New Experimental Tools for Exploring In-Medium Parton Propagation in QCD

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- Goal: study space-time properties of parton propagation and fragmentation in QCD:
  - Characteristic timescales
  - Partonic energy loss
  - Quantum interference effects
  - Current vs. target fragmentation
  - Partonic vs. hadronic interactions
  - Color transparency
  - Eventually: hadronization mechanisms
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• Use nuclei as spatial ‘filters’ with known properties:
  • sizes, densities, currents and interactions
  • *Unique kinematic window* at low energies
  • *Simpler physical picture* at high energies
Comparison of Parton Propagation in Three Processes

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Parton propagation and fragmentation in QCD matter

\[ \phi_{f_1/N}(x, Q^2) \]

\[ \phi_{f_2/N}(x, Q^2) \]

\[ \phi_{f_1/N}(x, Q^2) \]

\[ \phi_{f_2/N}(x, Q^2) \]

\[ D_{j}^{h}(z, Q^2) \]

\[ D_{j}^{h}(z, Q^2) \]

\[ \ell \rightarrow \ell' \]

\[ j \rightarrow j' \]

\[ f_1 \rightarrow h \]

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Fundamental ingredients in perturbative picture

\[ \ell \rightarrow h \]
\[ N \]
\[ \phi_{f_1/N}(x, Q^2) \]
\[ D_{j}^{h}(z, Q^2) \]

\[ e^+ \rightarrow j \]
\[ e^- \]

\[ \ell \rightarrow D_{j}^{h}(z, Q^2) \]
\[ N \]
\[ \phi_{f_1/N}(x, Q^2) \]

\[ \ell \rightarrow j \]
\[ j \rightarrow h \]

\[ \ell' \rightarrow j' \]
\[ j' \rightarrow h \]

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Deep Inelastic Scattering - Vacuum

- **production time** $\tau_p$ - propagating quark

- **formation time** $h\tau_f$ - dipole grows to hadron

- **partonic energy loss** - $dE/dx$ via gluon radiation in vacuum
Partonic multiple scattering: *medium-stimulated* gluon emission, broadened $p_T$
Partonic multiple scattering: *medium-stimulated* gluon emission, broadened $p_T$.

Hadron forms *outside* the medium; or...
Low-Energy DIS in Cold Nuclear Medium

Hadron can form *inside* the medium; then also have prehadron/hadron interaction
Low-Energy DIS in Cold Nuclear Medium

Hadron can form *inside* the medium; then also have prehadron/hadron interaction.

Amplitudes for hadronization *inside* and *outside* the medium can interfere.
Transverse momentum broadening:
\[ \Delta p_T^2 \equiv \langle p_T^2 \rangle_A - \langle p_T^2 \rangle_D \]

⇒ *partonic!*

(R. Dupré talk)
Transverse momentum broadening:
\[ \Delta p_T^2 \equiv \langle p_T^2 \rangle_A - \langle p_T^2 \rangle_D \]

\[ \Rightarrow \text{partonic!} \]

Hadronic multiplicity ratio  
Multi-hadron multiplicity ratios
Hadron-photon correlations
Bose-Einstein correlations
Centrality correlations
more....

Deuterium target
Heavy target

not in this talk.....
Comparison of $p_T$ broadening data - Drell-Yan and DIS

- New, high-precision data with identified hadrons!
- CLAS $\pi^+$: 81 four-dimensional bins in $Q^2$, $\nu$, $z_h$, and $A$
**Quark $k_T$ broadening vs. hadron $p_T$ broadening**

The $k_T$ broadening experienced by a quark is “diluted” in the fragmentation process.

$k$ is the **quark** momentum, $p$ is the **hadron** momentum.

\[
\vec{p}_T = z\vec{k}_T + \vec{j}_T
\]

\[
\langle p_T^2 \rangle = \langle z^2 k_T^2 \rangle + \langle j_T^2 \rangle
\]

\[
\Delta \langle p_T^2 \rangle = \Delta \langle z^2 k_T^2 \rangle + \Delta \langle j_T^2 \rangle
\]

\[
\Delta \langle p_T^2 \rangle \approx z^2 \Delta \langle k_T^2 \rangle
\]

Verified for pions to 5-10% accuracy for vacuum case, $z=0.4-0.7$, by monte carlo studies.
Basic questions at low energies:

Partonic processes dominate, or hadronic? in which kinematic regime? classical or quantum?

Can identify dominant hadronization mechanisms, uniquely? what are the roles of flavor and mass?

What can we infer about fundamental QCD processes by observing the interaction with the nucleus?

If $p_T$ broadening uniquely signals the partonic stage, can use this as one tool to answer these questions
New: dependence of $p_T$ broadening on Feynman $x$

- Feynman $x$ is the fraction $\pi p_L/\max\{\pi p_L\}$ in the $\gamma^*-N$ CM system
- Separate current ($x_F>0$) and target ($x_F<0$) fragmentation
- First observation that $p_T$ broadening originates in both regimes

$X_F>0$

$3.4<q<4, 1<Q^2<2$

$\Delta p_T^2 (GeV^2)$

$Z_{\pi^+}$

$Z$ vs. $X_F$

• $X_F$ and $z_h$ are partially correlated
New: dependence of $p_T$ broadening on Feynman $x$

- Feynman $x$ is the fraction $\pi p_L / \max{\pi p_L}$ in the $\gamma^*-N$ CM system.
- Separate current ($x_F>0$) and target ($x_F<0$) fragmentation.
- First observation that $p_T$ broadening originates in both regimes.

$X_F>0$ and $z_h$ are partially correlated.
New: dependence of $p_T$ broadening on $\phi_{pq}$

- Expectation within classical picture: any distribution seen in carbon will become more ‘washed out’ in heavier nuclei
- Not seen! first observation of quantum effect in $p_T$ broadening
  - related to parton density fluctuations in larger nuclei? J. Qiu: Boer-Mulders TMD $\otimes D^h_j(z, Q^2)$ in presence of non-vanishing dipole moment

**Curves shown contain terms in $\cos(\phi_{pq})$ and $\cos(2\phi_{pq})$**

**Only statistical uncertainties shown**
Production Time Extraction - Geometrical Effects

Quark Path Length * Nuclear Density vs. A^{1/3}

- $L_p = 20$ fm
- $L_p = 5$ fm
- $L_p = 3$ fm
- $L_p = 2$ fm
- $L_p = 1$ fm
- $L_p = 0.5$ fm

Mass number to the 1/3 power ($A^{1/3}$) vs. Quark Path Length * Nuclear Density
Production Time Extraction - Geometrical Effects

Quark Path Length * Nuclear Density vs. $A^{1/3}$

![Graph showing the relationship between quark path length and nuclear density for different values of $L_p$.](image)
Production Time Extraction - Geometrical Effects

Quark Path Length $\times$ Nuclear Density vs. $A^{1/3}$

- $L_p = 20$ fm
- $L_p = 5$ fm
- $L_p = 3$ fm
- $L_p = 2$ fm
- $L_p = 1$ fm
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Mass number to the $1/3$ power ($A^{1/3}$) vs. Quark Path Length $\times$ Nuclear Density
Production Time Extraction - Geometrical Effects

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Production Time Extraction - Geometrical Effects

Quark Path Length $\times$ Nuclear Density vs. $A^{1/3}$

<table>
<thead>
<tr>
<th>Mass number to the 1/3 power ($A^{1/3}$)</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>2.5</th>
<th>3</th>
<th>3.5</th>
<th>4</th>
<th>4.5</th>
<th>5</th>
<th>5.5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z$_i$-Scaled Broadening (GeV$^2$)</td>
<td>0</td>
<td>0.05</td>
<td>0.1</td>
<td>0.15</td>
<td>0.2</td>
<td>0.25</td>
<td>0.3</td>
<td>0.35</td>
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</table>

Fits of Z-Scaled Broadening vs. $A^{1/3}$

- $Q^2=3$ GeV$^2$, $\nu=3.5$ GeV, $Z=0.45$
- $Q^2=3$ GeV$^2$, $\nu=3.5$ GeV, $Z=0.55$
- $Q^2=3$ GeV$^2$, $\nu=3.5$ GeV, $Z=0.65$

JLab/CLAS preliminary
Geometrical model
Geometrical model

- Three-parameter model:
  - scale factor (∼proportional to transport coefficient)
  - production time (distributed exponentially)
  - effective absorption cross section
Geometrical model

- Three-parameter model:
  - scale factor (~proportional to transport coefficient)
  - production time (distributed exponentially)
  - effective absorption cross section
- Fourth parameter: quark dE/dx, also explored
Geometrical model

- Three-parameter model:
  - scale factor (~proportional to transport coefficient)
  - production time (distributed exponentially)
  - effective absorption cross section
- Fourth parameter: quark dE/dx, also explored
- Simultaneous fit of $p_T$ broadening and multiplicity ratio in the same 3-fold kinematic bin in $Q^2$, $\nu$, and $z$
Geometrical model

- **Three-parameter model:**
  - scale factor (∼proportional to transport coefficient)
  - production time (distributed exponentially)
  - effective absorption cross section
- **Fourth parameter:** quark dE/dx, also explored
- **Simultaneous fit** of $p_T$ broadening and multiplicity ratio in the same 3-fold kinematic bin in $Q^2$, ν, and z
- **Realistic nuclear densities**
  - Path begins at point with probability proportional to density
  - Part of path is quark, part of path is (pre-) hadron
Results from combined fit
3 or 4 parameter geometric model
various bins in $Q^2$, $\nu$, and $z$
fits are consistent with $\tau_p = 1.6 - 2$ fm/c ($<R_{\text{carbon}}/c$)
**Distributions of lengths within the medium for \( L_p = 1.6 \) fm**

**Partonic lengths**

- **Carbon**
  - Mean = 1.46 fm

- **Iron**
  - Mean = 1.53 fm

- **Lead**
  - Mean = 1.56 fm

**Hadronic lengths**

- **Carbon**
  - Mean = 3.1 fm

- **Iron**
  - Mean = 4.6 fm

- **Lead**
  - Mean = 6.5 fm
Hadronic broadening or partonic broadening?

$p_T$ broadening for Pb does not show any strong trend with pion energy, while hadronic elastic scattering cross section changes by an order of magnitude.
Expect some $Q^2$ dependence if there is partonic broadening.
No evidence of hadronic broadening - no peak at low energies, and carbon (N=Z) flatter than lead (N>>Z)
New: exploring a **direct measurement** of quark energy loss using $\pi^+$ energy spectrum

- Order of magnitude can be estimated from theory as $\sim 100$ MeV/fm, although factors of up to 10 are disputed

- Measurements of energy loss in cold nuclear matter have been attempted with 800 GeV protons

- $6 \text{ fm} \times 100 \text{ MeV/fm} = 600 \text{ MeV}$ ...not easy to see with Drell-Yan muon pairs from 800 GeV protons on tungsten; but should be ‘easy’ to see with 2 GeV pions produced in DIS
How to *directly* measure quark energy loss?

- Energy loss is predicted on very solid grounds to be *independent of energy* for a medium that is thin enough.
- “Thin enough” depends on energy, see next slide; if medium is thicker than “thin enough” it still loses energy.
- If the energy loss is independent of energy, it will produce a *shift* of the energy spectrum, for higher energies.
- We can look for a *shift* of the Pb energy spectrum compared to that of the deuterium energy spectrum.
Energy Loss in pQCD
(BDMPS-Z version)

\[ L < L_{\text{Critical}} \]
\[ - \frac{dE}{dx} \propto L \hat{q} \]

\[ L > L_{\text{Critical}} \]
\[ - \frac{dE}{dx} \propto \sqrt{E \hat{q}} \]

\[ \Delta E \]

\[ L \]

\[ L_{\text{Critical}} \]

at \( L = L_{\text{Critical}} \), \( L \hat{q} \propto \sqrt{E_q \cdot \hat{q}} \); \( L_{\text{Critical}} \propto \sqrt{\frac{E_q}{\hat{q}}} \)

\( E_q \approx \nu \approx \text{few GeV}, \hat{q} \approx 0.02 - 0.1 \text{ GeV}^2/\text{fm}, \)

\[ \sqrt{\frac{E_q}{\hat{q}}} \approx R_{\text{lead}} - R_{\text{carbon}} \]
Energy Loss in pQCD
(BDMPS-Z version)

\[ L < L_{\text{Critical}} \]
\[- \frac{dE}{dx} \propto L\hat{q} \]

\[ L > L_{\text{Critical}} \]
\[- \frac{dE}{dx} \propto \sqrt{E\hat{q}} \]

\[ \Delta E \]

\[ L_{\text{Critical}} \]

at \( L = L_{\text{Critical}} \), \( L\hat{q} \propto \sqrt{E_q \cdot \hat{q}} \); \( L_{\text{Critical}} \propto \sqrt{\frac{E_q}{\hat{q}}} \)

\[ E_q \approx \nu \approx \text{few GeV}, \ \hat{q} \approx 0.02 - 0.1 \text{ GeV}^2/\text{fm}, \]

(H. Ma talk)
(P. Gossiaux talk)
(S. Peigne talk)

“Coherent Radiative Parton Energy Loss beyond the BDMPS-Z Limit,” Zapp, Wiedemann 1202.1192
“Medium-induced emissions of hard gluons,” Apolinário, Armesto, Salgado 1204.2929
Full lineshapes, deuterium and Pb (CLAS EG2 data) with and without cut on \( x_{\text{Feynman}} \) (normalized to area 1.0)

\[
\begin{array}{|c|c|c|}
\hline
\text{Nu*Zh+0.} & \{\text{Nu*Zh>0.&&Nu*Zh<2.5-0.&&TargType==2}\} \\
\hline
\text{Entries} & 3345761 & \text{Mean} \\
& & 0.6749 \\
\hline
\text{RMS} & 0.4723 & \\
\hline
\end{array}
\]

\[
\begin{array}{|c|c|c|}
\hline
\text{d} & \\
\hline
\text{Entries} & 3181258 & \text{Mean} \\
& & 1.302 \\
\hline
\text{RMS} & 0.5012 & \\
\hline
\end{array}
\]
Minimize difference between shifted fitted spectra

Results look promising, but more systematic study of the shape analysis is needed.

Early indications suggest that energy loss $\Delta E \lessgtr \text{perturbative formula} \times L_p$

\[ \frac{dE}{dx} = \frac{\alpha_s N_c}{4} \Delta p_T^2 \]
Future Prospects

• p-A in 2012:
  • FNAL - E906, 120 GeV fixed-target Drell-Yan, commissioning now, running ~2013  J-C Peng talk
  • LHC: ATLAS, CMS, ALICE, LHCb: currently Oct 31-Nov 23, 5 TeV per NN collision

• e-A:
  • JLab - 11 GeV upgraded CLAS12, ~2015-2018  R. Dupré talk
  • EIC - Electron-Ion Collider  R. Ent talk
  • LHeC?

• A-A
  • RHIC, ongoing
  • LHC, 2015 (short run in 2012?)
New: p-Pb at the LHC

- p-Pb collisions tentatively planned for 2012
- 2011 accelerator feasibility test successful
- hoping for luminosities at level $1.5 \times 10^{29} \text{ cm}^{-2} \text{ s}^{-1}$
- beyond baseline for heavy ions: rich physics program!

- Saturation of partonic densities at low $x$, e.g. $R_{pPb}$
- Photon Drell-Yan
- Cronin effect (‘low’ $p_T$ behavior of $R_{pPb}$)
- Nuclear PDFs - jets (dijets, low energy?), EW bosons, prompt photons, quarkonia
- Ultrapерipheral collisions
- Modification of jets/hadronization process in-medium
- Cosmic-ray physics at ultra-high energies
Injected 2 bunches of protons, then 2 bunches of Pb ions
Ramped to full energy (4.4 TeV CM)
Forced both beams to same revolution frequency
Changed relative phase to synchronize collisions at the IPs

No collisions yet, but all ingredients proven to work!
LHC p-Pb: Recent Papers
(partial list: participants/organizers! apologies for omissions)


“Revisiting scaling properties of medium-induced gluon radiation,” Arleo, Peigne, Sami, 1006.0818

“Nuclear suppression of J/Psi: from RHIC to the LHC,” B.Z. Kopeliovich, I.K. Potashnikova, I. Schmidt


“Workshop: pA@LHC,” CERN, 4-8 June 2012, Weidemann, Strikman, Salgado

“QCD saturation at the LHC: comparisons of models to p+p and A+A data and predictions for p +Pb collisions” Tribedy, Venugopalan 1112.2445

“Prompt photon production and photon-hadron correlations at RHIC and the LHC from the Color Glass Condensate,” Jamal Jalilian-Marian, Amir H. Rezaeian, 1204.1319
DIS channels: stable hadrons, accessible with 11 GeV JLab experiment PR12-06-117
DIS channels: *stable* hadrons, accessible with 11 GeV JLab experiment PR12-06-117

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DIS channels: *stable* hadrons, accessible with 11 GeV
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Actively underway with existing 5 GeV data

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Electron Ion Collider

Simulation by R. Dupre
more at http://arxiv.org/abs/1108.1713v2
Electron Ion Collider

Example of one possibility at EIC - comparing partonic energy loss in light and heavy quark systems

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Conclusions
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• New tools:
  • $p_T$ broadening as *partonic* probe in nuclear systems
  • Direct measurement of quark energy loss
  • TeV parton beams to probe cold nuclear matter in p-A
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• $p$-$Pb$ collisions are coming this year at the LHC: parton propagation with TeV beams!
Backup Slides
Accessible energies and CM rapidities

Possible range of collision energies
Minimum p-Pb energy for equal revolution frequency.

Relations between these numbers are a simple consequence of the two-in-one magnet design

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<tbody>
<tr>
<td>$E / \text{TeV}$</td>
<td>0.45-7</td>
<td>287-574</td>
<td>(2.7-7, 287-574)</td>
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<tr>
<td>$E_{\text{cm}} / \text{TeV}$</td>
<td>0.45-7</td>
<td>1.38-2.76</td>
<td>(2.7-7, 1.38-2.76)</td>
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<tr>
<td>$\sqrt{s} / \text{TeV}$</td>
<td>7-14</td>
<td>73.8-1148</td>
<td>48.9-126.8</td>
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<td>$\sqrt{s_{\text{NN}}} / \text{TeV}$</td>
<td>7-14</td>
<td>0.355-5.52</td>
<td>3.39-8.79</td>
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<tr>
<td>$y_{\text{CM}}$</td>
<td>0</td>
<td>0</td>
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<tr>
<td>$y_{\text{NN}}$</td>
<td>0</td>
<td>0</td>
<td>+0.46</td>
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Charges $Z_1$, $Z_2$ in rings with magnetic field set for protons of momentum $p_p$

$\sqrt{s_{\text{NN}}} \approx 2c p_p \sqrt{\frac{Z_1 Z_2}{A_1 A_2}}$

$y_{\text{NN}} = \frac{1}{2} \log \frac{Z_1 A_2}{A_1 Z_2}$

J.M. Jowett, Europhysics Conference on High-Energy Physics, Grenoble, 23/7/2011
Preliminary 2012 LHC schedule for ion running

$z^2 l_p = z^2 \cdot z \frac{(ln(\frac{1}{z^2}) - 1 + z^2)}{1 - z^2}$

$\ln(\frac{1}{z^2}) - 1 + z^2$

Production length $l_p \sim \Delta p_T$ for thick medium

Additional $z^2$ factor converts quark broadening into hadron broadening. Expect to see the red curve in data (vs. $z$)
Exploring a *direct measurement* of quark energy loss using $\pi^+$ energy spectrum - *next steps*

- Radiative corrections
- Believe the results if:
  - robust, not sensitive to cuts
  - works over a wide energy range
  - the match in shape is extremely accurate
  - can’t find any other explanation for the shift
Some variations, but no systematic evidence for influence of resonance region
Radiative Corrections

\[ \text{HAPRAD\_CPP} = \text{HAPRAD}(2) + \text{Modified structure fnc from fit}(x, Q^2, z, p_T, \varphi) \text{ to CLAS data} \]

**RC coefficients in 5 dimensional bins**

\[ p_T^2 \text{ without radiative correction (red) and the same with radiative correction (black)} \]

Distribution of the RC coefficients calculated for \( 3(Q^2)x3(v)x3(z)x60(p_T)x\varphi(12) \) equidistant points

\[ \text{HAPRAD\_CPP code: } \]
\[ \text{https://github.com/usm-data-analysis/HAPRAD\_cpp} \]


H.Hakobyan, Sebastián Mancilla, Ricardo Oyarzun
Hermes $p_T$ broadening data

World’s first comparison between pion and $K^+$ $p_T$ broadening
Multiplicity ratios, fully corrected for radiative processes and acceptance, normalized to target thicknesses, not corrected for EMC effect
SIDIS

\[ Q^2 = -q^2 \] four-momentum transferred by the electron (1-4)GeV^2;
\[ v = E-E' \] (lab) energy transferred by the electron (1-4.2)GeV;
\[ z = \frac{E_h}{v} \] fraction of initial quark energy carried by hadron;
\[ p_T \] hadron momentum transverse to \( \gamma^* \) direction;
\[ \phi \] angle between leptonic and hadronic planes

CLAS/DIS kinematics: \( Q^2 > 1 \text{ GeV}^2, \ W > 2 \text{ GeV} \); 0.1 < x < 0.55, y < 0.85
\[ E_{\text{beam}} = 5 \text{ GeV} \]
Heuristic form for production length

\[ \tau_p \propto \nu \cdot z \cdot (1 - z) \left\| \frac{dE}{dx} \right\|_{\text{vacuum+medium}} \]

with \( z \equiv z_{\text{hadron}} = \frac{E_{\text{hadron}}}{\nu} \)

This form explicitly demonstrates the connection between the production length and the vacuum energy loss process.
Consistency between measured $\Delta E$ and the energy loss estimated from $p_T$ broadening

Pb: $\Delta E = 575$ MeV
(uncorrected for acceptance and radiation)

Pb $p_T$ broadening $\sim 0.04$ GeV$^2$ for $z=0.5$
production length found is 1.6 fm

$$\frac{dE}{dx} = \frac{\alpha_s N_c}{4} \Delta p_T^2$$

$$= \frac{0.5 \cdot 3}{4} \cdot \frac{0.04}{0.5^2} \text{ GeV}^2 \cdot 1.6 \text{ fm} \cdot \frac{1}{0.2 \text{ GeVfm}} = 0.5 \text{ GeV}$$
CEBAF Large Acceptance Spectrometer

- Charged particles angles 8°-144°
- Neutral particles angles 8°-70°
- Identification of e+/e-, γ, p, n, π+/π-, K+/K−

CLAS EG2

- Electron Beam 5.014 GeV
- Luminosity (1.3-2)10^{34} 1/s·cm^2
- Targets ²H, ¹²C, ⁵⁶Fe, ²⁰⁷Pb
Experimental details

Solid target
Carbon fiber

Liquid D₂
Rohacell foam scattering chamber

EG2 Experiment target in GEANT3
Solid (C, Al, Fe, Sn, Pb) target simultaneously with deuterium target

Quark Propagation and Hadron Formation with 11 GeV Beam

Dependency of observables (and thus derived quantities, such as production time, formation times, transport coefficient, in-medium cross section, etc.) on mass, flavor, and number of valence quarks.
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<td>4.4% (sys)</td>
</tr>
<tr>
<td>$p$</td>
<td>stable</td>
<td>0.94</td>
<td>ud</td>
<td>3.2% (sys)</td>
</tr>
<tr>
<td>$\bar{p}$</td>
<td>stable</td>
<td>0.94</td>
<td>ud</td>
<td>5.9% (stat)$^{**}$</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>79 mm</td>
<td>1.1</td>
<td>uds</td>
<td>4.1% (sys)</td>
</tr>
<tr>
<td>$\Lambda(1520)$</td>
<td>13 fm</td>
<td>1.5</td>
<td>uds</td>
<td>8.8% (sys)</td>
</tr>
<tr>
<td>$\Sigma^+$</td>
<td>24 mm</td>
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<td>us</td>
<td>6.6% (sys)</td>
</tr>
<tr>
<td>$\Sigma^-$</td>
<td>44 mm</td>
<td>1.2</td>
<td>ds</td>
<td>7.9% (sys)</td>
</tr>
<tr>
<td>$\Sigma^0$</td>
<td>22 pm</td>
<td>1.2</td>
<td>uds</td>
<td>6.9% (sys)</td>
</tr>
<tr>
<td>$\Xi^0$</td>
<td>87 mm</td>
<td>1.3</td>
<td>us</td>
<td>16% (stat)$^*$</td>
</tr>
<tr>
<td>$\Xi^-$</td>
<td>49 mm</td>
<td>1.3</td>
<td>ds</td>
<td>7.8% (stat)$^*$</td>
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</table>

$^*$in a bin in z from 0.7-0.8, integrated over all $\nu, p_T, \phi_{pq}$, and $Q^2>5$ GeV$^2$

$^{**}$in a bin in z from 0.6-0.7, integrated over all $\nu, p_T, \phi_{pq}$, and $Q^2>5$ GeV$^2$
Quark Propagation and Hadron Formation with 11 GeV Beam

<table>
<thead>
<tr>
<th>hadron</th>
<th>cτ</th>
<th>mass</th>
<th>flavor content</th>
<th>limiting error (60 PAC days)</th>
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<tbody>
<tr>
<td>π⁺</td>
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<td>π⁻</td>
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<tr>
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<tr>
<td>φ</td>
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<td>udūdss</td>
<td>5.0% (stat)*</td>
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<tr>
<td>f1</td>
<td>8 fm</td>
<td>1.3</td>
<td>udūdss</td>
<td>-</td>
</tr>
<tr>
<td>K⁰</td>
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<td>0.50</td>
<td>ds</td>
<td>4.7% (sys)</td>
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<tr>
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<td>us, us</td>
<td>4.4% (sys)</td>
</tr>
<tr>
<td>p</td>
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<td>0.94</td>
<td>ud</td>
<td>3.2% (sys)</td>
</tr>
<tr>
<td>̄p</td>
<td>stable</td>
<td>0.94</td>
<td>ud</td>
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</tr>
</tbody>
</table>

Dependency of observables (and thus derived quantities, such as production time, formation times, transport coefficient, in-medium cross section, etc.) on mass, flavor, and number of valence quarks.

*in a bin in z from 0.7-0.8, integrated over all ν, pT, φpq, and Q²>5 GeV²
**in a bin in z from 0.6-0.7, integrated over all ν, pT, φpq, and Q²>5 GeV²