Does Cronin Peak Disappear at LHC Energies?

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OUTLINE

0. Motivation
  – Nuclear Modification Factor and the Cronin effect
  – Historical survey of the Cronin effect from SPS to RHIC
  – Is the $R_{AA'}$ boring, ”flat” at high-$p_T$?

I. Theoretical Background
  – pQCD improved parton model for $pp$, $pA$ and $AA'$

II. Initial state effects at very high $p_T$
  – Analysing EMC effect in high-energy $AA'$ collisions
  – Predictions for LHC at $0.2 - 14$ TeV $dPb$ collisions

III. What can we learn from HOT Quenching?
  – Jet tomography results at $y = 0$ for $AuAu$ and $CuCu$
  – Is there room for COLD Quenching in $dA$ collisions?

IV. Does the Cronin Peak disappear at LHC?
Hunting for Nuclear Effects (Cronin) at High-$p_T$ \( R_{AA'} \)

Historically the Cronin effect:

increased particle production in

\[3 \text{ GeV} < p_T < 6 \text{ GeV}\] range (1975)

"increased" means more particles
are produced in $pA$ than expected
from $N_{bin}$ scaled $pp$ collisions

Nuclear Modification Factor (NMF)

\[ R_{AA} = \frac{1}{N_{bin}} \frac{dN_{AA}/dy}{dN_{pp}/dy} \frac{d^2p_T}{d^2p_T} \]
## History of the Experiments ”for” Cronin Effect

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$p$</th>
<th>Target</th>
<th>$\sqrt{s_{NN}}$ (GeV)</th>
<th>$y$ or $\eta$</th>
<th>$p_T$ (GeV)</th>
<th>Hadron</th>
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<tbody>
<tr>
<td>CP</td>
<td>$p$</td>
<td>$d, Be, Ti, W$</td>
<td>19.4; 23.7; 27.4</td>
<td>$\approx 0$</td>
<td>0.77; 6.91</td>
<td>$\pi^\pm, K^\pm, p^\pm, d^\pm$</td>
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<td>ITA</td>
<td>$p$</td>
<td>$C, W$</td>
<td>$p_{\text{inc}} = 50 - 275$</td>
<td>[0.7; 1.0]</td>
<td>0.2; 2.35</td>
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<td>$n$</td>
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<td>[4.0; 8.0]</td>
<td>0.1; 1.7</td>
<td>$h^\pm, \pi^+, p$</td>
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<tr>
<td>FNAL</td>
<td>$p$</td>
<td>$Be, W$</td>
<td>19.4; 23.7; 27.4</td>
<td>$\approx 0$</td>
<td>0.2; 4.5</td>
<td>$\pi^\pm, K^\pm, p^\pm, h^\pm$</td>
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<tr>
<td>CP</td>
<td>$\pi^-$</td>
<td>$p, Be, Cu, W$</td>
<td>19.4; 23.7</td>
<td>$\approx 0$</td>
<td>0.8; 5.78</td>
<td>$\pi^\pm, K^\pm, p^\pm$</td>
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<tr>
<td>E577/E672</td>
<td>$p$</td>
<td>$p, Be, C, Al, Cu, Pb$</td>
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<td>$[-0.75; 0.75]$</td>
<td>0.6; 11.5</td>
<td>$h^\pm$</td>
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<td>E605/E789</td>
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<td>0.5; 11.5</td>
<td>$h^\pm$</td>
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<tr>
<td>E605</td>
<td>$p$</td>
<td>$d, Be, W$</td>
<td>38.8</td>
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<td>0.5; 11.0</td>
<td>$\pi^\pm, K^\pm, p^\pm$</td>
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<tr>
<td>E706</td>
<td>$p$</td>
<td>$Be$</td>
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<td>1.0; 12.0</td>
<td>$\pi^0, \eta$</td>
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<td>$\pi^0, \gamma$</td>
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<td>$p, Au$</td>
<td>$p, d, Au$</td>
<td>130, 200</td>
<td>$</td>
<td>\eta</td>
<td>\leq 0.35; 2.0$</td>
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<td>BRAHMS</td>
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<td>$p, d, Au$</td>
<td>130, 200</td>
<td>$0.0; 1.0; 2.2; 3.2$</td>
<td>0.5; 6.0</td>
<td>$\pi^0, h^\pm$</td>
</tr>
<tr>
<td>STAR</td>
<td>$p, Au$</td>
<td>$p, d, Au$</td>
<td>130, 200</td>
<td>$</td>
<td>\eta</td>
<td>\leq 0.5; 2.0$</td>
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<td>PHOBOS</td>
<td>$p, Au$</td>
<td>$p, d, Au$</td>
<td>62.4; 130; 200</td>
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<td>0.5; 3.5</td>
<td>$K^\pm, p^\pm \pi^0, h^\pm$</td>
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</table>
Motivation for LHC – low-\(x\) physics

Suppression in \(h^+, h^-\) spectra in \(dAu\) by BRAHMS, \(\eta > 0\)

Testing small-\(x\) in heavy-ion collisions via analysing forward (\(\eta > 0\)) PHOBOS and BRAHMS
Motivation for LHC – high-$x$ and high-$p_T$ physics

$R_{AA'}$ and $\pi$ spectra in $dAu$ and $AuAu$ by PHENIX, $y = 0$

How will move the high-$p_T$ tail in $dAu$ at RHIC

Suppression in $AuAu$ at RHIC is really flat?
I. (SHORT) INTRODUCTION TO THE THEORETICAL BACKGROUND
I/1. pQCD Improved Parton Model for $pA$ Collisions

\[
E_{\pi} \frac{d\sigma_{pA}^{pA}}{d^3 p_\pi} \sim f_{a/p}(x_a, Q^2; k_T) \otimes f_{b/A}(x_b, Q^2; k_T, b) \otimes \frac{d\sigma_{ab \rightarrow cd}^{ab \rightarrow cd}}{dt} \otimes \frac{D_{\pi/c}(z_c, \hat{Q}^2)}{\pi z_c^2}.
\]

$f_{a/A}(x_a, Q^2; k_T, b)$: Nucl. Parton Dist. Function (PDF), at scale $Q^2$

$D_{\pi/c}(z_c, \hat{Q}^2)$: Fragmentation Function for $\pi$ (FF), at scale $\hat{Q}^2$

$\frac{d\sigma_{ab \rightarrow cd}^{ab \rightarrow cd}}{dt}$: Partonic cross section
I/2. Longitudinal 1-Dimensional PDFs and FFs in General

(a) Parton Distribution Functions (PDF) :

(LO case) GRV – Glück, Reya, Vogt
Z. Phys C 53 127 (1992)

(NLO case) MRST-(c-g) – A.D. Martin et al.
CTEQ5M – H. L. Lai et al.

(b) Fragmentation Functions (FF) :

KKP – Kniehl, Kramer, Pötter.
I/3. Phenomenological introduction of intrinsic $k_T$

Introducing intrinsic $k_T$ for colliding partons (in $pp$ coll.)

Phenomenological assumption: PDFs are modified
1 dimensional PDFs are changed to 1+2 dimensional ones

$$\int dx \, f_{a/p}(x, Q^2) \longrightarrow \int dx \, d^2k_T \, g_{pp}(\vec{k}_T) \, f_{a/p}(x, Q^2)$$

where $g(\vec{k}_T)$ is a Gauss distribution function:

$$g_{pp}(\vec{k}_T) = \frac{e^{-\vec{k}_T^2/\langle k_T^2 \rangle}}{\pi \langle k_T^2 \rangle} \quad \text{and} \quad \langle k_T^2 \rangle = \frac{4\langle k_T^2 \rangle^2}{\pi}$$

Baseline $\langle k_T^2 \rangle$ values for $pp$: Phys. Rev. C65 034903 (2002)

$\langle k_T^2 \rangle \sim$ value agrees with measured values by PHENIX,
Pion Production in $pp$ Collisions at RHIC Energies

\[ p+p \rightarrow \pi^0 + X \text{ at } s^{1/2} = 200 \text{ GeV} \]

- LO PQCD, $\kappa = 2/3$, $<k_t^2> = 2.5 \text{ GeV}^2$
- NLO PQCD, $\kappa = 2/3$, $<k_t^2> = 0.0 \text{ GeV}^2$
- NLO PQCD, $\kappa = 4/3$, $<k_t^2> = 2.5 \text{ GeV}^2$

Data/\overline{QCD}

- LO PQCD, $\kappa = 2/3$
- NLO PQCD, $\kappa = 2/3$
- NLO PQCD, $\kappa = 4/3$

\[ p_t (\text{GeV}) \]

P. Lévai, G. Papp, G.G. Barnaföldi, G. Fai nucl-th/0306019
I/4. Collision Geometry – Glauber Model in $pA \to \pi$

**Glauber model**: an incoming $p$ collides with **ALL** nucleons along its travelling tube at $b$ impact param.

\[
E_\pi \frac{d\sigma_{\pi}^{pA}}{d^3p} = \int d^2b \ t_A(b) \ \int \cdots f_{a/A} (x_a, Q^2; \cdots) \cdots
\]

**Nuclear thickness function**:

\[
t_A(b) = \int dz \ \rho(b, z) \text{ normalized as:}
\]

\[
A = \int_0^{b_{max}} t_A(b) d^2b
\]

where $\rho(b, z)$ is the nuclear density distribution

$\rho(b, z)$: for small $A$: sharp sphere: $t_A(b) = 2\rho_0 \sqrt{R_A^2 - b^2}$

Shadowing – PDFs are modified inside the nucleus:

\[
f_{a/A}(x, Q^2) = S_{a/A}(x, b) \left[ \frac{Z}{A} f_{a/p}(x, Q^2) + \left(1 - \frac{Z}{A}\right) f_{a/n}(x, Q^2) \right]
\]

\(S_{a/A}(x, b)\): Shadowing function (ex.: HIJING);
\(A\) atomic- and \(Z\) the proton number

\[
S_{a/A}(x) = 1 + 1.19 \ln^{1/6} A[x^3 - 1.5(x_0 + x_L)x^2 + 3x_0x_Lx]
- \left[ \alpha_A - \frac{1.08(A^{1/3} - 1)}{\ln(A + 1)} \sqrt{x} \right] e^{-x^2/x_0^2}
\]

where: \(\alpha_A = 0.1(A^{1/3} - 1)\) and \(x_0 = 1, x_L = 0.7\).


Measured by many different experimental collaborations
I/7. (b) Different Shadowing Parameterizations


I/8. Nuclear Modification Factor for $dAu$ at $\sqrt{s} = 200$ GeV

- **PHENIX data at** $y = 0$
  

- **Shadowing inside nucleus is small effect at PHENIX at** $y = 0 \iff$ we are at moderate-$x$ region ($\langle x \rangle \sim 0.05$)

  $S_i(x)$ shadowing functions

  - Quarks
  - Gluons

  Li, Wang: PLB527(2002)85

Calculations with ONLY nuclear shadowing is NOT enough!!!
I/9. From where Comes the Shadowing Contribution

- Cumulative probability

\[ P_{>}(x_{Au}) = \frac{\int_{0}^{x_{Au}} d\sigma(x') dx'}{\int_{0}^{1} d\sigma(x') dx'} \]

- substantial contribution from higher-\(x\) region

Can we understand high-\(x\) physics well?
I/10. Multiple Scattering – Cronin Effect

Improve Glauber model:
assuming saturation in the number of \( NN \) collisions

\[
E_\pi \frac{d\sigma_{pA}^{pA}}{d^3p} = \int d^2b \ t_A(b) E_\pi \frac{d\sigma_{pp}^{pp}(\langle k_T^2 \rangle_{pA}, \langle k_T^2 \rangle_{pp})}{d^3p}
\]

\[
\langle k_T^2 \rangle_{pA} = \langle k_T^2 \rangle_{pp} + C \ h_{pA}(b)
\]

Total broadening = \( pp \) baseline + nuclear broadening

See details in PRC\textbf{65} 034903 (2002) and hep-ph/0212249

\[ h(\nu_A(b) - 1) : \text{number of effective NN collisions} \quad \nu_{max} = 3 - 4 \]

\[ C : (\text{average mom. broadening})^2 / \text{coll.} \quad C \approx 0.35 \text{ GeV}^2 \]

\[ t_A(b) : \text{nuclear thickness function} \]
The Effect of Multiple Scattering in at SPS and RHIC

Nuclear Modification Factor (NMF)

→ theoretical def.: \( R_{AA'}^{\pi} := \frac{d\sigma^{AA' \to \pi} / d^3p}{d\sigma^{AA' \to \pi} / d^3p} \) ("shadowing+multiscattering")

\( \frac{d\sigma^{AA' \to \pi} / d^3p}{d\sigma^{AA' \to \pi} / d^3p} \) ("NO nuclear effect")
II. INITIAL STATE EFFECTS IN

VERY HIGH-\( p_T \) \( \pi^0 \) PRODUCTION IN \( dAu \)
Cronin effect at very high-$p_T$ in central $dAu$ collision

Extracting the slope of $R_{dAu}$ in $dAu$ collision at PHENIX

Comparing different shadowing parameterisations

Fit $8 < p_T < 30$ GeV/c range

Huge errors at peripheral collisions

Different parameterisations have the same slope for EMC region

Is there any room for nuclear effect in $0 - 40\%$ centrality region
Suppression can be strong at high-$p_T$ at the LHC energies.
Change of multiscattering at higher-$\sqrt{s_{NN}}$ in $dPb$

Cronin peak is slightly moving towards higher-$p_T$ values.
III. FROM HOT TO COLD QUENCHING

FINAL STATE EFFECTS IN $dA$ COLLISIONS?
III/1. Non-abelian Jet Energy Loss – Jet-Quenching

Energy loss of jets in hot, dense non-Abelian plasma:
— energy loss in a **THICK** plasma - BDMS, LCPI
— energy loss in a **THIN** plasma - GLV method

Medium induced radiative energy loss - for thin plasma: $L \sim \lambda_g$


GLV: time-ordered pQCD (Feynman diagramms)
  + OPACITY expansion ($N = 1, 2, 3, ...$)
  + kinematical cuts

\[
M_J \times M_0
\]

\[
M_{j_0, t_0}^{k_c}
\]

\[
M_{J, 1, 0, 0}^{k_c}
\]

\[
M_{J, 1, 1, 1}^{k_c}
\]

\[
\cdots
\]

\[
M_{n_s, m, l}^{n_s, m, l}
\]

where $l = 2^{n_s - m} - 1$
III/2. Calculations of Relative Energy Loss – Results

Energy dependence of GLV jet energy loss

\[ \Delta E_{GLV} \approx \Delta E_{GLV}^{(1)} \approx \frac{C_R \alpha_s}{N(E)} \frac{L^2 \mu^2}{\lambda_g} \log \frac{E}{\mu} \]

- \( \Delta E \) is \( E \)-dependent
  
  \( N(E) \) is a numerical function, \( N(E) \rightarrow 4 \) at \( E \rightarrow \infty \).

- \( \approx \) \( E \)-independent \( \Delta E/E \) in \( 3 < \text{GeV} \: E < 10 \text{ GeV} \)

- Opacity \( n = L/\lambda \)
III/3. \( \pi \)-suppression in \( AuAu \) collisions at RHIC energies

GLV jet-quenching in thin plasma approximation \( L \sim \lambda_g \):

\[
\Delta E_{GLV} \sim \frac{L^2 \mu^2}{\lambda_g} \log \frac{E}{\mu}
\]

Energy loss of jet decreases the \( p_c \) momenta of \( c \) before fragmentation:

\[
\frac{D_{\pi/c}(z_c, Q'^2)}{\pi z_c^2} \rightarrow \frac{z_c^*}{z_c} \frac{D_{\pi/c}(z_c^*, Q'^2)}{\pi z_c^2}, \text{ where } z_c^* = \frac{z_c}{1 - \Delta E/p_c},
\]
Jet tomography in \textit{AuAu} and \textit{dAu} collision at PHENIX

Jet-tomography at midrapidity in $AuAu$ and $CuCu$ collisions

Extracting opacities in all centralities for $p_T > 4$ GeV/c

All of these information is summarised →
Analysing opacity dependence in midrapidity $AA'$ collisions

\[ L \propto A^{1/3} \propto N_{\text{part}}^{1/3} \]

\[ \varepsilon = \Delta E/E \propto L^2 \propto N_{\text{part}}^{2/3} \]

$L/\lambda$ will NOT disappear at very peripherical collision $\implies$

WHAT DOES THIS MEAN?
WHAT KIND OF ANIMAL IS THIS?

KITTEN?, BUNNY? or something ELSE?
IS THERE ROOM FOR COLD QUENCHING

IN $dA$ COLLISIONS AT RHIC AND LHC?
Cold Quenching in \( dAu \) collision at PHENIX

Barnaföldi, Fai, Levai, Papp

Calculations for \( dAu \) with HKN shadowing

Cold quenching in \( dAu \) collision at a small \( n\sim1 \) opacity

and this effect is stronger at LHC energies....
Suppression at LHC?

C.M. Energy dependence of GLV jet energy loss

\[ \Delta E_{GLV} \approx \frac{C_R \alpha s}{N(E)} \frac{L^2 \mu^2}{\lambda_g} \log \frac{E}{\mu} = \frac{C_R \alpha s}{N(E)} \frac{1}{A_\perp} \frac{dN}{dy} \langle L \rangle \log \frac{E}{\langle \mu \rangle} \]

- For central \(AuAu\) collision at RHIC \(\frac{1}{A_\perp} \frac{dN}{dy} \approx 5.1\)

- For \(dAu\) collision at RHIC \(\frac{1}{A_\perp} \frac{dN}{dy} \approx 2.54\)

- Without suppression \(\frac{dN}{dy} \sim \ln \sqrt{s}\)

- At LHC this \(\frac{dN}{dy}\) will be \(\sim 1500 - 2000\)
SUMMARY: So, does the Cronin Peak Disapper at LHC?

⇒ Strong, 30 – 40% shadowing effect at intermediate $p_T$

⇒ Cronin peak moves towards higher $p_T$

⇒ Peripheral $AuAu$ and $CuCu$ collisons data and dAu data 'need' a $L/\lambda \sim 1$ quenching at RHIC.

⇒ There are strong suppression effects at LHC! – Hmmm?!
BACKUP SLIDES
Jet-tomography in AuAu Collisions at Large $\eta$

In the forward directions $L/\lambda$ is smaller, due to less matter.

$AuAu$, $dAu$ data for $\pi^0$ by PHENIX and $h^\pm$ and $\pi^+, \pi^-$ by BRAHMS
Jet-tomography in AuAu Collisions at 62.4 and 200 AGeV

Decreasing $\sqrt{s}$ the $L/\lambda$ is smaller, due

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$\sqrt{s_{NN}}$ (GeV)</th>
<th>$\epsilon_{Bj}$ (GeV/fm$^3$)</th>
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</thead>
<tbody>
<tr>
<td>$S + S$</td>
<td>17, 3</td>
<td>$\gtrsim$ 1, 3</td>
</tr>
<tr>
<td>$S + Au$</td>
<td>19, 4</td>
<td>$\gtrsim$ 2, 6</td>
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<tr>
<td>$Pb + Pb$</td>
<td>17, 3</td>
<td>$\gtrsim$ 3, 2</td>
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<td>$Au + Au$</td>
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<tr>
<td>$Au + Au$</td>
<td>130</td>
<td>$\gtrsim$ 4, 4</td>
</tr>
<tr>
<td>$Au + Au$</td>
<td>200</td>
<td>$\gtrsim$ 5, 0</td>
</tr>
</tbody>
</table>

Getting close to compare geometrical and $\epsilon$ properties