Phenomenology of prompt photon production in p A and A A collisions

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Motivations

- Hard QCD processes in nuclear collisions
- **Single $\gamma$ production in p A collisions**
  - Probing nuclear parton densities
  - Predictions at RHIC and LHC
- **$\gamma + Q$ production in A A collisions**
  - Probing heavy-quark energy loss in quark-gluon plasma
  - Preliminary estimates at LHC

References

Hard processes in QCD media

Hard processes are **ideal tools** to probe the hot QCD medium

- Can be computed in perturbative QCD
- Can be compared systematically to $p\ p$ collisions
- Sensitive to parton **energy loss processes**

![Diagram showing energy loss processes in A A collisions](image-url)
Schematically **two classes** of processes

### Medium sensitive
- Jets
- Large $p_{\perp}$ hadrons
- Heavy-quarkonia and open heavy flavour

### Medium insensitive
- Prompt photons
- $W^{\pm}/Z^0$ bosons
- Drell-Yan pair production
Jet quenching

Significant suppression of large-\(p_{\perp}\) hadrons in Au Au collisions at RHIC

One of the most important discoveries in heavy-ion collisions
Strong hadron suppression seen by ALICE

Significant asymmetries in jet production reported in central Pb Pb collisions by ATLAS and CMS
A robust interpretation of the data requires a quantitative understanding of hard processes in nuclear collisions

- Probing nuclear parton densities (nPDFs)
  - Essential to predict benchmark predictions in $pA$ and $AA$ collisions

- Probing energy loss processes
  - Variety of observables to investigate
Part I

Probing nuclear parton densities
Ratio of PDFs in nuclei over that in a proton

\[ R_i(x, Q^2) = \frac{f^P/A_i(x, Q^2)}{f^P_i(x, Q^2)} \]

poorly constrained especially at small \( x \) and in the gluon sector
Global fits

Global fit analyses of nuclear parton densities

- DIS and Drell-Yan data [EKS98, HKM, nDS, nDSg, nCTEQ]
- ... and hadron production at RHIC [EPS09]

![Graph showing nuclear parton densities](image-url)
Global fits

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  - [ EKS98, HKM, nDS, nDSg, nCTEQ ]
- ...and hadron production at RHIC
  - [ EPS09 ]

Nuclear Modifications for $g_{Pb/Pb}$ ($x, Q_o = 1.3$ GeV)

- nCTEQ decut3
- nCTEQ decut3g3
- nCTEQ decut3g9

[ nCTEQ Schienbein et al. 0710.4897 & 0907.2357 ]
Global fits

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Question

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

- which observables
- why prompt photons look promising
Comparing observables

Advantages and limitations

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

- **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
Comparing observables

Aurenche et al. 2006

Very good description of isolated/inclusive photon world-data
(x, Q^2) domain covered at the LHC

- Photons and jets are clearly **complementary**
- Photons cover **small** Q^2 where shadowing should be large
At leading order

- Compton scattering $q(\bar{q})g \rightarrow q(\bar{q})\gamma$

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

At high energy: Compton $\gg$ Annihilation

Simple relationship between prompt photon production and parton densities!
Nuclear production ratio

**Definition**

\[
R_{pA}(x_\perp) = \frac{1}{A} \frac{d^3\sigma}{dy \ d^2p_\perp} (p + A \rightarrow \gamma + X) \Bigg/ \frac{d^3\sigma}{dy \ d^2p_\perp} (p + p \rightarrow \gamma + X)
\]

**Most naive estimates**

- **Around mid-rapidity**
  \[
  R_{pA}(p_\perp, y) \simeq 0.5 \left[ R_{F_2}(x_\perp e^{-y}) + R_G(x_\perp e^{-y}) \right]
  \]

- **At (very) forward rapidity**
  \[
  R_{pA}(p_\perp, y) \simeq R_G(x_\perp e^{-y})
  \]

- **At (very) backward rapidity**
  \[
  R_{pA}(p_\perp, y) \simeq R_{F_2}(x_\perp e^{-y})
  \]
Caveats

Relationship between photon momenta and parton kinematics spoiled by fragmentation processes and higher-order corrections

- Photon fragmentation contribution

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

for particles in a cone

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

Relationship between photon momenta and parton kinematics spoiled by fragmentation processes and higher-order corrections

- Photon fragmentation contribution

- Next-to-leading order (NLO) corrections

- 3-body kinematics in the final state
Checking the approximation

Using nDSg in p A collisions at the LHC

![Graph](image)

Excellent matching between $R_{pA}$ and nuclear density ratios at the LHC

- $< 2-3\%$ at $y = 0$
- $\sim 5\%$ at $y = 2.5$
Prompt photon suppression $R_{pA}$ and $R_{AA}$ computed systematically

- NLO accuracy
- Using most recent nPDF sets available
  - nDS, EPS09, HKN
- At RHIC and LHC
  - RHIC: d Au and Au Au at $\sqrt{s_{NN}} = 200$ GeV
  - LHC: p Pb at $\sqrt{s_{NN}} = 8.8$ TeV and Pb Pb at $\sqrt{s_{NN}} = 5.5$ TeV
- Full error analysis
  - uncertainty computed from the 31 EPS09 error sets
Isospin effect

Due to QED coupling

\[
\frac{\sigma(ug \rightarrow u\gamma)}{\sigma(dg \rightarrow d\gamma)} = \frac{e_u^2}{e_d^2} = 4
\]

When valence quarks dominate (large \(x \sim 1\))

\[
\sigma(nn \rightarrow \gamma X) < \sigma(pn \rightarrow \gamma X) < \sigma(pp \rightarrow \gamma X)
\]

\[
\sigma(AA \rightarrow \gamma X) < \sigma(pA \rightarrow \gamma X) < \sigma(pp \rightarrow \gamma X)
\]
Isospin effect

Due to QED coupling

\[ \frac{\sigma(ug \to u\gamma)}{\sigma(dg \to d\gamma)} = \frac{e_u^2}{e_d^2} = 4 \]

When valence quarks dominate (large \( x \sim 1 \))

\[ \sigma(nn \to \gamma X) < \sigma(pn \to \gamma X) < \sigma(pp \to \gamma X) \]
\[ \sigma(AA \to \gamma X) < \sigma(pA \to \gamma X) < \sigma(pp \to \gamma X) \]

Consequence

\[ R_{pA}(x_\perp) < 1 \text{ at large } x_\perp \]

- large transverse momentum: \( 2p_\perp/\sqrt{s_{NN}} \sim 1 \)
- backward rapidity: \( e^{-y} \gg 1 \)
At mid-rapidity ($y = 0$)

- Interplay between anti-shadowing and EMC effect
- Large differences between the various nPDF sets
At forward rapidity \((y = 3)\)

- Important isospin effect from the deuteron projectile
- Interplay between shadowing and anti-shadowing
- Effects rather similar in the pion channel
At $y = 0$

- Interplay between **shadowing** and **anti-shadowing** (like at RHIC at forward rapidity)
- Future data should discriminate between the various predictions
Counting rates in $pA$ collisions

**Statistical accuracy in a year much better than the present spread of theoretical predictions**

- **RHIC-II** (assuming $\mathcal{L}_{\text{int}} = 0.7 \text{ pb}^{-1}$)
  
  $N > 100/\text{GeV}$ for $p_\perp \lesssim 35 \text{ GeV}$

- **LHC** (assuming $\mathcal{L}_{\text{int}} = 0.1 \text{ pb}^{-1}$)
  
  $N > 100/\text{GeV}$ for $p_\perp \lesssim 100 \text{ GeV}$

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Prompt photons in A A collisions

nPPDF effects magnified in A A collisions, roughly

\[ R_{AA} \sim R_{pA}^2 \sim (R_i^A)^2 \]

Ideal collisions to probe nPDF
nPDF effects magnified in A A collisions, roughly

$$R_{AA} \sim R_{pA}^2 \sim (R_{i^A})^2$$

Ideal collisions to probe nPDF

Caveat

Prompt photons may be sensitive to hot medium effects

- Jet-to-photon “conversion” in QGP due to Compton scattering
- Medium-induced photon emission due to parton multiple scattering
- Photon quenching due to the suppression of the fragmentation component
nPDF effects magnified in A A collisions, roughly

\[ R_{AA} \sim R_{pA}^2 \sim (R_i^A)^2 \]

Ideal collisions to probe nPDF

- Stronger quenching at small \( p_\perp \) where frag. processes are larger
- Effects extend to very large \( p_\perp \) at the LHC
- Caution: separation between direct and fragmentation not physical!
Part II

Probing energy loss processes
Energy loss of massive partons

- Heavy quark mass acts as a collinear cutoff for medium-induced gluon radiation, just like in vacuum (dead cone)  
  \[ \text{Doskhitzer Kharzeev 2001} \]
- Clear hierarchy expected

\[
\left( \Delta E|_g > \right) \Delta E|_q > \Delta E|_c > \Delta E|_b
\]
Energy loss of massive partons

- Heavy quark mass acts as a collinear cutoff for medium-induced gluon radiation, just like in vacuum (dead cone) [Dosshitzer Kharzeev 2001]
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The photon may be used to tag the energy of the massive parton

\[\gamma + Q\] unique tool to probe Q energy loss in the plasma
\( \gamma + Q \) in p A collisions will also probe the charm and the gluon nPDFs

- \( R_{pPb}^{\gamma+c} \) follows \( R_{g}^{Pb} \) very closely
- Almost no overlap between EPS09 and HKN07, and nCTEQ decut3
- Measurements with sufficiently small error bars should disentangle the various nPDF sets
Analysis in A A collisions

- Calculations performed at LO accuracy
- Heavy quark energy loss $\epsilon_Q$ estimated on an event-by-event basis from the quenching weight (probability distribution) obtained perturbatively

[ Armesto Dainese Salgado Wiedemann 2005 ]
Analysis in A A collisions

- Calculations performed at LO accuracy
- Heavy quark energy loss $\epsilon_Q$ estimated on an event-by-event basis from the quenching weight (probability distribution) obtained perturbatively
- Various observables investigated
  - Photon–jet energy asymmetry $A_J$
    \[ A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \Delta \phi > \pi/2 \]
  - Momentum imbalance $z_{\gamma Q}$
    \[ z_{\gamma Q} = -\frac{\vec{p}_{T\gamma} \cdot \vec{p}_{TQ}}{p_{T\gamma}^2} \]
  - Photon–jet pair momentum $q_{\perp}$
    \[ q_{\perp} = |p_{T\gamma} + p_{TQ}| \]
Pair momentum distribution

**Why \( q_\perp \) distribution**

\[ q_\perp \simeq \epsilon_Q \] at LO accuracy if the photon is produced directly

**Preliminary result** in Pb Pb collisions at \( \sqrt{s_{NN}} = 5.5 \text{ TeV} \)

- **Significant** medium modifications reported
- **Stronger effects** in \( \gamma + c \) than \( \gamma + b \) due to the larger energy loss
- Needs to be compared to \( \gamma + \) inclusive jet production
Why $q_\perp$ distribution

$q_\perp \simeq \epsilon_Q$ at LO accuracy if the photon is produced directly.

Preliminary result in Pb Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV

- Significant medium modifications reported
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Prompt photons in nuclear collisions extremely useful

- Single photons in p A collisions
  - Sensitive probe of the gluon PDF in nuclei
  - NLO calculations performed using various nPDF sets
  - Large rates expected at LHC

- $\gamma + Q$ production in A A collisions
  - Access to the mass hierarchy of parton energy loss in QCD plasma
  - Promising preliminary results at the LHC
Comparison between theory and Tevatron data

Measurements by DØ Collaboration [0901.0739] compared to NLO theory [Stavreva Owens 0901.3791]

- Excellent agreement between data and theory in the $\gamma + b$ channel
- $\gamma + c$ data above theory at large $p_T\gamma$
  - hint for intrinsic charm?