Novel phenomena at RHIC

- Strong “elliptic” flow ($v_2 > 0.1$)
- High-$p_T$ hadrons are suppressed w.r.t. p+p
- Baryons as abundant as mesons at high $p_T$
Scaled $\pi^0$ yield in Au+Au vs. p+p collisions
Central/peripheral comparison

Suppression of hadron emission saturates beyond 6 GeV/c.

STAR Preliminary $\sqrt{s_{NN}} = 200$ GeV

Binary scaling

Participant scaling

0-5%/40-60%

0-5%/60-80%

$\dagger$ 130 GeV

• 200 GeV
Centrality scaling in $p_T$ bins

Spectra normalized to yield at $N_{\text{part}} = 65$
Jet correlation strength vs centrality

- Same side jet
- Away side jet

\[ \Delta \phi \mid < 0.75, 4 < p_T(\text{trig}) < 6 \text{ GeV/c} \]
\[ \Delta \phi \mid > 2.25, 4 < p_T(\text{trig}) < 6 \text{ GeV/c} \]

Graph showing the variation of jet correlation strength with centrality.
The graph shows the $p/\pi$ ratio as a function of $p_T$ (GeV/c) for different centrality classes.

- **Central**:
  - 0-5% p/π0
  - 0-5% p/π+
  - 60-91.4% p/π0
  - 60-91.4% p/π+

- **Peripheral**:
  - Ratio increases with $p_T$.

The plot includes a line indicating pT independent systematic error band.

**Legend**:
- Red circle: 0-5% p/π0
- Red triangle: 0-5% p/π+
- Blue square: 60-91.4% p/π0
- Blue triangle: 60-91.4% p/π+

**Note**:
- $\sqrt{s_{NN}} = 200$ GeV
- PHENIX PRELIMINARY
Anisotropic or “elliptic” flow is sensitive to initial geometry

\[ \text{Force} = -\nabla P \]

More flow in collision plane than perpendicular to it.

\[ \Delta E \sim L \]

Less absorption in collision plane than perpendicular to it.

Observed elliptic flow suggests large transverse pressure at early times (\( \tau < 3 \text{ fm/c} \)).

Observed elliptic flow suggests high matter density at early times (\( \tau < 3 \text{ fm/c} \)).
Elliptic flow of $K^0$ and $\Lambda$

Hyperon $v_2$ saturates later and higher than kaon $v_2$.

Same effect observed for protons and pions.

Novel mechanism of baryon formation?
Jet quenching

The “sister of thermalization”

High-energy parton loses energy by rescattering in dense, hot medium.

Radiative energy loss $dE/dx$

Higher twist effect!

\[
\frac{dE}{dx} \sim \langle k_T^2 \rangle \sim L
\]

can be described as medium effect on parton fragmentation
Energy loss in QCD according to BDMS

Gluon radiation is suppressed due to multiple scattering by LPM effect. LPM suppression differs from QED due to rescattering of the radiated gluon. Critical frequency:

$$\omega_c = \frac{1}{2} \hat{q} L^2$$

with

$$\hat{q} = \rho \int q^2 dq^2 \frac{d\sigma}{dq^2}$$

Energy loss spectrum for a fast parton is:

$$\varepsilon D(\varepsilon) = \sqrt{\frac{\tilde{\alpha}^2 \omega_c}{2\varepsilon}} \exp \left( - \frac{\pi \tilde{\alpha}^2 \omega_c}{2\varepsilon} \right)$$

with

$$\tilde{\alpha} = 2\alpha_s C_R / \pi.$$
Radiative energy loss distribution for fixed $L$ must be convoluted with the steeply falling parton spectrum:

$$\Delta p_T = \left( \frac{dN}{d^2 p_T} \right)^{-1} \int \varepsilon D(\varepsilon) d\varepsilon \frac{dN(p_T + \varepsilon)}{d^2 p_T}$$

$pQCD$ with in-medium cutoffs predicts (Baier et al.):

$$\Delta p_T \approx \alpha_s \sqrt{\pi \hat{q} L^2 p_T / \nu}$$

with

$$dN / d^2 p_T \sim p_T^{-\nu}$$

With expansion:

$$\hat{q} L^2 \Rightarrow \hat{q}_0 L_{\text{eff}}^2 = \frac{2 \hat{q}_0}{\rho(r)} \int \pi d \tau \rho(r_\tau, \tau)$$
Geometrical considerations

\[ L = \sqrt{R^2 - r^2 \sin^2 \theta} - r \cos \theta \]

Momentum loss of parton:

\[ \Delta p_T = \eta p_T^\mu L \]

“Quenched” spectrum:

\[
\frac{d\tilde{N}}{d^2 p_T} = \frac{1}{2\pi^2 R^2} \int_0^{2\pi} d\theta \int_0^R d^2 r \frac{dN(p_T - \Delta p_T)}{d^2 p_T}
\]
Analytical model: Surface emission

Quenching factor: \[ \frac{d\tilde{N}}{d^2 p_T} = Q(p_T) \frac{dN}{d^2 p_T} \]

pQCD spectrum
\[ \frac{dN}{d^2 p_T} = N_0 \left(1 + \frac{p_T}{p_0}\right)^{-\nu} \]

Strong quenching limit
\[ Q(p_T) = \frac{2(p_0 + p_T)}{\pi R \eta (\nu - 1) p_T^\mu} \]

volume/R=surface

\[ \Delta p_T = \eta p_T (L \rho)_{\text{eff}} \]

Bethe-Heitler

\[ \Delta p_T = \eta p_T \sqrt{(L \rho)_{\text{eff}}} \]

“Random walk”
Refinements

- Transverse profile of hard scattering
  \[ T(r, b) = \rho_1(r)\rho_2(r - b) \]

- Transverse profile of absorbing medium
  \[ \rho_{med}(r) = \rho_1(r)\left[1 - e^{-\sigma_2(r-b)}\right] + \rho_2(r-b)\left[1 - e^{-\sigma_2(r)}\right] \]

- Expansion of absorbing medium
  \[ \rho_{med}(r, \tau) = \rho_{med}(r)(1 + \tau / \tau_0)^{-1} \]
$N_{\text{part}}$ dependence of quenching

Flat dependence of $Q(p_T)$ with $N_{\text{part}}$ (as claimed by PHOBOS) is best described by a "random walk" model of energy loss.
$p_T$ dependence of quenching

RHIC data do not yet support the increase of $Q(p_T)$ with $p_T$ predicted by the BDMS theory.
Is it possible to distinguish between different energy loss laws by correlating the amount of same-side and away-side suppression?
Quenching is not strong enough to generate $v_2$ of the observed magnitude.

$v_2 \neq 0$ from energy loss.
HIGH-ENERGY PHYSICS: Wayward Particles Collide With Physicists' Expectations

Charles Seife

EAST LANSING, MICHIGAN--At a meeting here last week, researchers announced results that, so far, nobody can explain. By slamming gold atoms together at nearly the speed of light, the physicists hoped to make gold nuclei melt into a novel phase of matter called a quark-gluon plasma. But although the experiment produced encouraging evidence that they had succeeded, it also left them struggling to account for the behavior of the particles that shoot away from the tremendously energetic smashups.
An alternative: Quark recombination?

Fragmentation

\[
\frac{\text{Baryon}}{\text{Meson}} \ll 1
\]

Recombination

\[
\frac{\text{Baryon}}{\text{Meson}} \approx 1
\]
Sudden recombination model

A.k.a. the “coalescence model”

Assumptions:

• Quarks and antiquarks recombine into hadrons locally “at an instant”:
  
  \[ q\bar{q} \rightarrow M \quad qqq \rightarrow B \]

• Hadron momentum \( P \) is much larger than average momentum \( \langle \Delta p^2 \rangle \) of the internal quark wave function of the hadron;

• Parton spectrum has thermal part (quarks) and a power law tail (quarks and gluons) from pQCD.
For thermal quark spectrum given by $w(p) = \exp(-p/T)$ and a Gaussian meson wave function with momentum width $\Lambda_M$, the meson spectrum is obtained as:

$$\frac{dN_M}{d^3P} = C_M \frac{V}{(2\pi)^3} \int \frac{d^3q}{(2\pi)^3} w\left(\frac{1}{2}P - q\right) w\left(\frac{1}{2}P + q\right) |\hat{\phi}_M(q)|^2$$

$$= C_M \frac{V}{(2\pi)^3} \left[ w\left(\frac{1}{2}P\right) \right]^2 \left(1 - \frac{2\Lambda_M^2}{TP} + \ldots \right)$$

Similarly for baryons:

$$\frac{dN_B}{d^3P} = C_B \frac{V}{(2\pi)^3} \left[ w\left(\frac{1}{3}P\right) \right]^3 \left(1 - O(\Lambda_B^2 / TP) \right)$$
Recombination of thermal quarks

Relativistic generalization using hadron light-cone frame:

\[ w_\alpha(r, p) = \text{Quark distribution function at “freeze-out”} \]

\[
E \frac{dN_M}{d^3P} = \int d\Sigma \frac{P \cdot u}{(2\pi)^3} \sum_{\alpha,\beta} \int dx w_\alpha(R, xP^+) \bar{w}_\beta(R, (1-x)P^+) |\bar{\phi}_M(x)|^2
\]

\[
E \frac{dN_B}{d^3p} = \int d\Sigma \frac{P \cdot u}{(2\pi)^3} \sum_{\alpha,\beta,\gamma} \int dx dx' w_\alpha(R, xP^+) w_\beta(R, x' P^+) w_\gamma(R, (1-x-x')P^+) |\bar{\phi}_B(x, x')|^2
\]

For a thermal distribution \( w(r, p) \sim \exp(-p \cdot u / T) \)

\[
w_\alpha(R, xP^+) \bar{w}_\beta(R, (1-x)P^+) = \exp(-P \cdot u / T)
\]

\[
w_\alpha(R, xP^+) w_\beta(R, x' P^+) w_\gamma(R, (1-x-x')P^+) = \exp(-P \cdot u / T)
\]
Recombination vs. Fragmentation

Fragmentation…

\[ E \frac{dN_h}{d^3P} = \int d\Sigma \frac{P \cdot u}{(2\pi)^3} \int_0^1 dz \sum_a w_\alpha (R, \frac{1}{z} P) D_{a \rightarrow h} (z) \]

… *never* competes with recombination for a thermal (exponential) spectrum:

\[ \left[ w(P/n) \right]^n = \exp(-P \cdot u / T) > \exp(-P \cdot u / zT) = w(P/z) \]

… but it wins out at large \( p_T \), when the spectrum is a power law \( \sim (p_T)^{-b} \):

\[ dN_{\pi}^{\text{frag}} \sim P^{-b} \quad dN_{\pi}^{\text{rec}} \sim P^{-2b} \]
**pQCD approach to parton recombination**

Double parton scattering scales:

\[
\frac{d\sigma}{dp_T^2} \sim A^2 \left( \frac{\alpha_s^2 \Lambda^2}{(\frac{1}{2} p_T)^4} \right)^2
\]

Single parton scattering and fragmentation scales:

\[
\frac{d\sigma}{dp_T^2} \sim A^{4/3} \left( \frac{\alpha_s^2}{(p_T / z)^4} \right)
\]

\[
\frac{\text{DPS}}{\text{SPS}} \sim \left( \frac{16\alpha_s A^{1/3} \Lambda^2}{z p_T^2} \right)^2
\]

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T. Ochiai, Prog. Theor. Phys. 75 (1986) 1184
Recombination vs. Fragmentation

Thermal proton/pion ratio:

\[
\frac{dN_p}{dN_{\pi^+}} = \frac{C_p}{C_{\pi^+}} \approx \frac{2 \times 3 \times 3 / 3!}{2} = 1.5
\]

R.J. Fries et al. (nucl-th/0302036)

STAR Data
$P_T$ range of parton recombination

- Quark recombination (coalescence) may dominate for all $p_T < p_0$. Combinatorical models (ALCOR, etc.) work well for total particle yields at SPS and RHIC.
- Low $p_T$ is not calculable, but calculation at moderate $p_T$ (few GeV) may be possible using hadron light-cone formalism.
- Transition from dense medium to dilute medium appears very rapid for fast partons ($\Delta \tau = \Delta x/\gamma$), validating sudden approximation.
- Focus on “high” $p_T$ evades problems of energy and entropy conservation in recombination: $E = (p^2 + m^2)^{1/2} \approx p$. 
Heuristic evidence: Parton Number Scaling of $v_2$

Recombination model suggests that hadronic $v_2$ reflects parton $v_2$:

$$\hat{v}_{\text{had}}(p_T) = [N_{\text{part}}(p_T/n)]^n$$

$$v_{\text{had}}^2 \approx n v_{\text{part}}^2$$

$$p_T^{\text{had}} \approx n p_T^{\text{part}}$$

Provides measurement of partonic $v_2$!
Baryons in the central rapidity region at RHIC

Substantial net baryon density at RHIC near $y\sim 0$
Origin of baryon excess?

- Energy deposition by glue fields ("color glass condensate") predicts that $y \approx 0$ region should be baryon-antibaryon symmetric.
- Transport of baryon number from beam rapidity $Y$ to $y \approx 0$ is difficult; average $\Delta y$ in p+p interaction is about $\frac{1}{2}$.
- RHIC data show that net $dB/dy \approx 20$ at $y = 0$.
- Baryon junctions?
- Look at net baryon number distribution in the nucleon, assuming that parton distribution is "shattered":

$$B(x) = \frac{1}{3} \sum_q [f_q(x) - f_{\bar{q}}(x)]$$
“Liberated” partons: \( y = y_{\text{beam}} + \ln x + \ln(M/Q) \)
$dN_{B-B\bar{B}}/dy$ from primary parton scattering follows net baryon distribution in the nucleon. Additional net baryon number at $y\sim 0$ is due to parton rescattering and fragmentation:
Other high-$p_T$ probes

- Quark-photon back-to-back correlations.

- In-medium Compton backscattering ($qg \leftrightarrow q\gamma$) at high $p_T$ measures gluon density

$$\frac{d\sigma}{dt} = \frac{\pi \alpha s}{s^2} \left( \frac{u}{s} + \frac{s}{u} \right)$$

$$P(\gamma / q) \approx 10^{-3}$$

Wang, Huang, Sarcevic (1996)

Conclusions

Competition between parton recombination and fragmentation naturally explains:

- $p/\pi$ ratio for intermediate $p_T$
- Lack of suppression of baryons for intermediate $p_T$
- Collective flow for baryons persists to 50% higher $p_T$ than for mesons and saturates higher
- “Soft” characteristics of hadron production up to 4-5 GeV/c.
- Net baryons at $y = 0$ can be explained as initial state and parton rescattering effect.