Energy loss and saturation at the LHC ?

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Workshop on Saturation Signals – October 2013

Outline

- Motivations
  - How to probe small x physics
  - How disentangle saturation from parton energy loss
- Revisiting energy loss
  - Some new results & phenomenology
- Observables at the LHC

References

- FA, S. Peigné, PRL 109 (2012) 122301 [1204.4609]
- FA, S. Peigné, JHEP 03 (2013) 122 [1212.0434]
- FA, R. Kolevatov, S. Peigné, M. Rustamova, JHEP 05 (2013) 155 [1304.0901]

Message from the organizers

- What is the x-sensitivity of different probes
- Do we understand the production mechanisms?
- How much model uncertainty is there? How large are NLO (or higher) effects?
- What other mechanisms can obscure the interpretation of the measurements
- What do current measurements do with respect to constraining low-x physics?
- What is the current level of uncertainties in saturation models?

x sensitivity

Consider hard process with energy scale Q

- Leading-order kinematics

$$x_1 \sim \frac{Q}{\sqrt{s}} \exp(+y) \quad ; \quad x_2 \sim \frac{Q}{\sqrt{s}} \exp(-y)$$

- Probing small x_2 in the nucleus
  - Small energy scale (or high energy) $Q \ll \sqrt{s}$ (LHC)
  - Large (forward) rapidity $\exp(-y) \ll 1$ (RHIC & LHC)

Caveat

Forward physics implies "large" $x_1 \gg x_2$

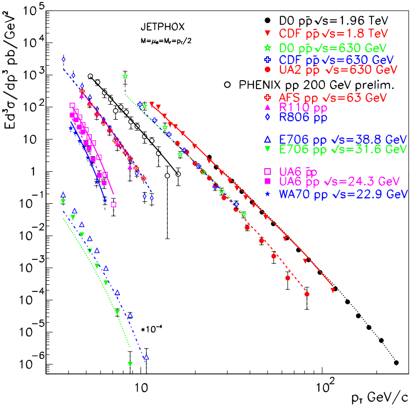
where other phenomena can occur

Comparing observables

Advantages and limitations

- Jets
  - high rates, rich phenomenology, forward rapidities
  - large scales $Q^2 \gtrsim 10^3$ GeV^2
- Large $p_\perp$ hadrons
  - high rates, forward rapidities, lower scales than jets
  - Uncertainty from fragmentation functions
- Drell-Yan
  - constraints on sea-quark shadowing
  - large background at low mass
- Weak 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

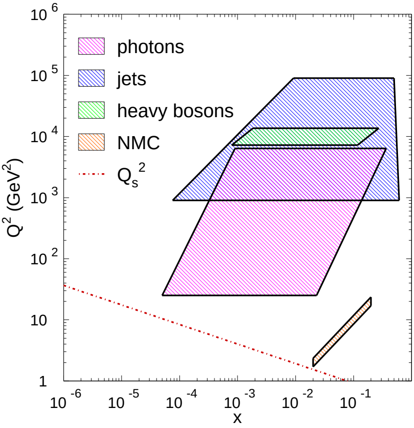
Comparing observables



[Aurenche et al. 2006]

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

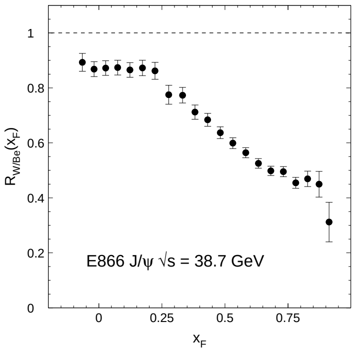
Kinematical range



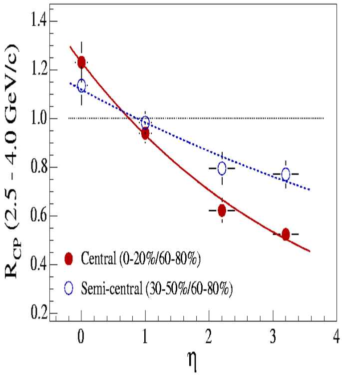
(x, Q^2) domain covered at the LHC

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

E866 $\sqrt{s} = 38.7$ GeV



BRAHMS $\sqrt{s} = 200$ GeV



- E866 J/ψ data cannot be attributed to saturation effects
- BRAHMS hadron data. . . maybe

Energy loss vs. saturation

Parton multiple scattering in the nucleus could affect hard process

How to disentangle saturation from parton energy loss?

Lesson from the past

Nuclear dependence of Drell-Yan production in p A collisions

A simple analysis [FA hep-ph/0201066]

- Sea quark shadowing not negligible when no energy loss is assumed
- Sizeable parton energy loss assuming no (or small) sea quark shadowing

Why could parton energy loss be important at the LHC ?

Common belief

- Induced gluon radiation needs to resolve the medium

$$t_f \sim \frac{\omega}{k_\perp^2} \lesssim L \qquad \omega \lesssim k_\perp^2 \; L \sim \hat{q} \; L^2$$

- Bound independent of the parton energy $\Delta E \sim \hat{q} \; L^2$
- Negligible energy loss (wrt parton energy) $\Delta E/E \to 0$ at the LHC

True only for "pure" initial-state of final-state energy loss !

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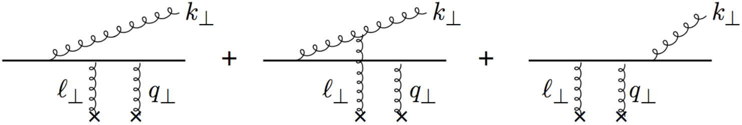
When ?

- No color flow in the initial or final state
  - hadron production in nuclear DIS and Drell-Yan in p A collisions
- Large angle particle production
  - jets and large $p_\perp$ hadrons in quark-gluon plasma

Revisiting energy loss scaling properties

Coherent radiation (interference) in the initial/final state

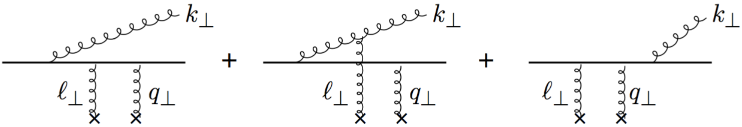


- IS and FS radiation cancels out in the induced spectrum
- Interference terms do not cancel in the induced spectrum !
- Induced gluon spectrum dominated by large formation times

$$\Delta E = \int d\omega\, \omega \left.\frac{dI}{d\omega}\right|_{\text{ind}} = N_c \alpha_s \frac{\sqrt{\Delta q_\perp^2}}{M_\perp} E$$

Revisiting energy loss scaling properties

Coherent radiation (interference) in the initial/final state



When ?

Color flow in the initial and final state & small angle scattering

- Production of light and open heavy-flavour hadrons at forward rapidities in the medium rest frame (nuclear matter or QGP)
- Production of heavy-quarkonium if color neutralization occurs on long time-scales $t_{\text{octet}} \gg t_{\text{hard}}$

(intermediate) Summary

- Incoherent energy loss (small formation time $t_f \sim L$)

$$\Delta E \propto \alpha_s \; \hat{q} \; L^2$$

  - prompt photons, Drell-Yan, weak bosons
  - should be negligible at LHC
  - important in hot media

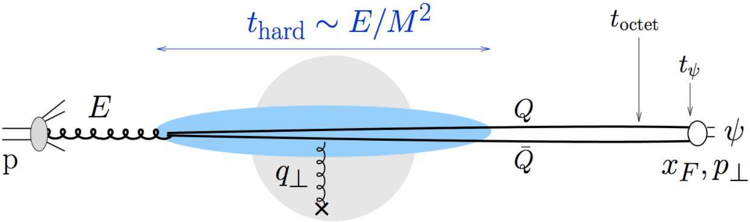
- Coherent energy loss (large formation time $t_f \gg L$)

$$\Delta E \propto \alpha_s \, \frac{\sqrt{\hat{q} \; L}}{M_\perp} \; E$$

  - needs color in the initial & final state
  - important at all energies, especially at large rapidity

Model for heavy-quarkonium suppression

Physical picture and assumptions



- Color neutralization happens on long time scales: $t_{\rm octet} \gg t_{\rm hard}$
- Hadronization happens outside of the nucleus: $t_\psi \gtrsim L$
- $c\bar{c}$ pair produced by gluon fusion
- Medium rescattering do not resolve the octet $c\bar{c}$ pair

Model for heavy-quarkonium suppression

Energy shift

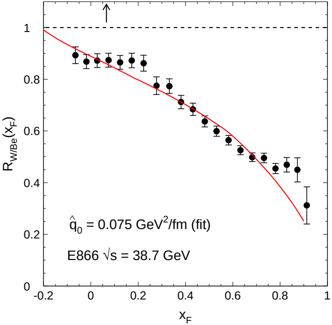
$$\frac{1}{A}\frac{d\sigma^{\psi}_{\mathrm{pA}}}{dE}\left(E,\sqrt{s}\right) = \int_0^{\varepsilon_{\max}} d\varepsilon\,\mathcal{P}(\varepsilon,E)\,\frac{d\sigma^{\psi}_{\mathrm{pp}}}{dE}\left(E+\varepsilon,\sqrt{s}\right)$$

Ingredients

- pp cross section fitted from experimental data
- Length L given by Glauber model
- $\mathcal{P}(\epsilon)$: probability distribution (quenching weight)

Procedure

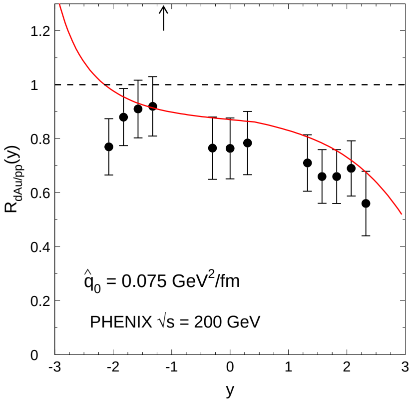
1. Fit $\hat{q}_0$ from J/ψ E866 data in p W collisions
2. Predict J/ψ and Υ suppression for all nuclei and c.m. energies



$\hat{q}_0 = 0.075 \text{ GeV}^2/\text{fm}$

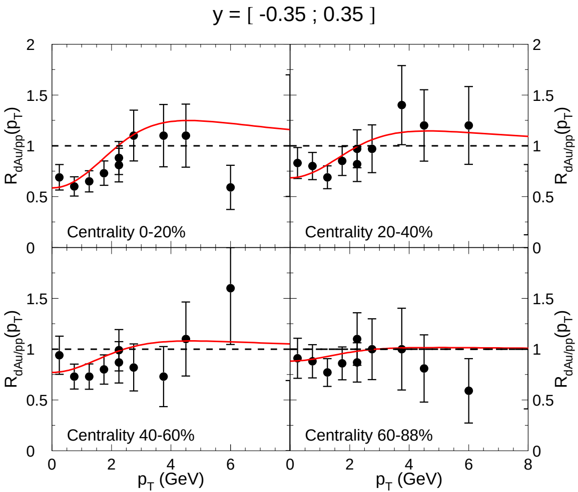
- Corresponds to $Q_s^2(x = 10^{-2}) = 0.11 - 0.14 \text{ GeV}^2$ consistent with fits to DIS data [Albacete et al AAMQS 2011]

RHIC predictions



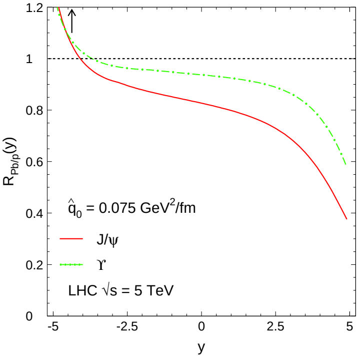
- Good agreement at all rapidity
- Does not exclude saturation which could improve the agreement

$p_\perp$ dependence at RHIC



- Good description of $p_\perp$ and centrality dependence

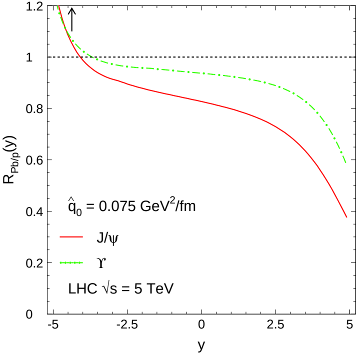
LHC predictions



- Moderate effects ($\sim 20\%$) around mid-rapidity, smaller at $y < 0$
- Large effects above $y \gtrsim 2 - 3$

Sizeable energy loss effects. . . precisely where saturation expected to play a role

LHC predictions



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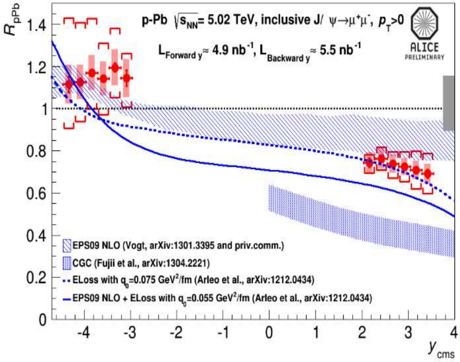
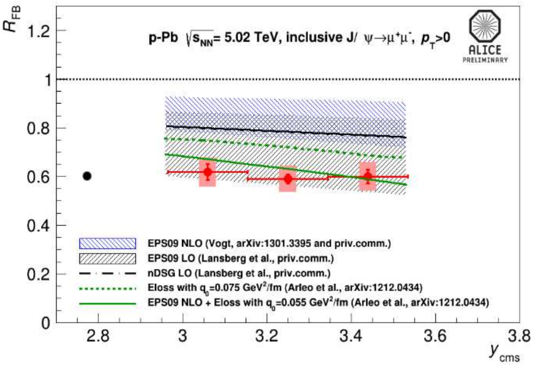
Moving to (ALICE) data...

Comparison with ALICE preliminary data

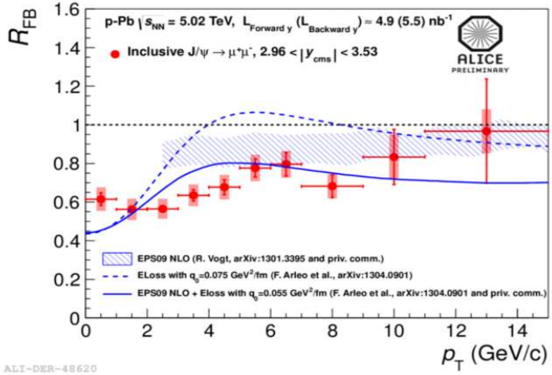


- $R_{\rm pA}(y)$: good agreement (despite large uncertainty on normalization)
- Too strong suppression in the CGC calculation [1304.2221]

Comparison with ALICE preliminary data

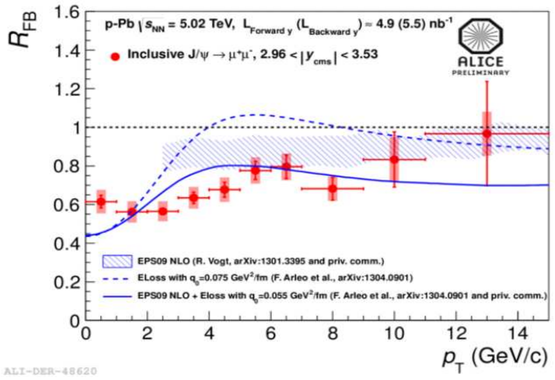


- $R_{\rm FB}(y)$: good agreement, better agreement with energy loss supplemented by shadowing



- $R_{\rm FB}(p_\perp)$: good agreement, better agreement with energy loss supplemented by shadowing

Comparison with ALICE preliminary data



- Role of saturation on J/ψ to be clarified
- Energy loss processes play a (significant) role especially at large x_1
- Need observables to disentangle energy loss from saturation effects

Which observables at the LHC ?

Large energy loss effects $\Delta E \propto E$

- Stronger at large rapidity
- Stronger at low $M_\perp$
- Color flow in the initial and in the final state

Which observables at the LHC ?

Large energy loss effects $\Delta E \propto E$

- Stronger at large rapidity
- Stronger at low $M_\perp$
- Color flow in the initial and in the final state

Consequences on

- Light and heavy hadrons
- Jets
- Heavy-quarkonia

Which observables at the LHC ?

Large energy loss effects $\Delta E \propto E$

- Stronger at large rapidity
- Stronger at low $M_\perp$
- Color flow in the initial and in the final state

"Ideal" probes insensitive to energy loss effects

- Prompt photons (!)
- Drell-Yan
- Color flow in the initial and in the final state

Summary

- Saturation expected at forward rapidity... where other phenomena occur
- Energy loss in cold matter can be large $\Delta E \propto E$ due to coherent radiation
  - Strong effects predicted on a variety of particle production
  - Preliminary J/ψ data in agreement with energy loss expectations
- Prompt photons might be ideal to probe saturation while being insensitive to energy loss effects