pp $\rightarrow$ $\pi^\ast X$
$\sqrt{s} = 38.8$ Gev
Solid line is CP data re-scaled
Dashed line is CCRS data re-scaled
$-.20 < \cos\theta' < 0.20$
Nuclear Effects Observed at High $P_T$
in Single Hadron Spectra and Hadron Pair Spectra at Fermilab

Bob McCarthy
SUNY at Stony Brook

High $P_T$ Phenomena at RHIC
BNL 11/1/2001
Hadron Production at High $p_T$ in Proton-Nucleus Collisions at $\sqrt{s} = 38.8\,\text{GeV}$

$\sqrt{s} = \text{total } p\text{-nucleon energy in CM}$

**LAB:**  
\[ P \xrightarrow{800\,\text{GeV}/c} N \]

**CM:**  
\[ P \rightarrow 19.4\,\text{GeV} \quad \text{or} \quad N \rightarrow 19.4\,\text{GeV} \]
detect single particles at 90° in CM

high $p_T \Rightarrow$ high luminosity

$10^{10}$ protons/s incident on target (interacting 10%)

Detector hides behind dump

typical momentum $\sim$ 100 GeV
E605 Detector

1. first magnet (8 GeV kick)
   sweeps high \( p_T \) particles
   into acceptance
   sweeps low \( p_T \) background out

2. tracking
   6 PWC planes
   12 drift planes
   5 counter planes

3. second magnet (1 GeV kick)
   re-measure momentum
   eliminate background

4. complete particle ID
   \( \mu/e/hadrons \) - electron calorimeter
   hadron calorimeter
   \( \mu \) proportional tube

\( \pi/K/p \) - RICH counter

(H. Glass et al., IEEE Transactions...
E605 Cherenkov Counter

spherical mirrors
16 segments
each 63.5 x 66 cm$^2$
f = 8.00 ± 0.01 m

n-vessel - aluminum
15.2 m x 3.1 m x 2.8 m
all joints welded
gas - helium 1 atm
$k_e \approx 118$
$O_2 \leq 2 \times 10^{-7}$

CaF$_2$ crystal windows
40 x 80 cm$^2$

multistep PWC's
40 x 80 cm$^2$
3 projections
He (97%) / TEA (3%)

observe ~ 2½ photons/Track
multistep PWC-projective readout
amplitude matching used to
reconstruct hit position

each photon measures raftangle

U CATH.

V CATH.
Radius vs. Momentum for 4 Photon Clusters.
Radius vs. Momentum for 2 Photon Clusters.
Data Recorded (in 1984!)

integrated luminosity/nucleon

\( \sigma \) (10^{39} \text{ cm}^{-2}) \Delta \sigma \sim 0.5

steradians

---

target

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Be</td>
<td>12.9</td>
</tr>
<tr>
<td>W</td>
<td>2.2</td>
</tr>
<tr>
<td>H₂</td>
<td>0.8</td>
</tr>
</tbody>
</table>

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All data are published:

$pp \rightarrow \pi^*X$
\[\sqrt{s} = 38.8 \text{ Gev}\]
Solid line is CP data re-scaled
Dashed line is CCRS data re-scaled
$-0.20 < \cos\theta' < 0.20$

\[E^2 \sigma / d^3 p \mid (\text{pb } c^3 \text{ / GeV}^2)\]

$P_T$ (Gev/c)

**CP:** Antreasyan et al.
*Phys. Rev. D19, 764 (1979)*

**CCRS:** Büsser et al.,

$\Rightarrow \nabla$ values agree with previous work
Valence Quark Content

\( \pi^+ = u \overline{d} \)

\( K^+ = u \overline{s} \)

\( p = u u d = u (u d) \)

Production of all 3 dominated by \( u \) quark scattering

\( p_T \) large fraction of \( \sqrt{s} \)

\( \Rightarrow \) must be valence

Only \( u \) quark scatters can make these positive particles

\( \text{no valence d} \)
$pp \rightarrow \pi^- X$

$\sqrt{s} = 38.8 \text{ Gev}$

Solid line is CP data re-scaled

Dashed line is CCRS data re-scaled

$-0.20 < \cos \theta^* < 0.20$
ratios independent of $P_T$ for $P_T > 6$ as $\sigma$'s change by orders of magnitude

$\Rightarrow$ probably a simple explanation in u-quark fragmentation

$\frac{\bar{s}/\bar{d}}{u/d} \approx \frac{K^+/\pi^+}{P/\pi^+} = 0.48 \pm 0.02$

$\langle u/d \rangle / \langle d \rangle \approx P/\pi^+ = 0.09 \pm 0.02$
Color strings fragment to produce observed hadrons
\rightarrow \text{ratios characteristic of } u \text{ quark fragmentation}

What about $3 < P_T < 6 \text{ GeV}$?
Observing diquark scattering

$P_{\pi^+}$ falls because diquark bond breaks. $K^+$ and $\pi^+$ still produced via $u$ quark.

Refs:
Fredriksson et al.
Negative particle ratios may also reach plateaus—harder to interpret.

Presume: $\pi^-$ mostly from d fragmentation

$K^-$, $\rho^-$ perhaps from fragmentation of nonvalence constituent

$\Rightarrow$ ratio should fall versus $P_T$
Conclusion

Single hadron production at $P_T \geq 3$ GeV appears to be dominated by the fragmentation of a single constituent. For positives with $P_T > 6$ GeV this constituent is a u quark. ($P_{LAB} \sim 100$ GeV $\Rightarrow$ fragments to hadron outside nucleus.)

A- Dependence

Now change the A of the target nucleus - increase the length of nuclear matter through which the above constituent must pass.
A-Ddependence

\[ \overline{\sigma}_A \propto A^\alpha \]

\( A \) = atomic weight

screening \( \Rightarrow \alpha < 1 \)

transparent \( \Rightarrow \alpha = 1 \)

CP \( \Rightarrow \alpha > 1 \) at \( P_T = 4 \text{ GeV}, 90^\circ \)

\( \Rightarrow \) collective effect

first guess: constituent
multiple scattering


Claim to reproduce data
But

Constituent cross sections diverge at small momentum transfer. Must be cut off. Cut off not physically well motivated and does affect results.


⇒ theories not yet satisfactory

perhaps they need to include color screening

Data:

We calculate $\alpha$ simply via

$$R_{W/Be} = \frac{\text{Rate}(W)}{\text{Rate}(Be)} = \left( \frac{A_W}{A_{Be}} \right)^{\alpha-1}$$
\[ \sqrt{s} = 38.8 \text{ GeV} \]

- CP - Antreasyan et al., Phys. Rev. D17, 764 (1979) \( \sqrt{s} = 27 \)

A Dependence for Singles \(-0.13 < X_r < 0.14\)

\[ \alpha \]

\( P_t \) (GeV/C)

\[ \beta, \gamma, \delta \]

\( P_t \) (GeV/C)

\[ \Rightarrow \text{anomalous nuclear enhancement fades away for } P_t \geq 8 \text{ GeV} \]

\text{decreases with increasing } s \]
A Dependence for Singles

$-0.13 < x_t < 0.14$

- h$^-$ vs. $P_t$(Gev/C)
- $\pi^-$ vs. $P_t$(Gev/C)
- K$^-$ vs. $P_t$(Gev/C)
- p$^-$ vs. $P_t$(Gev/C)
Energy Dependence

$\alpha$ at $\mathbf{p}_T = 4.61 \text{ GeV}$
Can also detect pairs

\[ P \rightarrow h^+ \rightarrow N \leftarrow h^- \downarrow h^+ \]

\[ h^+, h^- \text{ without regard to identification} \]
400 GeV  • McCarthy et al., P.R.L. 40, 213 (1978)  E494
400    • Finley et al., P.R.L. 42, 1031 (1979)
70     △ Abramov et al., JETP Lett. 38, 352 (1983)
800    ■ Straub et al., Submitted to PRL  E605

\[ \text{mass (GeV)} \]

\[ h^+ h^- \]
\( \sigma_m / \mu = 0.17\% \)
\( \sigma_m = 17 \text{ MeV} \)
Summary

1. Single hadrons appear to be produced by the fragmentation of single constituents for $p_T \approx 3 \text{ GeV}$. Study propagation of quarks in nuclear matter by varying $A$.

2. Single hadron production may be consistent with multiple scattering but a better theory is needed.

3. For single hadrons the anomalous nuclear enhancement fades away for $p_T \approx 8 \text{ GeV}$.

4. For $h^+h^-$ pairs $R_{w/Be}$ rises steeply versus $p_T$. This is expected in a constituent multiple scattering model.

5. For $h^+h^-$ pairs $R_{w/Be} < 1$ for $m > 8 \text{ GeV}$. Multiple scattering models cannot accommodate [K. Kastella, private communication]