Heavy Ion collisions

- High energy pp or ee collisions: search for new physics (SUSY or extra dimensions, ...)
- High energy AA collisions: create the high energy density over a larger region.
- Investigate a collective dynamics of the strong interactions.
- RHIC is a versatile, powerful machine
  - AA, (AuAu, CuCu), pp, dA
  - Different energies: 19.6, 62.4, 130, 200 GeV
  - Polarized beams
Space-time picture of heavy-ion collisions

z: beam axis

- Formation: strong fields
- Quarks and Gluons out of equilibrium
- Quarks and Gluons in equilibrium
- Hadrons in equilibrium
- Freeze-out
- Formation: strong fields
Lattice results for QCD at finite T

Energy density for 2 and 3 flavors

Lattice calculations indicate phase transition at critical temperature $T=173\ \text{MeV}$

Critical density

$\epsilon_c \sim 0.7\ \text{GeV}/\text{fm}^3$

Energy density in RHIC

$$\langle \epsilon \rangle = \frac{1}{\tau \pi R^2} \frac{dE_T}{dy} \sim 5 - 10\ \text{GeV}/\text{fm}^3$$

Much larger (>30x) than cold nuclear matter

$\epsilon_{NM} \approx 0.15\ \text{GeV}/\text{fm}^3$
Phase diagram

- Quark gluon plasma
- Hadron phase
- Deconfinement, chiral symmetry restoration
- Positions of the phase boundaries not known in detail
- Investigate experimentally
• Multiplicities
• Initial state
• Final state: Hard probes
Multiplicities
Multiplicities in Heavy Ion collisions

Increase with energy

AuAu similar to $e^+e^-$
Multiplicities depend only on energy of the system (and $N_{\text{part}}$)

pp lower: leading particle effect

Multiplicity at mid-rapidity

Consistent with $\ln s$ dependence

Huge uncertainties of theoretical predictions for LHC!
Rapidity distributions limiting fragmentation

Similar pattern observed in multiplicities e+e- when plotted vs y-Y(jet)

Proton-proton

Data scale when plotted vs \( \eta' = \eta - Y_{\text{beam}} \)

Limiting distribution is that of the broken target: momentum and quantum number transfer between the projectile and the target does not change when the energy is further increased.

Curves from Gelis, Stasto, Venugopalan
Limiting fragmentation

- Gluon production evaluated using Kt factorized formula.
- Parton density from nonlinear evolution equation.
- Limiting fragmentation: target density (large x) approximately flat in rapidity and independent of scale (Bjorken scaling).
- Rapidity distributions seem to be determined very early in the collisions, by the initial state.

Extrapolations to LHC: approximately factor 1.5-1.9 increase of dN/dy at $y=0$

_Gelis, Stasto, Venugopalan_
Initial state
Initial state: saturation of gluon density

Low energy - large $x$
Dilute system

High energy - small $x$
Dense system

$\frac{\alpha_s(Q_s^2)}{Q_s^2} x g(x, Q_s^2) \sim 1$

- Small coupling, but high density
- Saturation of gluon density
- Saturation scale $Q_s$
- Nonlinear evolution equation

Gribov, Levin, Ryskin;
Bartels, Wusthoff; Mueller, Qiu;
McLerran, Venugopalan, Kovner, Weigert,
Jalilian-Marian, Leonidov; Kovchegov,
Balitsky; Lipatov; ...
Transverse momentum distribution of partons

Gluon density from nonlinear equation:

- Typical transverse momentum of the gluon from nonlinear equation
- Peak shifts to higher momenta as energy increases
- Saturation scales increases with energy
- Nonlinearity provides with a natural cutoff at lower scales

\begin{equation}
\phi(x,k) = \alpha_s(x) Y^{1/2} \exp(-k^2/2m^2)
\end{equation}

\text{Gelis, Stasto, Venugopalan}
Saturation

• Very attractive approach:
  • Natural cutoff at infrared.
  • Small coupling but non-perturbative (even though from Feynman diagrams).

• Does it work?
  • RHIC lower energy than HERA, not always small $x$, need to go to forward rapidities. But, presence of nucleus helps: $Q_s^2 \sim A^{1/3} x^{-\lambda}$
  • Saturation scale rather small, <1 GeV at HERA.
  • Only gluons are consistently taken into account in this framework.

$Q_s^2 \sim A^{1/3} x^{-\lambda}$
Saturation: phenomenology at RHIC

\[ \eta = 2.2 \quad \eta = 3.2 \]

Rapidity distributions

Kharzeev, Kovchegov, Tuchin

dAu: suppression of the transverse momentum distribution at forward rapidities

Very good agreement with the data!

Kharzeev, Levin, Nardi
Final state:
Hard probes
Hard probes

- High $\text{Pt}$ light quarks/gluons
- Heavy quarks
- Provide an excellent measure of the properties of a dense medium
- Due to a presence of a hard scale, it is possible to use perturbative theory
- Compare with the pp cross sections
Transport properties of the medium

By comparing momentum distributions to the pp benchmark we obtain information about the medium created at heavy-ion collisions

\[ R_{AA} = \frac{\sigma_{pp}^{inel} \frac{d^2 N_{AA}}{dp_T d\eta}}{\langle N_{coll} \rangle \frac{d^2 \sigma_{pp}}{dp_T d\eta}} \]

Ratio of AA/pp scaled by # of binary NN collisions

Jet-like high pT hadron production

Partons propagate through medium before fragmentation

Plot from G. Roland ‘Physics at LHC’ 2006
General framework

• Use collinear factorization formula

• Assume that the hadronization takes place outside the medium (time formation)

• Supplement it with the additional parton energy loss function: quenching weight $P$

• Transport coefficient: average transverse momentum transfer in the gluon scattering in medium

\[
\sigma_{A B \rightarrow h}^{\text{med}} = \sigma_{A B \rightarrow f}^{\text{vac}} \otimes P(\Delta E, L, \hat{q}) \otimes D_{\text{vac}}^{f \rightarrow h}(z, \mu_F^2)
\]

\[
\sigma_{A B \rightarrow h}^{\text{vac}} = f_A(x_1, Q^2) \otimes f_B(x_2, Q^2) \otimes \hat{\sigma}(x_1, x_2, Q^2)
\]

Transport coefficient: $\hat{q} \simeq 4 - 14 \text{ GeV}/\text{fm}^2$
Nuclear modification for hadrons

- Quenching weight $P$: probability for parton to lose medium-induced energy as it propagates through the medium of length $L$
- Data favor large transport coefficient
- Flat spectrum for $R_{AA}$ at high $p_T$
- The medium is so dense that the shell emission dominates
- Expect that the suppression will persist at LHC even for highest momenta (100 GeV)

Eskola, Honkanen, Salgado, Wiedemann
Heavy flavors

Factorization theorem for production of heavy quarks in hadron-hadron collisions (Collins, Soper, Sterman)

\[ \sigma_{AB \rightarrow QX}(s, m_Q^2) = \sum_{i,j} \int dx_1 dx_2 \hat{\sigma}_{ij \rightarrow QX} f_i/A(x_1, \mu_F) f_j/B(x_2, \mu_F) + O\left(\frac{\Lambda}{m_Q}\right)^p \]

Parton distribution functions

Power suppressed corrections

For this process factorization is a conjecture: not proven.
Heavy quark production in pp collisions

Bottom production at Tevatron: Run II
Very good agreement (after proper extraction of the fragmentation function from LEP data) M.Cacciari
Heavy flavor production in pp collisions at RHIC

- PHENIX pp data
- Electrons from semi-leptonic decays of heavy flavors
- Charm+Beauty
- FONLL pQCD M.Cacciari
- \(|y|<0.35\)
- \(0.3<p_T<9.0\) GeV
- \(\text{DATA/THEORY}=1.72\)
- Shape of distribution correct (except at low momenta)
Heavy flavor production in pp collisions at RHIC

- STAR pp data, electron
- $1.2 < p_T < 10$ GeV
- DATA/THEORY = 5.5
- Excess more significant than for PHENIX
- FONLL curves with scale uncertainty
- B decay significant fraction at high $p_T$

Heavy flavor production in pp collisions not well understood at lower energies
Radiation off heavy quarks

- Radiation from heavy quarks differs from light quarks: *dead cone effect*

- Gluon radiation suppressed at angles smaller than the ratio \( \theta_0 = \frac{m_Q}{E} \)

\[
\begin{align*}
    dP_{m_q=0} &\sim \frac{\alpha_s C_F}{\pi} d\omega \frac{dk_T^2}{k_T^2} \\
    dP_{m_q \neq 0} &\sim \frac{\alpha_s C_F}{\pi} d\omega \frac{k_T^2 dk_T^2}{[k_T^2 + \omega^2 \theta_0^2]^2}
\end{align*}
\]

**Massless quarks**

**Massive quarks**

- One expects less suppression than for light quarks
Heavy quarks in medium

- Situation in medium more complicated: suppression at large angles, (moderate) enhancement at small angles
- Another effect: shorter formation time in case of heavy quarks
- Net effect: smaller energy loss than light quarks

Armesto, Salgado, Wiedemann
Heavy quarks in medium

Armesto, Cacciari, Dainese, Salgado, Wiedemann

\[ R_{AA}^e(p_T) = \frac{\frac{d^2N_{AA\to e}}{dp_Tdy|y=0}}{\langle N_{AA\text{ coll}} \rangle \frac{d^2N_{pp\to e}}{dp_Tdy|y=0}} \]

- Large suppression observed in electron spectra in AA collisions
- Calculations do not quite predict that strong suppression
- b/c ratio not known. Large sensitivity of calculations to that ratio.
- Sensitivity to transport coefficient \( \hat{q} \)
- pp cross section not well under control
Heavy quarks in medium

Other effects:

- Collisional energy loss of the heavy quark? Not sufficient to explain the large suppression. (Djordjevic, Gyulassy)

- Fragmentation does not occur outside? Final state interactions of D mesons? (Strikman)

- Is the use of (generalized) factorization justified in AA? Breakdown of the factorization formula for hadroproduction (two transverse momenta, kt dependent distributions) in proton-proton. (Collins, Qiu)

\[
E_3E_4 \frac{d\sigma^{AB\to h_3h_4}}{d^2p_{3T}d^2p_{4T}} = \sum_{ijkl} f_{A/i} \otimes f_{B/j} \otimes \hat{\sigma}_{ij\to kl} \otimes D_{k\to h_3} \otimes D_{l\to h_4}
\]
Jet quenching: Wilson loops in AdS/CFT
Jet quenching and Wilson loops

Recall DIS on cold nucleus

\[ \sigma^{DIS} = \int d^2 x_T d^2 y_T dz |\psi(x_T, y_T; z)|^2 P^{q\bar{q}}(x_T, y_T) \]

Dipole cross section

\[ P^{q\bar{q}} = 2 \langle 1 - \frac{1}{N_c} \text{Tr}[W_F(x_T)W_F^\dagger(y_T)] \rangle = 2(1 - \langle W(C_{\text{light-like}}) \rangle) \]

Correlator of two Wilson lines averaged over the field configurations of the target nucleus

\[ \langle W(C_{\text{light-like}}) \rangle \simeq \exp(-r^2 Q_s^2) \]

Dipole size

\[ r = |x_T - y_T| \]
Wilson loops in AdS/CFT

Quark-gluon plasma

\[ \langle W^F (C) \rangle_{\text{plasma}} = \exp(-\hat{q} r^2 L^-) \]

\( \hat{q} \) energy loss of a hard parton when traversing QGP

\( L^- \) light-cone distance (longitudinal distance)

In AdS/CFT

\[ \langle W^F (C) \rangle = \exp(iS(C) - iS_0) \]

where \( S \) is the Nambu-Goto action

\[ S = -\frac{1}{2\pi \alpha'} \int d\sigma d\tau \sqrt{-\det[G_{\mu\nu} \partial_\alpha X^\mu \partial_\beta X^\nu]} \]

with the metric on the 4+1 dimensional AdS space
Wilson loops in thermal background

In the nonzero temperature $T$:
The metric is given by the AdS Schwarzschild black hole

Taking the limit:
$$N_c, \lambda = \frac{R^4}{\alpha'^2} \to \infty$$

Problem becomes classical: finding the extremum of the action

Can evaluate the jet quenching parameter:
$$\hat{q}_{SYM} \simeq 5\text{GeV}^2/\text{fm}$$

Liu, Rajagopal, Wiedemann
Summary I

- Total multiplicities grow as $\ln^2 s$.
- Multiplicities in $ee$ the same as in $AA$ per participating pair.
- $pp$ are systematically lower due to effect of leading particle.
- Limiting fragmentation visible for various systems and centralities.
- This universality of rapidity distributions suggest that they are determined very early in the collisions, essentially by the initial state.
- At high energies and for heavy nuclei, one expects the saturation of the gluon density.
- But RHIC does not quite reach quite very values of Bjorken $x$; need to consider forward rapidity. Saturation effects enhanced by the mass number $A$.
- Saturation applied to the initial state provides with the reasonable description of the data: rapidity distributions, $dA$ $pt$ distributions.
Summary II

- Heavy quarks and pt jets are excellent hard probes of the medium produced.
- Significant attenuation observed, up to transverse momenta of about 10 GeV.
- Theoretical calculations based on a generalized factorization framework with the rescattering effects for the fast particle (pt jet/heavy quark) in medium.
- The spectrum of heavy quarks not quite well reproduced by the theory. In pp deficit of the overall cross section. In AA the predicted attenuation is too small.
- Possible effects: collisional energy loss, fragmentation inside medium, factorization formula too simplistic.
- Interesting approach to jet quenching using AdS/CFT. Many uncertainties (N=4 SYM vs QCD).
Backup slides
Charm production in pp collisions

CDF Run II: c to D data

Good agreement. Theory systematically little bit lower.