Probing gluon densities with prompt photons

François Arleo

LAPTH, Annecy

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Introduction

- Motivations
  - why probing small-x gluons
- Extracting gluon distributions
  - using pQCD prompt photon production in p A collisions
- Phenomenology
  - NLO predictions in p A collisions at LHC

Reference

FA, T. Gousset, Phys. Lett. B660 (2008) 181 [arXiv:0707.2944]

Gluon distributions at small x

Accurate knowledge of gluon density in a proton/nucleus is essential

- Fundamental pQCD ingredient for hard processes at LHC
- Probe of non-linear QCD evolution at small x

Strong activity over the last decade to probe proton densities

- Impressive results from HERA [H1, ZEUS]
- Important theoretical developments in global fit analyses [CTEQ, GRV, MRST, . . .]

Current precision

$G^p(x, Q^2)$ fairly well known over a large kinematical range

$$x \sim 10^{-4}\text{–}10^{-1} \text{ and } Q^2 \sim 10\text{–}10^5 \text{ GeV}^2$$

Gluon density in nuclei

Definition

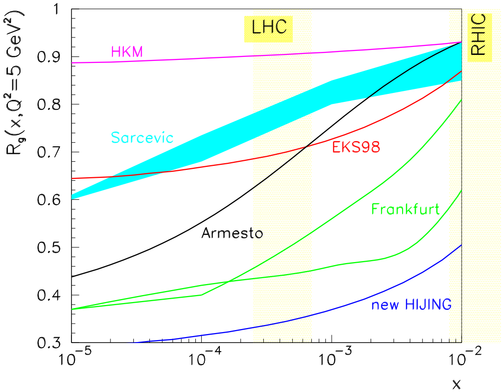
Ratio of gluon distributions in nuclei over that in a proton

$$R_G(x, Q^2) = G^A(x, Q^2)/G^p(x, Q^2)$$

Gluon density in nuclei

Global fit analyses

- DIS and Drell-Yan data [EKS, HKM, nDS, nDSg]
- . . . and hadron production at RHIC [EPS]



[Armesto, Salgado 2003]

Gluon density in nuclei

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Problem

R_{G} poorly constrained experimentally, especially at small x!

Question

How to probe small-x gluon shadowing at LHC?

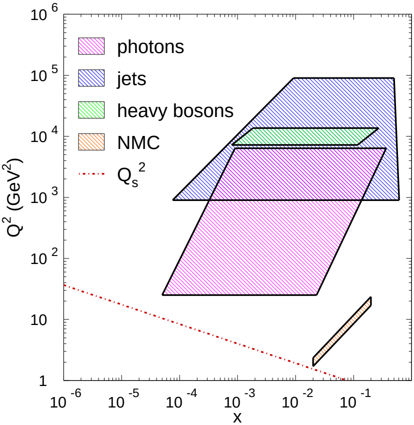
- why prompt photons look promising

Comparing observables

Advantages and limitations

- Jets
    - high rates, rich phenomenology, forward rapidities
    - large scales $Q^2 \gtrsim 10^3$ GeV^2
- Prompt photons
    - low $Q^2 \gtrsim 10$–10^3 GeV^2, rich phenomenology
    - parton-to-photon fragmentation process
- Large $p_\perp$ dileptons
    - no strong background
    - very low rates
- Heavy-bosons
    - constraints on sea-quark shadowing
    - large scales $Q^2 \gtrsim 10^4$ GeV^2

Kinematical range



(x, Q^2) domain covered at the LHC

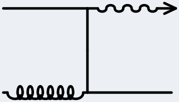
- Photons and jets are clearly complementary
- Photons cover small Q^2 where shadowing should be large

Perturbative production

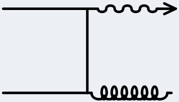
Dynamics

Leading-order $\mathcal{O}(\alpha\ \alpha_s)$ contributions

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



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



Approximation

At high energy, only the Compton scattering process is relevant

Perturbative production

LO production cross section in p A collisions
$(x_\perp \equiv 2p_\perp/\sqrt{s},\ F(x) \equiv F_2(x)/x)$

$$\frac{1}{A}\frac{\mathrm{d}^3\sigma^{pA}}{\mathrm{d}y\ \mathrm{d}^2p_\perp} = \int \mathrm{d}v\ F^p\left(\frac{x_\perp e^y}{2v}\right) G^A\left(\frac{x_\perp e^{-y}}{2(1-v)}\right) \hat{\sigma}(v) + \int \mathrm{d}v\ G^p\left(\frac{x_\perp e^y}{2v}\right) F^A\left(\frac{x_\perp e^{-y}}{2(1-v)}\right) \hat{\sigma}(1-v)$$

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Problem

The integration over the rapidity of the recoiling jet ($\leftrightarrow v$) does not allow for the arguments of F and G to be fixed

Single photon production not sufficient to probe parton densities

Extracting parton density ratios

Approximation

- R_{F_2} and R_G vary slowly as compared to F_2 and G
- Integrand peaked at $v = 1/2$

$$\begin{aligned}\frac{1}{A}\frac{\mathrm{d}^3\sigma^{pA}}{\mathrm{d}y\;\mathrm{d}^2p_\perp} &\simeq R_G(x_\perp e^{-y}) \int \mathrm{d}v\; F^p\left(\frac{x_\perp e^{y}}{2v}\right) G^p\left(\frac{x_\perp e^{-y}}{2(1-v)}\right)\hat{\sigma}(v) \\ &+ R_{F_2}(x_\perp e^{-y}) \int \mathrm{d}v\; G^p\left(\frac{x_\perp e^{y}}{2v}\right) F^p\left(\frac{x_\perp e^{-y}}{2(1-v)}\right)\hat{\sigma}(1-v)\end{aligned}$$

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+\ & R_{F_2}(x_\perp e^{-y}) \int \mathrm{d}v\ G^p\left(\frac{x_\perp e^y}{2v}\right) F^p\left(\frac{x_\perp e^{-y}}{2(1-v)}\right) \hat{\sigma}(1-v)
\end{aligned}
$$

Simple relationship between prompt photon production

and parton densities!

[NB: especially when one channel is negligible to another]

Nuclear production ratio

Definition

Nuclear production ratio in p A collisions

$$R_{pA}(x_\perp) = \frac{1}{A}\ \frac{\mathrm{d}^3\sigma}{\mathrm{d}y\ \mathrm{d}^2p_\perp}(p + A \to \gamma + \mathrm{X})\Big/\frac{\mathrm{d}^3\sigma}{\mathrm{d}y\ \mathrm{d}^2p_\perp}(p + p \to \gamma + \mathrm{X})$$

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

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

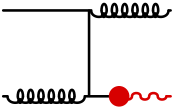
- At (very) backward rapidity

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

Limitations (1): Fragmentation photons

Problem

Photons can also be produced by fragmentation



The collinear divergence of this diagram is absorbed into non-perturbative quantities: quark/gluon fragmentation functions into a (collinear) photon

The $q \to q\,\gamma$ splitting process yields large terms $\ln(Q/\Lambda_{\rm QCD})$ making fragmentation functions into γ to be $\mathcal{O}\left(\alpha/\alpha_s\right)$

The above diagram actually is $\mathcal{O}\left(\alpha_s^2\right)\ D_{\gamma/k} = \mathcal{O}\left(\alpha\,\alpha_s\right) =$ LO !

Limitations (1): Fragmentation photons

Problem

Photons can also be produced by fragmentation

$$\frac{\mathrm{d}^3\sigma^{\mathrm{frag}}(p\,A \to \gamma\,\mathrm{X}\,)}{\mathrm{d}y\ \mathrm{d}^2p_\perp} \propto \int_0^1 \mathrm{d}z \int_0^1 \mathrm{d}v\ \ldots \left(x_\perp/z, Q^2\right)\ D_{\gamma/k}(z, Q^2)$$

The extra integration spoils the relationship $R_{pA} \Leftrightarrow R_{F_2}$ and R_G

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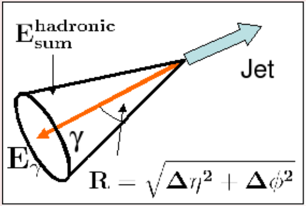
Solution

We get rid of (most of) them by means of isolation criteria

$$E^{\mathrm{had}} \leq E^{\mathrm{max}}$$

for particles in a cone

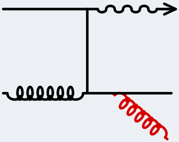
$$(\eta - \eta_\gamma)^2 + (\phi - \phi_\gamma)^2 \leq R^2$$



Limitations (2): NLO corrections

Problem

Next-to-leading order (NLO) corrections



3-body kinematics in the final state ⇒ needs to integrate over the momentum of the extra-particle radiated

Strategy

Let's compute $R_{pA}(x_\perp, y)$ at NLO and check the analytic estimate

Phenomenology

1. Checking the approximation

$R_{pA}(x_\perp, y)$ computed in p A collisions using NLO nDSg parton densities and compared to R_G

- p A collisions at LHC
  - $\sqrt{s_{\mathrm{NN}}} = 8.8$ TeV at $y = 0$ and 2.5

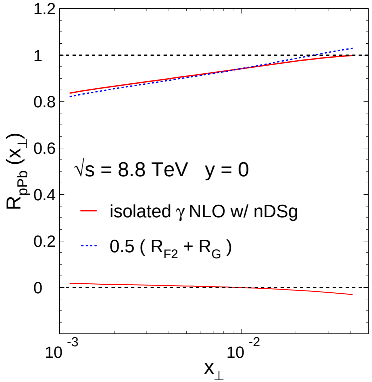
2. Comparing nPDFs

$R_{pA}(x_\perp, y)$ computed in p A collisions at RHIC and LHC

- In pQCD at NLO
  - using EKS, HKM, nDS, nDSg, EPS parton densities

Checking the approximation

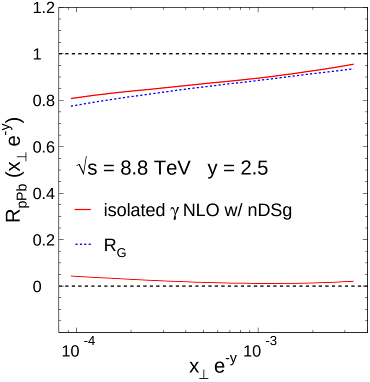
LHC at mid-rapidity



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

Checking the approximation

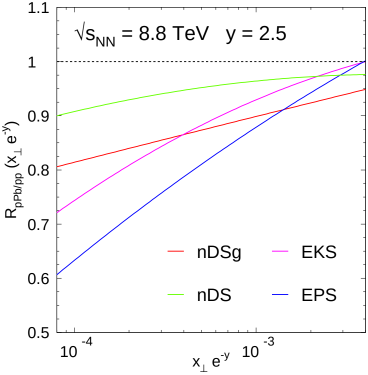
LHC at forward rapidity $y = 2.5$



- Gives "direct" access to R_G (within 5%) at $x = 10^{-4}$–10^{-3} !

Comparing nPDFs

LHC at forward rapidity $y = 2.5$



- Significant differences between the various nPDF sets
- Need to be compared with expectations from saturation

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 ?

Shadowing without p p data

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Proposal

Compare forward w/ backward production in p A collisions

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

$$\simeq R_G(x_\perp e^{-y})/R_{F_2}(x_\perp e^{y})$$

R_{F_2} at large x gives access to R_G at small x !

Shadowing without p p data

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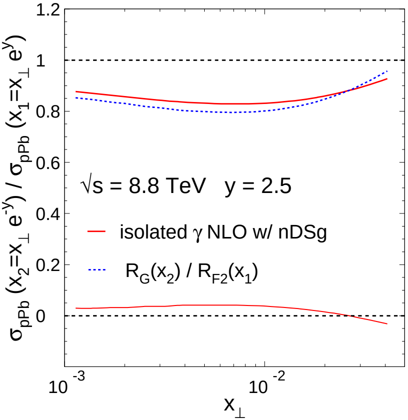

Counting rates

- p A at LHC $\left(\mathcal{L} = 1.4\ 10^{30}\ \mathrm{cm}^{-2} s^{-1},\ \Delta t = 10^6 \mathrm{s}\right)$

$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}y\ \mathrm{d}p_\perp}\right|_{p_\perp = 100\ \mathrm{GeV}} \simeq\ 8\ 10^2\ \mathrm{pb/GeV}\ \Rightarrow\ \mathcal{N} \sim 10^3/\mathrm{GeV}$$

Statistical accuracy in a year much better than the present spread of theoretical predictions for R_G at small x

Summary

- Essential to further constrain $G(x)$ at small x
  - needed for pQCD predictions at LHC
  - looking for saturation
- Prompt photon production in p A collisions
  - an ideal observable to probe parton densities
- Phenomenology at LHC
  - reliable estimate of R_G from R_{pA} at forward rapidity
  - comparing the predictions in QCD using various sets
  - extracting R_G witout p p data at the same energy