Theoretical Developments
in Light and Heavy Flavour Energy Loss

‘Science is the organized skepticism in the reliability of expert opinion.’ - R. P. Feynman

Ivan Vitev, Nuclear Theory, T-16, LANL

Quark Matter 2008, February 4-10, Jaipur, India
Outline of the Talk

Theoretical developments in light and heavy quark energy loss

- Radiative and collisional energy loss of fast quarks and gluons - toward a consistent picture
- Models of heavy flavor suppression - from the perturbative to the non-perturbative - and back
- Recent insights in the stopping power of cold nuclear matter

New theoretical and experimental opportunities for jet quenching physics at the LHC

- Jet finding algorithms and jet shapes in elementary N-N collisions
- Medium-induced jet shapes in QGP - a theoretical approach
- Toward a 2D tomography of jets - a differential test of parton interactions in the QGP

Outlook and Conclusions
The Stopping Power of Matter

Groom, D.E. et al. (2001)

Stopping power of Cu for $\mu^-$

- **Collisional energy loss**
  - medium excitation

  \[ \frac{d\Delta E^{\text{coll}}}{dz} \approx 4\pi\alpha_m^2 z^2 Z \rho_{num} \frac{1}{\beta^2 m^2} \ln B_q \]

  Bethe, H.A. (1930,1932)

- **Radiative energy loss**
  - bremsstrahlung

  \[ \frac{d\Delta E^{\text{rad}}}{dz} \approx \frac{16}{3} \alpha_m^3 z^4 \rho_{num} \frac{1}{M^2} E \ln(\lambda\gamma) \]

  Bethe, H. A. et al. (1934)
The Stopping Power of Matter

**The same qualitative behavior in QCD:**

\[ \Delta E_{\text{coll}}^{\text{rad}} = c_1 L \quad \text{Braaten, E. et al. (1991)} \]

\[ \Delta E_{\text{coll}}^{\text{rad}} = c_2 E L \quad \text{Bertsch, G et al. (1982)} \]

- **Collisonal energy loss**
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**Stopping power of Cu for \( \mu^- \)**

Groom, D.E. et al. (2001)

Los Alamos National Laboratory

Ivan Vitev
Toward Proper Comparison of $\Delta E^{\text{rad}} / \Delta E^{\text{coll}}$

- **LPM** - new path length and energy behavior

  - **Radiative E-loss:**
    $$ \frac{d\Delta E^{\text{rad}}}{dL} = \frac{2\alpha_s}{3} \frac{\mu^2 L}{\lambda_s} \log \left( \frac{2E}{\mu^2 L} \right) $$
  - **Collisional E-loss:**
    $$ \frac{d\Delta E^{\text{coll}}}{dL} = \frac{2\alpha_s}{3} \mu^2 \frac{1}{2} \log \left( \frac{TE}{\mu^2} \right) $$

  - Mustafa, M et al. (2005)
  - Wicks et al. (2006)
Toward Proper Comparison of $\Delta E^{\text{rad}} / \Delta E^{\text{coll}}$

- **LPM - new path length and energy behavior**

  Majumder, A. (2007)

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- **Comparison in the the same model of the medium / momentum exchanges**


  \[
  \frac{1}{\sigma} \frac{d\sigma}{dq} = \frac{\mu^2}{\pi \left( q^2 + \mu^2 \right)^2}
  \]
Toward Proper Comparison of $\Delta E^{\text{rad}} / \Delta E^{\text{coll}}$

- **LPM** - new path length and energy behavior
  
  Majumder, A. (2007)

  Radiative E-loss:
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  Collisional E-loss:
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- **Comparison in the the same model of the medium / momentum exchanges**


  
  \[ \frac{1}{\sigma} \frac{d\sigma}{d^2q} = \frac{\mu^2}{\pi (q^2 + \mu^2)^2} \rightarrow \frac{\mu^2}{\pi q^2 (q^2 + \mu^2)} \]


- **Inelastic E-loss dominates**

  \[ \gamma = \frac{E}{m} \geq \text{few} \]
Heavy Flavor: Perturbative Quenching or Not?

- Smaller contribution of the elastic compared to radiative energy loss, fluctuations.
- One can recast the under-quenching of $e^\pm$ into over-quenching of $\pi^0$ but not resolve both.
- LO HTL may lead to 30% correction in the QGP density estimates.

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Charm baryon enhancement

$N_{\Lambda_c} / N_D \sim 0.08$ in p+p, $N_{\Lambda_c} / N_D \sim 1$ in Au+Au
- Smaller branching fraction of $\Lambda_c$ to electrons
- About 25% suppression effect for $C_{\text{enhancement}} = 12$

$$R_{AA}^c = \frac{1 + \left( N_{\Lambda_c} / N_D \right)_{pp}}{1 + C \left( N_{\Lambda_c} / N_D \right)_{pp}} \times \frac{1 + C \left( N_{\Lambda_c \rightarrow e} / N_{D \rightarrow e} \right)_{pp}}{1 + \left( N_{\Lambda_c \rightarrow e} / N_{D \rightarrow e} \right)_{pp}}$$

Martinez-Garcia, G. et al. (2007)
Heavy Meson Dissociation at RHIC and LHC

Formation times of mesons/baryons

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

\[
\tau_{\text{form}} (p_T = 10 \text{ GeV}) = \frac{\pi}{20 \text{ fm}} \quad \frac{D}{1.5 \text{ fm}} \quad \frac{B}{0.4 \text{ fm}}
\]

Adil, A. et al. (2007)

- Application to heavy resonances

Markert, K. et al. (2008)
Heavy Meson Dissociation at RHIC and LHC

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\]

\[
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\]

20 fm 1.5 fm 0.4 fm

Adil, A. et al. (2007)

• Application to heavy resonances

Markert, K. et al. (2008)

• Direct and separate measurements of D- and B-meson \( R_{AA} \)

<table>
<thead>
<tr>
<th>Model</th>
<th>Partonic Energy Loss</th>
<th>Heavy Meson Dissociation</th>
<th>Heavy Baryon Enhancement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characteristic Feature</td>
<td>( R_{AA}^B \gg R_{AA}^D )</td>
<td>( R_{AA}^B \simeq R_{AA}^D )</td>
<td>( R_{AA}^B \gg R_{AA}^D )</td>
</tr>
<tr>
<td>( R_{AA}^\pi \gg R_{AA}^{\pi,h} )</td>
<td>( R_{AA}^\pi \approx R_{AA}^{\pi,h} )</td>
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<td></td>
</tr>
</tbody>
</table>

• Via experimental upgrades at RHIC, LHC
Jet quenching in SDIS - cold nuclei

- Can quarks and gluons become indistinguishable?
- Leading antiquark fragmentation is more suppressed than leading quark fragmentation

Zhang, B.W. et al. (2007)
**Coupling the Quark and Gluon Energy Loss**

Jet quenching in SDIS - cold nuclei

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Zhang, B.W. et al. (2007)

QGP application of jet conversion

- Indirect indication that $\Delta E^g \neq 2.25\Delta E^q$
- Non-asymptotic limits bring the q, g losses closer together
- Jet conversion may play a role but significant rate enhancement is needed

Liu, W. et al. (2007)

Theory of Cold Nuclear Matter Energy Loss

Scaling with $x_F (x_1)$, not $x_2$, indicates initial state energy loss

![Graphs showing scaling with $x_F$](image)

- (in nucleus) - Gavin, S. et al. (1992)
- Kopeliovich, B. et al. (2005)
Theory of Cold Nuclear Matter Energy Loss

Scaling with $x_F (x_1)$, not $x_2$, indicates initial state energy loss

\[
\Delta E_{IS} \approx \left( \frac{K_{LPM}}{L} \right) \frac{\Delta E_{BH}}{E} \approx \alpha_s \frac{\Delta E_{IS \text{ quark}} (\text{Pb, Au})}{E} \approx 5\%
\]

Advances in understanding the energy loss regimes

- Derivation of the Initial State energy loss
- Toward consistent phenomenology at forward rapidity / large $X_F$

Can be tested in DY at Fermilab’s E906 and J-PARC

\[ \sigma_A = \sigma_N A^\alpha \]

Gavin, S. et al. (1992)

Kopeliovich, B. et al. (2005)

A Note on Phenomenology

Particle correlations, combining quenching and hydro models, looking at the medium response

Developments Theory and Phenomenology

Wicks, S.  
Jet energy loss in rarer harder collisions
Roy, P.  
Quenching of light hadrons in the collisional energy loss scenario
Bass, S. A.  
Comparison of energy loss schemes in 3D hydro
Cassaldery-Solana, J.  
Energy dependence of the jet quenching parameter
Barnafoldi, G.G.  
Where does the energy loss lose strength
B. Betz,  
Mach cones in 3+1D ideal hydro
B. Mueller  
Mach cones in pQGP
W. Horowitz  
Falsifying AdS/CFT or pQCD
R. Mizukawa  
Jet quenching and the soft ridge

See also posters
A Note on Phenomenology

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Developments Theory and Phenomenology

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See also posters

- From very complex systems simplicity can emerge again
- For hard probes: transition 1, 2, …n particles \(\rightarrow\) jets
Jets: New Opportunities at the LHC

- Jets are **collimated showers** of energetic particles that carry a large fraction of the energy available in the collisions.

\[ R = \sqrt{(\eta - \eta_{jet})^2 + (\phi - \phi_{jet})^2} \]

\[ E_T = \sum_{i=1}^{\text{jet}} E_{T, i} \]

\[ \eta = \sum_{i=1}^{\text{jet}} \eta_{E_{T, i}} / E_T \]

\[ \phi = \sum_{i=1}^{\text{jet}} \phi_{E_{T, i}} / E_T \]

Sterman, G. et al. (1977)
Jets: New Opportunities at the LHC

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Jet algorithms:

• **K_T algorithm**: preferred, **collinear and infrared safe** to all orders in PQCD
• **“Seedless” cone algorithm**: **practically infrared safe**

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\]
\[
\phi = \sum_{i \in \text{jet}} \phi_{E_{T, i}} / E_T
\]

• Opportunity exists to **discover** and **characterize** jets in heavy ion collisions

Sterman, G. et al. (1977)  
Ellis, S.D. et al. (1993)  
Salam, G. et al. (2007)  
In p+p - STAR  
Abelev, B. I. et al. (2006)
Energy Flow in Jets from PQCD: the Baseline

- Energy distribution
\[ \Psi(r, R) = \sum_i E_i \Theta(r - R_{\text{jet}}) \]
- Shape function
\[ \psi(r, R) = \frac{d\Psi(r, R)}{dr} \]

An analytic approach to shape functions
\[ dP_a = \frac{\alpha_s}{2\pi} \frac{d\rho^2}{\rho^2} \frac{d\phi}{2\pi} dz P_{a\rightarrow bc} (z) \]

MLLA, initial state contribution, power corrections, `R_{sep}' algorithm adjustment factor

V., I et al. (2008)
Perez-Ramos, R et al. (2007)
Energy Flow in Jets from PQGD: the Baseline

- Energy distribution \( \Psi(r, R) = \frac{\sum_i E_i \Theta(r - R_{jet})}{\sum_i E_i \Theta(R - R_{jet})} \)

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MLLA, initial state contribution, power corrections, \`R_{sep}' algorithm adjustment factor

- Very similar jet shapes at the LHC

V., I et al. (2008)
Perez-Ramos, R et al. (2007)
Medim-Induced Jet Shape Functions

An intuitive approach to medium-induced jet shapes for non-experts

$\Delta E^{rad}$ LPM suppressed

- $M_q = 0 \text{ GeV}$
- $M_q = 1.3 \text{ GeV}$
- $M_q = 4.5 \text{ GeV}$

Final state E-loss

Los Alamos National Laboratory

Ivan Vitev
Medim-Induced Jet Shape Functions

An intuitive approach to medium-induced jet shapes for non-experts

$$\Delta E^{rad}$$ LPM suppressed $\xleftarrow{\frac{dI^{rad}}{d\omega}(\omega)}$ suppressed

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Los Alamos National Laboratory
EST 1943

Ivan Vitev
Medim-Induced Jet Shape Functions

An intuitive approach to medium-induced jet shapes for non-experts

\[
\Delta E^{\text{rad}} \quad \text{LPM suppressed} \quad \leftarrow \frac{dI^{\text{rad}}}{d\omega}(\omega) \quad \text{suppressed} \quad \leftarrow \int d\omega \frac{dI^{\text{rad}}}{d\omega dr}(r) \quad \text{suppressed}
\]

$E_{\text{jet}} = 20 \text{ GeV}$
Medim-Induced Jet Shape Functions

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\[ \Delta E^{\text{rad}} \] LPM suppressed \[ \frac{dI^{\text{rad}}}{d\omega}(\omega) \] suppressed \[ \int d\omega \frac{dI^{\text{rad}}}{d\omega dr}(r) \] suppressed

- Proven now to all orders in opacity
- Incompatible with Sudakov resummation (absence of large logs)
- Can be see in other approaches to the energy loss

Majumder, A. et al. (2005)

E_{\text{jet}} = 20 \text{ GeV}

Destructive interference

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National Laboratory
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Ivan Vitev
A Differential Approach to Particle Correlations

2D analysis reveals rich structure

\[
\frac{1}{2\pi} \frac{d\Psi_{\text{med}}}{dr dz} = \frac{1}{\Delta E_{\text{rad}}} \frac{dI_{\text{rad}}}{d(\omega / E_{\text{jet}})dr}
\]

- May be accessible via intra-jet particle correlations
- Medium-induced part only
A Differential Approach to Particle Correlations

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Relation to experimental correlation measurements remains speculative

Tomography of Jets

Determination of energy flow

\[ \frac{\Delta E_{\text{out}}(R^{\text{min}}, \omega^{\text{min}})}{E} = \frac{1}{E} \int_{R^{\text{min}}}^{R^{\text{med}}} dr \int_{\omega^{\text{min}}}^{\omega^{\text{med}}} d\omega \frac{dI_{\text{med}}}{d\omega dr}(\omega, r) \]

V, I. et al. (2008)
Tomography of Jets

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\[ \frac{\Delta E_{\text{out}}(R_{\text{min}}, \omega_{\text{min}})}{E} = \frac{1}{E} \int_{R_{\text{min}}} \int_{\omega_{\text{min}}} d\omega \frac{dI_{\text{med}}}{d\omega dr}(\omega, r) \]

Application to jet cross sections \( R_{AA}(R_{\text{min}}, \omega_{\text{min}}) \)

\[ \frac{d\sigma^{AA}(R_{\omega_{\text{min}}})}{d^2E_Tdy} = \int_{\epsilon=0}^1 P(\epsilon; R_{\omega_{\text{min}}}) \left( \frac{1}{(1-\epsilon)^2} \frac{d\sigma^{pp}(R_{\omega_{\text{min}}})}{d^2E_T^*dy} + \frac{1}{(1+\epsilon f(R/\omega_{\omega}/\infty))^2} \frac{d\sigma^{pp}(R_{\omega_{\text{min}}})}{d^2E_T^*dy} \right) \]

- Can be evaluated in MC
- Extendable to tagged, e.g. di-lepton tagged jets

Mironov, C. et al. (2007)

Lokhtin, I. et al. (2007)

\( R_{\text{jet}} = 0.5 \)
Outlook

Quantitative studies look promising

Intensity scale

$\psi(r)$

$R_x$  

$R_y$  

$E_T = 50$ GeV

$E_T = 20$ GeV, Medium
$E_T = 100$ GeV, Medium
$E_T = 20$ GeV, Vacuum
$E_T = 100$ GeV, Vacuum

$E_T = 20$ GeV Medium, $<r/R> = 0.44$
$E_T = 100$ GeV Medium, $<r/R> = 0.34$
$E_T = 20$ GeV Vacuum, $<r/R> = 0.22$
$E_T = 100$ GeV Vacuum, $<r/R> = 0.17$
Outlook

Quantitative studies look promising

- **Shape functions** in the medium and their generalization to **two dimensional tomography of jets** can ultimately reveal the mechanism of particle interactions in matter.

- **Jet topologies** with large number of jets and their **modifications** will become accessible at the LHC.
Conclusions

- First treatments of radiative and collisional energy loss of fast quarks and gluons in a consistent framework
- New models of heavy flavor suppression, both perturbative and non-perturbative; require experimental D, and B measurements
- Jet conversion processes in nuclear matter, understanding of SDIS, derivation of the initial state energy loss in large nuclei, valid forward rapidity phenomenology
- Developments of new jet finding algorithms for LHC experiments, seedless cone algorithm
- Determination of baseline jet shapes and jet topologies in p+p consistent with the Tevatron results
- Toward a 2D tomography of jets; understanding the medium induced jet shapes, energy corrections versus cone radius R, generalization of jet shape functions
Types of Energy Loss

**Elastic interactions:** \[ \sum_{\text{in}} \text{particles} = \sum_{\text{out}} \text{particles} \]

**Inelastic interaction:** \[ \sum_{\text{in}} \text{particles} < \sum_{\text{out}} \text{particles} \]

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Bethe, H.A. (1930,1932), Bloch, F. (1932)

- **Radiative energy loss**
  - gauge boson bremsstrahlung

\[
\frac{d\Delta E^{\text{rad}}}{dz} \approx \frac{16}{3} \alpha_s^3 Z^4 Z^2 \rho_{num} \frac{1}{M^2} E \ln(\lambda\gamma) \]

\[ \Delta E^{\text{rad}} = c_2 EL \]

Bethe, H. A. et al. (1934) Weizsacker, C. et al. (1934)
Jet Cross Sections: Comparison to LO and NLO PQCD

- Good comparison to the shape at LO.
  Meaningful K-factor

- Even better comparison at NLO.
Jet Shapes in QCD: the p-p Baseline

An analytic approach to the energy distribution of jet


QCD splitting kernel

\[ dP_a = \frac{\alpha_s}{2\pi} \frac{d\rho^2}{\rho^2} \frac{d\phi}{2\pi} d\zeta P_{a \rightarrow bc}(\zeta) \]

\[ P_{gq}^{(1)}(x) = C_2(F) \left( (1 + x^2) \left( \frac{1}{1 - x} \right) + \frac{3}{2} \delta(1 - x) \right) \]

\[ P_{gq}^{(2)}(x) = C_2(F) \left( (1 - x)^2 + \frac{1}{x} \right) \]

\[ P_{gq}^{(3)}(x) = T(F) \left[ (1 - x)^2 + x^2 \right] \]

\[ P_{qg}^{(1)}(x) = 2C_2(A) \left[ \frac{x}{1 - x} + \frac{1 - x}{x} + x(1 - x) \right] + \left( \frac{11}{6} C_2(A) - \frac{2}{3} T(F) n_f \right) \delta(1 - x) \]

Note: the Kinoshita, Lee, Nuenberg theorem does not guarantee collinear safety


Requires Sudakov resummation

\[ P_{Sudakov}(< r, R) = \exp(-P_1(> r, R)) \]

• The collinear divergence is essential

Power corrections

\[ \psi_{pow.}(r, R) \sim \frac{C_i}{2\pi} \left( Q_0 \frac{2}{r E_T} \right) (\bar{\alpha}_s(Q_0) + ...) \]

Initial state radiation

\[ \psi_{ini.}(r, R) \sim \frac{C}{2\pi} \left( \frac{1}{Z^2} - 1 \right) \]
Jet Physics at the LHC

Searches SUSY

- Based on tried and true symmetry principles
- Unification of the coupling constants
- Excellent candidate for cold dark matter (neutralino 30 GeV - 10 TeV)

\[ W = \sum_{L,E} \lambda_L LE^c H_1 + \sum_{Q,U} \lambda_Q QU^c H_2 + \sum_{Q,D} \lambda_Q QD^c H_1 + \mu H_1 H_2 \]


Searches for higher dimensions

- Generalization to 5D E&M+Gravity
- Numerous extensions

\[ ds^2 = (e^{-2ky}) \eta_{\mu\nu} x^\mu x^\nu - dy^2 \quad m_n = n / R \ (S^1) \]

Kaluza, T. (1921)  Klein, O. (1926)
Overdui, J. M. et al. (1999)

- Connecting HEP and NP
### Searching for Extra Dimensions and SUSY

**Observation at colliders**

**LHC**

![Excess Missing Energy at LHC](image)

Figure 3: Missing energy spectrum at the LHC.

**MSSM**

<table>
<thead>
<tr>
<th>Super-Multiplets</th>
<th>Boson Fields</th>
<th>Fermionic Partners</th>
<th>SU(3)</th>
<th>SU(2)</th>
<th>U(1)</th>
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<tbody>
<tr>
<td>gluon/gluino</td>
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<td>$\tilde{g}$</td>
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<td>0</td>
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<td>gauge/gaugino</td>
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<td>$\tilde{W}^\pm$, $\tilde{W}^0$</td>
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<td>3</td>
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<tr>
<td></td>
<td>$B$</td>
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<tr>
<td>slepton/lepton</td>
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<td>$(\nu, e^-)_L$, $\tilde{e}_R^-$</td>
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<td>2</td>
<td>$-1$</td>
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<tr>
<td></td>
<td>$\tilde{\nu}_R$, $\tilde{e}_R$</td>
<td>$\tilde{e}_R$, $e_R$</td>
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<td>1</td>
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<td>squark/quark</td>
<td>$(\tilde{u}_L, \tilde{d}_L)$</td>
<td>$(u, d)_L$, $u_R$, $d_R$</td>
<td>3</td>
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<td>Higgs/higgsino</td>
<td>$(H_d^0, H_d^-)$</td>
<td>$(\tilde{H}_d^0, \tilde{H}_d^-)$</td>
<td>1</td>
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<tr>
<td></td>
<td>$(H_u^+, H_u^0)$</td>
<td>$(\tilde{H}_u^+, \tilde{H}_u^0)$</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

124 parameters (18 are the SM)
Mass Spectrum in Minimal Super Gravity

Example of 100 GeV SUSY particles
Medium-Induced Radiation in the Final State

- Includes interference with the radiation from hard scattering

\[
\hat{R}_n = \hat{D}_n \hat{D}_n + \hat{V}_n + \hat{V}_n^\dagger
\]

Gyulassy, M. et al. (2000)
Medium-Induced Radiation in the Initial State

- **Bertsch-Gunion case with interference**

\[
k^+ \frac{dN}{dk^+ d^2 k_\perp} = \sum_{n=1}^{\infty} k^+ \frac{dN^n}{dk^+ d^2 k_\perp} = \sum_{n=1}^{\infty} C_R \alpha_s \left[ \prod_{i=1}^{n} \int_0^{L-\sum_{j=i+1}^{n} \Delta z_j} \frac{d\Delta z_i}{\lambda_g(z_i)} \int d^2 q_i \left( \frac{1}{\sigma_{el}} \frac{d\sigma_{el}}{d^2 q_i} - \delta^2(q_i) \right) \right] \\
\times \left[ B_{(2...n)(1...n)} \cdot B_{(2...n)(1...n)} + 2B_{(2...n)(1...n)} \cdot \sum_{m=2}^{n} B_{(m+1...n)(m...n)} \left( \cos \left( \sum_{k=2}^{m} \omega_{(k...n)} \Delta z_k \right) \right) \right]
\]

- **Realistic initial state medium induced radiation**

\[
k^+ \frac{dN}{dk^+ d^2 k_\perp} = \sum_{n=1}^{\infty} k^+ \frac{dN^n}{dk^+ d^2 k_\perp} = \sum_{n=1}^{\infty} C_R \alpha_s \left[ \prod_{i=1}^{n} \int_0^{L-\sum_{j=i+1}^{n} \Delta z_j} \frac{d\Delta z_i}{\lambda_g(z_i)} \int d^2 q_i \left( \frac{1}{\sigma_{el}} \frac{d\sigma_{el}}{d^2 q_i} - \delta^2(q_i) \right) \right] \\
\times \left[ B_{(2...n)(1...n)} \cdot B_{(2...n)(1...n)} + 2B_{(2...n)(1...n)} \cdot \sum_{m=2}^{n} B_{(m+1...n)(m...n)} \left( \cos \left( \sum_{k=2}^{m} \omega_{(k...n)} \Delta z_k \right) \right) \right] \\
- 2H \cdot B_{(2...n)(1...n)} \left( \cos \left( \sum_{k=2}^{n+1} \omega_{(k...n)} \Delta z_k \right) \right)
\]

Cold Nuclear Matter Effects for $\pi^0$ and Direct $\gamma$

- Where it starts from
  \[ x_F = x_1 - x_2 \approx x_1 \]

- Dynamical shadowing (coherent final state scattering)
- Cronin effect (initial state transverse momentum diffusion)
- Initial state energy loss (final state at these energies - negligible)
Cold Nuclear Matter Effects

• Initial-state E-loss

\[
\frac{\omega dN^g}{d\omega d^2k_\perp} = \frac{C_R\alpha_s}{\pi^2} \int_0^{s/4} d^2q_\perp \frac{\mu_{\text{eff}}^2}{(q_\perp^2 + \mu^2)^2} \left[ \frac{L}{\lambda_g} - q_\perp^2 \frac{k_\perp^2}{(k_\perp - q_\perp)^2} \lambda_g \right]^{k_\perp L} \left( 2 - 2q_\perp \cdot q_\perp k_\perp k^+ \right) \sin \left( k^2 L \right)
\]

Energy scale

\[ E = p_T \cosh(y_{\text{jet}} - y_{\text{target}}) \]

• Effect of cold nuclear matter energy loss is equal to the doubling of the parton rapidity density
A Note on PQCD Regimes

• An interesting idea ≠ valid physics explanation

• We don’t know the degree of coherence at the LHC. One has to understand PQCD and its E-loss regimes before embarking on the ambitious task of disproving PQCD itself

Measurable at the LHC

Ivan Vitev
Light Cone Wave Functions

From general theory of LCWF for the lowest-lying Fock state


• Expansion in Fock components

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

LO Fock component

\[ \left| \psi (\Delta k_\perp, x) \right|^2 \sim \exp \left[ -\frac{\Delta k_\perp^2 + 4m_0^2(1-x) + 4m_q^2(x)}{4\Lambda^2 x(1-x)} \right] \]

• Results for heavy flavor

• Models such as coalescence should use plausible wave functions, especially for heavy flavor
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 using GLV the multiple scattering in impact parameter (B,b) space

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

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

- Broadening (separation) the q q-bar pair:
\[ \psi_f(\Delta k_\perp, x) = a \psi_M(\Delta k_\perp, x) + (1-a) \psi_{q\bar{q} \text{ dissociated}}(\Delta k_\perp, x) \]