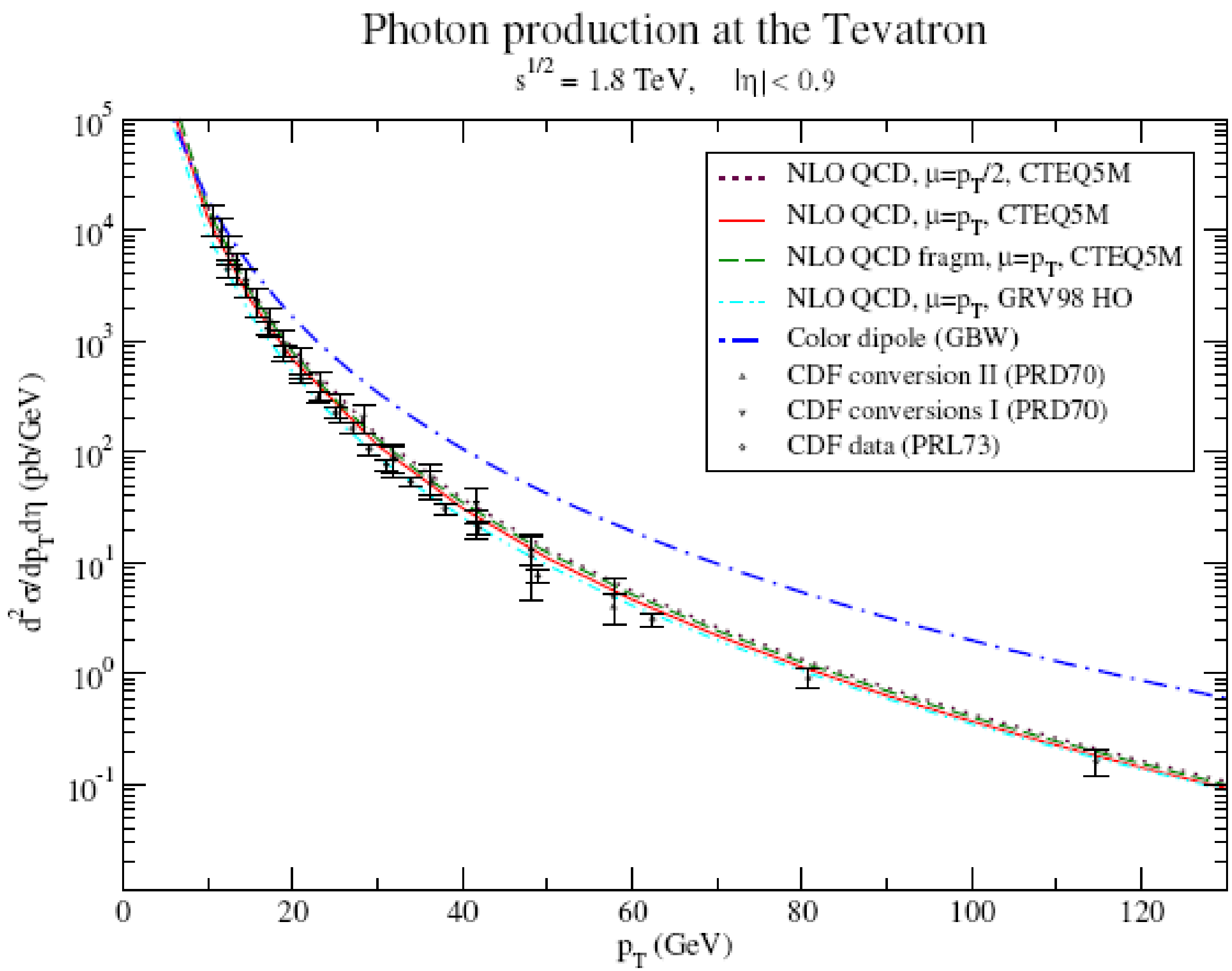
Prompt photons – pQCD approach

- Central rapidity: calculation for RHIC compared to a color dipole model (GBW, from Kopeliovich et al., 2007).



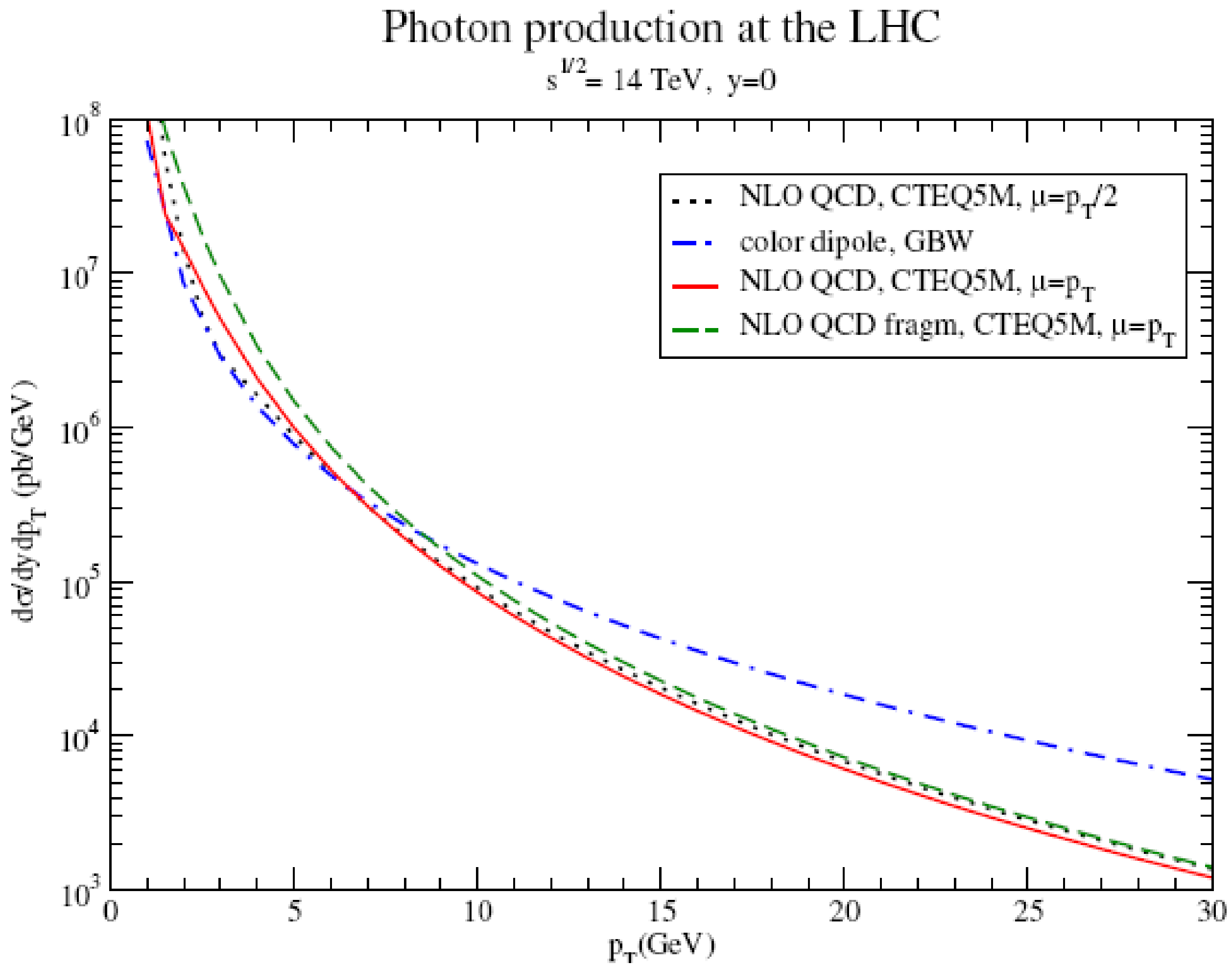
Prompt photons – pQCD approach

- Midrapidity: calculation for Tevatron compared to a color dipole model (GBW, from Kopeliovich et al., 2007).



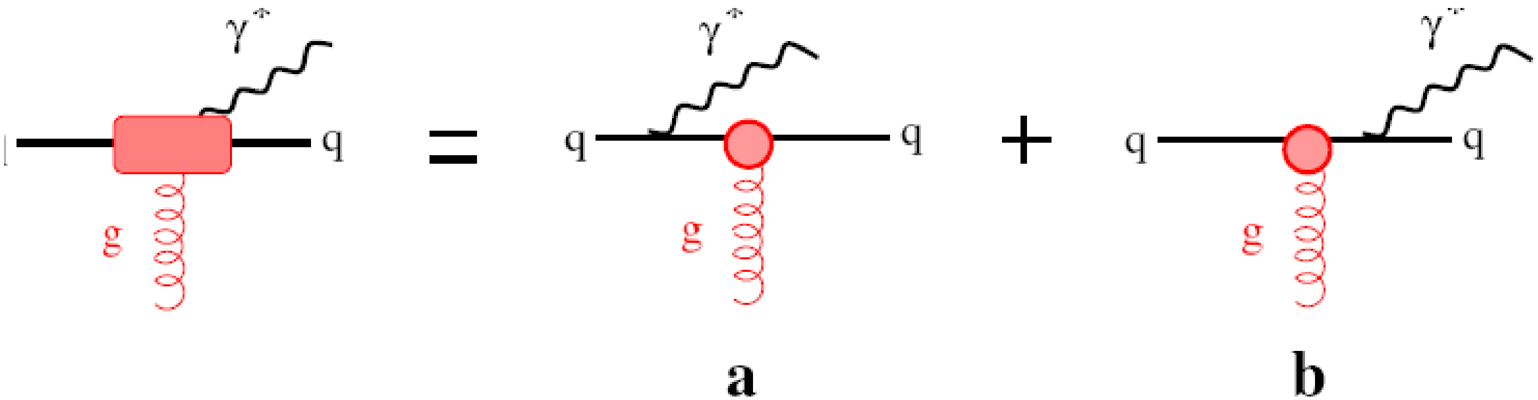
Prompt photons – pQCD approach

- Midrapidity: predictions for the LHC compared to a color dipole model (GBW, from Kopeliovich et al., 2007).



Prompt photons – dipole approach

- Color dipole formalism can be also applied to radiation.
- Although in the process of EM bremsstrahlung by a quark no dipole participates, cross section can be expressed via elementary cross section $\sigma_{q\bar{q}}$ of interaction of a $\bar{q}q$ dipole.



- In the target rest frame the DY (and direct photon) process looks like bremsstrahlung of a virtual (real) photon and in this frame both production processes are described in a unified framework.

Prompt photons – dipole approach

- The transverse momentum p_T distribution of photon bremsstrahlung in quark-nucleon interactions, integrated over the final quark transverse momentum is given by:

$$\frac{d\sigma^{qN}(q \to q\gamma)}{d(ln\alpha)d^2\vec{p}_T} = \frac{1}{(2\pi)^2}\sum_{in,f}\sum_{L,T}\int d^2\vec{r}_1 d^2\vec{r}_2 e^{i\vec{p}_T\cdot(\vec{r}_1-\vec{r}_2)}$$
$$\times \quad \phi^{\star T,L}_{\gamma q}(\alpha,\vec{r}_1)\phi^{T,L}_{\gamma q}(\alpha,\vec{r}_2)\Sigma_\gamma(x,\vec{r}_1,\vec{r}_2,\alpha),$$
$$\Sigma_\gamma(x,\vec{r}_{1,2},\alpha) = \frac{1}{2}\{\sigma_{q\bar{q}}(x,\alpha r_1)+\sigma_{q\bar{q}}(x,\alpha r_2)\} - \frac{1}{2}\sigma_{q\bar{q}}(x,\alpha(\vec{r}_1$$

- $\vec{r}_{1,2}$ are the quark-photon transverse separations in the two radiation amplitudes contributing to the cross section.
- $\phi^{T,L}_{\gamma q}(\alpha,\vec{r})$ are the light-cone (LC) wavefunctions of projectile quark γq fluctuation. Average over the initial quark polarization and sum over all final polarization states.

Prompt photons – dipole approach

- To obtain the hadron cross section one should sum up the contributions from quarks and antiquarks weighted with the corresponding parton distribution functions (PDFs),

$$\frac{d\sigma^{DY}(pp\to\gamma^\star X)}{dM^2 dx_F d^2\vec{p}_T} = \frac{\alpha_{em}}{3\pi M^2 \overline{X}} \int_{x_1}^{1} \frac{d\alpha}{\alpha} F_2^p\left(\frac{x_1}{\alpha},Q\right) \frac{d\sigma^{qN}(q\to q\gamma^\star)}{d(ln\alpha)d^2\vec{p}_T}$$

$$\frac{d\sigma^{\gamma}(pp\to\gamma X)}{dx_F d^2\vec{p}_T} = \frac{1}{\overline{X}} \int_{x_1}^{1} \frac{d\alpha}{\alpha} F_2^p\left(\frac{x_1}{\alpha},Q\right) \frac{d\sigma^{qN}(q\to q\gamma)}{d(ln\alpha)d^2\vec{p}_T}.$$

- The PDFs of the projectile enter in a combination which can be written in terms of proton structure function F_2^p.
- x_1 denotes the momentum fraction that the photon carries away from the projectile hadron in the target frame.
- Definitions: $x_2 = x_1 - x_F$, $x_F = 2p_L/\sqrt{s}$ is the Feynman variable, $\overline{X} = (x_1 + x_2)$ and M is the dilepton mass (for direct photons, $M = 0$ GeV)

Prompt photons – dipole approach

- Explicit expression for p_T distribution reads as:

$$\frac{d\sigma^{\gamma}(pp \to \gamma X)}{dx_F d^2\vec{p}_T} = \frac{\alpha_{em}}{2\pi^2(x_1+x_2)} \int_{x_1}^{1} \frac{d\alpha}{\alpha} F_2^p\left(\frac{x_1}{\alpha}, Q^2 = p_T^2\right) \times$$

$$\left\{ m_q^2 \alpha^4 \left[\frac{\mathcal{I}_1}{(p_T^2+\eta^2)} - \frac{\mathcal{I}_2}{4\eta} \right] + [1+(1-z)^2] \left[\frac{\eta p_T \mathcal{I}_3}{(p_T^2+\eta^2)} - \frac{\mathcal{I}_1}{2} + \frac{\eta \mathcal{I}}{4} \right.\right.$$

- where $\eta = \alpha \, m_q$ and

$$\mathcal{I}_1 = \int_0^\infty dr\, r J_0(p_T\, r) K_0(\eta\, r)\, \sigma_{dip}(x_2, \alpha r),$$

$$\mathcal{I}_2 = \int_0^\infty dr\, r^2 J_0(p_T\, r) K_1(\eta\, r)\, \sigma_{dip}(x_2, \alpha r),$$

$$\mathcal{I}_3 = \int_0^\infty dr\, r J_1(p_T\, r) K_1(\eta\, r)\, \sigma_{dip}(x_2, \alpha r).$$

- Rich phenomenology on the dipole cross section σ_{dip}

Dipole cross sections

- Several analytical versions for dipole cross section (parameters from fits to HERA data at small-x).

$$\sigma_{dip}^{\rm GBW}(x_2,\, r) = \sigma_0 \left[1 - \exp\left(- \frac{Q_s^2\, r^2}{4} \right) \right], \quad Q_s^2(x_2) = \left(\frac{x_0}{x_2} \right)^{\lambda} \,{\rm GeV}$$

- More recent parametrizations tested against RHIC data for hadron production.

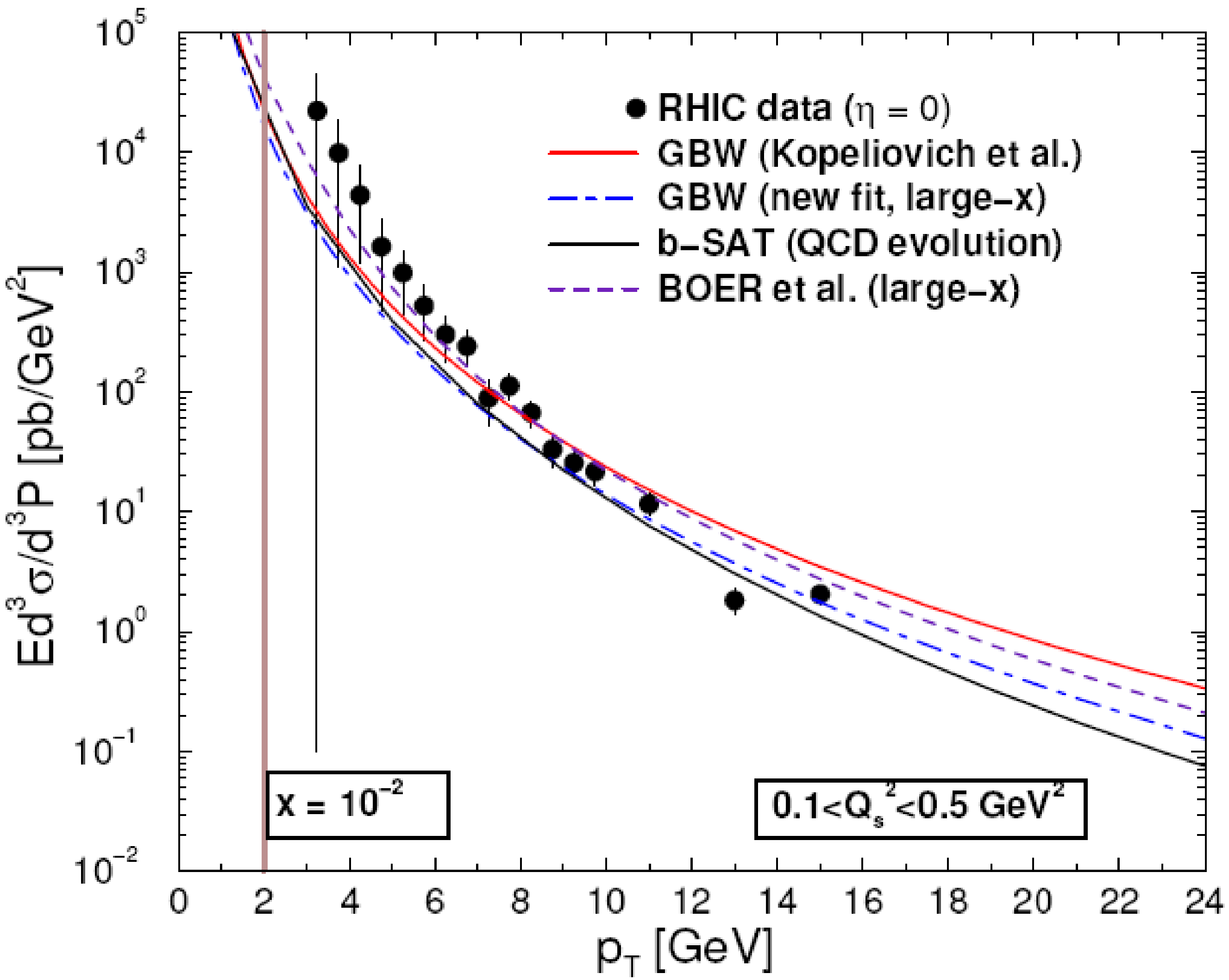
$$\sigma_{dip}^{\rm BOER}(x_2,\, r) = \sigma_0 \left[1 - \exp\left(- \frac{(Q_s^2\, r^2)^{\gamma}}{4} \right) \right],$$

$$\gamma = \gamma_s + (1-\gamma_s)\frac{(w^a - 1)}{(w^a-1)+b}; \;\; \gamma_s = 0.628 \text{ and } w = \frac{p_T}{Q_s}$$

- Several nice implementations in the market (including QCD evolution, impact parameter dependence, $\cdots$).

Phenomenology – Pt distribution

- Comparison for distinct dipole cross sections (midrapidity).



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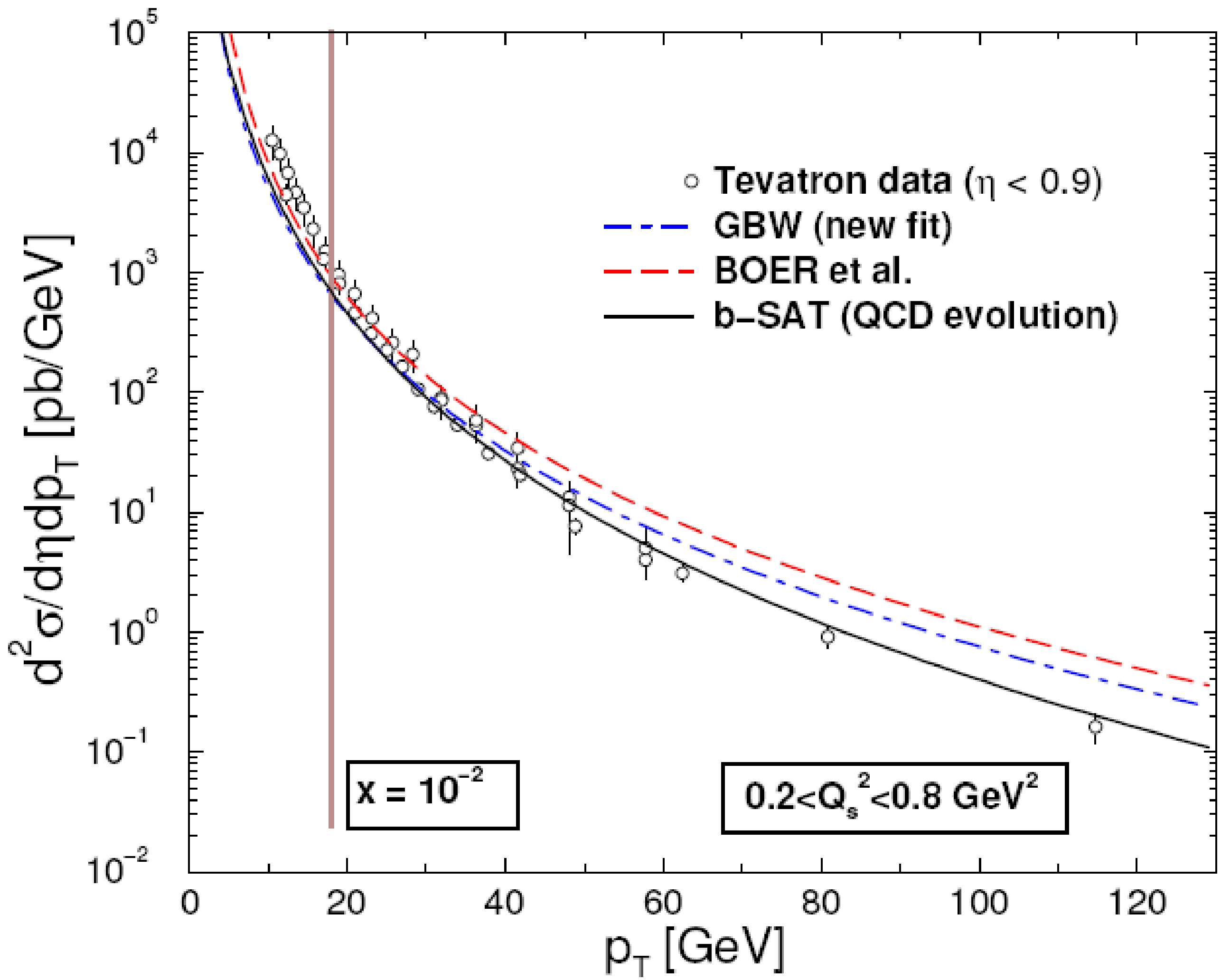

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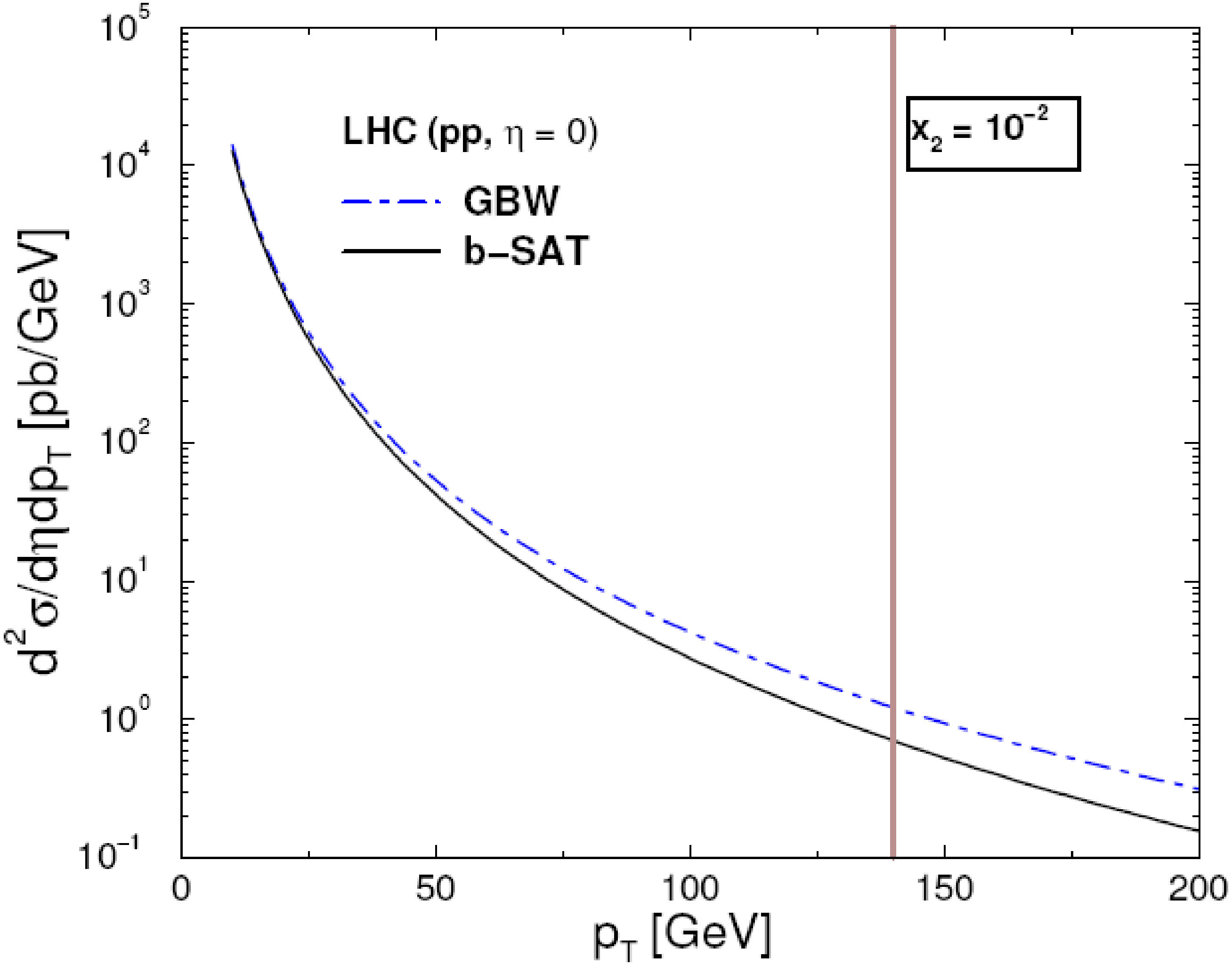


Dipole approach - analytical results

- In case of large p_T compared to saturation scale, $r \sim 1/p_T \ll 1/Q_s$, r-integration can be analytically done.
- Using GBW model, $\sigma_{dip}(r \to 0) \simeq \sigma_0 Q_s^2 r^2/4$.

$$\mathcal{I}_1 = \sigma_0 \int_0^\infty dr\, r\, J_0(p_T\, r) K_0(\eta\, r) \left(\frac{rQ_s}{2}\right)^2 = \sigma_0 Q_s^2 \frac{(\eta^2 - p_T^2)}{(p_T^2 + \eta^2)^3},$$

$$\mathcal{I}_2 = \sigma_0 \int_0^\infty dr\, r^2 J_0(p_T\, r) K_1(\eta\, r) \left(\frac{rQ_s}{2}\right)^2 = \sigma_0 Q_s^2 \frac{4\eta\,(\eta^2 - 2p_T^2)}{(p_T^2 + \eta^2)^4}$$

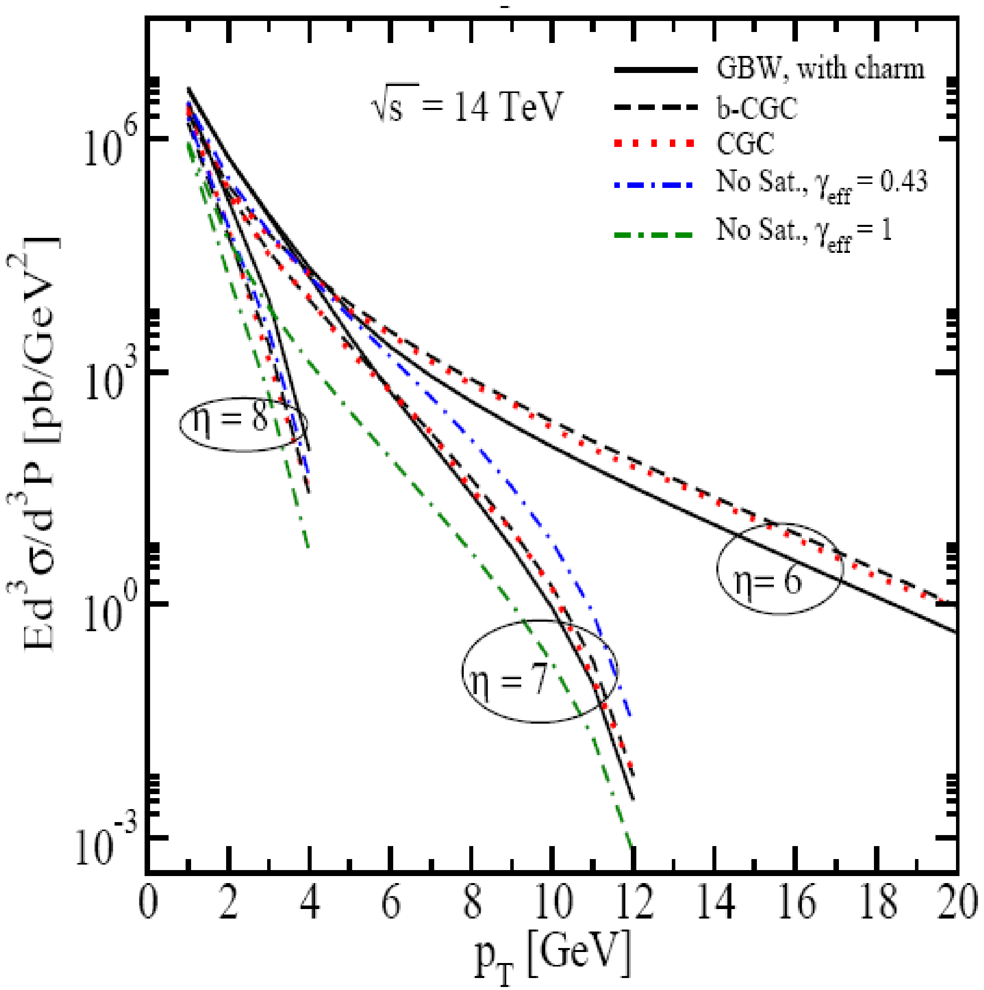
$$\mathcal{I}_3 = \sigma_0 \int_0^\infty dr\, r\, J_1(p_T\, r) K_1(\eta\, r) \left(\frac{rQ_s}{2}\right)^2 = \sigma_0 Q_s^2 \frac{2p_T\eta}{(p_T^2 + \eta^2)^3}.$$

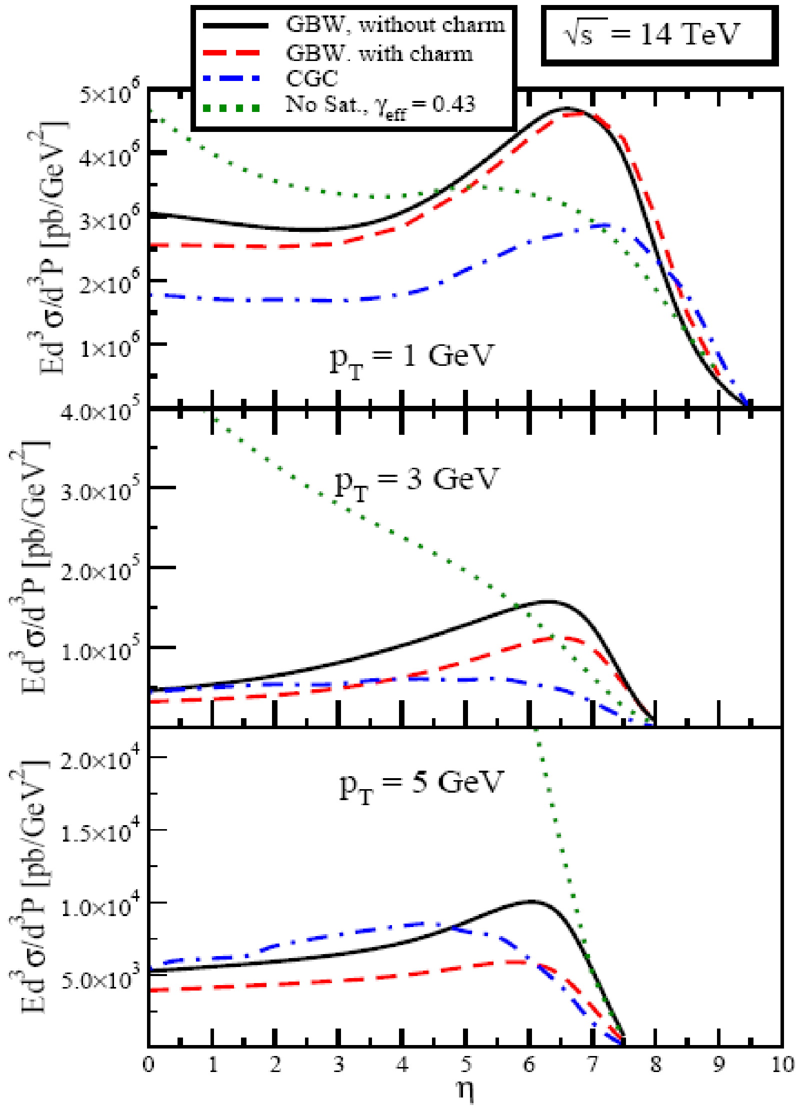
$$\frac{d\sigma^\gamma(pp \to \gamma X)}{dx_F d^2\vec{p}_T} \approx \frac{\alpha_{em}\, \sigma_0 Q_s^2(x_2)}{2\pi^2(x_1 + x_2)} \int_{x_1}^1 \frac{d\alpha}{\alpha} F_2^p\left(\frac{x_1}{\alpha}, Q^2 = p_T^2\right)$$

$$\times \left\{ m_q^2 \alpha^4 \left[\frac{p_T^2}{(p_T^2 + \eta^2)^4}\right] + [1 + (1 - z)^2] \left[\frac{p_T^4}{2(p_T^2 + \eta^2)^4}\right] \right\}$$

Related works in literature

- B. Z. Kopeliovich, E. Levin, A. H. Rezaeian, I. Schmidt, Phys. Lett. B675, 190 (2009).





Prompt photon – CGC formalism

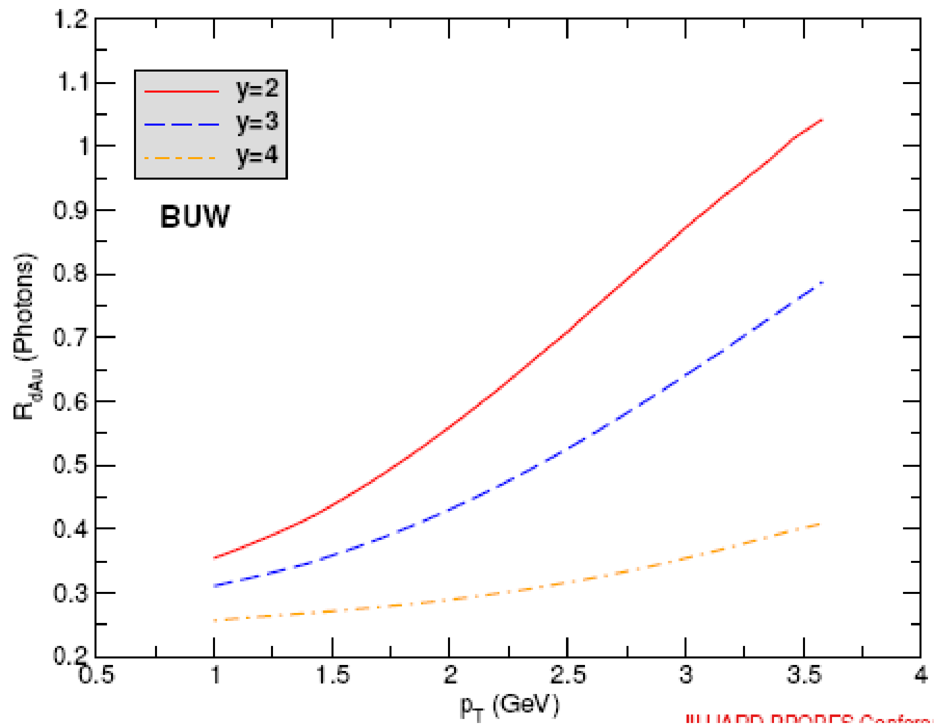
- Photon production is complementary to hadron production using CGC formalism (valid at forward rapidities).
- See Jamal Jalilian-Marian's talk for more details.

$$\frac{d^2\sigma^{ph\to\gamma X}}{dy d^2p_T} \propto \int_{x_F}^{1} \frac{x_1}{x_F}\left[f_{q/p}(x_1,p_T^2)\mathcal{N}_F^h\left(x_2,\frac{x_1}{x_F}p_T\right)D_{\gamma/q}\left(\frac{x_1}{x_F},p_T^2\right)\right]$$

- $\mathcal{N}_F$ is the fundamental representation of the forward dipole amplitude in momentum space (with $h = p$ or A).
- $D_{\gamma/q}$ is the quark-photon fragmentation function.
- Recently, nice phenomenology for nuclear ratios (AA and dA), photon-hadron correlations, $\cdots$

Prompt photon – CGC formalism

- For example, nuclear ratio in dA collisions.
- pp and dA minimum bias yields for photon production using CGC formalism (Boer et al. model for $\mathcal{N}_F$, labeled BUW).
- Ref.: V.P. Gonçalves and M.A. Betemps, arXiv:0806.1467.



Phenomenology – pA collisions

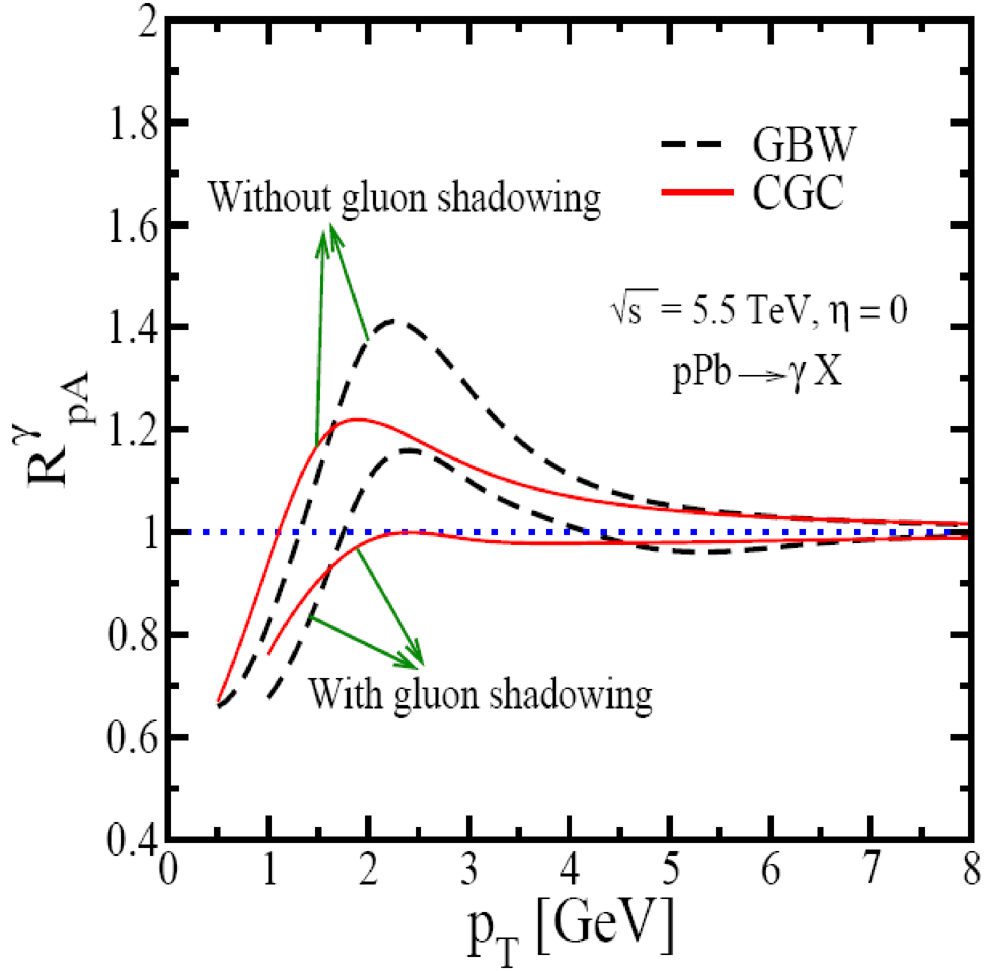
- The pp calculation is a calibration procedure.
- Color dipole formalism allow for simple implementations of nuclear efects, relevant for pA (or dA) collisions.
- For instance, using Glauber-Gribov formalism, the nuclear dipole cross section can be computed:

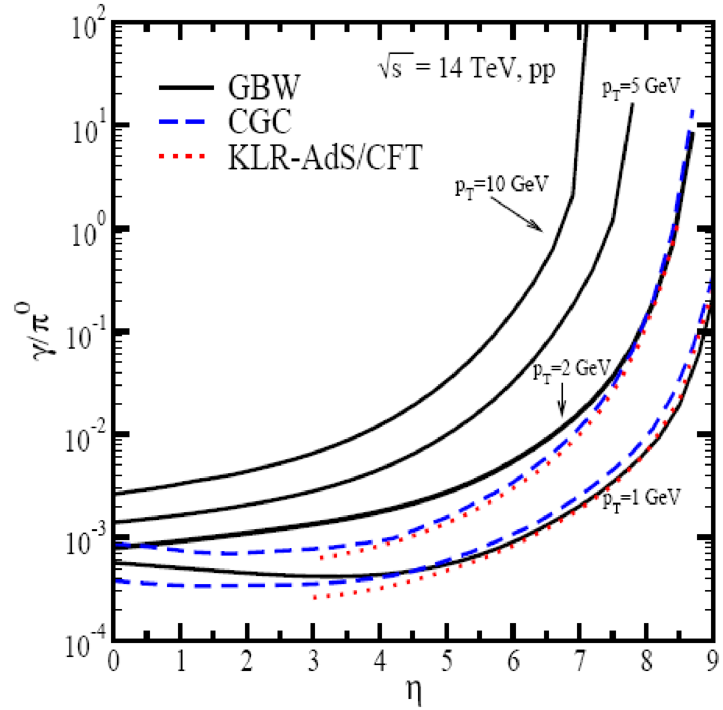
$$\sigma_A(x_2, r; A) = 2\int d^2b\left[1 - \exp\left(-\frac{1}{2}\sigma_{dip}(x_2, r)\, T_A(b)\right)\right]$$

- Different implementation of nuclear effects in Color Glass Condensate (CGC) formalism.
- Good place to investigate different models for nuclear shadowing.

Recent calculations – pA collisions

- Amir H. Rezaeian, Andreas Schaefer, **arXiv:0908.3695 [hep-ph]**





Summary

- We performed a comparison among different theoretical approaches for direct photon production at high energies.
- pQCD approach reasonably describes accelerator data with typical theoretical uncertainty of 20–30 % (scale choice).
- Color dipole formalism is able to describe data for DY dileptons and direct photon in a unified framework, using rich phenomenology for saturation models.
- QCD evolution for the dipole cross section is mandatory to describe large p_T spectrum.
- Starting point for studies in pA (efficient probe of gluon shadowing) and in AA (interplay of shadowing and energy loss effects). Saturation models suitable for forward kinematics.