A running coupling explanation of the surprising transparency of the QGP at LHC

Phys. Rev. Lett. 108, 0223101 (2012)
arXiv:1207.6020 (2012)

Alessandro Buzzatti
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Outline

- CUJET
  - Presentation of the model
  - Systematic errors
- Flavor dependent $R_{AA}$ at RHIC and LHC
  - Level crossing
- Alpha running
  - Comparison with CMS and ALICE data
- Conclusions
Jet Tomography

Jet Tomography: GLV, DGLV, WHDG, CUJET1.0

Gyulassy, Levai, Vitev, Djordjevic, Wicks, Horowitz, Buzzatti

Quark or Glue Jet probes:

\[(\eta, \ p_T, \ \phi - \phi_{\text{reac}}, \ M_Q)_{\text{init}}\]

Hadron jet fragments:

\[(\eta, \ p_T, \ \phi - \phi_{\text{reac}})_{\text{final}}\]

Measurements of hadronic/leptonic quenching patterns provides information about QGP density

\[
\Delta E^{\text{rad}} \sim \alpha_s^3 \int d\tau \ \tau \ \rho_{\text{QGP}} (\tau, \bar{r}(\tau)) \ \log \left( \frac{E_{\text{Jet}}}{T} \right)
\]

\[
\Delta E^{\text{elas}} \sim \alpha_s^2 \int d\tau \ \rho_{\text{QGP}}^{2/3} (\tau, \bar{r}(\tau)) \ \log \left( \frac{E_{\text{Jet}}}{T} \right)
\]
Energy loss – Radiative

Incoherent limit: Gunion-Bertsch

\[
\frac{dN}{dx dk_\perp} = \frac{1}{x} \frac{\alpha_s C_A}{\pi^2} \frac{q_\perp^2}{k_\perp^2 (q_\perp - k_\perp)^2}
\]

- Incoming quark is on-shell and massless
- The non-abelian nature of QCD alters the spectrum from the QED result
- Multiple scattering amplitudes are summed incoherently

Formation time physics

- \( \tau_f < \lambda < L \) Incoherent multiple collisions
- \( \lambda < \tau_f < L \) LPM effect (radiation suppressed by multiple scatterings within one coherence length)
- \( \lambda < L < \tau_f \) Factorization limit (acts as one single scatterer)
DGLV model

\[ x \frac{dN^{(n)}}{dx \, d^2k} = \frac{C_R \alpha_s}{\pi^2} \frac{1}{n!} \int \prod_{i=1}^{n} \left( \frac{d^2q_i}{\lambda_g(i)} \left( \frac{\vec{v}_i^2(q_i) - \delta^2(q_i)}{L} \right) \right) \times \left( -2 \tilde{C}_{(1, \ldots, n)} \cdot \sum_{m=1}^{n} \tilde{B}_{(m+1, \ldots, n)(m, \ldots, n)} \left[ \cos \left( \sum_{k=2}^{m} \Omega_{(k, \ldots, n)} \Delta z_k \right) - \cos \left( \sum_{k=1}^{m} \Omega_{(k, \ldots, n)} \Delta z_k \right) \right] \right) \]

Opacity series expansion \[ \rightarrow \left( \frac{L}{\lambda} \right)^n \]

Soft Radiation \((E \gg \omega, x \ll 1)\)
Soft Scattering \((E \gg q, \omega \gg k_T)\)

Radiation antenna \[ \rightarrow \] Cascade terms

\[ \tilde{C}_{(i_1 i_2 \ldots i_m)} = \frac{(k - q_{i_1} - q_{i_2} - \cdots - q_{i_m})}{(k - q_{i_1} - q_{i_2} - \cdots - q_{i_m})^2 + m_g^2 + M^2 x^2} , \]
\[ \tilde{B}_{(i_1 i_2 \ldots i_m)(j_1 j_2 \ldots j_n)} = \tilde{C}_{(i_1 i_2 \ldots j_m)} - \tilde{C}_{(j_1 j_2 \ldots j_n)} . \]

Gunion – Bertsch

\[ \tilde{B}_i = \tilde{H} - \tilde{C}_i \, , \]
\[ \tilde{H} = \frac{k}{k^2 + m_g^2 + M^2 x^2} \, , \]

Hard

LPM effect \[ \rightarrow \]

\[ \Omega_{(m, \ldots, n)} = \frac{(k - q_m - \cdots - q_n)^2}{2 x E} + \frac{m_g^2 + M^2 x^2}{2 x E} \]

Inverse formation time

Mass effects

Scattering center distribution \[ \rightarrow \]

\[ \Delta z_k = z_k - z_{k-1} \sim L/(n + 1) \]
CUJET

• Geometry
  – Glauber model
  – Bjorken longitudinal expansion

• Energy loss
  – DGLV – MD Radiative energy loss model
  – Energy loss fluctuations (Poisson expansion)
  – Full path length integration:

\[
\frac{dN_g}{dx}(x_\perp, \phi) = \frac{c_R\alpha_s}{\pi} \int d\tau \frac{d^2k}{\pi} \frac{d^2q}{\pi} \frac{1}{x q^2(q^2+\mu^2(\tau))} \times \frac{9\pi\alpha^2}{\frac{2}{2} k^2+\chi(\tau)} \left( \frac{(k+q)}{(k+q)^2+\chi(\tau)} \right) \times \\
\left( 1 - \cos \left[ \frac{(k+q)^2+\chi(\tau)}{2xE} \right] \right) \rho_{QGP}(x_\perp + \tilde{\phi} \tau, \tau) \\
\mu(\tau) = gT(x_\perp + \tilde{\phi} \tau, \tau) \quad \chi(\tau) = M^2 x^2 + m_g^2(\tau)(1 - x)
\]

– Elastic energy loss contributions

• Detailed convolution over initial production spectra
• In vacuum Fragmentation Functions
• Geometry
  – Glauber model
  – Bjorken longitudinal expansion

• Energy loss
  – DGLV – MD Radiative energy loss model
  – Energy loss fluctuations (Poisson expansion)
  – Full path length integration:

\[
\frac{d\sigma}{d\Omega}(d_\perp, \varphi) = C R \frac{\pi}{\sigma^2} \int d\varrho \frac{\pi}{\sigma^2} \left( \frac{1}{\sigma^2 + \varrho^2} \right) \times \frac{2(\mathbf{k} + \mathbf{q})}{(\mathbf{k} + \mathbf{q})^2 + \varrho^2} - \frac{\mathbf{k}}{\mathbf{k}^2 + \varrho^2} \frac{\varrho^2}{\mathbf{k}^2 + \varrho^2} \frac{dE}{d\varrho} \frac{Q}{Q^2} (d_\perp + \varphi \varrho) \]

– Elastic energy loss contributions
  – Detailed convolution over initial production spectra
  – In vacuum Fragmentation Functions

Possibility to evaluate systematic theoretical uncertainties such as sensitivity to formation and decoupling phases of the QGP evolution, local running coupling and screening scale variations, and other effects out of reach with analytic approximations;
Bjorken expansion

- The local thermal equilibrium is established at $\tau_0$

$$s(\tau) = s_0 \frac{\tau_0}{\tau} \quad \text{(entropy equation)}$$

$$s_0 \approx 3.6 \rho_0 = 3.6 \frac{1}{\pi R^2 \tau_0} \frac{dN}{dy}$$

($\frac{dN}{dy}$ is the observed rapidity density)

$$\rho_{QGP}(x_\perp, \tau) = \frac{1}{\tau_0} \frac{N_{part}}{\rho_{part}(x_\perp)} \frac{dN}{dy} f\left(\frac{\tau}{\tau_0}\right)$$

- Before equilibrium

Temporal envelopes: linear, divergent, freestreaming

$$f\left(\frac{\tau}{\tau_0}\right) = \begin{cases} \frac{\tau}{\tau_0}, \frac{\tau_0}{\tau}, 0 & (\tau < \tau_0) \\ \frac{\tau}{\tau_0}, \frac{\tau_0}{\tau} & (\tau > \tau_0) \end{cases}$$
Systematic errors

• Opacity order expansion
• Choice of interaction potential
• Pre-equilibrium phase
  – ALSO:
• pp Spectra
• Running coupling scales

1. One free parameter in the model: $\alpha_s^{\text{eff}}$

2. Fit $\alpha_s^{\text{eff}}$ to 10GeV RHIC Pion data $\alpha_s^{\text{eff}} \approx 0.3 \pm 10\%$

3. All other predictions are fully constrained
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$0 - 5\%$ centrality, $dN/dy = 1000$, $\alpha_s = 0.3$, $\tau_0 = 1\text{fm}/c$

Inversion of $R_{AA}$ flavor hierarchy at sufficiently high $p_t$

AB and M. Gyulassy, Phys. Rev. Lett. 108, 022301 (2012)
LHC Results

Parameters constrained by RHIC
\[ dN/dy = 2200 \]

Competing effect between Energy loss ordering...

\[ \Delta E(\text{light}) \approx \Delta E(c) > \Delta E(b) \]

...and pp Production spectra

\[ d\sigma(c, b) \text{harder than } d\sigma(\text{light}) \]

\[ RAA \sim (1 - \Delta E/E)^{n-2} \]

AB and M. Gyulassy, Phys. Rev. Lett. 108, 0223101 (2012)
CUJET solves the Heavy Quark puzzle...
AB and M. Gyulassy, Phys. Rev. Lett. 108, 0223101 (2012)

...but doesn’t excel at explaining the surprising transparency at LHC
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Alpha scales

• Introduce one-loop alpha running

\[ \alpha_s(Q^2) = \frac{2\pi}{9} \frac{1}{\log \left[ \frac{Q}{\Lambda} \right]} \]

B. G. Zakharov, JETP Lett. 88 (2008) 781-786

\[ \alpha_{MAX} \]

Radiative = \begin{cases} 
\frac{\alpha(q^2)^2}{\alpha(k^2)} \\
\frac{\alpha}{x(1-x)} \\
\mu = g(\alpha(2T^2))T
\end{cases}

S. Peigne and A. Peshier, Phys.Rev. D77 (2008) 114017

Elastic = \begin{cases} 
\alpha(ET) \\
\alpha(\mu^2)
\end{cases}
Alpha scales

• Introduce one-loop alpha running

\[ \alpha_s(Q^2) = \frac{2\pi}{9} \frac{1}{\log \left[ \frac{Q}{\Lambda} \right]} \]

B. G. Zakharov, JETP Lett. 88 (2008) 781-786

Systematic uncertainties:

Vary \( \alpha(Q^2) \):

\[ Q \rightarrow -50\% \]

\[ Q \rightarrow +25\% \]

Fit LHC Pion data at 40 GeV fixing \( \alpha_{MAX} = \{0.3, 0.4, 0.6\} \)
Focus on LHC

It is natural to use LHC results as our benchmark due to the extended $p_T$ range available

however

RHIC remains an essential tool to constraint our models

STAR HFT

sPHENIX
LHC Pions

See also B. Betz and M. Gyulassy, arXiv:1201.02181

Solid: LHC
Dashed: RHIC

CUJET effective alpha

$\alpha(Q)$

$\alpha=0.3$

$\text{ALICE, Pb+Pb}(2.76, 0-5\%) \rightarrow h^\pm$

$\text{CMS, Pb+Pb}(2.76, 0-5\%) \rightarrow h^\pm$
ALICE and CMS Pions

ALICE Collaboration

CMS Collaboration

**CMS Collaboration**

\[ \text{PbPb} \sqrt{s_{NN}} = 2.76 \text{ TeV} \]

\[ \int L \, dt = 7-150 \mu \text{b}^{-1} \]

- * (preliminary)
- Z (0-100%) \( p_T^Z > 20 \text{ GeV/c} \)
- W (0-100%) \( p_T^W > 25 \text{ GeV/c} \)
- Isolated photon (0-10%)
- b-quarks (0-100%)

(via secondary \( J/\psi \))

**Charged particles (0-5%)**

\[ p_T (\text{GeV/c}) \]

\[ p_T (m_T) (\text{GeV}) \]
ALICE and CMS Pions

ALICE Collaboration

CMS Collaboration

$R_{AA}$ vs $p_T$ (mjj) for PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

* Z (0-100%) $p_T > 20$ GeV/c
- W (0-100%) $p_T > 25$ GeV/c
- Isolated photon (0-10%)
- B-quarks (0-100%)
- Charged particles (0-5%)

Legend:
- Red squares: Z (0-100%) $p_T > 20$ GeV/c
- Yellow squares: W (0-100%) $p_T > 25$ GeV/c
- Blue circles: Isolated photon (0-10%)
- Pink squares: B-quarks (0-100%)
- Green squares: Charged particles (0-5%)

Integral: $\int L \, dt = 7-150 \, \mu b^{-1}$
PHENIX Pions

0-5% Centrality

PHENIX $\pi^0$ Au+Au 200GeV

$10^{-1}$

$p_T$ (GeV/c)

August 16th, 2012 – Quark Matter 2012, Washington DC

Alessandro Buzzatti – Columbia University
ALICE and CMS Heavy Flavors

ALICE Collaboration

CMS Collaboration

CMS-PAS HIN-12-014

CMS Preliminary

PbPb $s_{NN} = 2.76$ TeV

Non-prompt J/$\psi$
Conclusions

MODEL

- CUJET offers a reliable and flexible model able to compute leading hadron Jet Energy loss and compare directly with data
  - Satisfactory results when looking at flavor and density dependence of $R_{AA}$
  - Possibility to study systematic theoretical uncertainties
  - Easy to improve

ACHIEVEMENTS

- New RHIC electron predictions now consistent with uncertainties of data (Heavy Quark puzzle)
- Strong prediction of novel level crossing pattern of flavor dependent $R_{AA}$
- Evidence of running alpha strong coupling constant
  - Simultaneous agreement with RHIC and LHC data

FUTURE

- Necessity to fit as many orthogonal observable as possible
  - Non central collision $R_{AA}$
  - Elliptic flow $v_2$
Energy loss

- Consider a simplified power law model for Energy loss:

\[ \frac{\Delta E}{E} = \kappa E^{a-1} L^b \rho^c \]

W. A. Horowitz and M. Gyulassy, arXiv:1104.4958
B. Betz and M. Gyulassy, arXiv:1201.0218

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![Graphs showing energy loss for LHC and RHIC, with constant and running alpha values.](image_url)
Initial pQCD spectra

Competing effects between increased density and harder production spectra

- RHIC density and spectra
- LHC density, RHIC spectra
- LHC density and spectra

Initial quark production spectra

![Graph showing initial quark production spectra](image)

- GLUE
- UP
- CHARM
- BOTTOM

NLO-FONLL uncertainty
Initial pQCD spectra

Competing effects between increased density and harder production spectra

- RHIC density and spectra
- LHC density, RHIC spectra
- LHC density and spectra

Initial quark production spectra

RHIC

\[
\frac{d\sigma}{dp_T}
\]

\begin{align*}
\text{GLUE} & \quad \text{UP} \\
\text{CHARM} & \quad \text{BOTTOM}
\end{align*}

Ramona Vogt

NLO-FONLL uncertainty
Initial pQCD spectra

Competing effects between increased density and harder production spectra

- RHIC density and spectra
- LHC density, RHIC spectra
- LHC density and spectra

Initial quark production spectra

\[ \frac{d\sigma}{dp_T} \]

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

GLUE
UP
CHARM
BOTTOM

NLO-FONLL uncertainty

Ramona Vogt

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\( \tau_0 \) sensitivity

**THICK**: Linear with \( \alpha_s = 0.3 \)

**THIN**: Divergent with \( \alpha_s = 0.27 \) or Freestreaming with \( \alpha_s = 0.325 \)

**DAHSED**: Divergent or Freestreaming with \( \alpha_s = 0.3 \)
Effective Potential

**Static potential (DGLV)**

\[ |\vec{v}_i(q_i)|^2 = \frac{1}{\pi} \frac{\mu(z_i)^2}{(q^2 + \mu(z_i)^2)^2} \]

- Static scattering centers
- Color-electric screened Yukawa potential (Debye mass)
- Full opacity series

**Dynamical potential (MD)**

\[ |\vec{v}_i(q_i)|^2 = \frac{1}{\pi} \frac{\mu(z_i)^2}{q^2(q^2 + \mu(z_i)^2)} \]

- Scattering centers recoil
- Includes not screened color-magnetic effects (HTL gluon propagators)
- Only first order in opacity

**Interpolating potential (CUJET)**

\[ |\vec{v}_i(q_i)|^2 = \frac{N(\mu_m)}{\pi} \frac{\mu_e(z_i)^2}{(q^2 + \mu_e(z_i)^2)(q^2 + \mu_m(z_i)^2)} \]

- Introduces effective Debye magnetic mass
- Interpolates between the static and HTL dynamical limits
- Magnetic screening allows full opacity series
Beyond first order in opacity

Interpolate between DGLV and MD with a new effective potential

\[
\frac{1}{(q^2 + \mu^2)^2} \quad \text{DGLV} \quad \frac{1}{(q^2 + \mu_m^2)(q^2 + \mu_e^2)} \quad \text{MD} \quad \frac{1}{q^2(q^2 + \mu^2)}
\]

It is possible to study the limit \( \mu_m \to 0 \) for values of \( \mu_m \gtrsim \mu_e / 3 \)

- The mean free path \( \frac{1}{\lambda} = \int dq \frac{d\sigma}{dq} \rho \)
  is divergent for \( \mu_m = 0 \)

\( \frac{\Delta E_u}{\Delta E_b} \) ratio improves for \( N > 1 \) and \( \mu_m \to 0 \), but likely not enough.
Magnetic monopoles

Magnetic monopole enhancement

- Nonlinear density dependence near $T_c$

AdS/CFT

Jinfeng Liao, arXiv:1109.0271
Elastic energy loss and Fluctuations

Bjorken elastic collisions

\[
\frac{dE}{dx} = -C_R \pi \alpha^2 T^2 \log[B]
\]

- Soft scattering
- Thoma-Gyulassy model

\[
B_{TG} = \frac{4pT}{E-p+4T}/\mu
\]

Energy loss fluctuations

- The probability of losing a fractional energy \( \varepsilon = \frac{\Delta E}{E} \) is the convolution of Radiative and Elastic contributions

\[
P(\varepsilon) = \int dx \; P_{rad}(\varepsilon) \; P_{el}(x - \varepsilon)
\]

- Radiative: \( P_{rad}(\varepsilon) = P_0 \delta(\varepsilon) + \tilde{P}(\varepsilon)|_0 + P_{stop}\delta(1 - \varepsilon) \)
- Elastic: \( P_{el}(\varepsilon) = e^{-<N_c>\delta(\varepsilon)} + Ne^{\frac{(\varepsilon-\bar{\varepsilon})}{4T\bar{\varepsilon}}} \)

Poisson expansion of the number of INCOHERENTLY emitted gluons

Gaussian fluctuations
$k_T$ distribution

En=20GeV, $x=0.25$, bottom quark, plasma thickness 5fm
Order in opacity equal to N

\[ dN^0 \sim \frac{k_T^2}{(k_T^2 + x^2 M_q^2)^2} \]

- $N=1$ (thin plasma)
- $N=5$ (finite opacity)
- $N=\infty$ (thick plasma)

dead cone effect

ASW soft scattering
Energy loss

Energy loss vs L

Ratio u/b and u/c

Ratio Rad and El to Total

Convergence for m>>E

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Temporal envelope

\[ f \left( \frac{\tau}{\tau_0} \right) = \begin{cases} \frac{\tau}{\tau_0}, & (\tau < \tau_0) \\ \frac{\tau_0}{\tau}, & (\tau > \tau_0) \end{cases} \]

Energy loss vs L

Differential Energy Loss \( \frac{d<\Delta E/E>}{dx} \)

Ratio L/D and L/F

Linear, Divergent, Freestreaming.

UP

BOTTOM
\( k_T \) sensitivity

- Collinear approximation: \( x_E = x_+ \left( 1 + O \left( \frac{k_T}{x_+ E^+} \right)^2 \right) \)
  - DGLV formula has the same functional form for \( x_E \) or \( x_+ \)
  - Different kinematic limits:
    \[ k_T^{\text{max}} = x_E E \]
    \[ k_T^{\text{max}} = 2EMin[x_+, 1 - x_+] \]

\( L = 5, \) bottom quark

Solid lines: MD  
Dashed lines: DGLV

\[
\frac{dN^J_g}{dx_E}(x_E) = \int x_E E \sin(\theta_{\text{max}}) \frac{dk_T}{dx_E} \frac{dx_+}{dx_E} \frac{dN}{dk_T}(x_+(x_E)),
\]

\[
\frac{dx_+}{dx_E} = \frac{1}{2} \left[ 1 + \left( 1 - \left( \frac{k_T}{x_E E} \right)^2 \right)^{-1} \right].
\]
• BDMPS predicts the scaling of the induced intensity x-spectrum with 

\[ \hat{q} \sim \mu^2 / \lambda \]

through the z variable

\[ z \equiv |\omega_0^2| L^2, \quad \omega_0^2 \equiv -i \frac{[(1 - x)C_A + x^2 C_s] \hat{q}}{2x(1 - x)E} \]

\[ E=100, \ x=0.05, \ M_q=0.25, \ \hat{q}=0.25, \ \mu=\sqrt{\hat{q}} \lambda, \ m_g=\mu/\sqrt{2}, \ L=1-5 \ (adj.) \]

\[ \lambda=0.5  |  \lambda=1  |  \lambda=2  |  \text{BDMFS} \]

\[ \frac{1}{\hat{P}_{s\rightarrow g}(x)} \frac{dN(t^+ \rightarrow s)}{dx} \]