Prompt photon production at LHC: a “multi-purpose” observable

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Last Call for Predictions
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Outline

- Single photon in p A collisions
  - probing gluon shadowing with isolated photons

- Single photon in A A collisions
  - probing energy loss with inclusive photons

- Double photon and pion in A A collisions
  - probing medium-modified fragmentation functions

[ FA, Gousset, in preparation ]
[ FA, JHEP 09 (2006) 015 ]
Isolated photons in p A collisions:
measuring gluon shadowing
Gluon shadowing

Gluon distributions in nuclei over that in a proton

\[ R_G(x, Q^2) = \frac{G_A(x, Q^2)}{G_p(x, Q^2)} \]

poorly constrained experimentally!
Gluon shadowing

From NMC data

- Tiny constraints from the scaling violation of $F_2^A(x, Q^2)$
- Fairly large $x \sim 10^{-2} - 10^{-1}$
Isolated photons in p A

Gluon shadowing

Observables

Photons in pQCD

Predictions

Inclusive photons in A A

Photon-tagged correlations

Summary

Back-up

Gluon distributions in nuclei over that in a proton

\[ R_G(x, Q^2) = \frac{G_A(x, Q^2)}{G_p(x, Q^2)} \]

poorly constrained experimentally!

How to probe small-\(x\) gluon shadowing at LHC?

- which observables
- why prompt photons
Choose your favourite one!

- **Jets**
  
  :-) high rates, rich phenomenology, forward rapidities
  
  :-( large scales $Q^2 > 10^3 \text{ GeV}^2$

- **Large $p_{\perp}$ dileptons**

  :-) no strong background
  
  :-( very low rates

- **Heavy-bosons**

  :-) constraints on sea-quark shadowing
  
  :-( large scales $Q^2 > 10^4 \text{ GeV}^2$

- **Prompt photons**

  :-) low $Q^2 > 10^{1-3} \text{ GeV}^2$, rich phenomenology
  
  :-( parton-to-photon fragmentation process
Observables

- Good description of isolated/inclusive photon world-data

[ Aurelche et al. 2006 ]
Choose your favourite one!

- **Jets**
  
  :-) high rates, rich phenomenology, forward rapidities
  
  :-( large scales $Q^2 \gtrsim 10^3 \, \text{GeV}^2$

- **Large $p_T$ dileptons**
  
  :-) no strong background
  
  :-( very low rates

- **Heavy-bosons**
  
  :-) constraints on sea-quark shadowing
  
  :-( large scales $Q^2 \gtrsim 10^4 \, \text{GeV}^2$

- **Prompt photons**
  
  :-) low $Q^2 \gtrsim 10-10^3 \, \text{GeV}^2$, rich phenomenology
  
  :-( parton-to-photon fragmentation process
- Photons and jets are clearly **complementary**
- Photons cover **small** $Q^2$ where shadowing should be large
Photons in pQCD

At leading-order $\mathcal{O}(\alpha \alpha_s)$

- **Compton scattering** $q \ g \rightarrow q \ \gamma$

- **Annihilation process** $q \ \bar{q} \rightarrow g \ \gamma$

At high energy, only the Compton scattering process is relevant
Photons in pQCD

At leading-order $\mathcal{O}(\alpha \alpha_s)$

$$
\frac{d^3 \sigma(p A \rightarrow \gamma X)}{dy \ d^2 p_\perp} \propto \int_0^1 dv \ \tilde{F}_2^p \left( \frac{x_\perp e^y}{2v} \right) G^A \left( \frac{x_\perp e^{-y}}{2(1 - v)} \right) |\mathcal{M}|^2(v) \\
+ \ G^p \left( \frac{x_\perp e^y}{2v} \right) \tilde{F}_2^A \left( \frac{x_\perp e^{-y}}{2(1 - v)} \right) |\mathcal{M}|^2(1 - v)
$$
Photons in pQCD

At leading-order $\mathcal{O}(\alpha\alpha_s)$

$$
d^3\sigma(pA \rightarrow \gamma X) \quad \propto \quad \int_0^1 dv \, \tilde{F}_2^p \left( \frac{x_\perp e^y}{2v} \right) G^A \left( \frac{x_\perp e^{-y}}{2(1 - v)} \right) |\mathcal{M}|^2(v) \\
+ \quad G^p \left( \frac{x_\perp e^y}{2v} \right) \tilde{F}_2^A \left( \frac{x_\perp e^{-y}}{2(1 - v)} \right) |\mathcal{M}|^2(1 - v)
$$

Since $R_G(x)$ and $R_{F_2}(x)$ vary slowly wrt $G(x)$ and $F_2(x)$

$$
R_{pA}(p_\perp, y) \approx c(y) \, R_{F_2}(x_\perp e^{-y}) \quad + \quad [1 - c(y)] \, R_G(x_\perp e^{-y})
$$
Photons in pQCD

At leading-order $\mathcal{O}(\alpha \alpha_s)$

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\frac{d^3\sigma(p A \rightarrow \gamma X)}{dy \, d^2p_\perp} \propto \int_0^1 dv \ \tilde{F}_2^p \left( \frac{x_\perp e^y}{2v} \right) G^A \left( \frac{x_\perp e^{-y}}{2(1 - v)} \right) |\mathcal{M}|^2(v) + G^p \left( \frac{x_\perp e^y}{2v} \right) \tilde{F}_2^A \left( \frac{x_\perp e^{-y}}{2(1 - v)} \right) |\mathcal{M}|^2(1 - v)
\]

Since $R_G(x)$ and $R_{F_2}(x)$ vary slowly wrt $G(x)$ and $F_2(x)$

\[
R_{pA}(p_\perp, y) \simeq c(y) \ R_{F_2}(x_\perp e^{-y}) + [1 - c(y)] \ R_G(x_\perp e^{-y})
\]

but ...
Caveat

Photons can also be produced by fragmentation

\[
\frac{d^3\sigma^{\text{frag}}(pA \rightarrow \gamma X)}{dy \ d^2p_{\perp}} \propto \int_0^1 dz \int_0^1 dv \ \ldots \left(\frac{x_{\perp}}{z}, Q^2\right) \ D_{\gamma/k}(z, Q^2)
\]

The extra integration spoils the relationship \(R_{pA} \Leftrightarrow R_{F2}\) and \(R_G\)
Caveat

Photons can also be produced by fragmentation

\[
\frac{d^3\sigma^\text{frag}(pA \rightarrow \gamma X)}{dy\ d^2p_\perp} \propto \int_0^1 dz \int_0^1 dv \cdots (x_\perp/z, Q^2)\ D_{\gamma/k}(z, Q^2)
\]

The extra integration spoils the relationship \( R_{pA} \leftrightarrow R_{F_2} \) and \( R_G \)

We get rid of them by means of isolation criteria

\[
E_{\text{had}}^\text{max} \leq E_\perp
\]

for particles in a cone

\[
(\eta - \eta_\gamma)^2 + (\phi - \phi_\gamma)^2 \leq R^2
\]
Predictions

Isolated photons in p A at LHC

- Around mid-rapidity

\[ R_{pA}(p_{\perp}, y) \simeq \frac{1}{2} \left[ R_{F_2}(x_{\perp} e^{-y}) + R_G(x_{\perp} e^{-y}) \right] \]

- At (very) forward rapidity

\[ R_{pA}(p_{\perp}, y) \simeq R_G(x_{\perp} e^{-y}) \]

- At (very) backward rapidity

\[ R_{pA}(p_{\perp}, y) \simeq R_{F_2}(x_{\perp} e^{-y}) \]
Predictions

Isolated photons in p A at LHC

- Around mid-rapidity

\[ R_{pA}(p_\perp, y) \simeq \frac{1}{2} \left[ R_{F2}(x_\perp e^{-y}) + R_{G}(x_\perp e^{-y}) \right] \]

- At (very) forward rapidity

\[ R_{pA}(p_\perp, y) \simeq R_{G}(x_\perp e^{-y}) \]

- At (very) backward rapidity

\[ R_{pA}(p_\perp, y) \simeq R_{F2}(x_\perp e^{-y}) \]

To illustrate/check this

let’s compute \( R_{pA}(x_\perp, y) \) at \( y = 0, 2.5, -2.5 \) at NLO using nDSg nuclear PDF in p A collisions (\( \sqrt{s_{NN}} = 8.8 \text{ TeV} \))
Predictions

Mid-rapidity

- 20% attenuation at $x_\perp \sim 10^{-3}$ measurable (statistically)
- perfect ($< 2-3\%$) matching between $R_{pA}$ and nuclear density ratios
Forward rapidity $y = 2.5$

- Gives “direct” access to $R_G$ (within 5%) at $x = 10^{-4} - 10^{-3}$!
Shadowing without p p data

Problem: no p p collision at $\sqrt{s} = 8.8$ TeV

How to measure $R_G(x)$ without any p p reference data?
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How to measure $R_G(x)$ without any p p reference data?

Compare forward w/ backward production in p A collisions

$$\frac{d\sigma(pA \rightarrow \gamma^+(+y)X)}{d\sigma(pA \rightarrow \gamma^-(−y)X)} = R_{pA}(x_\perp, +y)/R_{pA}(x_\perp, −y)$$

$$\simeq R_G(x_\perp e^{-y})/R_{F_2}(x_\perp e^y)$$
Shadowing without \( p p \) data

**Problem:** no \( p p \) collision at \( \sqrt{s} = 8.8 \) TeV

How to measure \( R_G(x) \) without any \( p p \) reference data?

Compare forward w/ backward production in \( p A \) collisions

\[
\frac{d\sigma(pA \to \gamma(+)X)}{d\sigma(pA \to \gamma(-)X)} = R_{PA}(x_\perp, +y)/R_{PA}(x_\perp, -y)
\]

\[
\simeq R_G(x_\perp e^{-y})/R_{F2}(x_\perp e^{y})
\]

\( R_{F2} \) at large \( x \) gives access to \( R_G \) at small \( x \)!
Shadowing without $p\, p\, p$ data

- Encouraging yet a larger $y$ would be better
- Need to correct for trivial isospin effects
Inclusive photons in A A collisions: probing energy loss effects (?)
You said “energy loss”?

Naively

Photons are not sensitive to quark-gluon plasma formation because they are colour neutral (“initial-state observable”)

You said “energy loss”? 

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Photons are not sensitive to quark-gluon plasma formation because they are colour neutral (“initial-state observable”)
Naively

Photons are not sensitive to quark-gluon plasma formation because they are colour neutral ("initial-state observable")

... may not be that true because of the fragmentation component

[NB: Recall however that "direct" and "fragmentation" photons is to a great extent arbitrary beyond LO]
The idea

The multiple scattering of hard partons leads to jet quenching

... may also apply for collinear photons

Jet quenching implies quenching of fragmentation photons!

[ Jalilian-Marian, Orginos, Sarcevic 01 ]
[ FA, Aurenche, Belghobsi, Guillet 04 ]
RHIC data

Quenching factors measured by PHENIX (preliminary)

- Data are slightly below 1 at large $p_\perp$
- Isospin does half the job at $p_\perp = 18$ GeV
The medium seems to (slightly) suppress the prompt photon yield in A A collisions.
Extrapolating to LHC

In a Bjorken expansion (with $t_0 \ll L$)

$$\omega_c \sim \hat{q}(t_0) t_0 L$$

$$\sim Q_s^2 \sim \left(\sqrt{s_{NN}}\right)^\lambda$$

Using $\lambda = 0.3$ (DIS) and $\omega_c = 20$ GeV (RHIC)

$$\omega_c^{LHC} \sim 50 \text{ GeV}$$

The calculation is carried out at *leading-order* using

- CTEQ6M PDF
- nDSg nuclear distribution ratios
- BFG fragmentation functions into photons
- Modified w/ finite-energy BDMPS quenching weights
- All scales $M = \mu = M_F = p_\perp$
Predictions

- Significant photon quenching below $p_\perp \lesssim 50$ GeV
- Weaker energy loss effects at forward rapidity
Photon-tagged correlations:
probing (medium) fragmentation functions
Momentum imbalance

To leading-order in $\alpha_s$
To leading-order in $\alpha_s$

Introducing the momentum imbalance variable

$$z_{\gamma\pi} \equiv -\frac{P_{\perp\pi} \cdot P_{\perp\gamma}}{|P_{\perp\gamma}|^2}$$

LO kinematics

$$z_{\gamma\pi} \approx \frac{P_{\perp\pi}}{P_{\perp\gamma}}$$

Momentum conservation

$$P_{\perp\gamma} = k_{\perp}$$
Momentum imbalance

To leading-order in $\alpha_s$

Introducing the momentum imbalance variable...

...allows for the estimate of the fragmentation variable $z$!

(exp.) $\bar{z}_{\gamma\pi} \iff z$ (th.)
Momentum imbalance

To leading-order in $\alpha_s$

Momentum imbalance distributions in p p et A A collisions to probe fragmentation functions at LHC

[Wang, Huang, Sarcevic 96]
[FA, Aurenche, Belghobsi, Guillet 04]
Predictions

- Reminiscent of the fragmentation functions
- The larger the $p_{\perp,\gamma}^{\text{cut}}$, the better
Predictions

- Reminiscent of the fragmentation functions
- The larger the $p_{\perp \gamma}^{\text{cut}}$, the better
Multi-purpose prompt photons

- **Isolated photons in p A collisions**
  - efficient probe of gluon shadowing
  - $R_G / R_{F_2}$ accessible without p p data at 8.8 TeV

- **Inclusive photons in A A collisions**
  - interplay of shadowing and (possible) energy loss effects
  - significant quenching at low $p_{\perp}$ at LHC

- **Photon-tagged correlations**
  - provide interesting constraints on (medium) fragmentation functions
Back-up
Pion quenching

\[ R_{\text{PbPb}}(p_{\perp}) \]

- \( w/o \) nDSg
- \( w/ \) nDSg
- \( w/ \) nDSg \( \omega_c = 50 \text{ GeV} \)

\[ \pi^\pm \ \sqrt{s}=5.5 \text{ TeV} \ y=0 \]

\[ p_{\perp} \text{ (GeV)} \]