QCD Factorization at Forward Rapidities

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Forward physics: opportunities and dangers

- Light-front momentum fraction for projectile, target: \( x_{1,2} = \frac{m_T}{\sqrt{s}} e^{\pm y} \)

- Feynman variable: \( x_F = x_1 - x_2 = \frac{2 m_T}{\sqrt{s}} \sinh(y) \)

- In hadronic collisions minimal Bjorken \( x \) can be reached at forward rapidities \( y \rightarrow y_{\text{max}} \) i.e. when \( x_2 = x_1 - x_F \rightarrow 0 \).

- Forward rapidity ↔ the beam fragmentation region at large \( x_F \):
  - Projectile: \( x_1 \approx 0.5 - 1 \), mostly valence quarks contribute
  - Target: \( x_2 < 0.01 \), gluons dominate

- At large \( y \), the target \( x_2 \) is \( e^y \) times smaller, than at mid-rapidities (\( \sim 10^2 \) at RHIC and \( \sim 10^4 \) at LHC)

- Opportunities to study interesting phenomena: parton saturation, Color Glass Condensate, ...

- Dangers to confuse the above phenomena with the effects of energy conservation
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Forward rapidity \( \leftrightarrow \) the beam fragmentation region at large \( x_F \):

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At small $x_2$, coherent phenomena (shadowing, CGC) are expected to suppress particle yields.

No consensus so far on the strength of gluon shadowing and CGC. Data to be explained are just fitted. [D. Kharzeev et al., Phys.Lett.B599:23,2004]

Saturation/CGC interpretation has problems: recent global LO analysis including besides DIS also this RHIC d+Au data [K. Eskola et al., JHEP 0807:102,2008. (EPS08)] leads to grossly exaggerated gluon shadowing.
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\[ R_{dAu}^{Y} = \frac{\sigma_{pp}^{\text{inel}}}{<N_{\text{bin}}>\sigma_{\text{hadr}}^{dAu}} \frac{Ed^3 \sigma/dp^3 (d+Au \rightarrow Y+X)}{Ed^3 \sigma/dp^3 (p+p \rightarrow Y+X)} \]
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Gluon clouds of different nucleons undergo a weaker Lorentz contraction at small, than at large $x$. They may overlap and fuse, leading to reduction of the gluon density at small $x$ in a nucleus - gluon shadowing.

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p+A fixed target reactions at forward rapidities

**p+Pb at $E_{lab} = 158$ GeV**

![Graph showing NA49 data for p+Pb at $E_{lab} = 158$ GeV.]

**Small-$p_T$ hadrons, $A^\alpha$, $E_{lab} = 70 - 400$ GeV**

![Graph showing data for small-$p_T$ hadrons at different $x_F$.]

**Drell-Yan at $E_{lab} = 800$ GeV**

![Graph showing E772 data for Drell-Yan at $E_{lab} = 800$ GeV.]

**$A^\alpha$: $J/\psi$ and $\psi'$ at $E_{lab} = 800$ GeV**

![Graph showing data for $J/\psi$ and $\psi'$ at $E_{lab} = 800$ GeV.]

Any reaction observed so far at any energy is nuclear suppressed.
p+A fixed target reactions at forward rapidities

$p+Pb$ at $E_{lab} = 158\text{GeV}$

$R_{p+Pb}$ vs $p_T$ (GeV/c)

$R_{p+Pb}$
- $\pi^+$
- $\pi^-$

$\times F = 0.025$
$\times F = 0.375$

NA49 data

$Drell-Yan$ at $E_{lab} = 800\text{GeV}$

$R_{W/D}(x_1)$
- E772 data for $Drell-Yan$

$6 < M < 7\text{ GeV/c}^2$

$\times GBW$ with charm
$\times GBW$
$\times KST$

$A^\alpha$: $J/\Psi$ and $\Psi'$ at $E_{lab} = 800\text{GeV}$

$\alpha(x_F)$
- E866 data for $J/\Psi$
- E866 data for $\Psi'$

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Energy loss in nuclear matter

- All those fixed target experiments have too low energy for the coherent effects in gluon radiation to occur. 
  $x_2$ isn’t small enough and so the coherence length $\ell_c \propto 1/(x_2 m_N)$ is still shorter than the mean inter-nucleon spacing.

What is the mechanism of nuclear suppression?

- The projectile hadron and its debris dissipate energy when propagating through the nucleus. As a result, the probability of production of a particle carrying the substantial fraction $x_F$ of the initial momentum decreases compared to a free proton target case. [B.Kopeliovich et al., Phys.Rev.C72:054606,2005].

- This can be equivalently viewed as:
  - Reduced survival probability for LRG processes in nuclei
  - Enhanced resolution of higher Fock states by nuclei
  - Effective energy loss that rises linearly with energy
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Two types of energy loss

- **Energy loss proportional to energy**
  Compared to the proton target the nuclear target (via multiple interactions) resolves higher multiparton Fock components of the projectile hadron and thus produces more intense gluon radiation ⇒ the suppression is a consequence of **induced energy loss**.
  - Energy loss caused by on-mass-shell production of such partons rises with energy, $dE/dz \propto E$.
  - Nuclear suppression is energy independent and scales with $x_F$.

- **Energy loss independent of energy**
  - Energy independence results from $dn/d\omega_g \sim 1/\omega_g$.
  - The mean fractional energy of a radiated gluon is negligibly small $\sim 1/E$, and nuclear suppression vanishes at high energies.
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E-loss and AGK cutting rules

- For the nuclear target the leading parton distribution involves higher multiparton Fock states and thus must fall off steeper at $x_F \rightarrow 1$ than in the proton target case.

- Each of multiple interactions produces an extra suppression factor $S(x_F)$, the weight factors are given by the AGK cutting rules:

$$\frac{d\sigma_A}{dx_F d^2b} = \frac{d\sigma_N}{dx_F} T_A(b)e^{-[1-S(x_F)]\sigma_{in}T_A(b)}$$

and $S(x_F) \approx (1 - x_F)$ is survival probability of a large rapidity gap.

- The effective PDF of the beam hadron is target-dependent
  \(\Rightarrow\) interaction with a nuclear target does not obey factorization!!!

- The lack of factorization does not disappear with increasing scale
  \(\Rightarrow\) the factorization is violated via leading twist effect.
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Large-$p_T$, forward rapidity: d+Au at RHIC

$d+Au$ at $\sqrt{s_{NN}} = 200\text{GeV}$

- The description is parameter-free.
- No other model has been able so far to explain the sharp drop of the cross section between the rapidities $\eta = 3.2 - 4$
Forward rapidity: p+A at FNAL and SPS

Drell-Yan at $\sqrt{s} = 38.3\text{GeV}$

- E772 data for DY
- $6 < M < 7 \text{ GeV/c}^2$
- GBW with charm
- GBW
- KST

$A^\alpha$: $J/\Psi$ at $\sqrt{s} = 17.3\text{GeV}$

- NA3 data for $J/\Psi$
- NA38 data for $J/\Psi$

$A^\alpha$: $J/\Psi$ and $\Psi'$ at $\sqrt{s} = 38.3\text{GeV}$

- E866 data for $J/\Psi$
- E866 data for $\Psi'$
Large-$p_T$, mid-rapidity: $d+Au$ at RHIC

One can approach the kinematic limit increasing either $x_F = \frac{2m_T}{\sqrt{s}} \sinh(y)$ or $x_T = \frac{2p_T}{\sqrt{s}}$. In both cases the energy constraints lead to nuclear suppression.

- At small-medium $p_T$ the ratio $R_{d+Au}$ at $\eta = 0$ was first described by B. Z. Kopeliovich et al.; PRL 88, 232303-1(2002). Vital for correct description of the Cronin effect is inclusion of gluon multiple rescattering.

- Solid/dashed (thick/thin) lines correspond to calculations with/without energy conservation restrictions in multiple parton rescatterings, (with/without finite coherence length correction), respectively.

- With QCD factorization one expects at large transverse momenta $R_{d+Au} \rightarrow 1$ (with a small corrections for isotopic effects).

- Energy conservation leads to a considerable suppression, which seems to be confirmed by the data.
Prompt photons produced in a hard reaction are not expected to have any final state interaction, either energy loss, or absorption. Besides Cronin enhancement and small isotopic corrections no nuclear effects are expected.

So far no explanation of observed suppression has been given.

Production of prompt photons with large $p_T$ is again subject to energy sharing constraints.

Isospin effects lead to the value $R_{\text{Au+Au}} \rightarrow 0.8$. 
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Midrapidity production of direct photons in Au+Au


- PHENIX data
- without energy conservation
- with energy conservation, SCL
- with energy conservation, LCL

- PHENIX data
- $s^{1/2} = 200$ GeV

- PHENIX data
- $s^{1/2} = 62.4$ GeV

- SCL
- LCL
Jet quenching in heavy ion collision

- Suppression of high-$p_T$ hadrons produced in ultra-relativistic heavy ion collisions does not vanish even at $p_T > 10\text{GeV}$ but remains constant. This is in apparent conflict with the QCD factorization which would demand $R_{AA}$ to rise with $p_T$.

- In the limit of a very dense medium the mean free path of produced (pre)hadron vanishes, and $R_{AA}$ is completely controlled by the product-ion length $\ell_c$. $R_{AA} = \langle \ell_c^2 \rangle / R_A^2$, where $\ell_c = z(1-z)E_{\text{jet}}/p_T^2$ and $R_A$ is the nuclear radius. This should cause considerable suppression at large $p_T$.

B.Z. Kopeliovich et al., arXiv:0707.4302 [nucl-th]
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![Graph: $R_{AA}(p_T)$ of pions in central AA collisions ($A \approx 200$) at $\sqrt{s} = 200\text{GeV}$ (solid) and $\sqrt{s} = 5500\text{GeV}$ (dashed line).]
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$R_{AA}(p_T)$ of pions in central $AA$ collisions ($A \approx 200$) at $\sqrt{s} = 200\text{GeV}$ (solid) and $\sqrt{s} = 5500\text{GeV}$ (dashed line).
Although measurement at forward rapidities allow to access smallest Bjorken $x$, one should be careful with interpretation. Assuming that suppression at RHIC is due to gluon saturation only, one arrives at astonishingly small amount of gluons in nuclei and conflict with unitarity.

Factorization requires the nucleus to be an universal filter for different Fock components of the projectile hadron. This is not the case in the vicinity of the kinematic limit where sharing of energy between the constituents becomes an issue. Higher Fock components are resolved better, so the projectile parton distribution becomes softer.

This effect can be treated as an effective energy loss proportional to energy. The nonperturbative fluctuations resolved by the nucleus carry finite fractions of the total momentum, and this is the source of energy loss which is proportional to energy.
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$dE/dz \propto E$ leads to a nuclear suppression at any energy and predicts $x_F$-scaling of the suppression. This explains why any high-energy reaction is at large $x_F$ nuclear suppressed and solves the long-standing puzzle of the $x_F$-scaling in $J/\psi$ suppression.

One can also approach the kinematic limit in $p_T$, e.g. at $\eta = 0$. Effects of energy conservation now show up when the Cronin enhancement at medium-high $p_T$ switches to nuclear suppression at larger $p_T$ approaching the $A^{-1/3}$-behavior. This unexpected behavior is signaled by the RHIC data on pion production in d+Au collisions and even by direct high-$p_T$ photons from Au+Au.

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