Probing parton densities and energy loss processes using photons in p A and A A collisions

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LAPTH, Annecy

High $p_\perp$ Probes of High Density QCD – May 2011

Introduction

- Motivations
    - Hard QCD processes in nuclear collisions
- Single γ 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

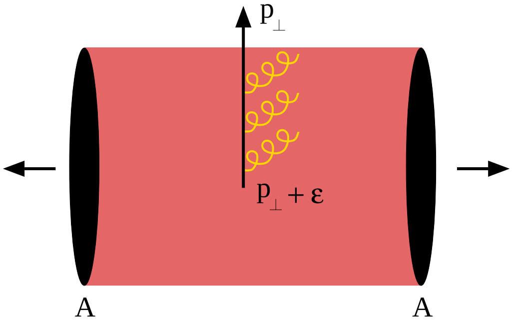
References

- FA, K. Eskola, H. Paukkunen, C. Salgado, JHEP 04 (2011) 055 [arXiv:1103.1471]
- T. Stavreva et al., JHEP 01 (2011) 152 [arXiv:1012.1178] + work in progress

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



Hard processes in QCD media

Schematically two classes of processes

Medium sensitive

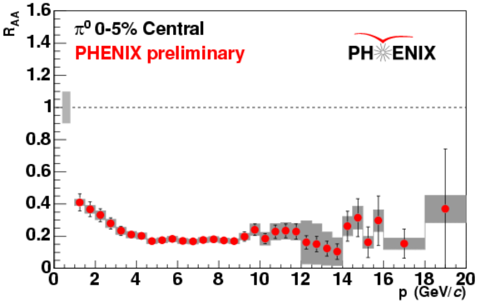
- Jets
- Large $p_\perp$ hadrons
- Heavy-quarkonia and open heavy flavour

Medium insensitive

- Prompt photons
- $W^\pm/Z^0$ bosons
- Drell-Yan pair production

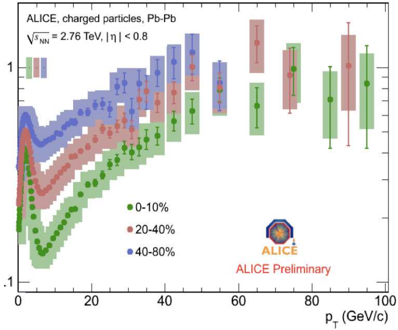
Jet quenching

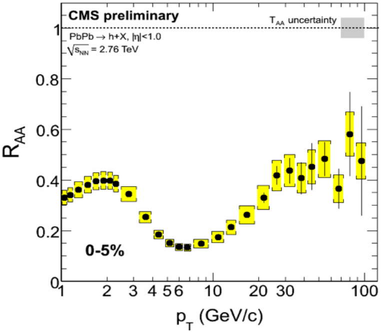
Significant suppression of large-$p_\perp$ hadrons in Au Au collisions at RHIC



One of the most important discoveries in heavy-ion collisions

First LHC measurements





- Strong hadron suppression seen by ALICE
- Significant asymmetries in jet production reported in central Pb Pb collisions by ATLAS and CMS

First LHC measurements

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 p A and A A collisions
- Probing energy loss processes
  - Variety of observables to investigate

Part I

Probing nuclear parton densities

Present constraints on nPDFs

Ratio of PDFs in nuclei over that in a proton

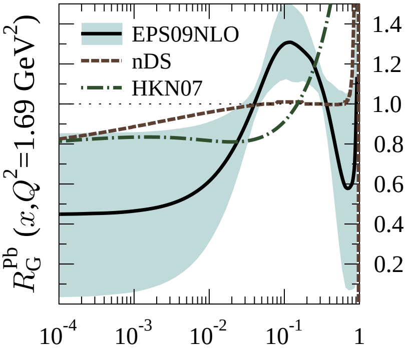
$$R_i(x, Q^2) = f_i^{p/A}(x, Q^2)/f_i^p(x, Q^2)$$

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]



[EPS09 Eskola, Paukkunen, Salgado 0902.4154]

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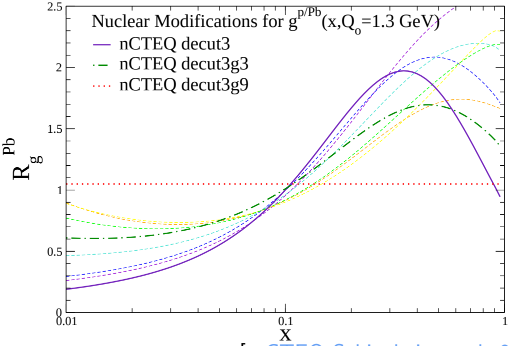

[nCTEQ Schienbein et al. 0710.4897 & 0907.2357]

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Question

How to probe small-x gluon shadowing at LHC ?

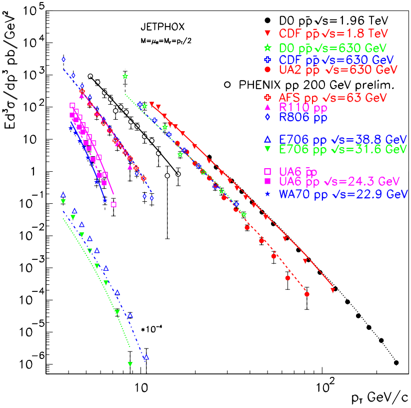
- which observables
- why prompt photons look promising

Comparing observables

Advantages and limitations

- Jets
  - high rates, rich phenomenology, forward rapidities
  - large scales $Q^2 \gtrsim 10^3$ GeV^2
- Heavy-bosons
  - constraints on sea-quark shadowing
  - large scales $Q^2 \gtrsim 10^4$ GeV^2
- Prompt photons
  - low $Q^2 \gtrsim 10$–10^3 GeV^2, rich phenomenology
  - parton-to-photon fragmentation process

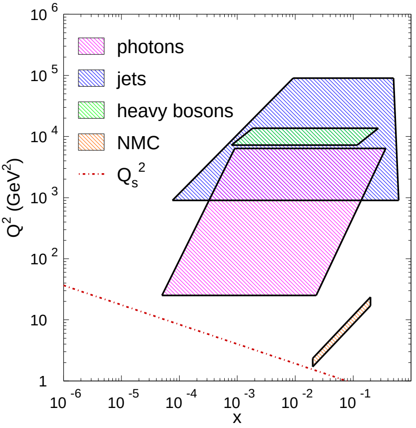
Comparing observables



[Aurenche et al. 2006]

- Very good description of isolated/inclusive photon world-data

Kinematical range



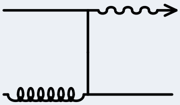
(x, Q^2) domain covered at the LHC

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

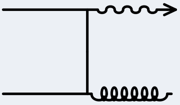
Dynamics

At leading order

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



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



At high energy: Compton $\gg$ Annihilation

Simple relationship between prompt photon production

and parton densities !

Nuclear production ratio

Definition

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

Most naive estimates [FA Gousset 2008]

- 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

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

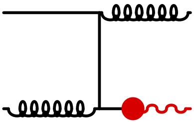
- At (very) backward rapidity

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

Caveats

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

- Photon fragmentation contribution

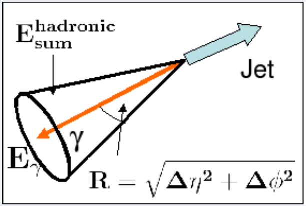


This component very much reduced using isolation criteria

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

for particles in a cone

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



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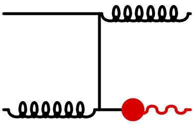
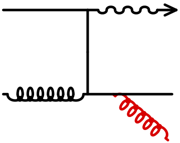


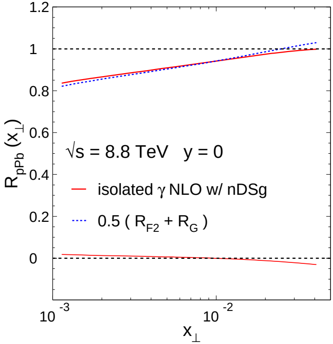
- Next-to-leading order (NLO) corrections



  - 3-body kinematics in the final state

Checking the approximation

Using nDSg in p A collisions at the LHC



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

- < 2–3% at $y = 0$
- $\sim 5\%$ at $y = 2.5$

Set-up

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

$$\sigma(ug \to u\gamma)/\sigma(dg \to d\gamma) = e_u^2/e_d^2 = 4$$

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

$$\sigma(nn \to \gamma\ \mathrm{X}) \quad < \quad \sigma(pn \to \gamma\ \mathrm{X}) \quad < \quad \sigma(pp \to \gamma\ \mathrm{X})$$

$$\frac{1}{\mathrm{AA}}\sigma(\mathrm{AA} \to \gamma\ \mathrm{X}) \quad < \quad \frac{1}{\mathrm{A}}\sigma(p\mathrm{A} \to \gamma\ \mathrm{X}) \quad < \quad \sigma(pp \to \gamma\ \mathrm{X})$$

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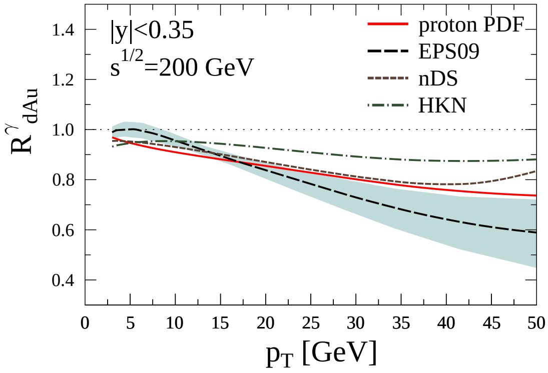
Consequence

$R_{p\mathrm{A}}(x_\perp) < 1$ at large $x_\perp$

- large transverse momentum: $2p_\perp/\sqrt{s_{\mathrm{NN}}} \sim 1$
- backward rapidity: $e^{-y} \gg 1$

RHIC

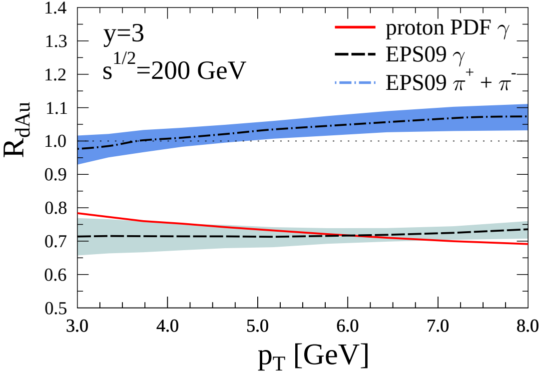
At mid-rapidity ($y = 0$)



- Interplay between anti-shadowing and EMC effect
- Large differences between the various nPDF sets

RHIC

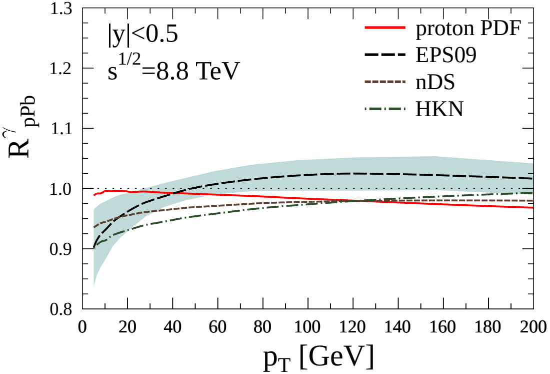
At forward rapidity ($y = 3$)



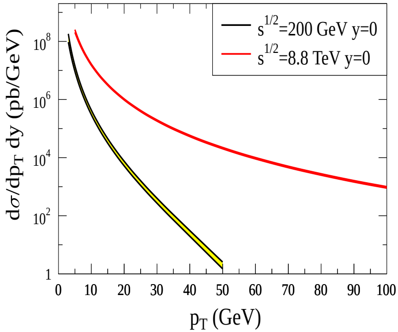
- Important isospin effect from the deuteron projectile
- Interplay between shadowing and anti-shadowing
- Effects rather similar in the pion channel

LHC

At $y = 0$



- Interplay between shadowing and anti-shadowing (like at RHIC at forward rapidity)
- Future data should discriminate between the various predictions



RHIC-II (assuming $\mathcal{L}_{\rm int} = 0.7\ {\rm pb}^{-1}$)

$\mathcal{N} > 100/\text{GeV}$ for $p_\perp \lesssim 35$ GeV

LHC (assuming $\mathcal{L}_{\rm int} = 0.1\ {\rm pb}^{-1}$)

$\mathcal{N} > 100/\text{GeV}$ for $p_\perp \lesssim 100$ GeV

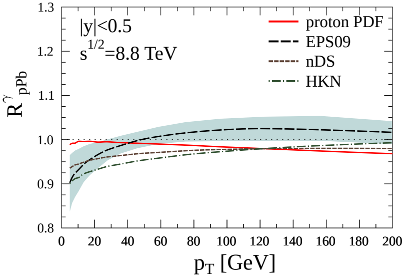
Statistical accuracy in a year much better than
the present spread of theoretical predictions

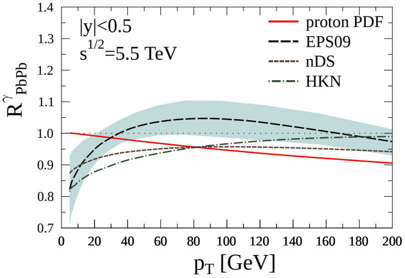
Prompt photons in A A collisions

nPDF effects magnified in A A collisions, roughly

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

Ideal collisions to probe nPDF





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Ideal collisions to probe nPDF

Caveat

Prompt photons may be sensitive to hot medium effects

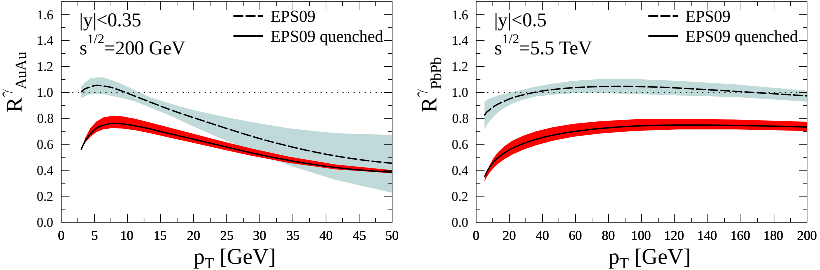
- Jet-to-photon "conversion" in QGP due to Compton scattering
- Medium-induced photon emission due to parton multiple scattering
- Photon quenching due to the suppression of the fragmentation component

Prompt photons in A A collisions

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

Probing (massive) parton energy loss in QGP

Energy loss of massive partons

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

$$\left(\Delta E\big|_g >\right) \Delta E\big|_q > \Delta E\big|_c > \Delta E\big|_b$$

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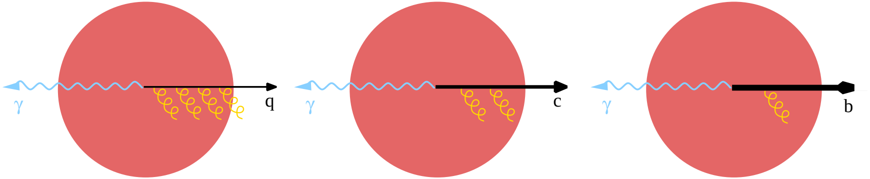
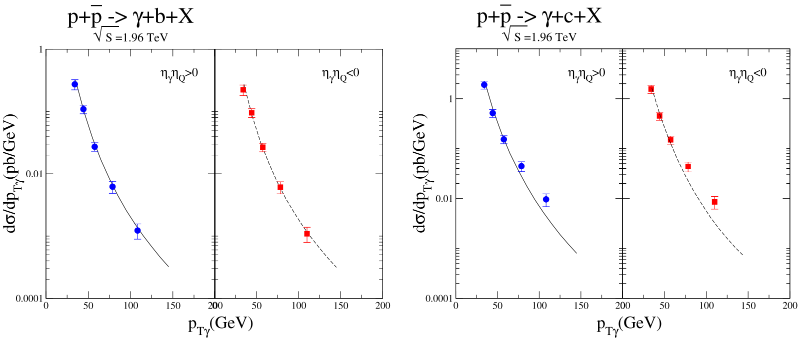


The photon may be used to tag the energy of the massive parton

$\gamma + Q$ unique tool to probe Q energy loss in the plasma

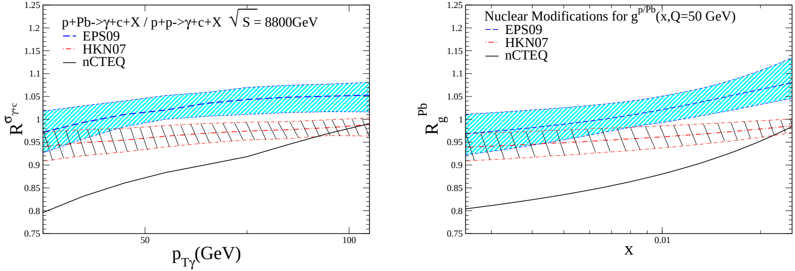
Measurements by DØ Collaboration [0901.0739] compared to NLO theory [Stavreva Owens 0901.3791]



- 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?

$\gamma + Q$ in p A collisions

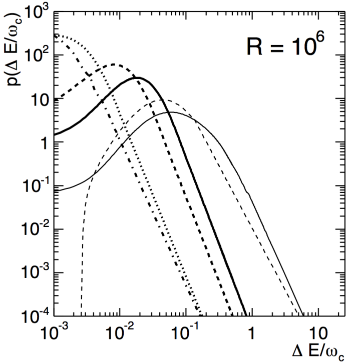
$\gamma + Q$ in p A collisions will also probe the charm and the gluon nPDFs



- $R^{\gamma+c}_{pPb}$ follows R^{Pb}_{g} 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 ϵ_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 ϵ_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 $z_{\gamma Q}$

$$z_{\gamma Q} = -\frac{\vec{p}_{T\gamma} . \vec{p}_{TQ}}{p_{T\gamma}^2}$$

  - Photon–jet pair momentum $q_\perp$

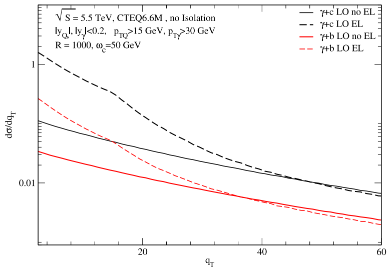
$$q_\perp = |p_{T\gamma} + p_{TQ}|$$

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 $\sqrt{s_{\rm NN}} = 5.5$ TeV



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- Stronger effects in $\gamma + c$ than $\gamma + b$ due to the larger energy loss
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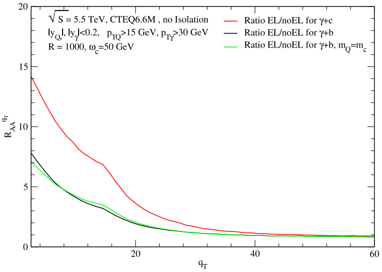

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Summary

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