RHIC II Physics Overview

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Outline of the Talk

What are the **new physics questions** that can be addressed with **detector and luminosity upgrades** at RHIC?

**Spin physics with RHIC upgrades / RHIC II**
- Example of transverse spin observables

**The A+A program with RHIC upgrades / RHIC II**
- Precision physics with high-$p_T$ jets, high-$p_T$ particle correlations
- Direct measurements of open heavy flavor
- Direct photon physics, photon-hadron correlations

**The d+A program with RHIC upgrades / RHIC II**
- Possibility for gluon saturation physics at forward rapidity, eRHIC case
- Longitudinal dynamics, energy loss, dynamical shadowing

**Other compelling questions to benefit from RHIC upgrades / RHIC II**
- Thermalization of the QGP, viscosity, elliptic flow, quarkonia, dileptons …
Drell-Yan Physics with Possible New Detector

Transversity: correlation between transverse proton spin and quark spin

\[ A_{TT} \propto \delta q(x_1) \delta q(x_2) \]

Sivers: correlation between transverse proton spin and quark transverse momentum

\[ A_T \propto q(x_1) \cdot f_{1T}^q(x_2, k_{2\perp}) \cdot \frac{(\hat{P} \times \vec{k}_T) \cdot \vec{S}_P}{M} \]

Boer/Mulders: correlation between transverse quark spin and quark transverse momentum

\[ N(\phi) \propto h_{1T}^q(x_1, k_{1\perp}) \cdot \frac{(\hat{P} \times \vec{k}_{1\perp}) \cdot \vec{S}_q}{M} \cdot h_{1\perp}^q(x_2, k_{2\perp}) \cdot \frac{(\hat{P} \times \vec{k}_{2\perp}) \cdot \vec{S}_{\bar{q}}}{M} \]
Process Dependence in QCD

• The generalized (lack of) universality of the Sivers function (effect)

  SDID to DY change sign

• Analogy to unpolarized coherent scattering in nuclei


• Extremely interesting to access experimentally, understand process dependences and multiple parton interactions high twist / leading twist
Sivers - Asymmetries, $A_T$ in Drell-Yan

**STAR for 125 pb$^{-1}$**

**T–SPHINX**

1250 pb$^{-1}$

- 10 o'clock $\rightarrow$ 100% transverse polarization
- mini-quad
- acceptance: $-3 < \eta < 3$

$\Rightarrow \times 300 \text{ in } \int L dt$

Precision measurement of Sivers distributions!
II. Jet Quenching

物理评论快报

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物理评论快报
An Active Field of Heavy Ions

A. Majumder, (2007)

- GW model 1994
  - Gylassy, Levai, Vitev, 2000
    - Djordjevic, GLV-2004
      - Adil, Horowitz, Wicks, DGLV, 2005-06

- Braaten, Pisarski, HTL 1990
  - Aurenche, et.al.  Θ Enhancement 1998
  - AMY 2001
    - Turbide, Jeon, Gale, - AMY 2005

- Qiu, Sterman, Higher twist 1991
  - Luo, Qiu, Sterman A enhancement, 1994
    - Guo, Wang Modified fragmentation 2000
      - Wang, Wang, Zhang, Majumder HT-2002-2005

- GW model 1994
  - BDMPS-Zakharov 1997
  - Wiedemann 2000
  - ASW 2004
    - Eskola, Honkanen PQM 2004-05
      - Renk, 2005

Radiative energy loss formalisms and subsequent refinements

- Agreement between 3 schemes: GLV, AMY, HT

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Energy Loss and Jet Tomography

- Small systems: deep quantum coherence regime (LPM)

\[ \Delta E^{(1)} \approx \frac{C_R \alpha_s}{4} \frac{\mu^2 L^2}{\lambda_g} \log \frac{2E}{\mu^2(L)L} + \ldots, \]

- Static medium

\[ \Delta E^{(1)} \approx \frac{9\pi C_R \alpha_s^3}{4} \frac{dN^g}{A_L} \frac{1}{\Delta y} \log \frac{2E}{\mu^2(L)L} + \ldots, \]

- 1+1D Bjorken

- Goal: characterize the intuitive an easy to interpret characteristics of the QGP

\[ T, \, \varepsilon \sim T^4, \, \rho \sim T^3 \]

Principles of jet tomography

\[ I(r) = e^{-\int_0^r \frac{dr}{\lambda_{abs}(r')}} = e^{-\int_0^r \frac{dr}{\rho(r')\sigma(r')}} \]


Limitations of the Current High $p_T$ Data

$6 \leq \langle \hat{q} \rangle \leq 24 \text{ GeV}^2/\text{fm}$  
(Probability $> 10\%$)

C. Loizides (2006)

$1000 \leq \frac{dN_g}{dy} \leq 2000$  
(Probability $> 10\%$)

I. Vitev (2006)

$600 \leq \frac{dN_g}{dy} \leq 1600$  
(Probability $> 10\%$)

W. Horowitz (2006)
Improvement with RHIC II Luminosity

\[ R_{AA}(p_T, \eta) = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{d^2\sigma^{AA}}{d\eta dp_T} \times \frac{d^2\sigma^{NN}}{d\eta dp_T} \]

Example: ~ 1000 N+N collisions in central Au+Au

• Data Quality:
  RHIC II for precision QGP studies

• Critical for:
  - Precision determination of the QGP properties
  - Exploring the really high \( p_T \) region at RHIC

\[ s^{1/2} = 200 \text{ GeV} \]
\[ \pi^0 \text{ in Au+Au} \]

No nuclear effect

Excellent Fair Does not exist
High $p_T$ Di-Hadron Correlations

- Alternative ways to improve the sensitivity to the properties of the QGP medium - di-hadron correlations
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Statistical analysis

III. Direct Photons

• Direct photons: argued to be only weakly interacting

\[
d\sigma^{(1)} \sim \phi_1(x_1, Q^2) \otimes \phi_2(x_2, Q^2) \otimes \frac{1}{2\hat{s}} |M|^2 \otimes D_1(z_1, Q^2)
\]
Direct Photon at RHIC (II) versus LHC

- Measurements of direct photon observables, especially in A+A are statistics (and systematics) limited \( |M|^2 \sim \alpha_s \alpha_{em} \)

**Prompt photons**

\[ D_{\gamma/\gamma}(z) = \delta(z - 1) \]

**Fragmentation photons**

\[ D_{\gamma/q}(z) \]
\[ D_{\gamma/g}(z) \]

\[ R = \frac{d\sigma / dy d^2p_T (\text{fragmentation})}{d\sigma / dy d^2p_T (\text{prompt})} \]

Advantage: RHIC
QGP Induced Bremsstrahlung and Jet Conversion

- Jet conversion
- Photon bremsstrahlung

\[ \frac{dN^h}{dyd^2p_Td\phi} = \frac{1}{2\pi} \frac{dN^h}{dyd^2p_T} \left(1 + 2v_2\cos(2\phi) + \ldots\right) \]

Negative \(v_2\)


- Better statistics is needed to exclude theoretical models

S. Turbide et al., (2005)
Single Inclusive Photon Modification

Photon bremsstrahlung, jet conversion

Energy loss of quarks - fragmentation $\gamma$

- Lead to the same conclusion: data is suggestive (but not conclusive) of quenching of fragmentation photons

We have to rethink the “golden” energy loss channel
Photon-Hadron Correlations

• Original idea to determine the energy loss of quarks

\[
I_{AA}(p_T) = \frac{\frac{d\sigma^{(2)}}{dp_T^1 dp_T^2} / \frac{d\sigma^{(1)}}{dp_T^1}}{\frac{d\sigma^{(2)}}{dp_T^1 dp_T^2} / \frac{d\sigma^{(1)}}{dp_T^1}_{pp}} \approx \frac{D^\gamma_{AA}(z = p_T / E_\gamma)}{D^\gamma_{pp}(z = p_T / E_\gamma)}
\]

In light of the recent results

• While this still remains the method to most directly access the energy loss of quarks it is not as bias free as previously thought

• Not only gamma-jet but also single inclusive hadron measurements are needed

IV. Heavy Flavor

- Expected to be **perturbatively computable**
- Fixed order, next-to-leading log calculations
- **Systematic deviations** for non-photonic electrons between the calculation, the data and the two experiments
- How would it compare to direct measurements of D-, B-mesons?

Non-Photonic Electron / Heavy Flavor Quenching

Radiaive and collisional energy loss

Langevin simulation of heavy quark diffusion

- Ratio: $\Delta E_{coll} / \Delta E_{rad}$
- Opacity $L / \lambda_g$ of the QGP
- Diffusion coefficient $D$ and eventually $\eta / s$
- Existence of heavy resonances near $T_c$ in the QGP


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Heavy Flavor Elliptic Flow and Suppression

Test coalescence model fits to the $v_2$ of light hadrons via heavy flavor

Understand the structure of mesons light cone wave functions

Sensitive to the opacity of the QGP and its formation time $\tau_0$

$$v_{2,B}(x, p_T) \approx \sum_{i=\alpha,\beta,\gamma} v_{2,i}(x, p_T, i), \quad v_{2,M}(x, p_T) \approx \sum_{i=\alpha,\beta} v_{2,i}(x, p_T, i)$$


A. Adil, I. Vitev, (2006)
The Path Forward

• An interesting idea ≠ valid physics explanation

• To understand heavy flavor modification in the QGP we need direct and separate measurements of D- and B-mesons, excellent statistics

Measurable at RHIC

\[ \frac{R_{AA}^c(p_T)}{R_{AA}^b(p_T)} = 1 \]

<table>
<thead>
<tr>
<th>PT [GeV]</th>
<th>Radiative dissociation</th>
<th>PQCD, Transport</th>
<th>String theory AdS/CFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-15</td>
<td>50-100</td>
<td>Never</td>
<td>P_T [GeV]</td>
</tr>
</tbody>
</table>

Measurable at the LHC

A. Adil, I. Vitev, (2006)

V. Forward Rapidity Physics: Saturation Models

A. Mueller, J. Qiu, (1986)

- Nonlinear gluon evolution 2-to-1 processes

L. McLerran, R. Venugopalan, (1994)

- Classical Yang-Mills fields

\[ Q_s^2 \sim \frac{\alpha_s x G_A(x, Q_s^2)}{\pi R^2} \sim A^{1/3} \frac{1}{x^{0.3}} \]
Forward Rapidity Suppression

• Particle production via 2 to 1 processes (monojets)

\[ \frac{dN_g}{dy d^2x_T dp_T} \propto \frac{1}{p_T} \int d^2k_T \phi_A(x_1, \frac{\vec{p}_T + \vec{k}_T}{2}) \phi_B(x_2, \frac{\vec{p}_T - \vec{k}_T}{2}) \]


• Elaborated to include quark scattering on CGC

• Brahms hadron forward suppression pattern

Particle Production Mechanism

- Suggestive of di-jet production mechanism

Di-jets:

\[
\frac{d\sigma_{NN}^{h_1 h_2}}{dy_1 dy_2 dp_T^1 p_T^2} = 2\pi \sum_{abcd} \int_{z_1 \text{ min}}^{1} dz_1 \frac{D_{h_1/c}(z_1)}{z_1} D_{h_2/d}(z_2) \frac{\phi(\vec{x}_a)\phi(\vec{x}_b)}{\vec{x}_a \vec{x}_b} \frac{\alpha_s^2}{S^2} |\vec{M}_{ab-cd}|^2
\]

Monojets:

\[
\frac{dN_g}{dy d^2 x_T dp_T} \propto 1 \frac{1}{p_T^2} \int d^2 k_T \phi_A(x_1, \vec{p}_T + \vec{k}_T) \phi_B(x_2, \vec{p}_T - \vec{k}_T)
\]

\[
I_{d+Au}^c = \frac{N_{d+Au}}{N_{d+Au}^{asso}} \quad \frac{N_{p+p}}{N_{asso}^{p+p}} \quad \frac{N_{trig}}{N_{asso}^{trig}}
\]

\[
p+p \rightarrow \pi^0 + h^\pm + X \quad S = 0.100 \pm 0.014
\]

\[
d+Au \rightarrow \pi^0 + h^\pm + X \quad S = 0.020 \pm 0.013
\]

\[
25 < E_{\pi} < 30 \text{ GeV} \quad 0.1 \quad 0.2 \quad 0.1 \quad 0.2 \quad 0.1 \quad 0.2
\]

\[
S = 0.154 \pm 0.024
\]

\[
30 < E_{\pi} < 55 \text{ GeV} \quad 0.1 \quad 0.2 \quad 0.1 \quad 0.2 \quad 0.1 \quad 0.2
\]

\[
S = 0.093 \pm 0.040
\]

\[
0-40\% \text{ d+Au} \quad 40-88\% \text{ d+Au}
\]

\[
\begin{align*}
0.4 \quad 0.8 \quad 1.2 \quad 1.6 \quad 2.0 \quad 2.4 \quad 2.8 \quad 3.2 \\
0.4 \quad 0.8 \quad 1.2 \quad 1.6 \quad 2.0 \quad 2.4 \quad 2.8 \quad 3.2
\end{align*}
\]

\[
C. \text{ Zhang et al., (2006)}
\]

- L. Bland et al., (2005)

\[
\begin{align*}
\varphi_{\pi} - \varphi_{\text{LCP}} & = 1.06 \text{ GeV/c} \\
\varphi_{T_{\pi}} & = 1.36 \text{ GeV/c}
\end{align*}
\]

\[
\begin{align*}
\varphi_{T_{\text{LCP}}} & = 0.28 \\
\varphi_{x_T} & = 1.37 \text{ GeV/c}
\end{align*}
\]

\[
\begin{align*}
\varphi_{x_T} & = 1.36 \text{ GeV/c} \\
\varphi_{x_T} & = 0.38
\end{align*}
\]
Evidence for Energy Loss in Cold Nuclei

Cross section scaling: \( \sigma_A = A^\alpha \sigma_N \)

Universal scaling

M. Leitch et al. PHENIX, EA866 and NA3 data

B. Kopeliovich et al. (2006)

- Energy loss is a dominant mechanism in the forward rapidity / large \( x_F \) suppression (Sudakov suppression)

\( x_F = x_1 - x_2 \)

\( \sigma = \frac{d^2 \sigma}{dx_1 dx_2} \)

\( dE/dx \)
Nuclear Effects at Forward Rapidity

- Theoretical developments in parton E-loss:

\[
\frac{\Delta E}{E} \bigg|_{IS} = \frac{1}{\kappa_{LPM}} \frac{\Delta E}{E} \bigg|_{BH}
\]

\[\kappa_{LPM} \approx 6\]

I. Vitev (2007)

- Original incoherent result:

\[M \downarrow \gamma_{\uparrow} \, \gamma_{\uparrow} \, \gamma_{\uparrow} \, \gamma_{\uparrow} \, \gamma_{\uparrow} \downarrow \gamma_{\uparrow} \, \gamma_{\uparrow} \downarrow \gamma_{\uparrow} \, \gamma_{\uparrow} \downarrow \gamma_{\uparrow} \downarrow M^*\]


- Note the different contributions to an overall suppression effect

Coexistence with ongoing effort: E906 Fermilab - the first precise determination of quark energy loss in nuclei

From RHIC II to eRHIC

Forward rapidity physics is a complex superposition of nuclear effects: Cronin, energy loss / nuclear stopping, and shadowing / gluon saturation effects

- To begin to disentangle initial- versus final-state effects at RHIC one needs weakly interacting probes such as Drell-Yan $q + ar{q} \rightarrow \mu^+ + \mu^-$ (require high luminosity)

- To understand the origin of nuclear shadowing and explore non-linear small-x physics DIS at eRHIC is needed
Other Compelling Physics Questions

To benefit from detector upgrades / RHIC II

• What is the thermalization mechanism of the quark-gluon plasma?

• What is the viscosity of the quark-gluon plasma? How imperfect is the “perfect fluid”?

• What is the plasma response to jets?

• Di-leptons and chiral symmetry restoration?

B. Jacak (2007)
Summary I

**Fundamental** thermal field theory, many-body QCD at high energies, small-x physics, and the origin of spin
Summary II

Specific examples given

Spin physics
  Longitudinal and transverse spin observables, Sivers

The A+A program with RHIC upgrades / RHIC II
  • Precision physics with high-$p_T$ jets, high-$p_T$ particle correlations
  • Direct measurements of open heavy flavor
  • Direct photon physics, photon-hadron correlations

The p+A program with RHIC upgrades / RHIC II
  • Possibility for gluon saturation physics at forward rapidity, eRHIC case
  • Longitudinal dynamics, energy loss, dynamical shadowing

Other compelling questions to benefit from RHIC upgrades / RHIC II
  • Thermalization of the QGP, viscosity, elliptic flow, quarkonia, dileptons …
Rare Hard Probes of the QGP

- Heavy Flavor
- Direct Photons

A+A physics

Assisted by precise jet tomography of the QGP
Transport + Quenching Approach

Numerical results for c, b diffusion

<table>
<thead>
<tr>
<th>p_T [GeV]</th>
<th>R_AA</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>1.5</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>0.5</td>
</tr>
<tr>
<td>4</td>
<td>0.25</td>
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<tr>
<td>5</td>
<td>0</td>
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Elliptic flow (azimuthal asymmetry)

<table>
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<tr>
<th>p_T [GeV]</th>
<th>v_2 [%]</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>5</td>
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<td>10</td>
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<tr>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
</tr>
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</table>

- The suppression and $v_2$ are large with E-loss and q-resonance interactions combined
- Normal hierarchy: c quarks are significantly more suppressed than b-quarks
- Measurements can constrain the QGP parameters in a correlated way

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\[ \varepsilon_0 \approx 15 \text{ GeV/fm}^3, \quad \tau_0 \approx 0.6 \text{ fm, } \quad T_0 \approx 370 \text{ MeV, } \quad dN^g/dy \approx 1000 \]
Quenching of Non-Photonic Electrons

- Full semi-leptonic decays of C- and B- mesons and baryons included. PDG branching fractions and kinematics. PYTHIA event generator

\[ R_{AA}^{e^\pm}(p_T) = \frac{d\sigma_{AA}^{e^\pm} / dy d^2 p_T}{\langle N_{coll} \rangle d\sigma_{pp}^{e^\pm} / dy d^2 p_T} \]

- B-mesons are included. They give a major contribution to \((e^+e^-)\)

Note on applicability

D-, B-mesons to \(R_{AA}(D) = R_{AA}(B)\)

\((e^+e^-)\) to 25 GeV
e-h correlations in p+p: bottom vs. charm

See Xiaoyan Lin’s talk for STAR

- Understand charm and bottom production is a key point to understand suppression and flow
- Direct measurement is very complicated
- One possible idea: electron-hadron correlations
  - Near side peak dominated by decay kinematics
- Preliminary e-h correlations from p+p collisions in STAR
  - Extract relative bottom contribution for different electrons $p_T$

\[
\Delta \phi_{\text{exp}} = R \cdot \Delta \phi_B + (1 - R) \cdot \Delta \phi_C
\]
e-h correlations in p+p: bottom vs. charm

See Xiaoyan Lin’s talk for STAR

- FONLL has large uncertainties in the b/(c+b) ratio
  - Could the data nail it down?

- First measurement of open-bottom at RHIC
  - Non-zero contribution of bottom
  - Very close to FONLL predictions
Open Heavy Flavors – Energy Loss in Medium

- In vacuum, gluon radiation suppressed at $\theta < m_Q/E_Q$
  - "dead cone" effect implies lower energy loss (Dokshitzer-Kharzeev, '01)
  - Energy distribution $\omega d\Omega/d\omega$ of radiated gluons suppressed by angle-dependent factor

- Smaller energy loss would probe inside the medium

- Collisional E-loss: $qg \rightarrow qg, \ qq \rightarrow qq$
  - $dE/dx \propto \ln p$ - small?
Nuclear Shadowing

\[ F_T(x, Q^2) = \frac{1}{2} \sum_f Q_f^2 \int d\lambda_0 e^{i\lambda_0} \left\langle p \left| \frac{\gamma^+}{2p^+} \Psi(0) \Psi(\lambda_0) \right| p \right\rangle \]
\[ = \frac{1}{2} \sum_f Q_f^2 \phi_f(x, Q^2) + O(\alpha_s) \]
\[ x_B = \frac{Q^2}{2m_N v} \]

- Simplistic view: modification of the nuclear wave function

Longitudinal size: \( \sim \frac{1}{2m_N} x \)

If \( x < 0.1 \) then \( \Delta z > r_0 \)

\[ F_T^A(x, Q^2) \approx A F_T^{(LT)} \left( x + \frac{x_0^2 (A^{1/3} - 1)}{Q^2}, Q^2 \right) = A F_T^{(LT)} \left( x \left( 1 + \frac{m_{\text{dyn}}^2}{Q^2} \right), Q^2 \right) \]

Alternative model: “leading twist” \( \sim \ln Q^2 \)


- Shadowing is dynamically generated in the hadronic collision y coherent final state scattering

Deviation from A-scaling: \( \sigma_A \neq A \times \sigma \)
The QCD Phase Transition

Asymptotic freedom:

\[ T \gg gT \gg g^2T \]

\[ \alpha_s(Q^2, n_f) = 4\pi / \left(11 - \frac{2}{3} n_f\right) \ln \frac{Q^2}{\Lambda_{QCD}^2} \]

\[ \alpha_s(Q^2, n_f) = \alpha_s^{LO}(Q^2, n_f) \left[ 1 - \frac{1}{4\pi} \frac{102 - 36}{11 - \frac{2}{3} n_f} \alpha_s^{LO}(Q^2, n_f) \ln \frac{Q^2}{\Lambda_{QCD}^2} \right] \]

\[ \varepsilon_{SG}/T^4 \]

3 flavor, \( N_c = 4 \), \( p4 \) staggered

\( m_\pi = 770 \) MeV

\[ 3p/T^4 \]

\[ \varepsilon/T^4 \]

\[ \frac{15\%}{\text{dev.}} \]


- Deviation from Stefan-Boltzman: the log running of \( \alpha_s \)

Note: Recent results \( T_c \approx 190 \) MeV vs \( T_c \approx 175 \) MeV

- Hard thermal loop calculations: improved resummation of the perturbation series

- Agreement between HTL and Lattice for \( T \geq 3T_c \)

Note on LHC versus RHIC: strongly versus weakly coupled plasmas, beware of logarithmic running
Beam energy of 120 GeV eliminates shadowing region.
• For radiation lengths $X_0 = 1 \times 10^{-13}$ m achieve sensitivity $\sim 20\%$

Non-QCD $X_0(W)=3.5\times10^{-3}$ m

• Clearly distinguish between leading models for dependence of E-loss ($5\sigma$)

$-\Delta E \sim A^{1/3}$ (or $\sim L$)

$-\Delta E \sim A^{2/3}$ (or $\sim L^2$)
Light Cone Wave Functions

- Expansion in Fock components

\[
|\psi_M; P_\perp, P^+\rangle = \sum_{i=2}^{n} \int \frac{dx_i}{\sqrt{2x_i}} \frac{d^2 k_{\perp i}}{\sqrt{(2\pi)^3}} \psi_i(k_{\perp i}, x_i) \\
\times \delta\left(\sum_{i=2}^{n} x_i - 1\right) \delta\left(\sum_{i=2}^{n} k_{\perp i}\right) |i; k_{\perp i} + x_i P_\perp, x_i P^+\rangle
\]


- Fixing the transverse momentum scale

Cornell potential

\[
V(r) = -\frac{g}{r} + br
\]

\[
\left\{ \alpha \cdot p + V + (m + S) \beta + \frac{p^2}{2M_Q} + \frac{\alpha \cdot p}{2M_Q}, V \right\} + \frac{1}{4M_Q}[\alpha \cdot p, [p^2, W]] \psi = E\psi
\]

\[
a_0 \to \text{max}(r^2 \rho(r)), \quad a_0 = 2 - 3 \text{ GeV}^{-1}
\]


Fix two momentum scales

\[
P_\perp \quad q, g
\]

Fourier transform to momentum space

\[
\psi(r) \sim e^{r^2/(2a_0^2)} \quad \to \quad \psi(k) \sim e^{k^2a_0^2/2}
\]

Typical transverse momentum squared

\[
\langle k_{\perp}^2 \rangle = \frac{1}{2a_0^2}
\]
Light Cone Wave Functions

• Results for heavy flavor

- Fixing the longitudinal momentum fractions

\[
\left( \frac{m_{\perp i}^2}{x_i} = \frac{m_{i}^2 + k_{\perp i}^2}{x_i} \right) = \left( \frac{m_{\perp j}^2}{x_j} = \frac{m_{j}^2 + k_{\perp j}^2}{x_j} \right)
\]

Meson boost – equal quark longitudinal rapidity

• Begin to understand hadron structure and parton distributions from first principles

\[
\phi_{Q/M}(x) = \int dKd^2\Delta k_{\perp} \left| \psi (K, \Delta k_{\perp}, x, m_1, m_2) \right|^2
\]

• Duality between FFs ad PDFs

• Models such as coalescence should use plausible wave functions, especially for heavy flavor

From general theory of LCWF for the lowest-lying Fock state
Heavy Meson Propagation in Dense Matter

\[ R = \left( \begin{array}{ccc}
\infty & \infty & \infty \\
1/\mu & < \lambda & \\
\end{array} \right)^n \]

• Single scattering in the medium

• Solve for the color and kinematic structure of this operator which automatically ensures unitarity

\[ \sim \int d^2 q_{\perp} d^2 q'_{\perp} M_1^*(p - q_{\perp}) M_2(p - q'_{\perp}) \frac{d\sigma\text{el}}{d^2 q_{\perp}} \delta^2(q_{\perp} - q'_{\perp}) \]

\[ \sim \left( -\frac{1}{2} \right) \int d^2 q_{\perp} d^2 q'_{\perp} M_1^*(p - q_{\perp} - q'_{\perp}) M_2(p) \frac{d\sigma\text{el}}{d^2 q_{\perp}} \delta^2(q_{\perp} + q'_{\perp}) \]
Medium-Modified Heavy Meson

Initial distribution:

\[ |\psi_f(\Delta k_\perp, x)|^2 = \left[ \delta^2(K_\perp) \right] \times \left[ \text{Norm}^2 e^{-\frac{\Delta k_\perp^2}{4x(1-x)\Lambda^2}} e^{-\frac{m_1^2(1-x)+m_2^2x}{x(1-x)\Lambda^2}} \right] \]

Resum multiple scattering in impact parameter (B,b) space

- Heavy meson acoplanarity:
  \[ \langle K_\perp^2 \rangle = 2 \left( 2\mu^2 \frac{L}{\lambda_q} \right) - 2 \left( 2\mu^2 \frac{L}{\lambda_q} \right) \equiv \int_0^L 2 \left( 2\mu^2(l) \frac{1}{\lambda_q(l)} \xi \right) dl \]

\[ |\psi_f(\Delta k_\perp, x)|^2 = \left[ \frac{-\frac{K_\perp^2}{e^4\mu^2\xi}}{4\chi \mu^2 \xi} \right] \times \left[ \text{Norm}^2 \frac{x(1-x)\Lambda^2}{\chi \mu^2 \xi + x(1-x)\Lambda^2} e^{-\frac{\Delta k_\perp^2}{4(\chi \mu^2 \xi + x(1-x)\Lambda^2)}} e^{-\frac{m_1^2(1-x)+m_2^2x}{x(1-x)\Lambda^2}} \right] \]

- Broadening (separation) the q q-bar pair:

\[ \psi_f(\Delta k_\perp, x) = a \psi_M(\Delta k_\perp, x) + (1-a) \psi_{q\bar{q} \text{ dissociated}}(\Delta k_\perp, x) \]
Dissociation Rate and Rate Equations

- **Distortion** of the light cone wave function leads to meson decay

  **Meson survival probability:**
  \[
  P_{\text{surv.}} \left( \frac{\mu^2}{\lambda} L \xi \right) = \left| \int \! \! dx \! \! d^2 \! \Delta k \! \! \psi^* \! \! \psi \! \! (x, \Delta k) \right|^2
  \]

  **Dissociation time:**
  \[
  \langle \tau_{\text{diss}} \rangle = \frac{d}{dt} \ln \left( 1 - P_{\text{surv.}} \left( \frac{\mu^2}{\lambda_q} L(t) \xi \right) \right)
  \]

\[
\begin{align*}
\partial_t f^Q(p_T, t) &= -\frac{1}{\langle \tau_{\text{form}}(p_T, t) \rangle} f^Q(p_T, t) \\
&+ \frac{1}{\langle \tau_{\text{diss}}(p_T / \bar{x}, t) \rangle} \int_0^1 dx \; \frac{1}{x^2} \phi_{Q/\bar{H}}(x) f^H(p_T / x, t)
\end{align*}
\]

\[
\begin{align*}
\partial_t f^H(p_T, t) &= -\frac{1}{\langle \tau_{\text{diss}}(p_T, t) \rangle} f^H(p_T, t) \\
&+ \frac{1}{\langle \tau_{\text{form}}(p_T / \bar{z}, t) \rangle} \int_0^1 dz \; \frac{1}{z^2} D_{\bar{H}/Q}(z) f^Q(p_T / z, t)
\end{align*}
\]

Solve with the initial conditions

\[
\begin{align*}
f^Q(p_T, t) &= \frac{d\sigma^Q(p_T, t)}{dyd^2p_T}, \quad f^H(p_T, t) = \frac{d\sigma^H(p_T, t)}{dyd^2p_T} \\
f^Q(p_T, t = 0) &= \frac{d\sigma^{\text{PQCD}}}{dyd^2p_T}, \quad f^H(p_T, t = 0) \equiv 0
\end{align*}
\]

Find the asymptotic solutions

\[
t \gg \max(L_{QGP}, \tau_{\text{form}})
\]
Langevin Simulation of Heavy Quark Diffusion

Input in a Langevin simulation of heavy quark diffusion

\[ \frac{df(p,t)}{dt} = \frac{\partial}{\partial p_i} \left( p_i A_i(p,t) + \frac{\partial}{\partial p_i} B_{ij}(p,t) \right) df(p,t) \]

- Drag coefficient:
  \[ A_i(p,t) = \frac{1}{p_i} \left\langle \delta p_i \right\rangle \]
  [ Fractional momentum loss per unit time ]

- Diffusion coefficient:
  \[ B_{ji}(p,t) = \frac{1}{2} \left\langle \delta p_j \delta p_i \right\rangle \]

Equilibration is imposed by Einstein’s fluctuation-dissipation relation:

\[ B_{||}(p,t) = T(t)E(p)A_i(p,t) \]

- Radiative energy loss is dominant except for b-quarks and very small systems
Situation at the LHC

- The asymptotic solution in the QGP - sensitive to $t_0 \sim 0.6 \text{ fm}$ and expansion dynamics
- Features of energy loss
- Suppression at the LHC not different when compared to RHIC

- Harder spectra at the LHC

- Electrons spectra from B-mesons and D-mesons decays contribute cross at higher $p_T$
Critical Future Directions

- Dynamical nuclear shadowing

\[ \Delta E \propto \frac{L}{\lambda_g} \times \ln \frac{Q_0}{\mu} \]


- Dynamical nuclear shadowing

Experimental \( y = 1.4-2.2 \)

Very similar behavior of charm quarks (D-mesons) to light hadrons

\[ d + A \rightarrow \pi^0 + X \quad d + A \rightarrow D + X \]


Carry systematic calculations in A+A at forward rapidity

Experimental Tools for Heavy Mesons

- Vertex detectors at midrapidity
- Vertex detectors at forward rapidity

Experimentally validate / disprove theories

Collisional dissociation

Mainstream approach

\[ R_{AA}(p_T; B) \cong R_{AA}(p_T; D) \]
\[ R_{AA}(p_T; B) \gg R_{AA}(p_T; D) \]

- Best reason to measure D- and B-mesons separately
Summary of Open Heavy Flavor Modification

Cold nuclear matter effects on open heavy flavor
- Determined the baseline heavy flavor production in p+p collisions
- Calculated dynamical shadowing from coherent final state interactions
- Progress in understanding cold nuclear matter initial state energy loss

Collisional QGP-induced B- / D-meson dissociation
- Derived formation and dissociation times in the QGP. They are short
- Improved description of non-photonic electron quenching
- B-mesons are as suppressed as D-mesons at $p_T \sim 10$ GeV, unique

Langevin simulation of heavy quark diffusion
- Calculated drag and diffusion from the collisional and radiative e-loss
- Normal suppression hierarchy: B- much less suppressed than D- mesons

Future directions
- Combine cold nuclear matter effects with the QGP suppression models to predict the open heavy flavor modification at forward rapidity
Heavy Quark Production in p+p Collisions

- Gluon fusion is not the dominant hard process in single inclusive open charm (bottom) production

\[ p + \bar{p} \rightarrow D + X \]

\[ c + g \rightarrow c + g \quad c + q(\bar{q}) \rightarrow c + q(\bar{q}) \]

- Comparable to “NLO” results: (under-predicts the cross section by 30% - x 2 )


Los Alamos National Laboratory

Ivan Vitev
Perturbative Expansion for Heavy Mesons

Single inclusive D - mesons

\[ d\sigma^{(1)} \sim \phi_1(x_1, Q^2) \otimes \phi_2(x_2, Q^2) \\otimes \frac{1}{2\delta} |M|^2 \otimes D_1(z_1, Q^2) \]

\[ d\sigma^{(2)} \sim \phi_1(x_1, Q^2) \otimes \phi_2(x_2, Q^2) \\otimes \frac{1}{2\delta} |M|^2 \otimes D_1(z_1, Q^2) \otimes D_2(z_2, Q^2) \]

D - meson triggered back-to-back correlations

Advantages:
- Faster convergence of the hard scatter
- Much faster convergence in $\alpha_s^n$ of the hard scatter $|M|^2$

Two different expansions

Flavor excitation

Flavor creation

Fragmentation Probability for Heavy Quarks

Recall:
\[ \Delta y^+ (z, m_h, M_Q, p^+) = \frac{1}{\Delta p^-} = \frac{(0.2 \text{ GeV.fm})}{k_-^2 + (1 - z) m_h^2 - z (1 - z) M_Q^2} \]

\[ \tau_{\text{form}} (z, m_h, M_Q, p^+) = \Delta y^+ / (1 + \beta_Q) \]

- Fragmentation probability

\[ \int_0^1 D_{D_i, B_i / c, b} (z, Q^2) dz = f_i (D_i, B_i / c, b) \]

\[ \sum_{i=1}^n f_i (B / b; D / c) = 1 \quad \text{Universal in the QCD factorization approach} \]

\[ \langle \tau_{\text{form}} \rangle = \sum_i \int_0^1 \tau_{\text{form}} (z, m_{h_i}, M_Q, p^+) D_{h_i / Q} (z, Q^2) dz \]

FFs from heavy quark EFT


- Time-dependent implementation

\[ N_Q (t) = N_Q (0) \exp \left[ -\frac{t}{\langle \tau_{\text{form}} \rangle} \right] \]
A New Paradigm

D-mesons, B-mesons

Time evolution

C

\overline{u}
Cold Nuclear Matter Effects in PQCD

- Shadowing arises from coherent final-state multiple scattering

\[ F(x_b) = \frac{\phi(x_b)}{x_b} |\overline{M}_{cd}^{2}|, \quad F(x_b) \to F \left( x_b + x_b C_d \frac{g^2}{-1 + m_d^2} (A^{1/2} - 1) \right) \]

- Cold nuclear matter energy loss plays an important role (may be dominant) in p+A

- Experimental \( y = 1.4 - 2.2 \)

![Graph showing experimental data for light pions and D mesons](image)


Very similar behavior of charm quarks (D-mesons) to light hadrons
Strategy for Calculating HF Suppression

- **Calculate** the baseline D- and B-meson cross sections in p+p collisions

- **Calculate** the fragmentation probability of heavy quarks

- **Calculate** the QGP-induced dissociation probability for heavy mesons

- **Solve** the system of coupled rate equations and predict the heavy quark (single electron) suppression
Detailed Analysis to LO

Single inclusive D - mesons

\[ \frac{d\sigma_{NN}^{D_1}}{dy_1 d^2p_T} = K_{NLO} \sum_{abcd} \int_{x_{1,2} \leq 1} dy_2 \int_{x_{1,2} \leq 1} dz_1 \times \frac{1}{z_1^2} D_{D_1/c}(z_1) \frac{\phi_a/N(x_a)\phi_b/N(x_b)}{x_ax_b} \frac{\alpha_s^2}{S^2} |M_{ab\rightarrow cd}|^2 \]

D - meson triggered back-to-back correlations

\[ \frac{d\sigma_{NN}^{D_1} h_2}{dy_1 dy_2 dp_T^1 dp_T^2} = K_{NLO} \sum_{abcd} 2\pi \int_D dz_1 D_{D_1/c}(z_1) D_{h_2/d}(z_2) \times \frac{\phi_a/N(x_a)\phi_b/N(x_b)}{x_ax_b} \frac{\alpha_s^2}{S^2} |M_{ab\rightarrow cd}|^2 \]

Flavor excitation

\[ \begin{align*}
\text{(a)} \quad & p_1^c \quad c \quad k_1^c \\
\text{(b)} \quad & p_1^c \quad c \quad k_1^c
\end{align*} \]

Flavor creation

\[ \begin{align*}
\text{(a)} \quad & p_1^c \quad c \quad k_1^c \\
\text{(b)} \quad & p_1^c \quad c \quad k_1^c
\end{align*} \]

Faster convergence of the perturbative series

Slower convergence of the perturbative series


Two different expansions

Los Alamos National Laboratory
Langevin Simulation of Heavy Quark Diffusion

Input in a Langevin simulation of heavy quark diffusion

\[
\frac{\partial f(p,t)}{\partial t} = \frac{\partial}{\partial p_i} \left( p_i A_i(p,t) + \frac{\partial}{\partial p_i} B_{ji}(p,t) \right) f(p,t)
\]

- **Drag coefficient:**
  \[
  A_i(p,t) = \frac{1}{p_i} \left\langle \delta p_i \right\rangle
  \]

- **Diffusion coefficient:**
  \[
  B_{ji}(p,t) = \frac{1}{2} \left\langle \delta p_j \delta p_i \right\rangle
  \]

Equilibration is imposed by Einstein’s fluctuation-dissipation relation:

\[
B_{\parallel}(p,t) = T(t) E(p) A_i(p,t)
\]

Radiative energy loss is dominant except for b-quarks and very small systems.
Transport + Quenching Approach

Numerical results for heavy quark diffusion

Results are preliminary

- The suppression and $v_2$ are large when e-loss and q-resonance interactions are combined
- Normal hierarchy: c quarks are significantly more suppressed than b-quarks

H. van Hees, I.V., R. Rapp, in preparation
Summary of Open Heavy Flavor Modification

Collisional QGP-induced B- / D-meson dissociation
- Derived formation and dissociation times in the QGP. They are short
- Solved the set of coupled rate equations. More sensitive to QGP properties and formation / expansion dynamics than e-loss
- B-mesons are as suppressed as D-mesons at $p_T \sim 10$ GeV, unique

Langevin simulation of heavy quark diffusion
- Calculated drag and diffusion from the collisional and radiative e-loss
- Normal suppression hierarchy: B- much less suppressed than D- mesons

Cold nuclear matter effects on open heavy flavor
- Calculated dynamical shadowing from coherent final state interactions
- Calculated the cold nuclear matter initial state energy loss
- Combine with the QGP suppression to make predictions at forward rapidity
Comparison to Other Models

PHENIX Preliminary

How do you build from $T = 400$ MeV

\[
\hat{q} = \frac{\mu^2}{\lambda_s} = 10 \text{ GeV}^2 / \text{fm}
\]

LHC: from $T = 1$ GeV

\[
\hat{q} = \frac{\mu^2}{\lambda_s} = 100 \text{ GeV}^2 / \text{fm}
\]

Wicks et al.
Differences Between Models

\[ \hat{q}_{200 \text{ GeV}} \approx 14 \text{ GeV}^2/\text{fm} \quad 350 \text{ GeV} \quad \sim 10000 \]

\[ \hat{q}_{5500 \text{ GeV}} \approx 100 \text{ GeV}^2/\text{fm} \quad 2650 \text{ GeV} \quad \sim 100000 \]

Typical gluon energy \( \omega_c = \frac{\hat{q}L^2}{2} \quad R = \omega_c L \)

• Note that the region of \( P_T \) at RHIC is 10-20 GeV and at the LHC 100-200 GeV

\[ \Delta E \]
Non-Photonic Electron / Heavy Flavor Quenching

Proceed to A+A collisions

- Single electron measurements (presumably from heavy quarks) may be problematic for mainstream theory
- Is it accidental or is it symptomatic?

• Hadron formation time

\[ \Delta y^+ = \frac{1}{\Delta p^-} = \frac{(0.2 \text{ GeV.fm})}{k_{\perp}^2 + (1-z)m_h^2 - z(1-z)M_q^2} \]

QGP extent \( \sim 5 \text{ fm} \)

- New approach needed
Scope of PQCD Heavy Flavor Effort

Publications

• Ivan Vitev, NON-ABELIAN ENERGY LOSS IN COLD NUCLER MATTER. Submitted to Phys.Rev.C (2007)
• Hendrik van Hees, Ivan Vitev, Ralf Rapp, HEAVY FLAVOR MODIFICATION IN A COMBINED TRANSPORT+QUENCHING APPROACH. In preparation

Collaborators

• T. Goldman, M. Johnson, T-16 and P-25 Los Alamos National Laboratory
• LDRD DR project team, T-8 and P-25 Los Alamos National Laboratory

Presentations

• Ivan Vitev, Strangeness in Quark Matter, UCLA, Los Alnegles, CA, March 2006
• Ivan Vitev, Quark Matter 2006, Shanghai, China, November 2006
• Ivan Vitev, Heavy Flavor Workshop, Beijing, China, November 2006
• Ivan Vitev, T-16 Seminar, Los Alamos, March 2007
Heavy Meson Dissociation Rates

- Light cone wavefunctions for heavy mesons

\[ \left| \psi(\Delta k_\perp, x) \right|^2 \sim \exp \left[ -\frac{\Delta k_\perp^2 + 4m_q^2(1-x) + 4m_q^2(x)}{4\Lambda^2 x(1-x)} \right] \]

- Coupled rate equations

\[
\partial_t f^Q(p_T, t) = -\frac{1}{\langle \tau_{\text{form}}(p_T, t) \rangle} f^Q(p_T, t) + \frac{1}{\langle \tau_{\text{diss}}(p_T / x, t) \rangle} \int_0^1 dx \frac{1}{x^2} \phi_{Q/H}(x) f^H(p_T / x, t)
\]

\[
\partial_t f^H(p_T, t) = -\frac{1}{\langle \tau_{\text{diss}}(p_T, t) \rangle} f^H(p_T, t) + \frac{1}{\langle \tau_{\text{form}}(p_T / z, t) \rangle} \int_0^1 dz \frac{1}{z^2} D_{H/Q}(z) f^Q(p_T / z, t)
\]

... which we solve with the initial conditions

\[
f^Q(p_T, t = 0) = \frac{d\sigma^Q(p_T, t)}{dyd^2p_T}, \quad f^H(p_T, t = 0) = \frac{d\sigma^H(p_T, t)}{dyd^2p_T}
\]

\[
f^Q(p_T, t = 0) = \frac{d\sigma_{\text{PQCD}}^Q}{dyd^2p_T}, \quad f^H(p_T, t = 0) \equiv 0
\]

... to find the asymptotic solutions

\[ t \gg \max(L_{\text{QGP}}, \tau_{\text{form}}) \]
Quenching of Non-Photonic Electrons

- **PYTHIA** used to decay all B- and D-mesons / baryons into \((e^+e^-)\)

\[ \sum_{i=1}^{n} f_i(B/b;D/c) = 1 \]

- Suppression \(R_{AA}(p_T) \sim 0.25\) is large

\[ R_{AA}^{e^\pm}(p_T) = \frac{dN_{AA}^{e^\pm}/dyd^2p_T}{\langle N_{coll} \rangle d\sigma_{pp}^{e^\pm}/dyd^2p_T} \]

- Similar to light \(\pi^0\), however, different physics mechanism

- B-mesons are included. They give a major contribution to \((e^+e^-)\)

Predictions also made for Cu+Cu (RHIC) and Pb+Pb (LHC)
Comparing $\pi^0 R_{AA}$ to theory

$$6 \leq \langle \hat{q} \rangle \leq 24 \text{ GeV}^2/fm$$
(Probability > 10%)

$$1000 \leq \frac{dN_g}{dy} \leq 2000$$
(Probability > 10%)

$$600 \leq \frac{dN_g}{dy} \leq 1600$$
(Probability > 10%)

Add stat and uncorr point-to-point syst err in quadrature – $\chi^2$ minimization fit to obtain the probability of a given parameter

Then offset the data points by +/- 1 RMS of the correlated syst errors and do the same

Sum up 1 & 2 to obtain the curves above

Little sensitivity to model parameters
D- and B-meson Suppression at RHIC and LHC

- Suppression $R_{AA}(p_T) \sim 0.25$ is large
- Similar to light $\pi^0$, however, different physics mechanism
- B-mesons as suppressed as D-mesons at $p_T \sim 10$ GeV (unique feature)
- A chance to really determine the physics of heavy flavor suppression

Velocity factor $\beta = p/E$ important at small/intermediate $p_T$