Phenomenology of $\gamma + Q$ production in p A and A A collisions

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Heavy ion collisions in the LHC era

Introduction

- Motivations
  - Hard QCD processes in nuclear collisions
  - Comparison to Tevatron data
- $\gamma + Q$ 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

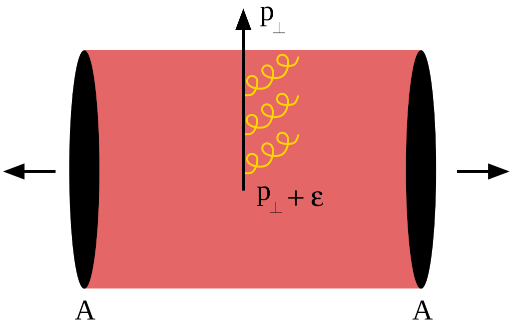
Reference

T. Stavreva et al., JHEP 01 (2011) 152 + 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

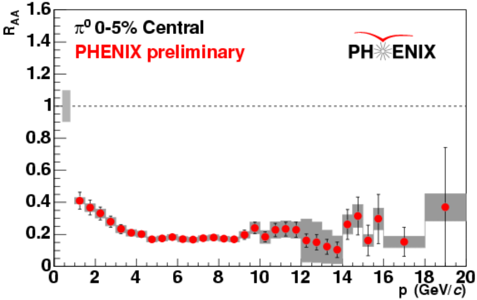
- Jets
- Large $p_\perp$ hadrons
- Heavy-quarkonia and open heavy flavour

Medium insensitive

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

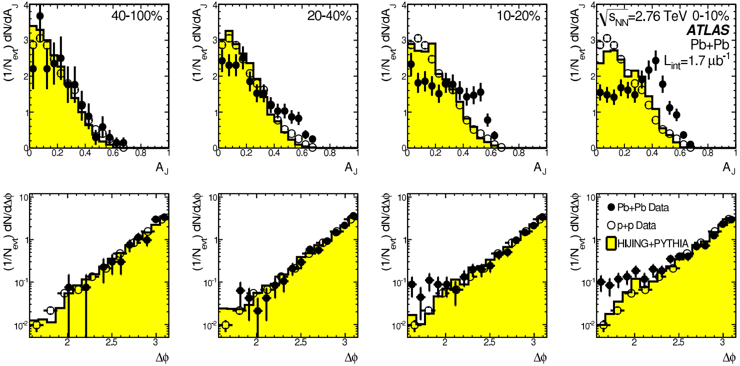
Jet quenching

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



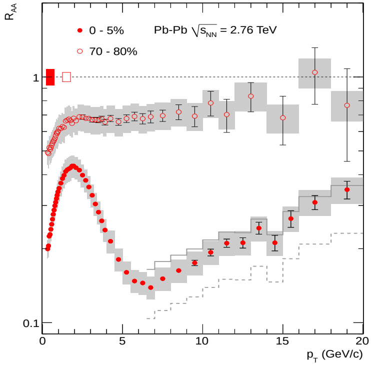
One of the most important discoveries in heavy-ion collisions

First LHC measurements



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

First LHC measurements



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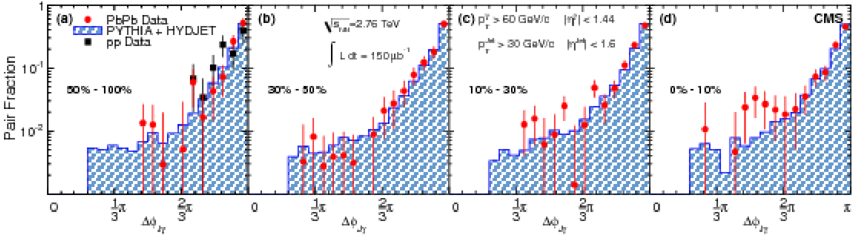
First LHC measurements

More recently: first γ – jet measurements by CMS !

[CMS 1205.0206]



First LHC measurements

A robust interpretation of the data requires a quantitative understanding of hard processes in nuclear collisions

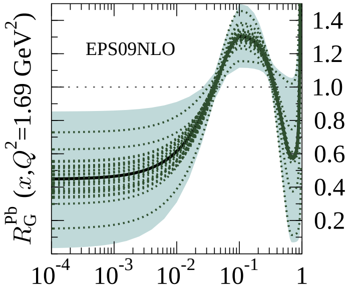
- Probing parton densities in nuclei (nPDFs)
    - Essential to predict benchmark predictions in p A and A A collisions
- Probing energy loss processes
    - Variety of observables to investigate

Nuclear PDFs

Ratio of PDFs in nuclei over that in a proton

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

poorly constrained especially at small x and in the gluon sector



[EPS09 Eskola, Paukkunen, Salgado 0902.4154]

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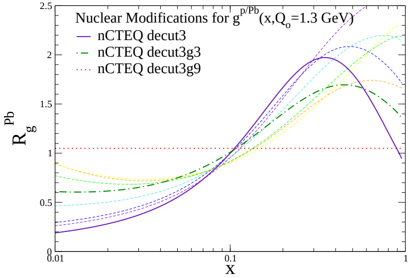

[nCTEQ Schienbein et al. 0710.4897]

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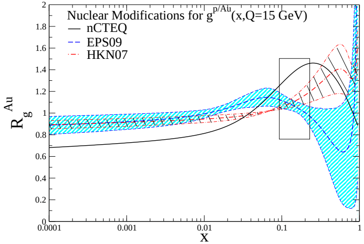
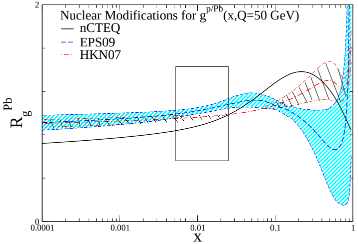
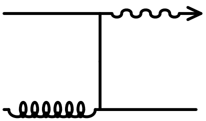




$\gamma + Q$ production in p A collisions

$\gamma + Q$ production from p p to A A collisions dominated by the LO Compton scattering process $Qg \to Q\gamma$



Offers a unique access to

- heavy-quark nuclear PDF
- gluon nuclear PDF through QCD evolution

$\gamma + Q$ production in p A collisions

Caveats

- NLO corrections
  - $2 \to 3$ hard-scattering subprocesses - $\mathcal{O}(\alpha\alpha_s^2)$

$$g + g \to Q + \bar{Q} + \gamma \qquad Q + Q \to Q + Q + \gamma$$
$$g + Q \to g + Q + \gamma \qquad Q + \bar{Q} \to Q + \bar{Q} + \gamma$$
$$Q + q \to q + Q + \gamma \qquad q + \bar{q} \to Q + \bar{Q} + \gamma$$
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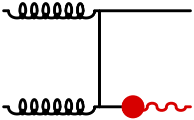
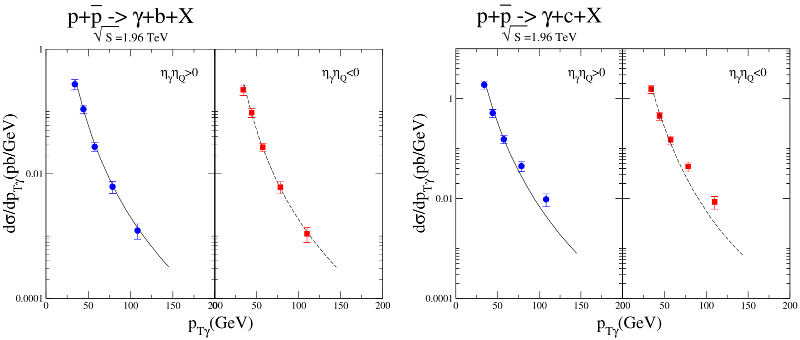
- Photon fragmentation contribution



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?

Predictions in p A collisions

- NLO calculations assuming that charm PDF is radiatively generated ($c(x, \mu = m_c) = 0$)

$$\frac{dc(x,Q)}{dt} = \frac{\alpha_s}{2\pi} \int \frac{dy}{y} [c(x/y) P_{Q \leftarrow Q}(y) + g(x/y) P_{g \leftarrow Q}(y)]$$

in the variable flavour number scheme

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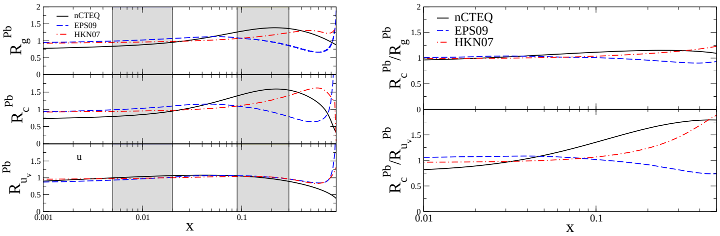
Probing charm nPDF allows for constraining the gluon sector



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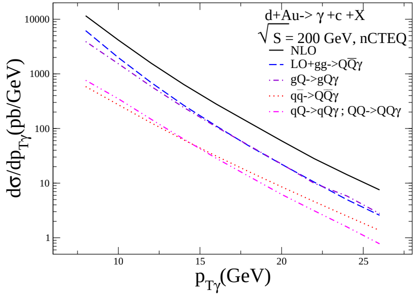
  in the variable flavour number scheme
- Predictions at RHIC and LHC
  - RHIC: d Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV
  - LHC: p Pb collisions at $\sqrt{s_{\rm NN}} = 8.8$ TeV
- Calculation of quenching factors

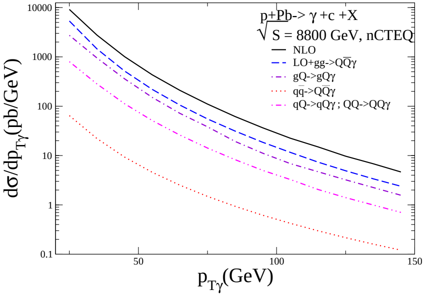
$$R_{pA}^{\gamma Q} = \frac{\sigma\left(pA \to \gamma\ Q\ \mathrm{X}\right)}{A\ \sigma\left(pp \to \gamma\ Q\ \mathrm{X}\right)}$$

  using different nPDF sets then available: nCTEQ, EPS09, HKN07

Spectra and rates

Absolute cross sections





- Cross section dominated by Compton scattering
- Important NLO corrections

Spectra and rates

Expected rates at RHIC (PHENIX kinematics)

Assuming $\mathcal{L}^{year} = 0.74\ \text{pb}^{-1}$

Photon + charm

- $\mathcal{N} \simeq 3 \times 10^4$ for $p_{T_\gamma} > 7$ GeV
- $\mathcal{N} \simeq 10^2$ for $p_{T_\gamma} > 20$ GeV

Photon + bottom

- < 100 events for $p_{T_\gamma} > 17$ GeV

Spectra and rates

Expected rates at LHC (ALICE kinematics)

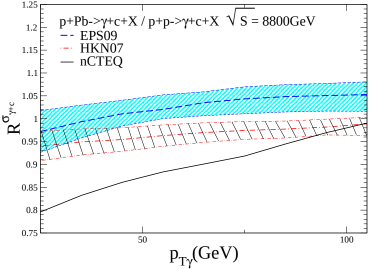
Assuming $\mathcal{L}^{year} = 0.1 \text{ pb}^{-1}$

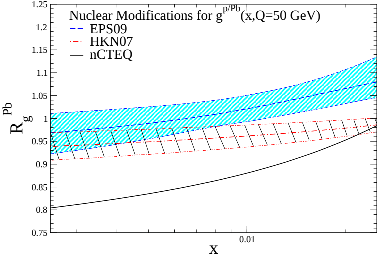
	$\sigma^{pPb}_{\gamma+Q}$	$N^{pPb}_{\gamma+Q}$
$\gamma + c$ PHOS	22700 pb	2270
$\gamma + b$ PHOS	3300 pb	330
$\gamma + c$ EMCal	119000 pb	11900
$\gamma + b$ EMCal	22700 pb	2270

- Large for $\gamma + c$ and $\gamma + b$ events at LHC

Constraining the gluon nPDF

LHC

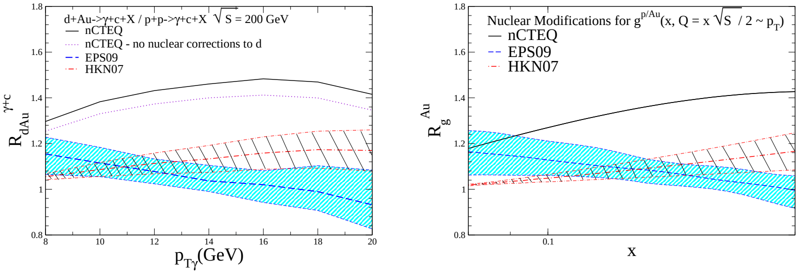




- $R_{pPb}^{\gamma+c}$ follows R_g^{Pb} very closely
- Almost no overlap between EPS09 and HKN07, and nCTEQ decut3
- Measurements with sufficiently small error bars should disentangle the various nPDF sets

Constraining the gluon nPDF

RHIC



- Same observation than at LHC : $R_{dAu}^{\gamma+c} \simeq R_g^{Au}$
- Kinematic region probed at RHIC ($x = 10^{-1}$–2×10^{-1}) complementary to that at LHC ($x = 5 \times 10^{-3}$–2×10^{-2})

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]
- Clear hierarchy expected

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

Energy loss of massive partons

- Heavy quark … m-induced gluon radiation, ju … itzer Kharzeev 2001]
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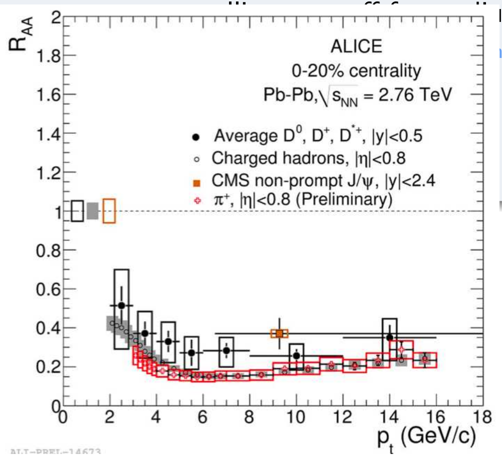

[N. Bastid talk]

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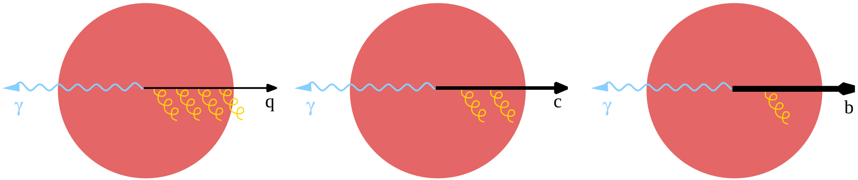
$\gamma + Q$ unique tool to probe Q energy loss in the plasma



Analysis in A A collisions

- Calculations performed at NLO accuracy at $\sqrt{s} = 5.5$ TeV
- 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]
- 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 $z_{\gamma Q}$

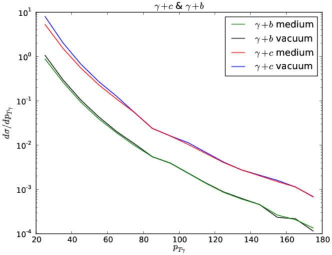
$$z_{\gamma Q} = -\frac{\vec{p}_{T\gamma} . \vec{p}_{TQ}}{p^2_{T\gamma}}$$

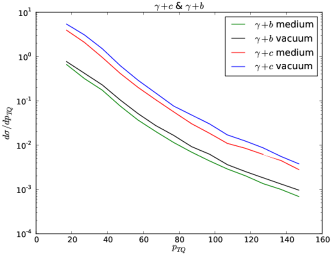
  - Photon–jet pair momentum $q_\perp$

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

Transverse momentum distributions

Comparing photon and jet $p_\perp$ spectra

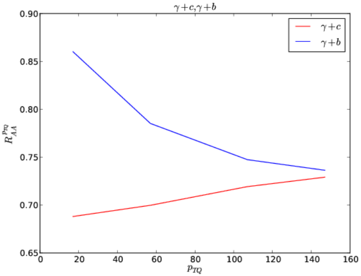




- No (or little) modifications of the photon $p_\perp$
- Stronger effects on the heavy quark jet spectrum

Transverse momentum distributions

Nuclear production ratios R_{AA}

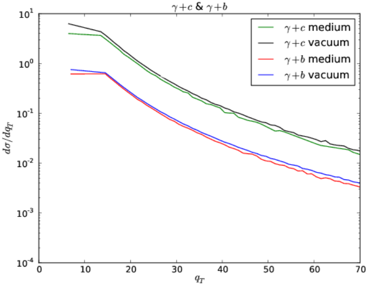


- Stronger effects in $\gamma + c$ than $\gamma + b$ due to the larger energy loss assumed in the calculation
- Needs to be compared to $\gamma+$ inclusive jet production

Pair momentum distribution

Why $q_\perp$ distribution

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



- The shift in the $q_\perp$ distributions should reflect the strength of heavy quark energy loss in the medium

Summary

$\gamma + Q$ in nuclear collisions extremely useful

- p A collisions
  - Sensitive probe of the gluon and heavy quark PDF in nuclei
  - NLO calculations performed using various nPDF sets
  - Large rates expected at LHC
  - Could include more recent nPDF sets e.g. DSSZ & EPS09s
- A A collisions
  - Access to the mass hierarchy of parton energy loss in QCD plasma
  - Promising preliminary results at the LHC