A brief introduction of coherent energy loss

Kaifeng Shen
University of Science and Technology of China
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Cold nuclear matter effects

p + p

p + A / d-A

A + A

CNM

An accurate study of cold nuclear matter (CNM) effects, due to the presence of a nucleus, not related to the creation of QGP

- the modification of the effective partonic luminosity in colliding nuclei (shadowing, anti-shadowing and EMC)
- the multiple scattering of partons in the nucleus before and/or after the hard scattering (parton energy-loss (either radiative or collisional), transverse momentum broadening (know as the Cronin effect))
- the absorption or break-up of $Q\bar{Q}$ bound states, inelastic cross section of a heavy-quarkonium state with a nucleon
- Heavy quarkonia can be dissociated by comovers (the partons or hadrons produced in the collision in the vicinity of the heavy-quarkonium state)

$$R_{\mathrm{pA}}^{C} = \frac{N_{\mathrm{pA}}^{C}}{\langle T_{\mathrm{pA}} \rangle_{C}\, \sigma_{\mathrm{pp}}}.$$

In "minimum-bias" p-A collisions

$$R_{\mathrm{pA}} = \frac{\sigma_{\mathrm{pA}}}{A\, \sigma_{\mathrm{pp}}},$$

Eur. Phys. J. C (2016) 76 :107

Multiple scattering of partons

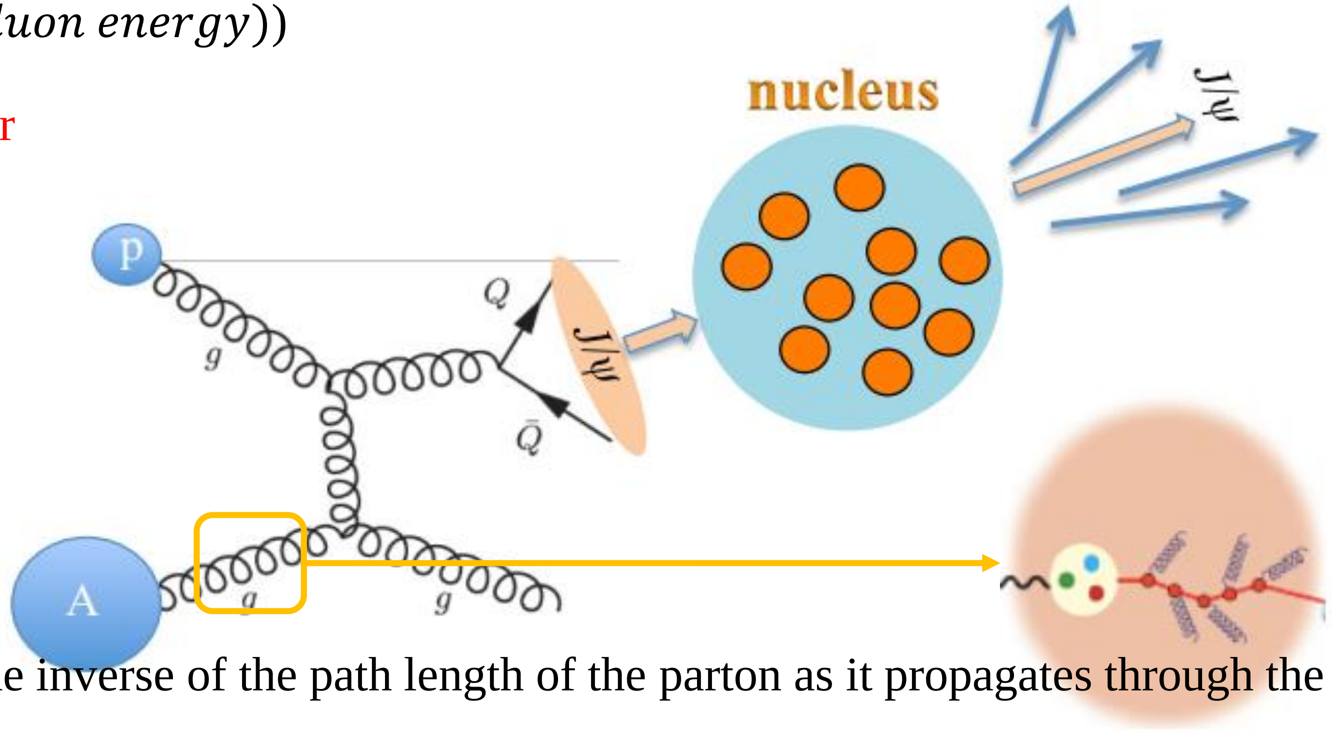
Eur. Phys. J. C (2016) 76 :107

parton multiple scattering

- $Q\bar{Q}$ propagation in nuclei (LHC, the coherent time $\tau_c \gg R_A$), impact parameter dependence
- initial-and final-state energy loss (the transport properties of large nuclei for quarks and gluons, scattering or multiple scattering)
- coherent energy loss (medium-induced radiative, high-energy gluon cross a nuclear medium and being scattered to small angle, $\Delta E \propto E(gluon\ energy)$)

parton scattering from the medium

- coherent: lead to attenuation or shadowing
- incoherent: transverse momentum broadening, Cronin-like enhancement of the cross sections at intermediate pT ~ few GeV/c



longitudinal momentum transfer is small compared to the inverse of the path length of the parton as it propagates through the nucleus, the scattering becomes coherent

Coherent energy loss

- The behavior $\Delta E \propto E$ arises from soft gluon radiation which is fully coherent over the medium, and the coherent energy loss is expected in all situations where the hard partonic process looks like forward scattering of an incoming parton to an outgoing compact and colourful system of partons

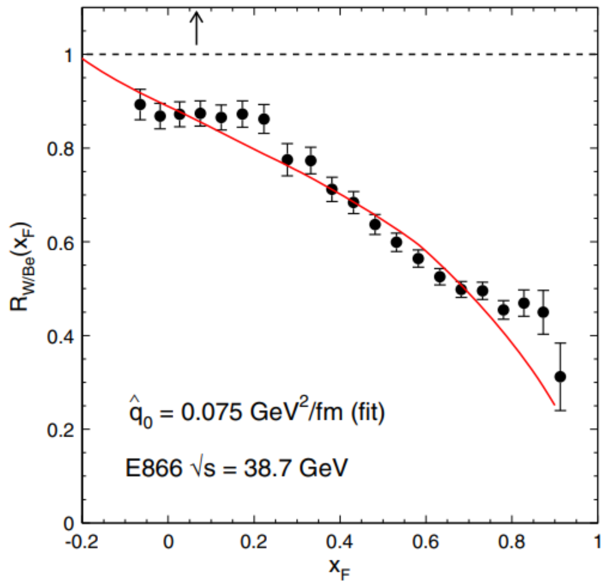


Fig. 31 *Left* J/ψ suppression due to coherent energy-loss effects, fitted to E866 data in p–W collisions at $\sqrt{s_{NN}} = 38.7$ GeV, as a function of Feynman-x, $x_F \simeq 2p_z^{J/\psi}/\sqrt{s}$. The *vertical arrow* indicates below

for J/ψ hadroproduction at low pT $\leq m_{J/\psi}$, in the target rest frame

- incoming: gluon
- outgoing : colour octet ccbar pair

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Coherent energy loss

arXiv:1212.0434 [hep-ph]

$$\tau_{Q\bar{Q}} \sim 1/M$$

$$t_{\rm hard} = \tau_{Q\bar{Q}} \cdot (E/M) \sim E/M^2.$$

gg → QQ¯ partonic subprocess, viewed in the nucleus rest frame as the splitting g → QQ¯ of the incoming gluon (a)

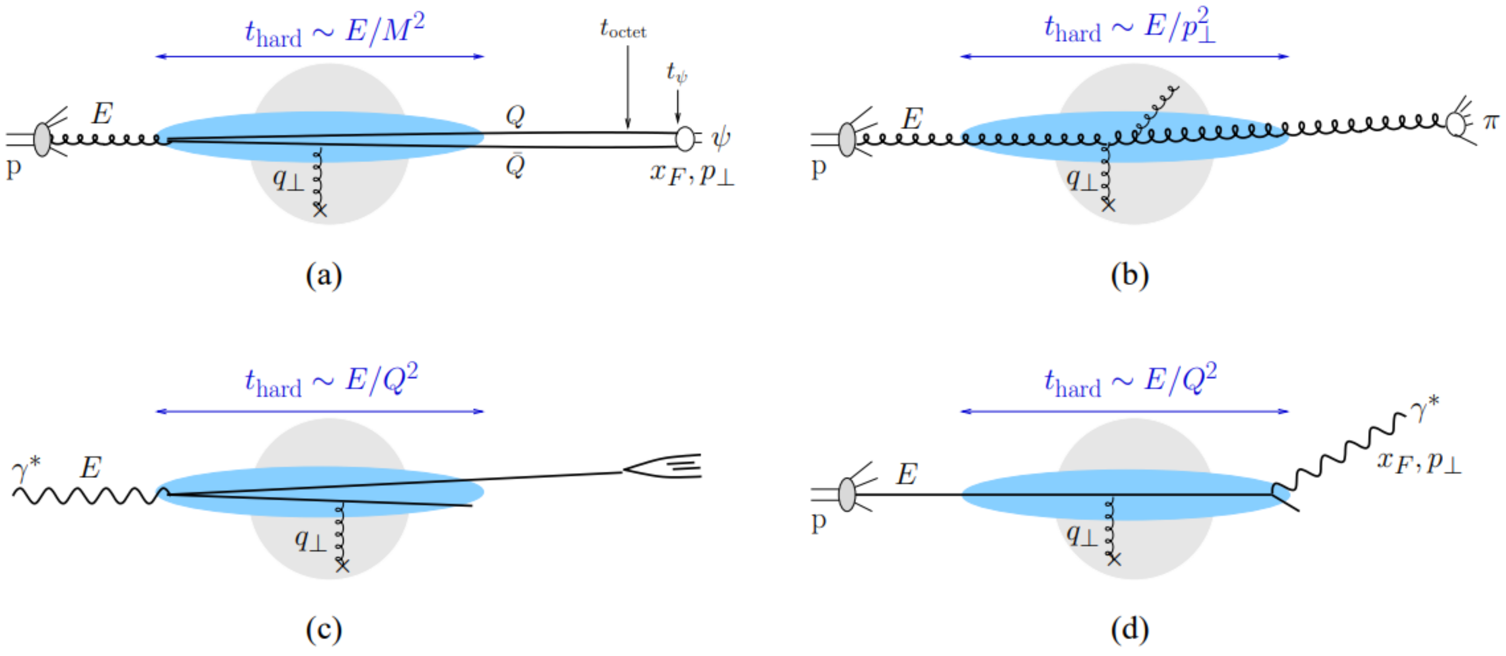


Figure 1. Generic processes of (a) heavy-quarkonium hadroproduction (b) light hadron hadroproduction (c) deep inelastic scattering and (d) Drell-Yan production, at large E in the target nucleus rest frame. The ellipse represents the hard subprocess occurring within the time $t_{\rm hard}$. Cases (a) and (b) are similar to small angle scattering of an asymptotic charge.

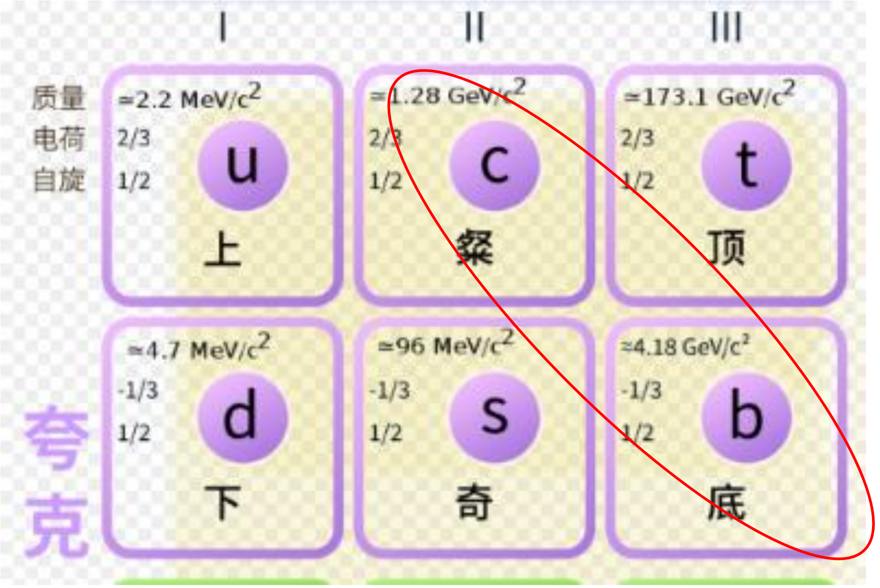
Coherent energy loss

arXiv:1405.4241 [hep-ph]

- The behavior $\Delta E \propto E$ arises from soft gluon radiation with formation time t_f scaling as E, i.e., being fully coherent over the size L of the medium ($t_f \gg$ L at large E)
- coherent radiative energy loss arises from the interference between emission amplitudes off the incoming and outgoing particles, and is thus expected in all situations where the hard partonic process is effectively equivalent to the forward scattering of an incoming parton to an outgoing compact colored system of partons
- Coherent energy loss should play an important role in the high-energy hadroproduction of hadrons, but should be absent in (inclusive) Drell-Yan production, as well as in hadron photoproduction

Back up

Relativistic Heavy Ion Collider



Study the quarkonium production in different collision systems

- Proton and nucleus structure at high energy
- Properties of the Quark-Gluon Plasma

The time scale of $c\bar{c}$ or $b\bar{b}$ production: $\Delta\tau \sim \frac{1}{Q}$

- for $c\bar{c}$, $\Delta\tau \sim \frac{1}{3GeV} \sim$ 0.07 fm/c
- for $b\bar{b}$, $\Delta\tau \sim \frac{1}{10GeV} \sim$ 0.02 fm/c

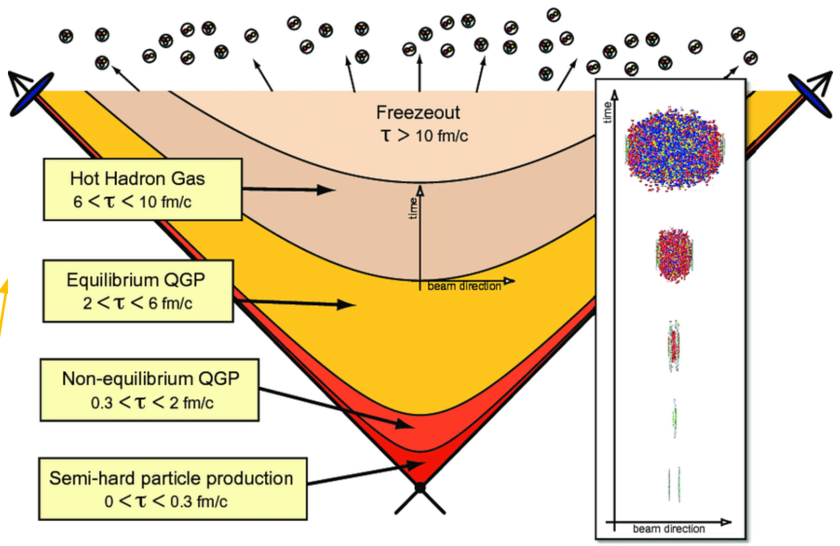
$< \tau_0 \sim$ 0.1-1 fm/c

Heavy-flavor and quarkonium production

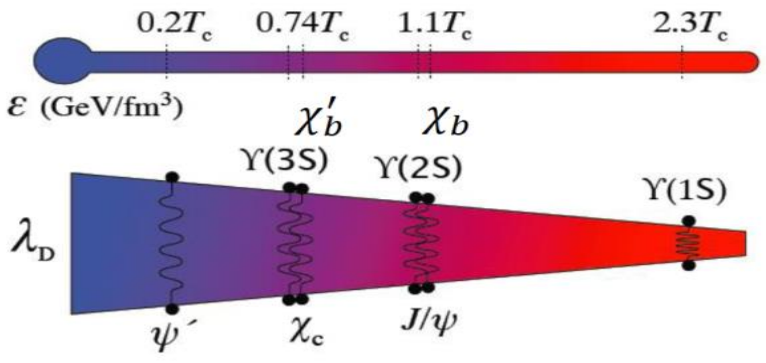
p + p

p + A / d-A

A + A



Quarkonium:
- $c\bar{c}$: J/ψ, 3.096 GeV(93 keV), ~10^{-20}s
- b$\bar{b}$: ϒ, 9.460 GeV(54 keV)

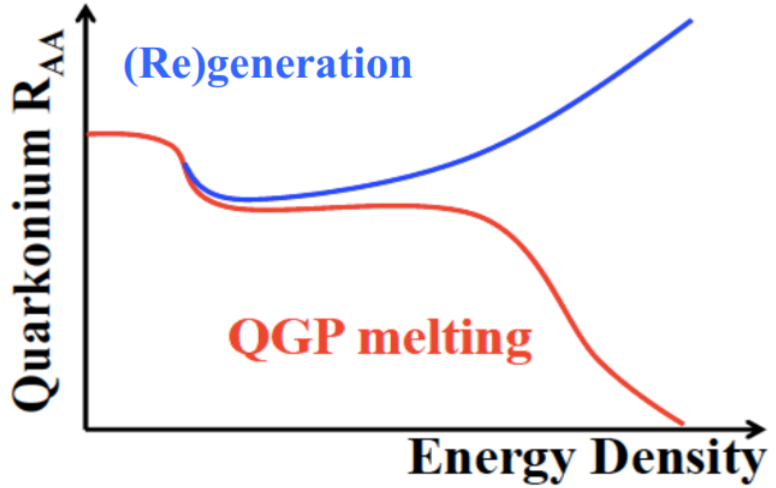


S. Diagl, P. Petreczky and H. Satz, PLB514, 57 (2001)

Dissociation

competing effects

Regeneration



T>T_c ≈ 150-200MeV (1.3 keV, Center of sun)
or ρ(baryon) > ρ_c (several times of ρ_{nm})

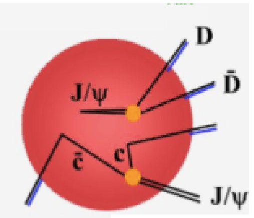
Complications

Other effects:

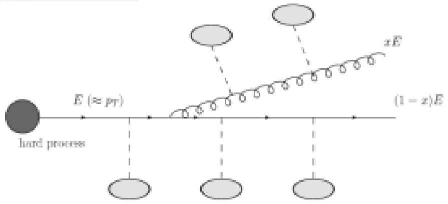
- Medium-induce energy loss
  - Color-octet states; parton fragmentation
- Formation time
  -High p_T hadrons fly out of medium faster
- Feed-down contributions
  -Depend on species, $\sqrt{s}$, p_T, etc

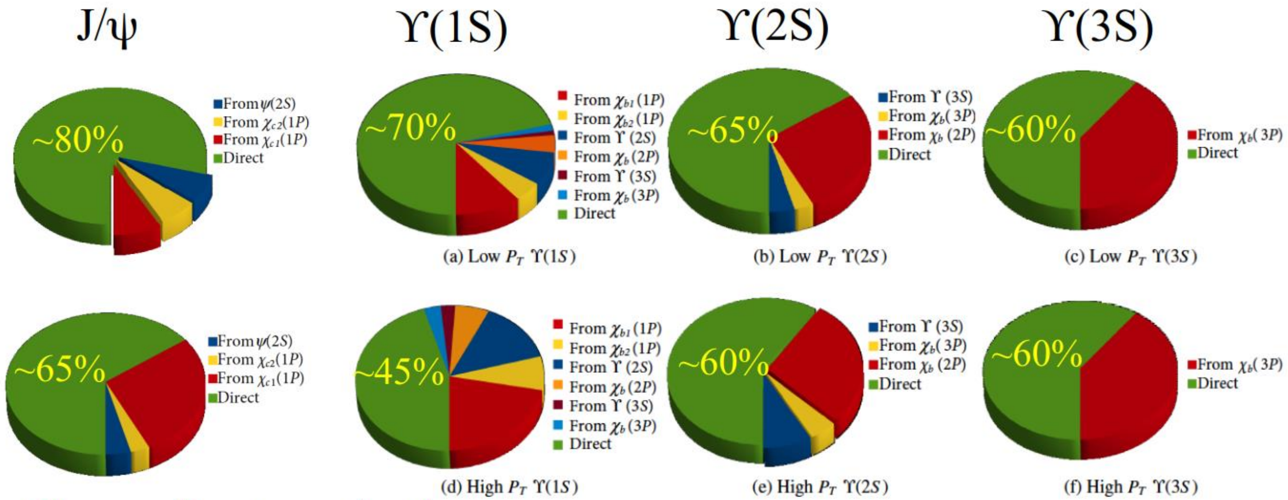
$Full\ width$: $\psi(2S)$: $8keV$; $\chi_{c1}(1P)$: $0.04MeV$; $\chi_{c2}(1P)$: $0.09MeV$

- Cold Nuclear Matter Effects



Central AA collisions	SPS 20 GeV	RHIC 200 GeV	LHC 5 TeV
N_{ccbar}/event	~0.2	~10	~115





Green: direct production

The typical times

The typical time

- τ_c: coherent time
  - to produce a heavy-quark pair $Q\bar{Q}$
  - $\tau_c \sim 1/m_{Q\bar{Q}} \lesssim 0.1$ fm/c (in the $Q\bar{Q}$ rest frame)
  - $t_c = E_{Q\bar{Q}}/m^2_{Q\bar{Q}}$ (in the rest frame of the target nucleus)
  - can be larger than the nuclear size, leading to shadowing effects due to the destructive interferences from the scattering on different nucleons
- τ_f: formation time
  - time needed to produce the quarkonium state(0.3-0.4 fm/c), much larger than the coherence time, also much larger than the nuclear size
  - time to produce a heavy-quark hadrons is longer than for quarkonium production (1 fm/c)
- time needed for $Q\bar{Q}$ to neutralise its colour
  - colour singlet model: the emission of a perturbative gluon, comparable to τ_c
  - colour octet model: a soft process, order of τ_f
- τ_{cross}: crossing time of the nucleus

$$\tau_{\rm cross} = L/(\beta_z\,\gamma)$$

nPDF). Quite schematically three regimes can be identified for the nPDF to PDF ratio of parton flavour i, $R_i(x, Q^2)$, depending on the values of x: a depletion ($R_i < 1$) – often referred to as *shadowing* and related to phase-space saturation – at small $x \lesssim 10^{-2}$, a possible enhancement $R_i > 1$ (*anti-shadowing*) at intermediate values $10^{-2} \lesssim x \lesssim 10^{-1}$, and the EMC effect, a depletion taking place at large $x \gtrsim 10^{-1}$. The $R_i(x, Q^2)$ parametrisations are determined from a global fit analyses of lepton–nucleus and proton–nucleus data (see Sect. 3.2.2).

Sect. 3.2.2).

- The physics of *parton saturation* at small x can also be described within the *Colour Glass Condensate (CGC)* theoretical framework. Unlike the nPDF approach, which uses DGLAP linear evolution equations, the CGC framework is based on the Balitsky–Kovchegov or JIMWLK non-linear evolution equations (see Sect. 3.2.3).

For a $2 \to 1$ partonic process giving a particle of mass m, at leading order there is a direct correspondence between the momentum fractions and the rapidity y of the outgoing particle in the nucleon–nucleon centre-of-mass (CM) frame,

$$x_1 = \frac{m}{\sqrt{s_{\mathrm{NN}}}} \exp(y) \quad \text{and} \quad x_2 = \frac{m}{\sqrt{s_{\mathrm{NN}}}} \exp(-y). \tag{17}$$

For a $2 \to 2$ partonic process, the extra degree of freedom coming from the transverse momentum results in a less direct correspondence leading to the following useful relations:

open heavy-flavour (D and B mesons...)

$$x_2 \approx \frac{2m_{\mathrm{T}}}{\sqrt{s_{\mathrm{NN}}}} \exp(-y), \tag{18}$$

quarkonia(J/ψ, Υ...)

$$x_2 \approx \frac{m_{\mathrm{T}} + p_{\mathrm{T}}}{\sqrt{s_{\mathrm{NN}}}} \exp(-y). \tag{19}$$

where $m_{\mathrm{T}} = \sqrt{m^2 + p_{\mathrm{T}}^2}$ is the transverse mass of the outgoing particle of mass m, transverse momentum p_{T} and rapidity y in the centre-of-mass frame. So, the typical resolution scale should be of the order of the transverse mass of the particle produced.

$$
\begin{aligned}
&\sigma^{\mathrm{CEM}}_{\mathrm{pPb}\to\Phi+X}[\sqrt{s}] \\
&= A \cdot F_\Phi \sum_{i,j} \int_{4m_{\mathrm{Q}}^2}^{4m_H^2} \mathrm{d}\hat{s} \int_0^1 \mathrm{d}x_i \int_0^1 \mathrm{d}x_j \; f_i(x_i, \mu_F^2) \\
&\quad \times R_j^{\mathrm{Pb}}(x_j, \mu_F^2)\, f_j(x_j, \mu_F^2)\; \mathcal{J}\; \hat{\sigma}_{ij\to Q\overline{Q}+X}[\hat{s}, \mu_F^2, \mu_R^2],
\end{aligned}
\tag{20}
$$

In LHC Run 1 p–Pb collisions, protons have an energy of 4 TeV and the Pb nuclei an energy $Z/A(4\text{TeV}) = 1.58$ TeV ($Z = 82$, $A = 208$), leading to $\sqrt{s_{\rm NN}} = 5.02$ TeV and a relative velocity of the CM with respect to the laboratory frame $\beta = 0.435$ in the direction of the proton beam. The rapidity of any particle in the CM frame is thus shifted, $y = y_{\rm lab} - 0.465$. Applying those experimental conditions to heavy-flavour probes such as D and B mesons and quarkonia, and according to Eqs. (18) and (19), leads to a large coverage of x_2 from 10^{-5} for the D meson at forward rapidity, to 0.5 for 10 GeV/c Υ at backward rapidity, as reported in Fig. 25.

EMC effect

The EMC effect is the surprising observation that the cross section for deep inelastic scattering from an atomic nucleus is different from that of the same number of free protons and neutrons (collectively referred to as nucleons). From this observation, it can be inferred that the quark momentum distributions in nucleons bound inside nuclei are different from those of free nucleons. This effect was first observed in 1983 at CERN by the European Muon Collaboration, hence the name "EMC effect". It was unexpected, since the average binding energy of protons and neutrons inside nuclei is insignificant when compared to the energy transferred in deep inelastic scattering reactions that probe quark distributions. While over 1000 scientific papers have been written on the topic and numerous hypotheses have been proposed, no definitive explanation for the cause of the effect has been confirmed. Determining the origin of the EMC effect is one of the major unsolved problems in the field of nuclear physics.

Wikipedia

Data from: Wikipedia

Suggest an edit

Initial- and final-state energy loss, power corrections and Cronin effect The approach by Sharma and Vitev is now described. The basic premiss of this approach is that CNM can be evaluated and related to the transport properties of large nuclei for quarks and gluons [391]. At one extreme, when the scattering from the medium is largely incoherent, the parton modification is dominated by transverse momentum broadening. It leads to a Cronin-like enhancement of the cross sections at intermediate $p_T \sim$ few GeV$/c$. At the other extreme, when the longitudinal momentum transfer is small compared to the inverse of the path length of the parton as it propagates through the nucleus, the scattering becomes coherent, which can lead to attenuation, or shadowing. The coherent limit is described differently in different approaches and its effects are calculated in terms of nuclear-enhanced power corrections to the cross sections. Multiple scattering also leads to medium-induced radiative corrections that, in the soft gluon emission limit, have the interpretation of energy loss [392].

The effects are implemented via modifications to the kinematics of hard parton scattering $a+b \to c+d$. For example, in p–A collisions