Direct Measurement of Initial-State Energy Loss in Cold Nuclear Matter at Fermilab E906/SeaQuest

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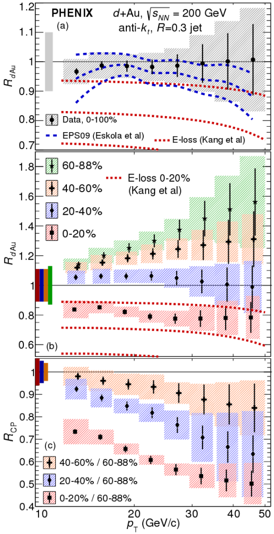
Jet quenching and cold nuclear matter

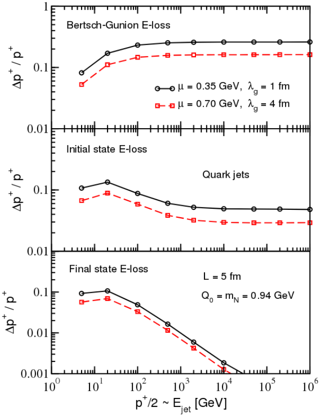
- Jet quenching in heavy-ion collisions is a key probe of the QGP
- R_{AA} shows clear suppression in $A + A$ relative to $p + p$, attributed to parton energy loss in final-state interaction
- But cold nuclear matter effects also contribute:
  - Nuclear modification of PDFs
  - Parton energy loss in initial-state interaction
- $p + A$, $d + A$ at RHIC/LHC are used to benchmark CNM effects
  - We see modification relative to $p + p$: what is the cause?



Adare et al, Phys. Rev. Lett. 116, 122301 (2016)

Initial-state energy loss

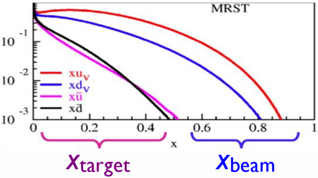
- Models suggest significant radiative energy loss in CNM, initial-state energy loss in particular
- Energy loss is certainly not the whole story in cold nuclear matter, but we must understand it
  - CNM energy loss is a crucial benchmark for QGP measurements
  - Fixed-target experiments (SIDIS, Drell-Yan) have unique power in isolating effects

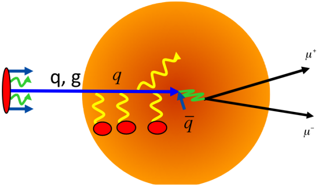


Vitev, Phys.Rev. C75, 064906 (2007)

Energy loss measurement with Drell-Yan

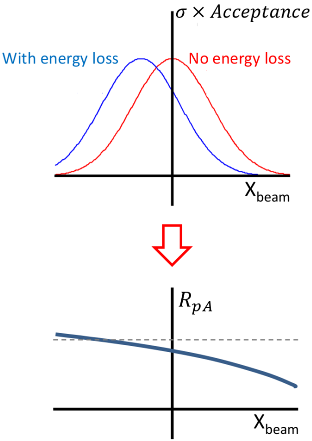
- Quark (antiquark) in beam proton annhilates with antiquark (quark) in target nucleus
  - Fixed-target spectrometer (large x_{beam}) selects beam valence quark and target sea antiquark
- Beam quark is subject to initial-state energy loss; dimuon final state interacts minimally with medium (EM interaction, much weaker than strong interaction)
- Different models of initial-state energy loss predict different nuclear dependence:
  - Gavin and Milana: $\Delta x_{beam} = -\kappa_1 x_{beam} A^{1/3}$
  - Brodsky and Hoyer: $\Delta x_{beam} = -\frac{\kappa_2}{s} A^{1/3}$
  - Baier et al: $\Delta x_{beam} = -\frac{\kappa_3}{s} A^{2/3}$





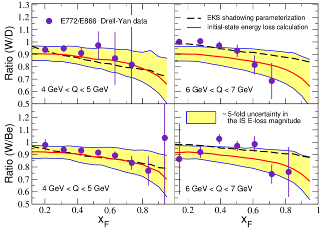
Energy loss measurement with Drell-Yan

- Measure DY rate with different nuclear targets: D or C target with negligible energy loss (and minimal isospin effects), and a range of heavier targets
- The beam parton loses energy, shifting x_{beam}: measurable as nuclear modification $R_{pA} = \frac{\sigma^{pA}}{A\sigma^{pD}}$
  - Expect steeply falling R_{pA} at large x_{beam} or x_F



Previous DY measurement: E772/E866

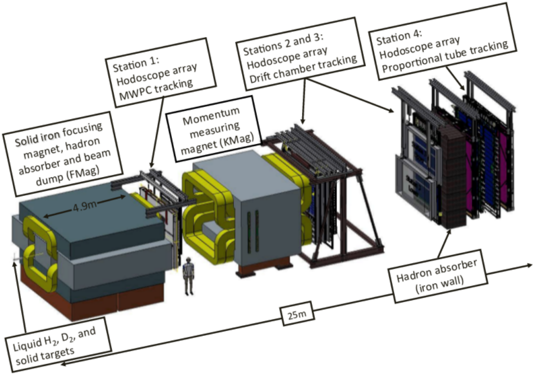
- Measured $R_{pA}(x_F)$ using Be, Fe, W targets and the 800 GeV Tevatron proton beam, and observed significant nuclear modification
- Drell-Yan acceptance covered $x_{beam} \in [0.21, 0.95]$, $x_{target} \in [0.01, 0.12]$
  - Small $x_{target} \rightarrow$ substantial shadowing in the target nuclear PDF
- Interpretations of the result differ:
  - All shadowing, no measurable energy loss: Vasiliev et al., PRL 83 (1999)
  - Different shadowing model shows significant energy loss: Johnson et al., PRC 65 025203 (2002)
- A lower beam energy would access larger x_{target} and avoid shadowing



Neufeld et al., Phys. Lett. B 704 (2011) 590

The E906/SeaQuest experiment

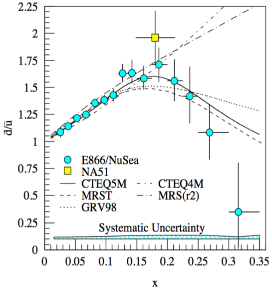
- Fixed-target muon spectrometer, 120 GeV Main Injector proton beam
- Thin ($\sim 10\% \lambda_I$) rotating targets: LH2, LD2, C, Fe, W
- Iron-filled dipole magnet focuses muons and absorbs everything else
- Drift chambers for tracking, scintillator hodoscopes for trigger

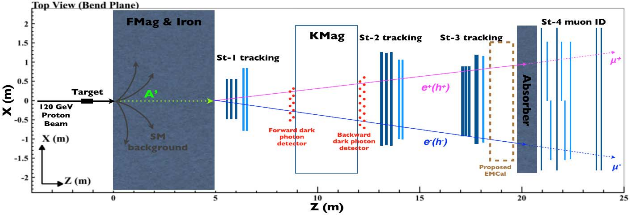


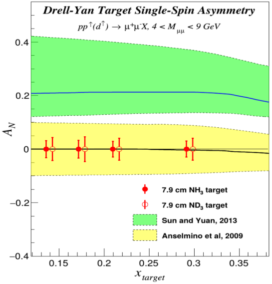
arXiv:1706.09990

Other SeaQuest programs

- Flavor asymmetry of sea quarks: extend E866/NuSea measurement to larger x (other E906 focus)
- Sea quark Sivers function, using polarized target (E1039, coming soon!)
- Dark photon search: parasitic search for BSM physics (started during E906 and will continue)

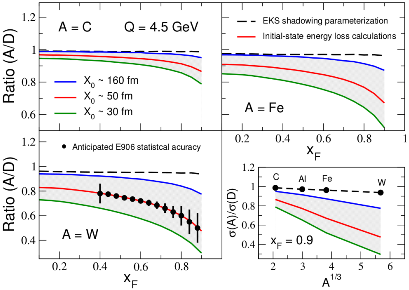






Expectations for E906

- Drell-Yan acceptance covers $x_{beam} \in [0.4, 0.9]$, $x_{target} \in [0.1, 0.4]$
- Avoids the shadowing region of the nuclear PDFs: nuclear dependence is clearly due to energy loss
- x_{beam} range of 50–100 GeV is relevant to parton energies at RHIC and LHC



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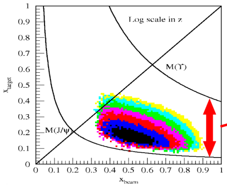
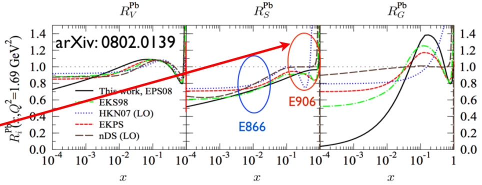
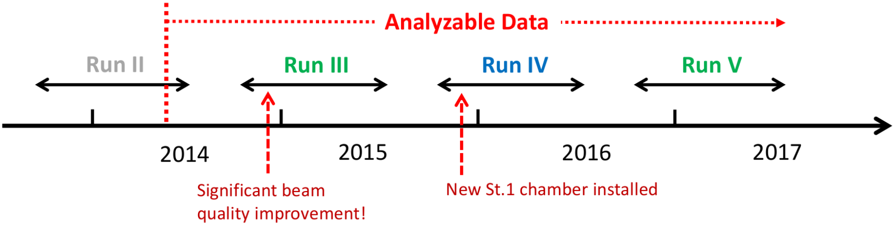




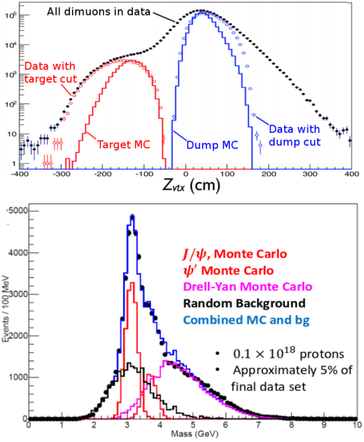
E906 timeline

- First beam in 2012, first production-quality data in 2014
- Steady detector and beamline improvements
- Data taking ended July 2017
  - Transitioning to E1039, with the same spectrometer but new polarized target



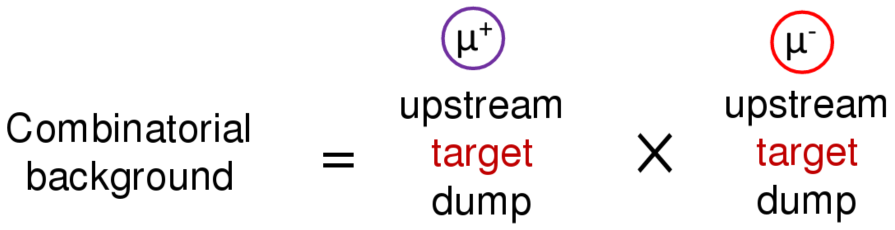
Analysis

- Our observable is the Drell-Yan cross-section $\sigma^{pA}_{DY}(x_F)$ for each target
  - Cuts reject dimuons from the beam dump
  - Correct for detector and reconstruction efficiencies
  - Use mass cuts and fits to isolate Drell-Yan rate from charmonia and coincidence background



Coincidence background

- Random coincidences share the Drell-Yan kinematic range
- Simulate coincidences using event mixing: take μ^- and μ^+ from different events ("mixed data")
- What is the correct normalization of the mixed data?
  - Insufficient statistics in like-sign dimuon data
- Does the mixed data accurately reflect the coincidence background?

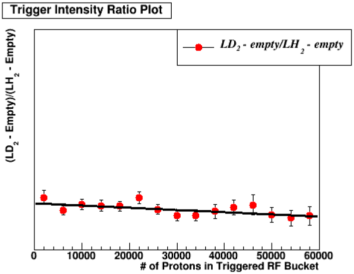


Rate dependence

- Main Injector shows strong bunch-by-bunch intensity variations: beam intensity monitor vetoes high-intensity buckets and records event-by-event intensity
- At high occupancies, we lose chamber hit efficiency and track reconstruction efficiency
  - We embed simulated Drell-Yan events in random-triggered data events to measure the intensity-dependent efficiency
- There should be no coincidence background at zero intensity; coincidence "cross-section" should scale with intensity
  - We can use this directly (extrapolate to zero intensity) to extract the rate of true dimuons, but at a statistical penalty
  - We can extract the coincidence background, and use it to check and normalize the mixed data

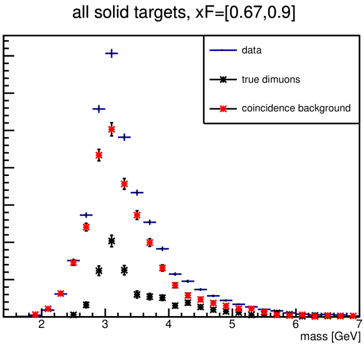
Extrapolation to zero intensity

- We could use intensity extrapolation to get the cross-sections for each target, and take ratios
- Since what we really want is a ratio of two cross-sections, we can extrapolate the ratio instead
  - Avoid systematic effects
- Working on understanding the correct functional form and treatment of errors



Extraction of coincidence background

- Correct for luminosity and efficiencies, then a linear fit vs. intensity gives us both the true dimuon and coincidence background distributions
- Validating this technique:
  - Comparing coincidence background to mixed data
  - Comparing true dimuon distribution to charmonia and DY Monte Carlo



The outlook for 2019

- E906 energy loss analysis is making good progress on the key analysis issues; we expect a result this year
- E1039 will take first beam this year
  - Crucial test of sea quark orbital angular momentum
  - Dark photon program continues, with first physics data for a world-leading BSM search
  - Collaborators welcome!