Particle ratios change with centrality!

Protons less absorbed in nuclear collisions than pions!

Central

Peripheral

The $p/\pi^+$ and $\bar{p}/\pi^-$ ratios as a function of $p_T$ increase dramatically to values $\sim 1$ as a function of centrality in Au + Au collisions at RHIC which was totally unexpected and is still not fully understood.

"Baryon Anomaly"

The $p/\pi^+$ and $\bar{p}/\pi^-$ ratios as a function of $p_T$ increase dramatically to values $\sim 1$ as a function of centrality in Au + Au collisions at RHIC which was totally unexpected and is still not fully understood.

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November 17, 2008


Novel Heavy-Ion Phenomena

Stan Brodsky
SLAC
Crucial Test of Leading-Twist QCD:
Scaling at fixed $x_T$

$$x_T = \frac{2p_T}{\sqrt{s}}$$

$$E \frac{d\sigma}{d^3p}(pN \rightarrow \pi X) = \frac{F(x_T, \theta_{CM})}{p_T^{n_{eff}}}$$

**Parton model:** $n_{eff} = 4$

**As fundamental as Bjorken scaling in DIS**

**Conformal scaling:** $n_{eff} = 2n_{active} - 4$
\( \sqrt{s^n} E \frac{d\sigma}{d^3p} (pp \rightarrow \gamma X) \) at fixed \( x_T \)

Scaling of direct photon production consistent with PQCD
\[ pp \rightarrow \gamma X \]

\[ E \frac{d\sigma}{d^3p}(pp \rightarrow \gamma X) = \frac{F(\theta_{cm},x_T)}{p_T^4} \]

\[ gu \rightarrow \gamma u \]

\[ n_{active} = 4 \]

\[ n_{eff} = 2n_{active} - 4 \]

\[ n_{eff} = 4 \]
$pp \rightarrow HX$ at high $p_T$

Hadron created from jet fragmentation

PQCD Factorization: $p/\pi$ ratio universal. Same as $e^+e^- \rightarrow HX$.
**QCD prediction:** Modification of power fall-off due to DGLAP evolution and the Running Coupling

\[
E \frac{d\sigma}{d^3 p} (pN \rightarrow \pi X) = \frac{F(x_T, \theta_{CM})}{p_T^{n_{eff}}} \quad x_T = \frac{2p_T}{\sqrt{s}}
\]

\(n_{eff} \sim 4 \text{ to } 5\)

**Key test of PQCD:** power-law fall-off at fixed \(x_T\)
Protons produced in AuAu collisions at RHIC do not exhibit clear scaling properties in the available $p_T$ range. Shown are data for central (0 – 5%) and for peripheral (60 – 90%) collisions.

**Leading twist:**

$$E \frac{d\sigma}{d^3p} (pN \rightarrow pX) = \frac{F(x_T, \theta_{CM})}{p_T^{n_{eff}}} x_T^{n_{eff}}$$

**Continuous rise of $n_{eff}$ with $x_T$.**

$\bullet$ $n_{eff} = 4$

$\circ$ $n_{eff} = 5$

RHIC

PHENIX

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\[ E \frac{d\sigma}{d^3 p} (pp \rightarrow HX) = \frac{F(x_T, \theta_{cm} = \pi/2)}{p_T^{n_{eff}}} \]

Clear evidence for higher-twist contributions

Chicago Princeton
Fermilab, ISR data

Continuous Rise of \( n_{eff} \)
Baryon Anomaly: Particle ratio changes with centrality!

Protons less absorbed in nuclear collisions than pions

Proton/pion ratio changes with centrality.


Central

Peripheral

Sickles, sjb

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\[ \sqrt{s_{NN}} = 130 \text{ and } 200 \text{ GeV} \]

**Proton power changes with centrality!**

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$pp \rightarrow HX$ at high $p_T$

Proton created from jet fragmentation

Color Opaque

$n_{active} = 4$

$n = 2n_{active} - 4$

$n = 4$

Novel Heavy-Ion Phenomena
Baryon can be made directly within hard subprocess

Coalescence within hard subprocess

\[ b_\perp \simeq 1/p_T \]

Collision can produce 3 collinear quarks

\[ uu \rightarrow p\bar{d} \]

\[ \phi_p(x_1, x_2, x_3) \propto \Lambda_{QCD}^2 \]

Small color-singlet
Color Transparent
Minimal same-side energy

\[ n_{active} = 6 \]
\[ n_{eff} = 2n_{active} - 4 \]
\[ n_{eff} = 8 \]
Baryon made directly within hard subprocess

\[ b_\perp \simeq 1 \text{ fm} \]

\[ b_\perp \simeq 1/p_T \]

\[ uu \rightarrow p \bar{d} \]

Formation Time proportional to Energy

Small color-singlet
Color Transparent
Minimal same-side energy

\[ n_{\text{active}} = 6 \]

\[ n_{\text{eff}} = 2n_{\text{active}} - 4 \]

\[ n_{\text{eff}} = 8 \]
Protons less absorbed in nuclear collisions than pions because of dominant color transparent higher twist process.

Particle ratio changes with centrality!

Protons less absorbed in nuclear collisions than pions because of dominant color transparent higher twist process.

Central

Peripheral
Proton production more dominated by color-transparent direct high-$n_{\text{eff}}$ subprocesses
Novel Heavy-Ion Phenomena

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Power-law exponent $n(x_T)$ for $\pi^0$ and $h$ spectra in central and peripheral Au+Au collisions at $\sqrt{s_{NN}} = 130$ and 200 GeV


Proton production dominated by color-transparent direct high $n_{eff}$ subprocesses
Lambda can be made directly within hard subprocess

Coalescence within hard subprocess

$\Lambda \rightarrow ud \Lambda \bar{s}$

Small color-singlet
Color Transparent
Minimal same-side energy

$n_{active} = 6$

$n_{eff} = 2n_{active} - 4$

$n_{eff} = 8$

$\bar{s}$ produced on away side

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Sickles, sjb
Baryon Anomaly: Evidence for Direct, Higher-Twist Subprocesses

- Explains anomalous power behavior at fixed $x_T$
- Protons more likely to come from direct higher-twist subprocess than pions
- Protons less absorbed than pions in central nuclear collisions because of color transparency
- Predicts increasing proton to pion ratio in central collisions
- Proton power $n_{\text{eff}}$ increases with centrality since leading twist contribution absorbed
- Fewer same-side hadrons for proton trigger at high centrality
- Exclusive-inclusive connection at $x_T = 1$
Remarkably Strong Nuclear Dependence for Fast Charmonium

Violation of PQCD Factorization!

\[ \frac{d\sigma}{dx_F} (pA \rightarrow J/\psi X) \]

Violation of factorization in charm hadroproduction.

J/ψ nuclear dependence vrs rapidity, x_{Au}, x_F

PHENIX compared to lower energy measurements

Kopeliovich, NP A696:669, 2001
E866: PRL 84, 3256 (2000)

\[ \frac{d\sigma}{dx_F} (pA \rightarrow J/\psi X) \]

Hoyer, Sukhatme, Vanttinen

Huge “absorption” effect at large x_F

Violates PQCD factorization!

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Two Components

\[ \frac{d\sigma}{dx_F}(pA \rightarrow J/\psi X) = A_1 \frac{d\sigma_1}{dx_F} + A_2/3 \frac{d\sigma_{2/3}}{dx_F} \]

\( A^1 \) component

Identify with Fusion

Conventional PQCD subprocesses

\[ \frac{d\sigma_1}{dx_F}(\pi A \rightarrow J/\psi X) \]
Novel Heavy-Ion Phenomena

\[ \frac{d\sigma}{dx_F}(pA \rightarrow J/\psi X) = A^1 \frac{d\sigma_1}{dx_F} + A^{2/3} \frac{d\sigma_{2/3}}{dx_F} \]

Excess beyond conventional PQCD subprocesses

\[ pA \rightarrow J/\psi X \]

\[ \pi A \rightarrow J/\psi X \]

\[ p \text{ 200 GeV/c} \]

\[ \pi \text{ 200 GeV/c} \]

Identify with IC

High \( x_F \)

Remarkably Flat Distribution

J. Badier et al, NA3

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First Evidence for Intrinsic Charm

DGLAP / Photon-Gluon Fusion: factor of 30 too small

Measurement of Charm Structure Function


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- **EMC data**: \( c(x, Q^2) > 30 \times \text{DGLAP} \)
  \( Q^2 = 75 \ \text{GeV}^2, \ x = 0.42 \)

- **High** \( x_F \) \( pp \rightarrow J/\psi X \)
- **High** \( x_F \) \( pp \rightarrow J/\psi J/\psi X \)
- **High** \( x_F \) \( pp \rightarrow \Lambda_c X \)
- **High** \( x_F \) \( pp \rightarrow \Lambda_b X \)
- **High** \( x_F \) \( pp \rightarrow \Xi(ccd) X \) (SELEX)

**Factorization-breaking nuclear dependence**

\[
\pi A \rightarrow J/\psi X \quad pA \rightarrow J/\psi X \quad A^\alpha(x_F) \neq A^\alpha(x_2)
\]

**IC Structure Function: Critical Test of QCD**

*Novel Heavy-Ion Phenomena*
In QCD, the probability for fluctuation in a proton is given by

\[ \sim \frac{\Lambda_{QCD}^2}{M_Q^2} \]

where \( \Lambda_{QCD} \) is the QCD scale parameter and \( M_Q \) is the charm quark mass.

In QED, the probability for fluctuation in positronium is

\[ \sim \left( \frac{m_e \alpha}{M_\ell^4} \right) \]

where \( m_e \) is the electron mass and \( M_\ell \) is the lepton mass.

The distribution peaks at equal rapidity (velocity), indicating that heavy particles carry the largest momentum fractions.

High \( x_c \) charm!

\[ \hat{x}_i = \frac{m_{\perp i}}{\sum_j \frac{m_{\perp j}}{m_{\perp j}}} \]

Hoyer, Peterson, Sakai, sjb

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Color-Opaque IC Fock state interacts on nuclear front surface

Scattering on front-face nucleon produces color-singlet \( c\bar{c} \) pair

Octet-Octet IC Fock State

No absorption of small color-singlet

\[
\frac{d\sigma}{dx_F}(pA \rightarrow J/\psi X) = A^{2/3} \times \frac{d\sigma}{dx_F}(pN \rightarrow J/\psi X)
\]

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10% to 15% of DIS events are diffractive!

Fraction $r$ of events with a large rapidity gap, $\eta_{\text{max}} < 1.5$, as a function of $Q_{DA}^2$ for two ranges of $x_{DA}$. No acceptance corrections have been applied.

Final State Interactions in QCD

Feynman Gauge

Light-Cone Gauge

Result is Gauge Independent

Novel Heavy-Ion Phenomena
QCD Mechanism for Rapidity Gaps

Wilson Line: \( \overline{\Psi}(y) \int_0^y dx e^{iA(x) \cdot dx} \psi(0) \)

Origin of Diffractive DIS
Reproduces lab-frame color dipole approach

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Hoyer, Marchal, Peigne, Sannino, sjb
Integration over on-shell domain produces phase i

Need Imaginary Phase to Generate Pomeron

Need Imaginary Phase to Generate T-Odd Single-Spin Asymmetry

Physics of FSI not in Wavefunction of Target

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Nuclear Shadowing in QCD

Shadowing depends on understanding leading twist-diffraction in DIS

Nuclear Shadowing not included in nuclear LFWF!

Dynamical effect due to virtual photon interacting in nucleus

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Integration over on-shell domain produces phase $i$

Need Imaginary Phase to Generate Pomeron.

Need Imaginary Phase to Generate T-Odd Single-Spin Asymmetry

Physics of FSI not in Wavefunction of Target

Antishadowing (Reggeon exchange) is not universal!

Schmidt, Yang, sjb

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\[ Q^2 = 5 \text{ GeV}^2 \]

- SLAC/NMC data
- Extrapolations from NuTeV

Scheinbein, Yu, Keppel, Morfin, Olness, Owens

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Universal Frame-Independent Light Front virtual photon and proton Wavefunctions

\[ \Psi^*_\gamma (x_a, \vec{k}_{\perp a}) \]

\[ \Psi_B (x_b, \vec{k}_{\perp b}) \]

\[ x_a \vec{l}_{\perp} + \vec{k}_{\perp a} \]

LF time of first interaction
Physics of Rescattering

- Diffractive DIS
- Non-Unitary Correction to DIS: Structure functions are not probability distributions
- Nuclear Shadowing, Antishadowing - Not in Target WF
- Single Spin Asymmetries -- opposite sign in DY and DIS
- DY angular distribution at leading twist from double ISI -- not given by PQCD factorization -- breakdown of factorization!
- Wilson Line Effects not 1 even in LCG
- Must correct hard subprocesses for initial and final-state soft gluon attachments
- Corrections to Handbag Approximation in DVCS!

Hoyer, Marchal, Peigne, Sannino, sjb
Single-spin asymmetries

**Pseudo-\(T\)-Odd**

\[ i \vec{S}_p \cdot \vec{q} \times \vec{p}_q \]

**Light-Front Wavefunction**

**S and P-Waves**

**Leading Twist Sivers Effect**

Hwang, Schmidt, sjb

Collins, Burkardt

Ji, Yuan

**QCD S- and P-Coulomb Phases --Wilson Line**

Moreno

**Novel Heavy-Ion Phenomena**

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<table>
<thead>
<tr>
<th>Static</th>
<th>Dynamic</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Square of Target LFWFs</td>
<td>Modified by Rescattering: ISI &amp; FSI</td>
</tr>
<tr>
<td>• No Wilson Line</td>
<td>Contains Wilson Line, Phases</td>
</tr>
<tr>
<td>• Probability Distributions</td>
<td>No Probabilistic Interpretation</td>
</tr>
<tr>
<td>• Process-Independent</td>
<td>Process-Dependent - From Collision</td>
</tr>
<tr>
<td>• T-even Observables</td>
<td>T-Odd (Sivers, Boer-Mulders, etc.)</td>
</tr>
<tr>
<td>• No Shadowing, Anti-Shadowing</td>
<td>Shadowing, Anti-Shadowing, Saturation</td>
</tr>
<tr>
<td>• Sum Rules: Momentum and J^z</td>
<td>Sum Rules Not Proven</td>
</tr>
<tr>
<td>• DGLAP Evolution; mod. at large x</td>
<td>DGLAP Evolution</td>
</tr>
<tr>
<td>• No Diffractive DIS</td>
<td>Hard Pomeron and Odderon Diffractive DIS</td>
</tr>
</tbody>
</table>

\[
\psi_n(x_i, \vec{k}_\perp i, \lambda_i)
\]
Evolution of 5 color-singlet Fock states

\[ \Psi^d_n(x_i, \vec{k}_\perp i, \lambda_i) \]

\[ \sum_i^n \vec{k}_\perp i = \vec{0}_\perp \]
\[ \sum_i^n x_i = 1 \]

\[ \Phi_n(x_i, Q) = \int^{k^2_{\perp i}<Q^2} \prod_{i<j}^n d^2k_{\perp j} \psi_n(x_i, \vec{k}_{\perp j}) \]

5 x 5 Matrix Evolution Equation for deuteron distribution amplitude
Define “Reduced” Form Factor

\[ f_d(Q^2) \equiv \frac{F_d(Q^2)}{F_p\left(\frac{Q^2}{4}\right)F_n\left(\frac{Q^2}{4}\right)} \]

Elastic electron-deuteron scattering

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QCD Prediction for Deuteron Form Factor

\[ F_d(Q^2) = \left[ \frac{\alpha_s(Q^2)}{Q^2} \right]^5 \sum_{m,n} d_{mn} \left( \ln \frac{Q^2}{\Lambda^2} \right)^{-\gamma_n^d - \gamma_m^d} \left[ 1 + O(\alpha_s(Q^2), \frac{m}{Q}) \right] \]

Define “Reduced” Form Factor

\[ f_d(Q^2) \equiv \frac{F_d(Q^2)}{F_N Q^2 / 4} \cdot \]

Same large momentum transfer behavior as pion form factor

\[ f_d(Q^2) \sim \frac{\alpha_s(Q^2)}{Q^2} \left( \ln \frac{Q^2}{\Lambda^2} \right)^{-\left(2/5\right)C_F/\beta} \]

FIG. 2. (a) Comparison of the asymptotic QCD prediction \( f_d(Q^2) \propto (1/Q^2) \ln (Q^2/\Lambda^2)^{-1-(2/5)C_F/\beta} \) with final data of Ref. 10 for the reduced deuteron form factor, where \( F_N(Q^2) = [1 + Q^2/(0.71 \text{ GeV}^2)]^{-2} \). The normalization is fixed at the \( Q^2 = 4 \text{ GeV}^2 \) data point. (b) Comparison of the prediction \( [1 + (Q^2/m_\pi^2)] f_d(Q^2) \propto [\ln (Q^2/\Lambda^2)]^{-1-(2/5)C_F/\beta} \) with the above data. The value \( m_\pi^2 = 0.28 \text{ GeV}^2 \) is used (Ref. 8).
Deuteron Reduced Form Factor
≈ Pion Form Factor × 15%

- Large Magnitude: Evidence for Hidden Color in the Deuteron

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Diffractive dissociation of color-octet deuteron to two high transverse momentum clusters

Hidden Color Fock State

Rapidity gap between high transverse momentum clusters

Target left intact

Diffraction, Rapidity gap

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Novel Heavy-Ion Phenomena

- AdS/QCD: Coherent Quark-Gluon State!-- Origin of $v_2$, ridge
- AdS/QCD: Relativistic radial S-Eq predicts spectra, LFWFs, form factors
- Gluon cascade sets up initial coherent state
- Ridge originates from initial-state radiation, not trigger hadron
- Baryon anomaly: Baryons more likely to come from direct higher-twist subprocess than mesons; explains $p_T$ scaling at fixed $x_T$
- Protons produced directly at high $p_T$; less absorbed than pions in central nuclear collisions because of color transparency
- Intrinsic Charm explains shape and $A^{2/3}$ dependence of quarkonium at high $x_F$
- Hidden-Color phenomena
- Static vs. Dynamic Structure Functions