# Probe Cold Nuclear Matter Effects in Fixed Target Experiments with Hadron Beams

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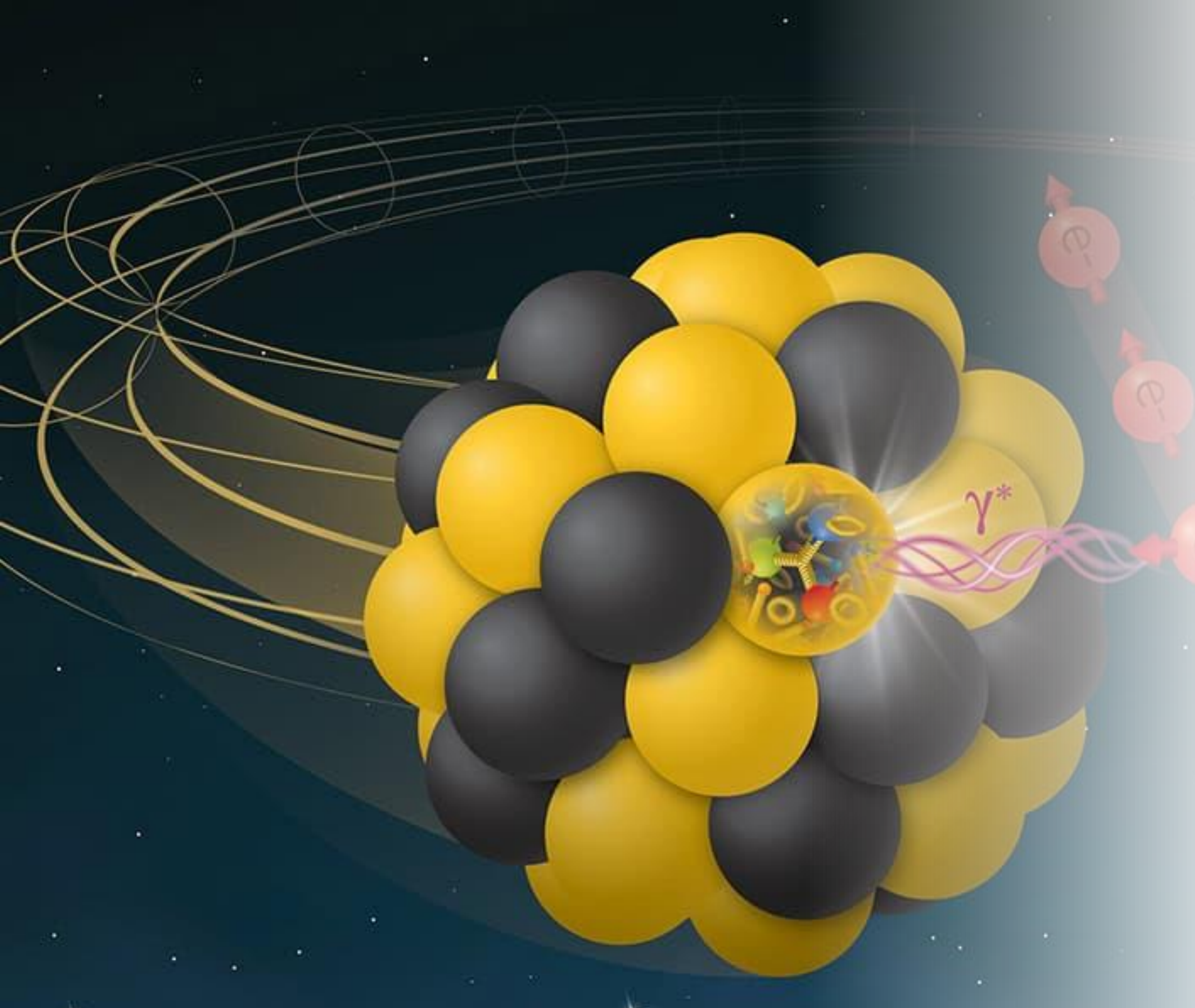
Workshop on Cold Nuclear Matter Effects: from LHC to EIC
January 13-16, 2025




# Outline

- Not a review, but selected topics for discussions
- Experimental efforts
  - BNL, FNAL, CERN, DESY …
- Big questions and EIC

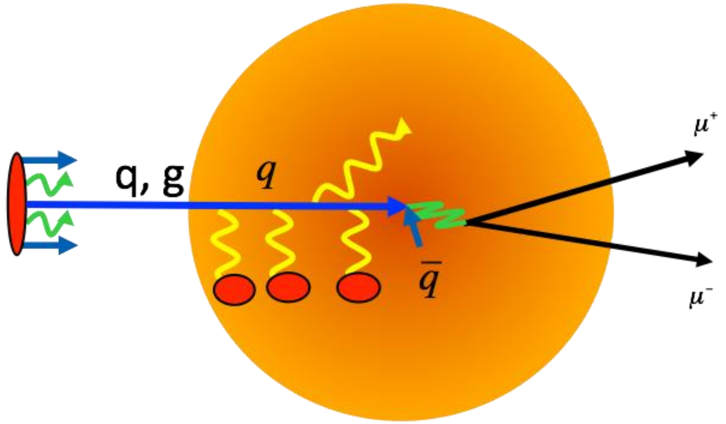
# Cold-Nuclear Matter, and QGP

**High energy "pA" collisions:**
Nuclear modification factor $R_{pA}$,
- many contributing factors

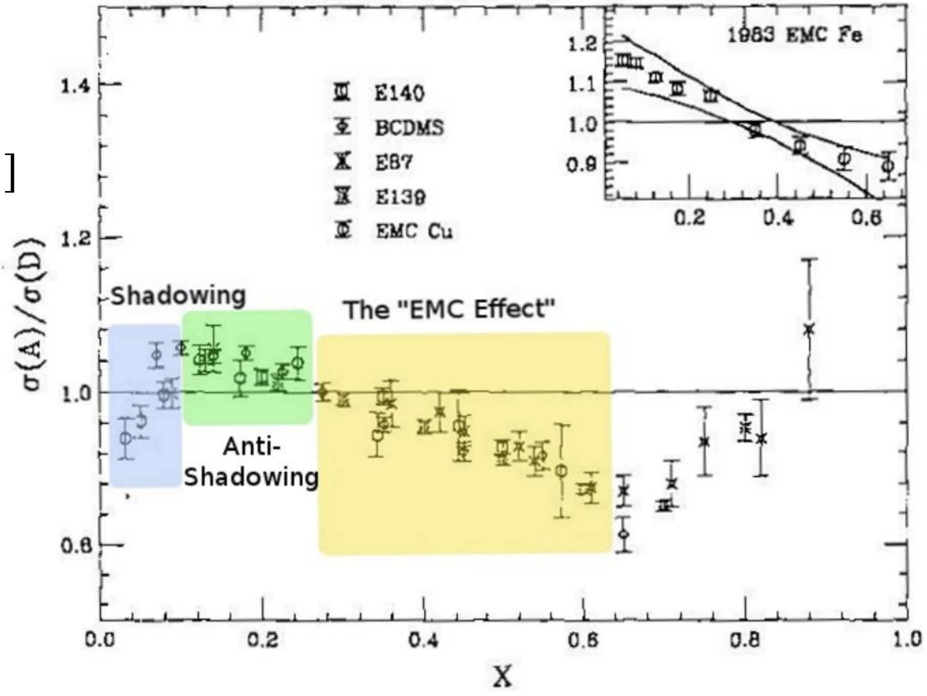
$$R_{pA} = \frac{1}{A} \frac{d\sigma_{pA}}{dyd^2p_T} \Big/ \frac{d\sigma_{pp}}{dyd^2p_T}$$

Drell-Yan in p+A: the simplest hard process
- nPDF modification
- Initial state interactions

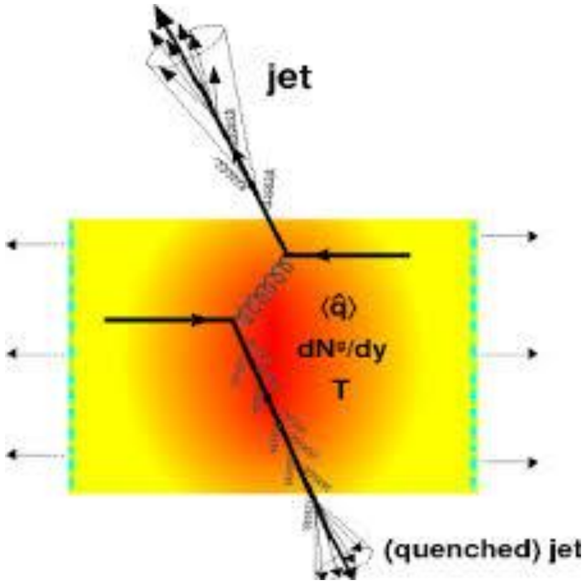
$$\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{9xbxt} \sum e^2 \left[qb(x_b)\bar{q}_t(x_t) + \bar{q}_b(x_b)q_t(x_t)\right]$$

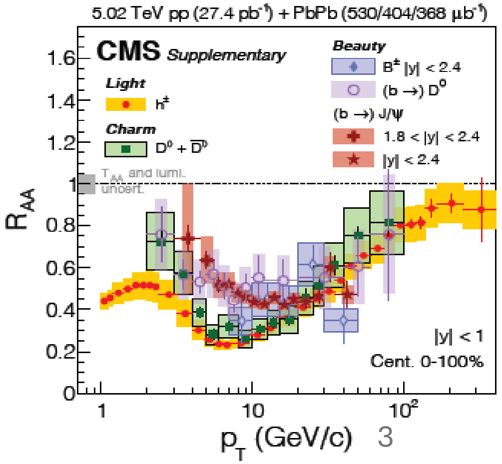



Very rich physics from CNM already!



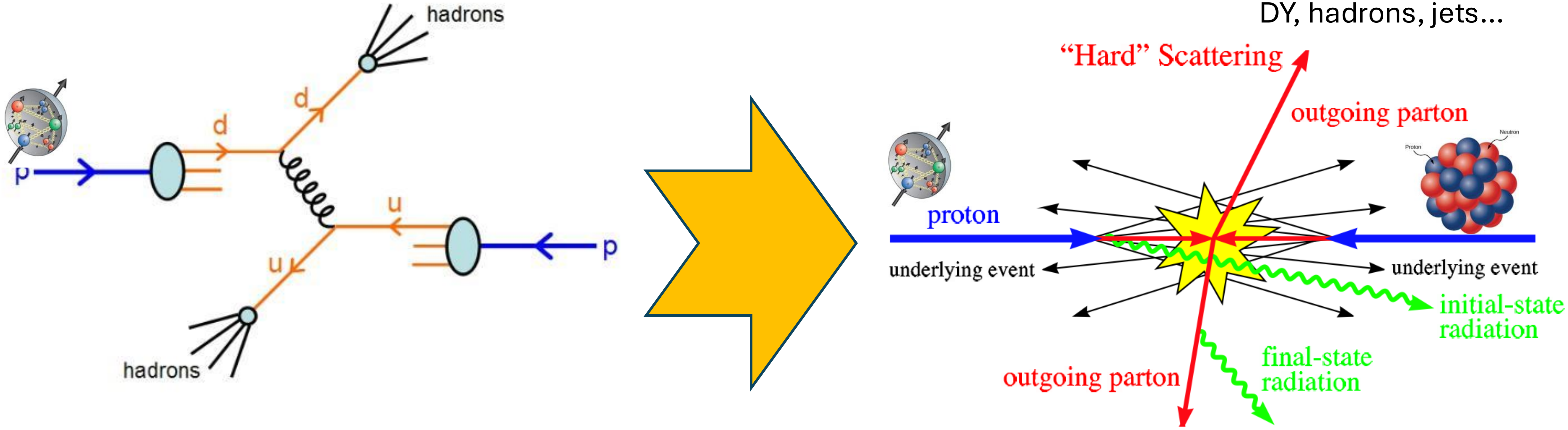

**AA collisions:**
Nuclear modification R_AA dominated by final state interactions with QGP



# Hard Probes for CNM Study - pQCD at High Energy

- ***pA study "simple" medium: static, known density profile …***
- *Very complex p+p/A collisions could be simplified for hard-scattering processes, pQCD applicable*




$\sigma \sim f(x_1) \otimes f(x_2)\hat{\sigma}^{x_1+x_2 \to h_1+h_2+X}$ **& CNM Effects…**

**CNM: nPDF, initial/final state interactions; dynamic nuclear shadowing, Saturation at small-x …**

# Key Findings and Our Understanding of the CNM Physics

- It has been a long way to get to this point ....

**1. Nuclear Modification of Parton Distribution Functions (PDFs)**

- **Shadowing** and **anti-shadowing**: At low parton momentum fraction x, the nuclear PDFs can be reduced (shadowing), while at slightly higher x, they can be enhanced (anti-shadowing).
- **EMC effect**: At intermediate to large x, modifications to the quark distributions in nuclei lead to the well-known EMC slope and depletion patterns.

**2. Multiple Scattering (Cronin Effect)**

- When high-energy partons traverse a nucleus, they undergo multiple soft scatterings, leading to an observed broadening of transverse momentum distributions (the "Cronin effect").
- This effect helps disentangle initial-state from final-state modifications, since p+A systems are not expected to form a hot quark–gluon plasma but still exhibit momentum broadening due to cold matter interactions.

**3. Initial- vs. Final-State Interactions**

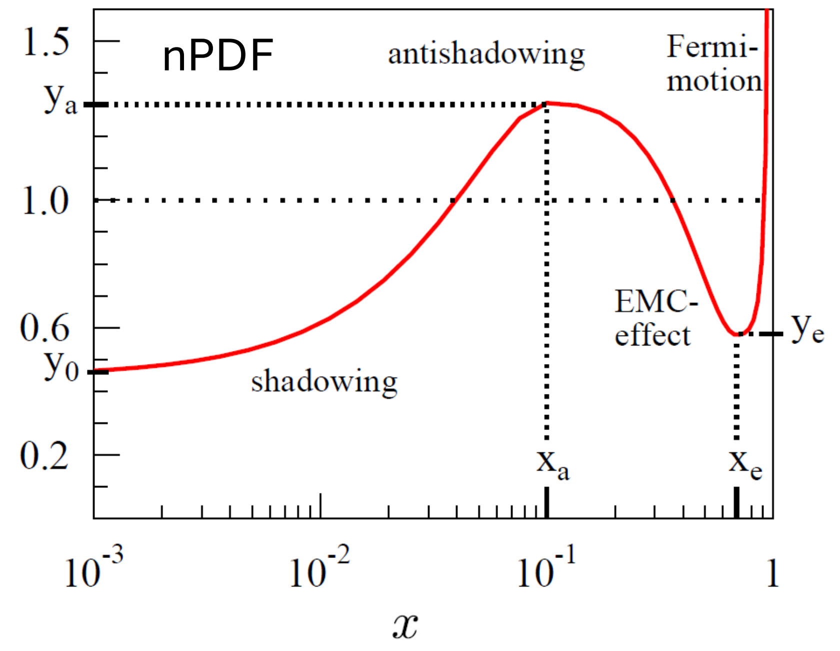
- **Initial-state effects**: Parton scattering and nuclear PDF modifications that happen before the hard scattering process.
- **Final-state effects**: Interactions that occur after the parton has scattered, such as energy loss in cold nuclear matter or absorption of quarkonia (e.g., charmonium, bottomonium) within the nucleus before hadronization is complete.

**Quarkonium Suppression and Modification**

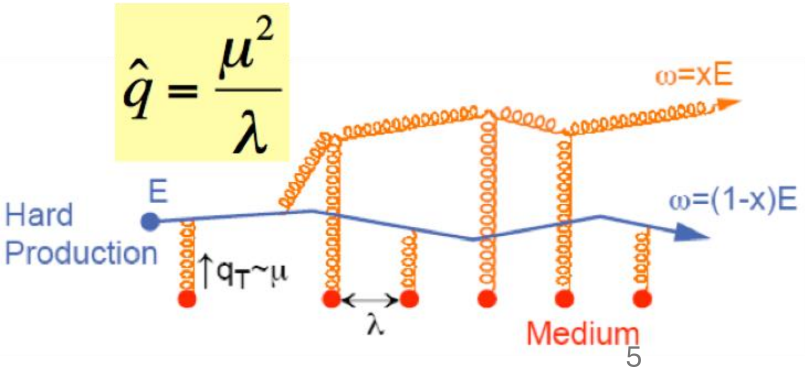
- Studies of bound states of heavy quarks (e.g., J/\psi, \Upsilon families) in p+A collisions have revealed significant nuclear-dependent suppression patterns unrelated to the hot medium found in A+A collisions.
- These can arise from breakup of pre-resonant quark–antiquark pairs in the nucleus, as well as from modifications to gluon PDFs at small x.

**Energy Dependence and Kinematic Reach**

- Across different collision energies (from fixed-target to RHIC to LHC), the relevance of shadowing, saturation, and gluon-density effects changes, illustrating the complexity of nuclear effects as a function of energy and momentum fraction.




Parton multiple scattering in medium



# Some Fixed Target "CNM Physics" Experiments in the last 30 Years

| Experiment | Lab | Beam (Energy) | Operation | Key CNM Topics |
|---|---|---|---|---|
| E910 | BNL (AGS) | $p$, 6–12.9 GeV/$c$ | 1996–1999 | Hadron production on nuclear targets |
| E772 | FNAL | $p$, 800 GeV | 1987–1988 | Drell–Yan, $J/\psi$ nuclear dependence |
| E789 | FNAL | $p$, 800 GeV | 1988–1989 | Heavy-flavor production, nuclear dependence |
| E866/NuSea<br>E906/E1039 | FNAL | $p$, 800 GeV | 1996–1997 | Drell–Yan, quarkonium in $pA$, sea-quark asym. |
| NA50/NA38 | CERN (SPS) | $p$ (400–450 GeV) + heavy ions | 1994–2000 (NA50) | Dimuon production ($J/\psi$, Drell–Yan) in $pA$ and $AB$ |
| NA60 | CERN (SPS) | $p$ (400 GeV) + heavy ions | 2002–2004 | Low-mass dimuons, charm in $pA$ reference |
| NA61/SHINE | CERN (SPS) | $p, \pi, K$ (13–400 GeV/$c$) | 2007–present | Hadroproduction for nuclear targets (CNM, hadron yields) |
| COMPASS (NA58)<br>AMBER (NA66) | CERN (SPS) | $\pi, p, K$ (up to ~280 GeV/$c$) | 2002–present (hadron program ~2008+) | Drell–Yan nuclear dependence, hadron spectroscopy |
| HERA-B | DESY (HERA) | $p$ (920 GeV, beam halo) | 1999–2003 | Quarkonium ($J/\psi$) production in $pA$ |

A long history of fixed target experiments:
https://www.phy.bnl.gov/history/experiments.php

# BNL, pre-RHIC at AGS

## E910 (AGS)

- **Beam / Energy**: Proton beam, 6–12.9 GeV/c
- **Targets**: Be, Cu, Au, and others
- **Goals**: Measure particle production (charged hadrons, strangeness) in pA collisions to study (among other topics) how hadronic processes scale with nuclear size. Although modest in energy compared to the SPS or Tevatron, E910 data have been used to tune models of hadronic reinteractions and nuclear effects.
- **Data-taking period**: **1996–1999**

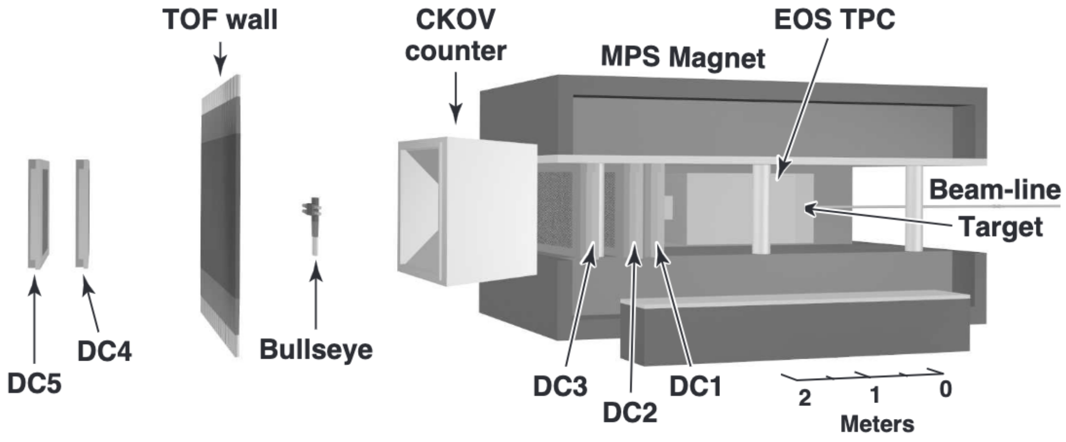



FIG. 2: The E910 spectrometer layout.

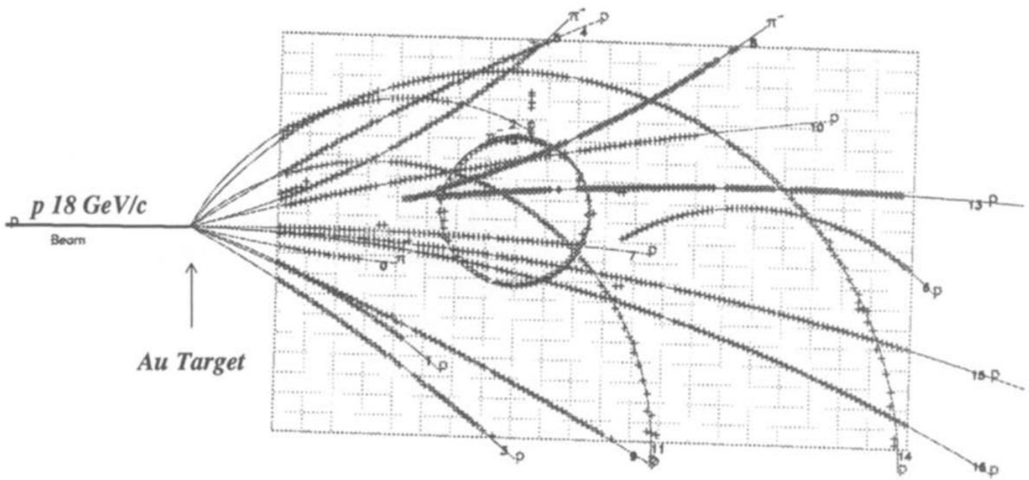



Figure 2. A sample E910 p-Au event with a Λ decaying in the TPC

# Fermilab: Dimuon Exp.

## 1. E772

- **Beam / Energy**: 800 GeV protons
- **Targets**: H, Be, C, Ca, Fe, and W
- **Goals**: Measured Drell–Yan and quarkonium (J/psi, psi') production to study nuclear dependence and parton energy loss in nuclear matter.
- **Data-taking period**: **1987–1988**

## 2. E789

- **Beam / Energy**: 800 GeV protons
- **Targets**: Be, Cu, Au
- **Goals**: Focused on heavy-flavor production (J/psi, open charm) and its nuclear dependence.
- **Data-taking period**: **1988–1989** (mostly overlaps with E772 era)

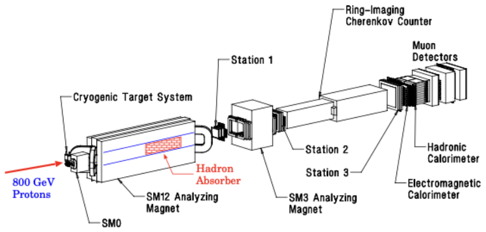
## 3. E866 / NuSea

- **Beam / Energy**: 800 GeV protons
- **Targets**: H, D, Be, Fe, W
- **Goals**:
- Drell–Yan measurements to extract the \bar{d}/\bar{u} asymmetry in the proton.
- Proton–nucleus studies of nuclear dependence in Drell–Yan and quarkonium production (continuing E772/E789 line of research).
- **Data-taking period**: **1996–1997**

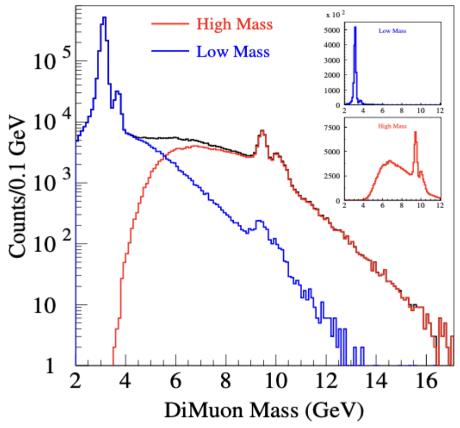
## 4. E906/E1039 (on-going, more later)

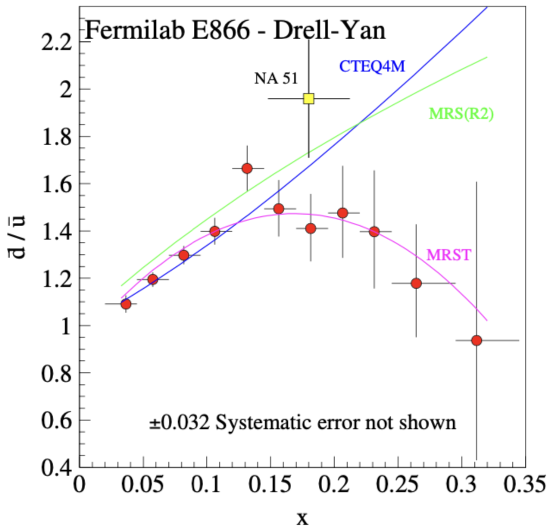
**A measurement of $\bar{d}(x)/\bar{u}(x)$**
**Antiquark asymmetry in the Nucleon Sea**
**FNAL E866/NuSea**

ACU, ANL, FNAL, GSU, IIT, LANL, LSU, NMSU, UNM, ORNL, TAMU, Valpo.




800 GeV $p + p$ and $p + d \to \mu^+\mu^- X$




**Also, E769 / E791 / E706** (briefly)

- These experiments used mainly **pion/kaon beams** (in the 200–600 GeV range) on nuclear targets to study hadroproduction of charm or direct photons, with some emphasis on nuclear effects. Most were active in the late 1980s to mid-1990s.
- Operation periods varied roughly **1987–1995** depending on the specific experiment.

# CERN (SPS North Area)

1. **NA50 / NA38**

   • **Beam / Energy**: Primarily heavy-ion beams at 158–200 GeV per nucleon, but they also took **400–450 GeV proton** data on nuclear targets.

   • **Goals**: Studied dimuon production (J/psi, psi', Drell–Yan) in pA, AB collisions to explore quarkonium suppression mechanisms, parton energy loss, and other CNM effects.

   • **Data-taking period**:

   • NA38: ~1986–1990 (heavy-ion focus, but with some pA)

   • NA50: ~**1994–2000** (included significant pA reference runs)

2. **NA60**

   • **Beam / Energy**: Primarily 158 GeV/n heavy ions from the SPS, but also took some **proton–nucleus** data.

   • **Goals**: Detailed dimuon production studies (including low-mass dileptons and charm). The pA data served as a crucial baseline for heavy-ion results and to investigate cold nuclear matter effects.

   • **Data-taking period**: **2002–2004**

3. **NA61/SHINE**

   • **Beam / Energy**: Various hadron beams (protons, pions, kaons) at **13–400 GeV/c**, depending on the run.

   • **Targets**: p, Be, C, O, Pb, Xe, etc.

   • **Goals**: Systematic study of hadron production in p + A, pi + A, and nucleus–nucleus collisions for neutrino beam predictions (for T2K) and cosmic-ray physics, as well as to understand baryon stopping, strangeness production, and nuclear effects at different energies. Although often associated with hadroproduction for neutrino experiments, these data are also used to study cold nuclear matter effects.

   • **Data-taking period**: **2007–present**

4. **COMPASS (NA58) /AMBER (NA66)** – Hadron Program

   • **Beam / Energy**:

     • Muon beams (160–200 GeV/c) for spin-structure studies.

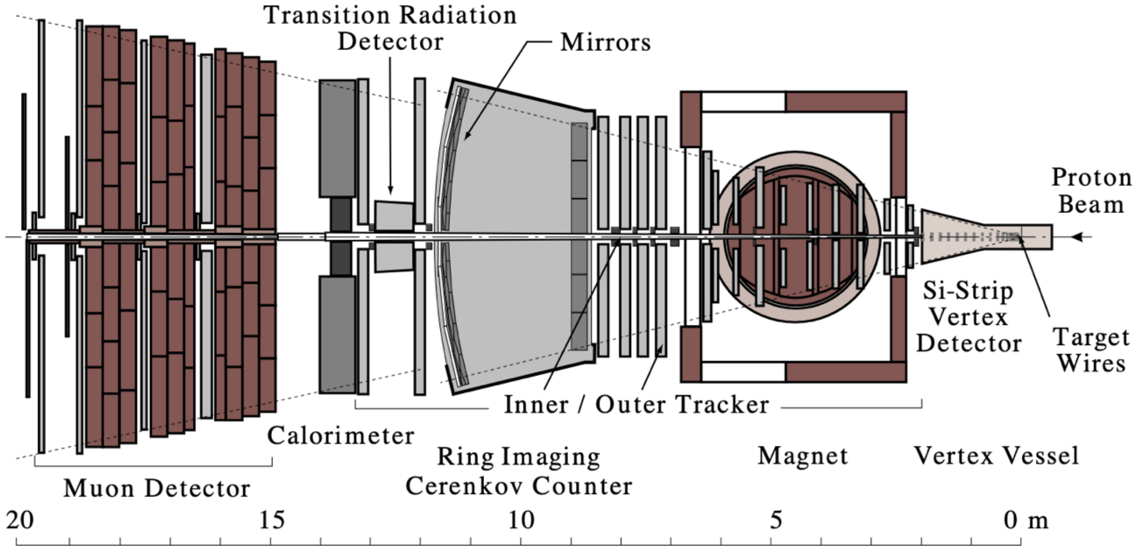
     • **Hadron beams** (pions, protons, kaons) typically in the 100–280 GeV/c range for hadron spectroscopy and hadron–nucleus scattering.

   • **Targets**: Mostly polarized targets for the muon program, but also nuclear targets (e.g., Pb, W) in the hadron program.

   • **Goals**: Investigate partonic structure via Drell–Yan with pion beams on nuclear targets, measure GPDs, study exotic mesons, etc. Some runs specifically examined nuclear dependence in Drell–Yan.

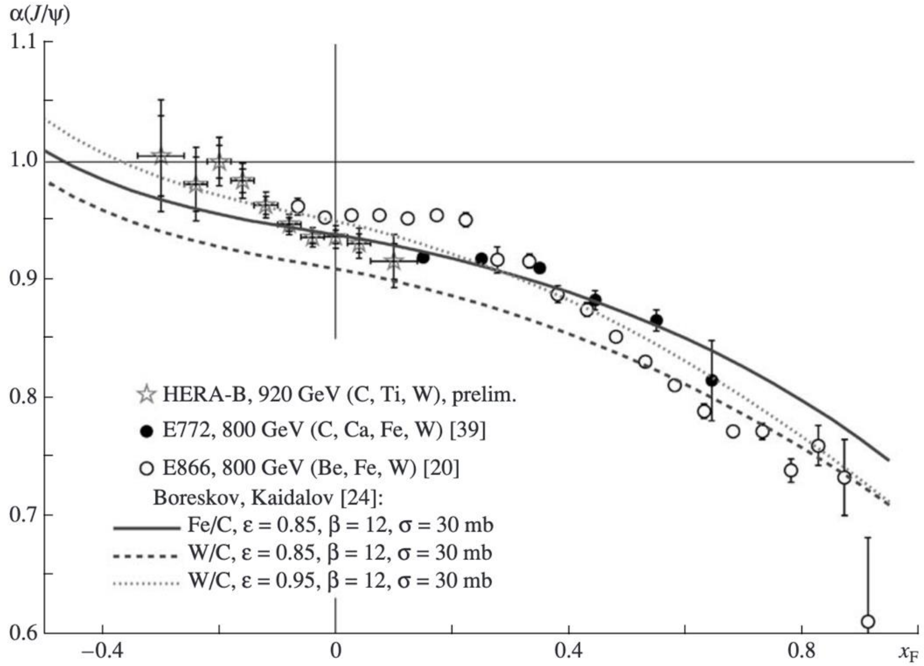
   • **Data-taking period**: Started in **2002**, with dedicated hadron running in various periods from ~**2008** onward.

# HERA-B (DESY)




**HERA-B**

- **Beam / Energy**: 920 GeV proton beam (halo)
- **Targets**: W, C, Ti, Al (thin wire targets)
- **Goals**: Originally designed to measure B-meson production in a high-rate environment, HERA-B also collected important data on J/psi and psi' production in pA collisions. These measurements were used to study nuclear suppression, parton shadowing, and overall CNM effects at high energy.
- **Data-taking period**: **1999–2003**

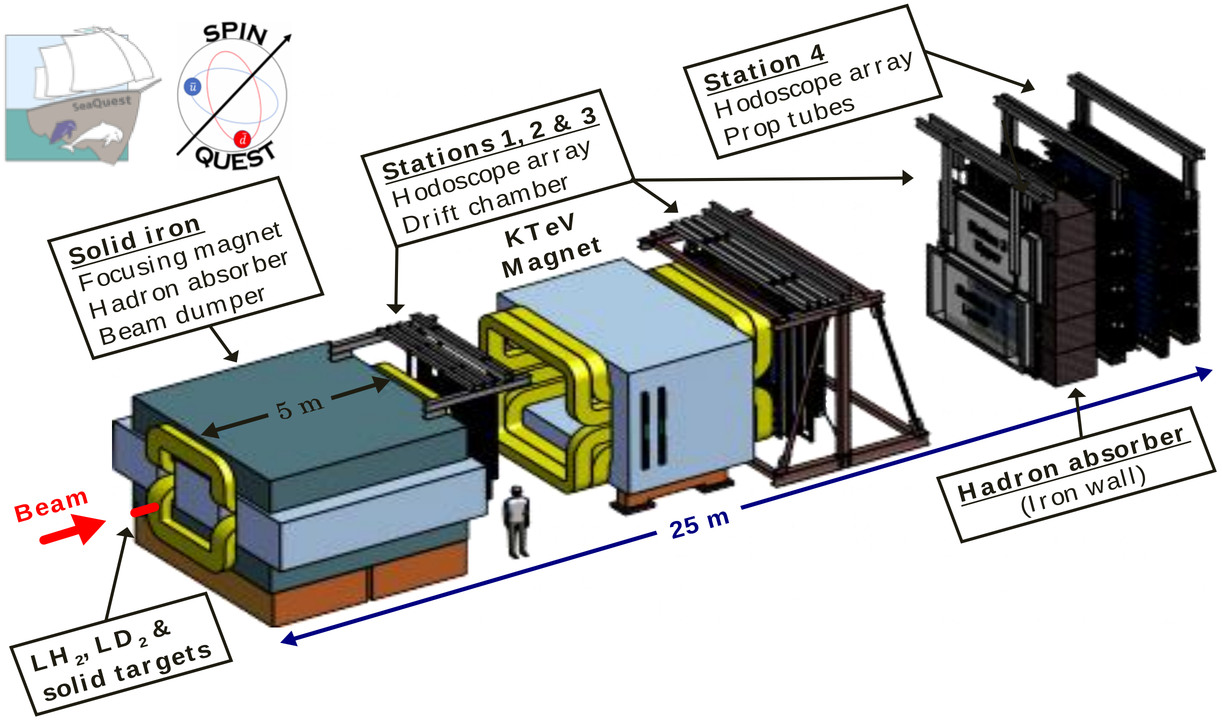



Nuclear suppression parameter α:

$$\frac{\sigma_{pA_2}}{\sigma_{pA_1}} = \left(\frac{A_2}{A_1}\right)^{\alpha}$$

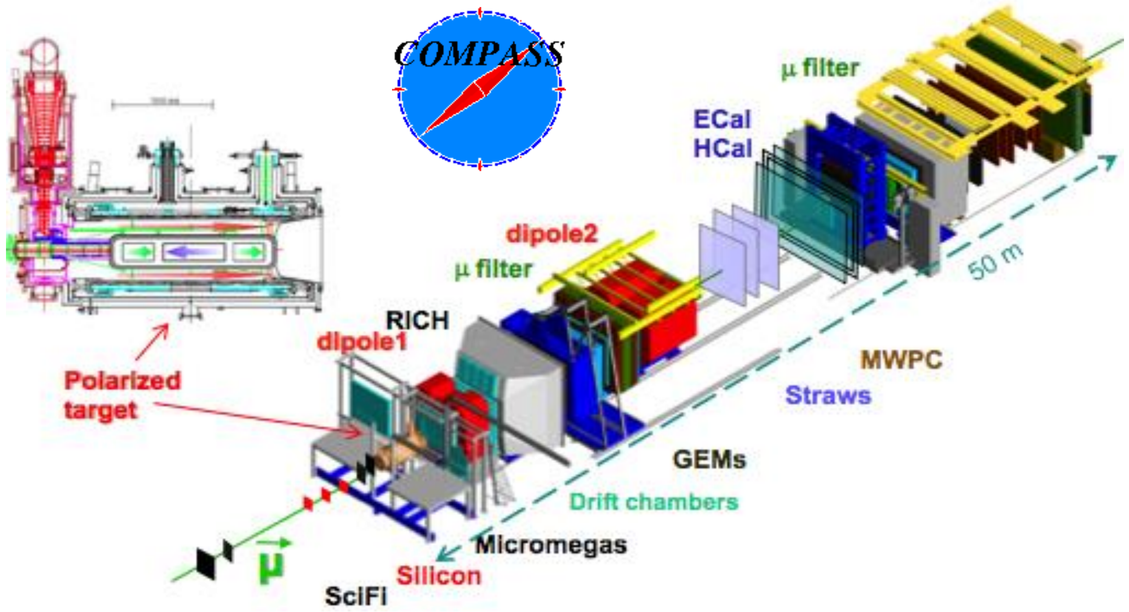
# Active Fixed Target Experiments with Hadron Beams for CNM

## SeaQuest/SpinQuest at FNAL




## COMPASS/AMBER at CERN

AMBER
Apparatus for Meson and Baryon Experimental Research



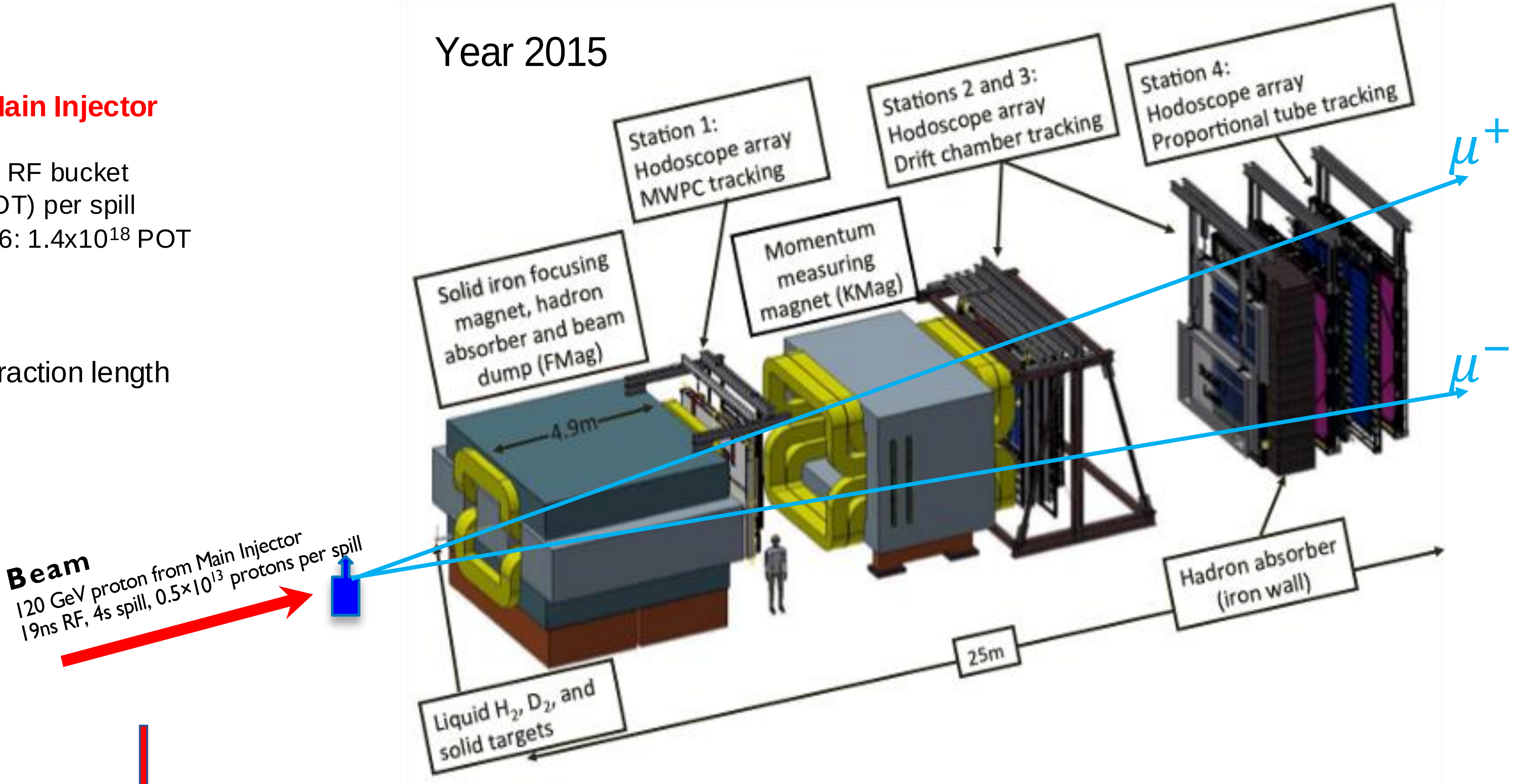
# SeaQuest/E906 Dimuon Spectrometer

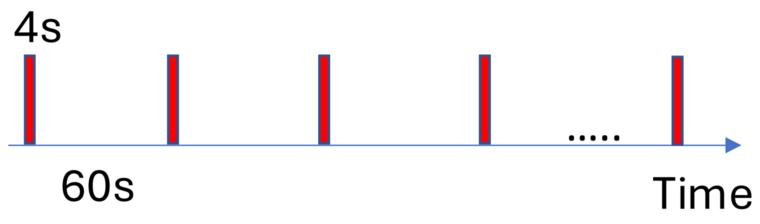
**120 GeV protons from the Main Injector**

- 4s beam spill very 60 sec
- 19ns RF, ~10s K protons per RF bucket
- $5x10^{12}$ Proton On Target (POT) per spill
- Total integrated POT for E906: $1.4x10^{18}$ POT

**Thin targets:**

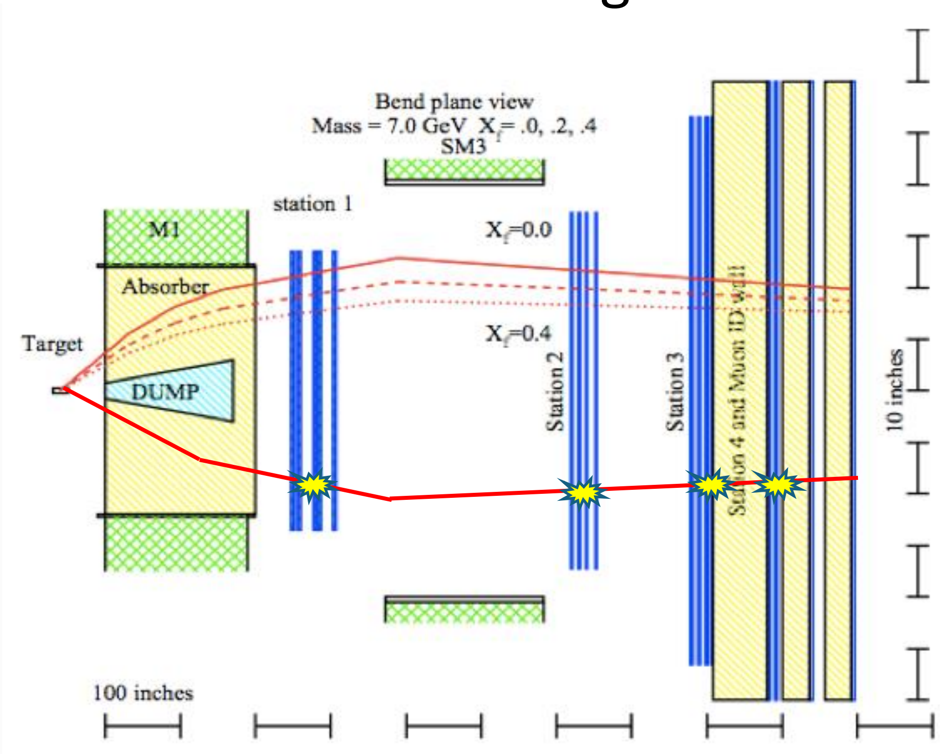
- $^{1}H$, $^{2}D$, $^{12}C$, $^{56}Fe$, $^{184}W$
- About 10% of nuclear interaction length

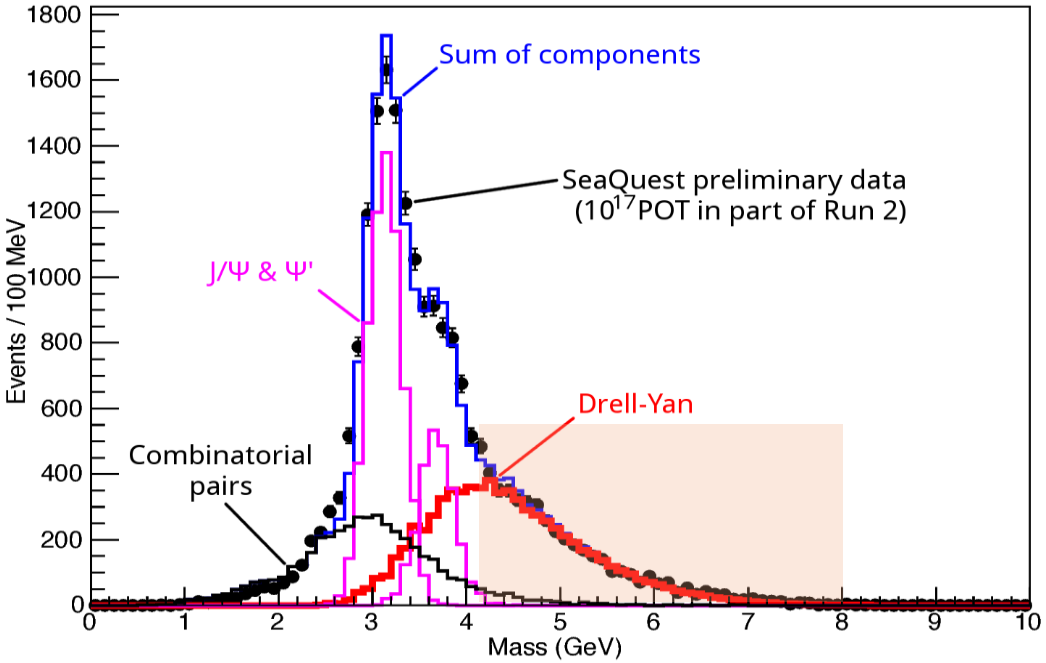


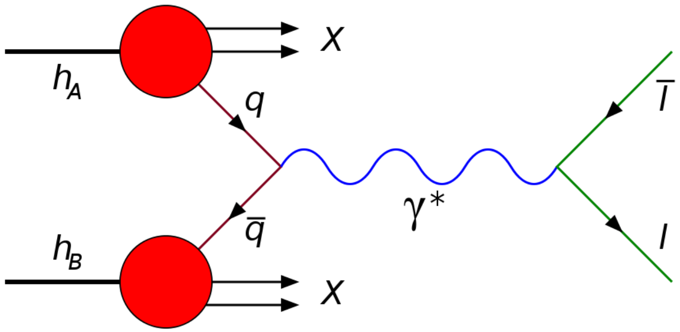
# SeaQuest/SpinQuest: Nuclear Physics with Drell-Yan

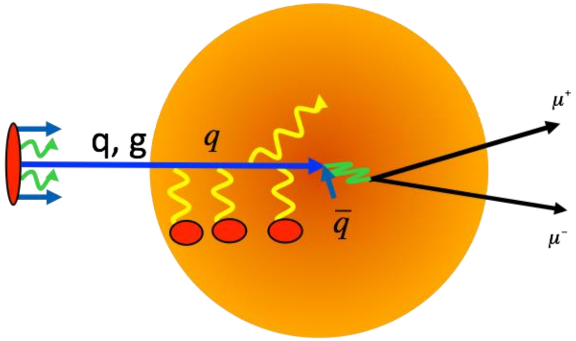
Data Taking: 2008-2017(E906), 2024-2025+(E1039)




High mass Drell-Yan:
4<M<8 GeV

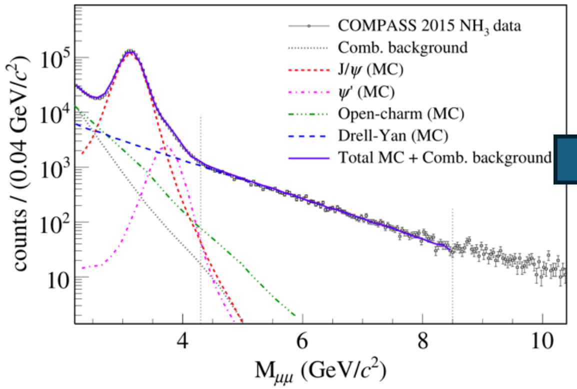


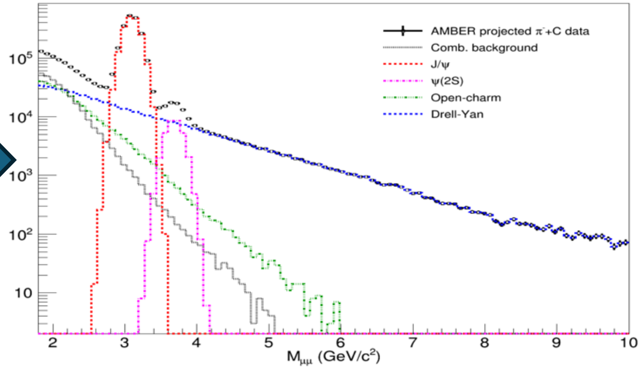




Quark Energy Loss dE/dx in p+A collisions

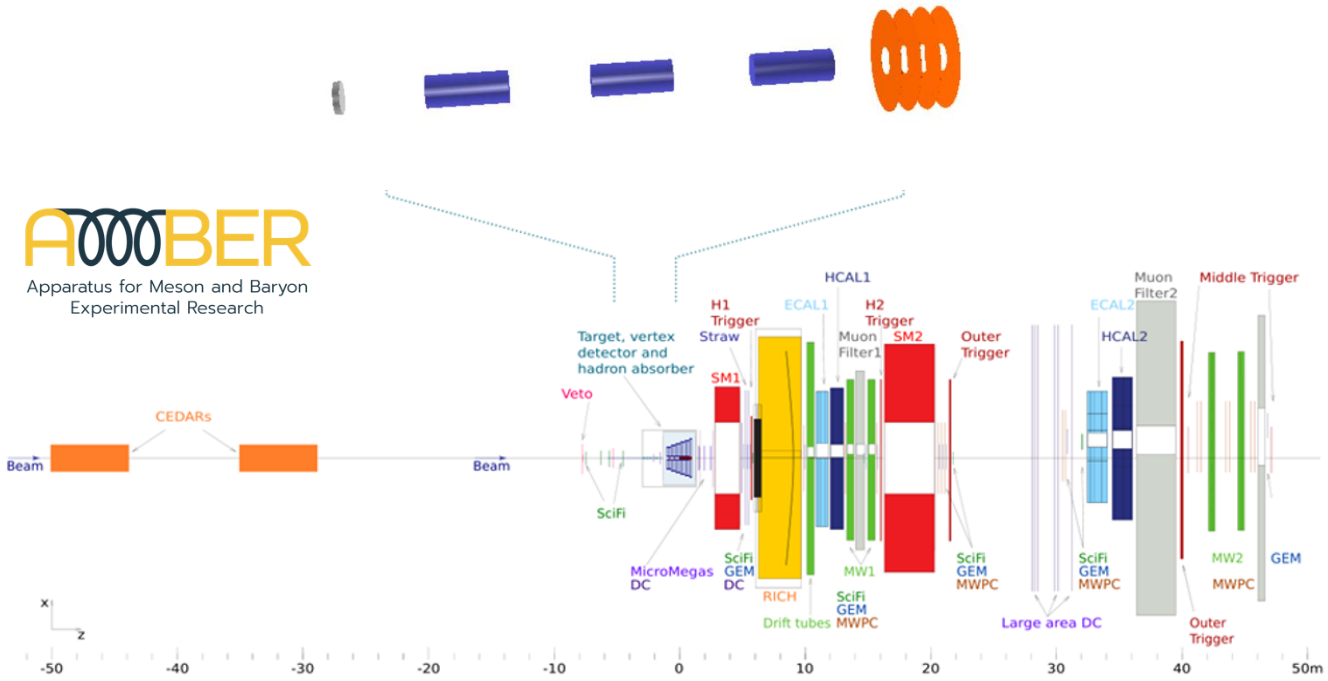
# AMBER DY and Charmonia Program

- A new silicon strip vertex detector right after the last carbon target to improve the vertex and mass reconstruction
- Prototype detector planed for 2025 pilot run, and full detector planed for the long run after LS3
- H,D, and Solid targets possible




AMBER
Apparatus for Meson and Baryon Experimental Research



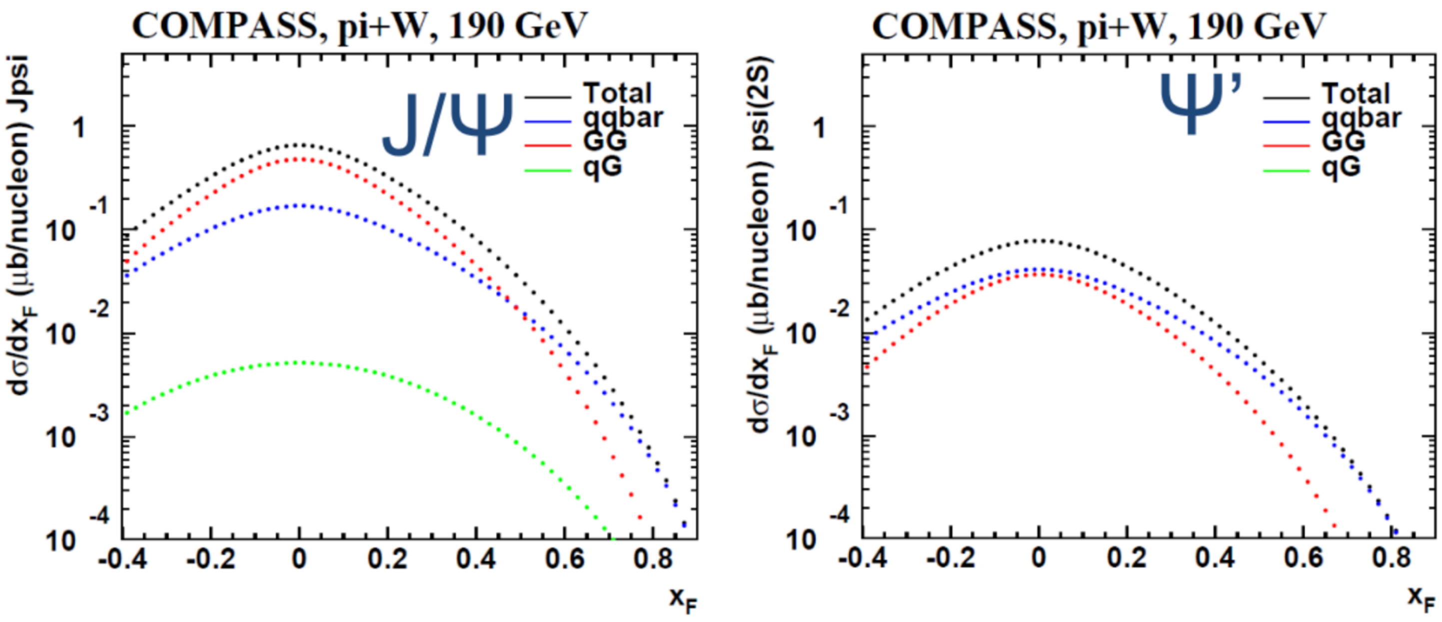

Preliminary simulation shows that the addition of vertex detector improves the mass resolution from ~200 MeV down to 100-150 MeV, the vertex resolution from ~12 cm down to <3 cm

- Allows a lower mass cut for DY (4.3 GeV -> 4 GeV)
- Suppresses the combinatorial background through tighter vertex cut
- Might even allow us to access low-mass DY events
- Enables clean access to $\psi'$

# Charmonia Production at AMBER

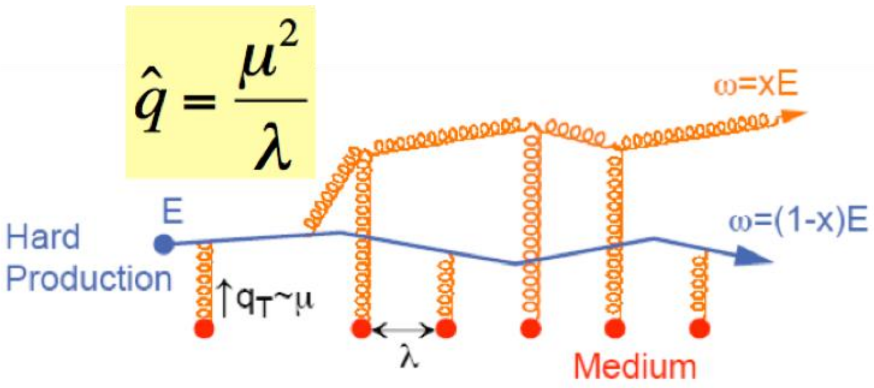
- Improved mass resolution from the vertex detector enables access to parallel $\psi'$ production
  - Additional access to the gluon content in the meson
  - Free from the feed down from $\chi_{cJ}$ states
  - Insights into the charmonia production mechanism

NRQCD calculation from Wen-Chen, J.C. Peng et al



# 1. Cold Nuclear Matter Multiple Scattering
## - Initial vs Final States

Parton multiple scattering in medium




Parton multiple scattering, lose energy energy due to medium-induced gluon bremsstrahlung, as well as elastic energy loss, effectively shift in "$x_a$"

**Additional observables:**

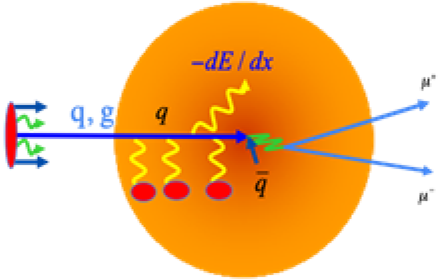
1. Event track multiplity in the relevant phase space, enhanced multiplicity around hard prob (J/Psi for e.g.)
2. Distinguish from general multi-parton interactions in pp, pA , high multiplicity in other phase space
3. pT broadening vs A

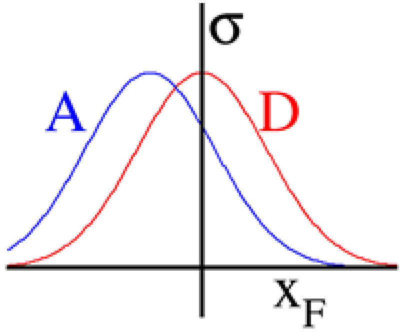
$$f_{q/p}(x_a,\ Q^2) \rightarrow f_{q/p}\left(\frac{x_a}{1-\varepsilon},\ Q^2\right)$$

I. Vitev, et al., Phys. Rev. D74 (2006) 054010
Z. B. Kang, I. Vitev, H. X. Xing, Phys. Lett. B718 (2012) 482

# Initial State Energy Loss Study, E906

**Nuclei targets:**
p+p, p+d, p+C, p+Fe and p+W

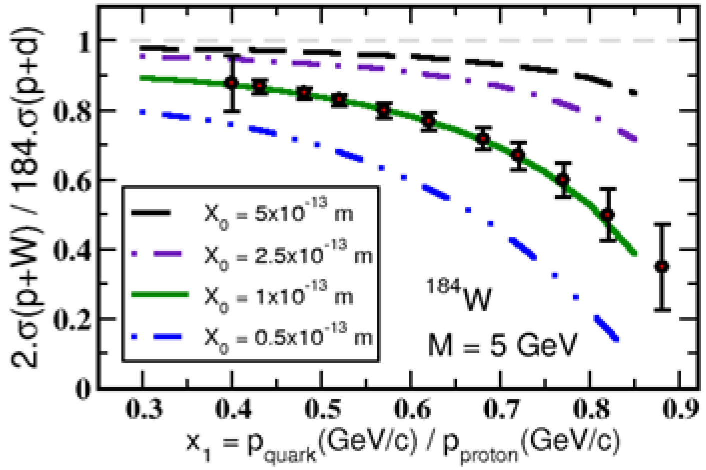


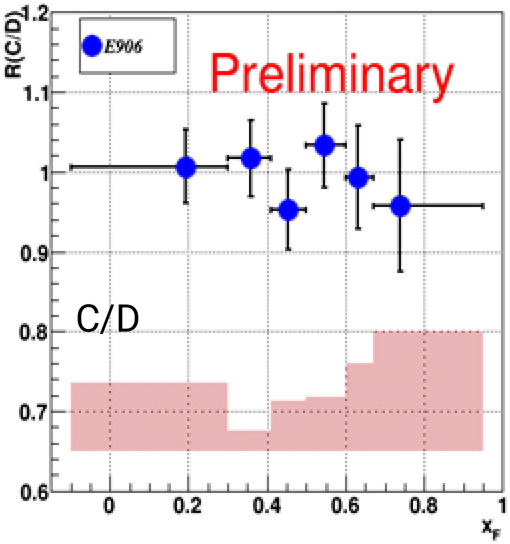



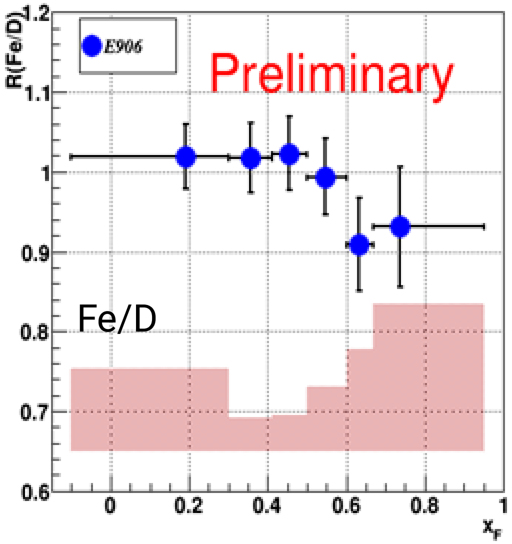

**Nuclear modification factor:**

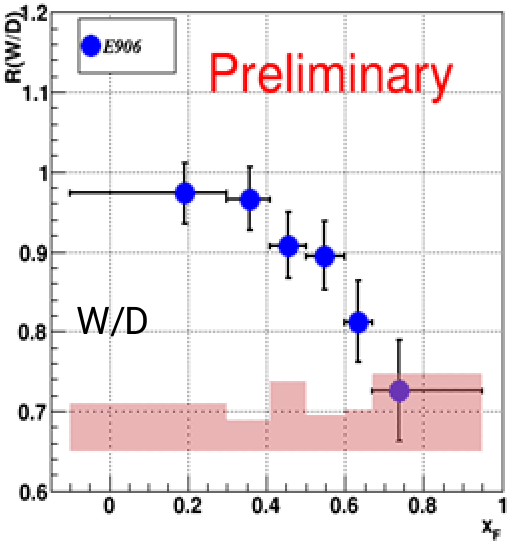
$$R_{pA} = \frac{2\sigma^{pA}}{A \times \sigma^{pD}}$$

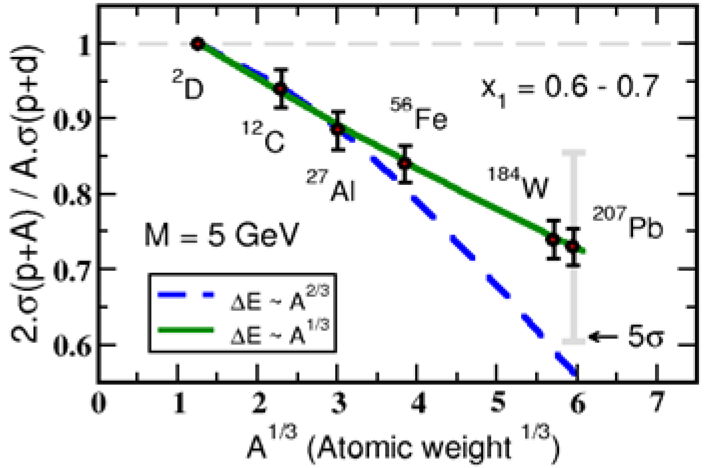
I. Vitev et al



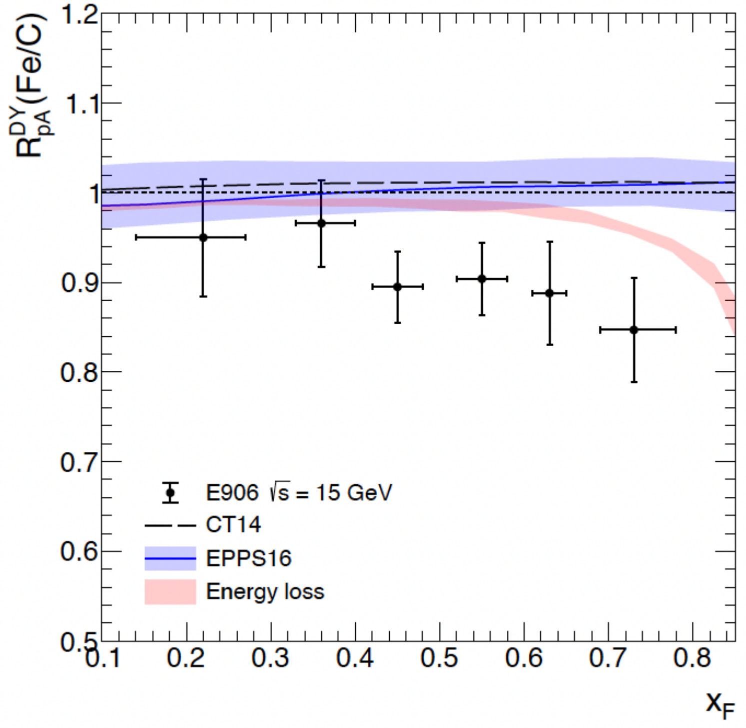



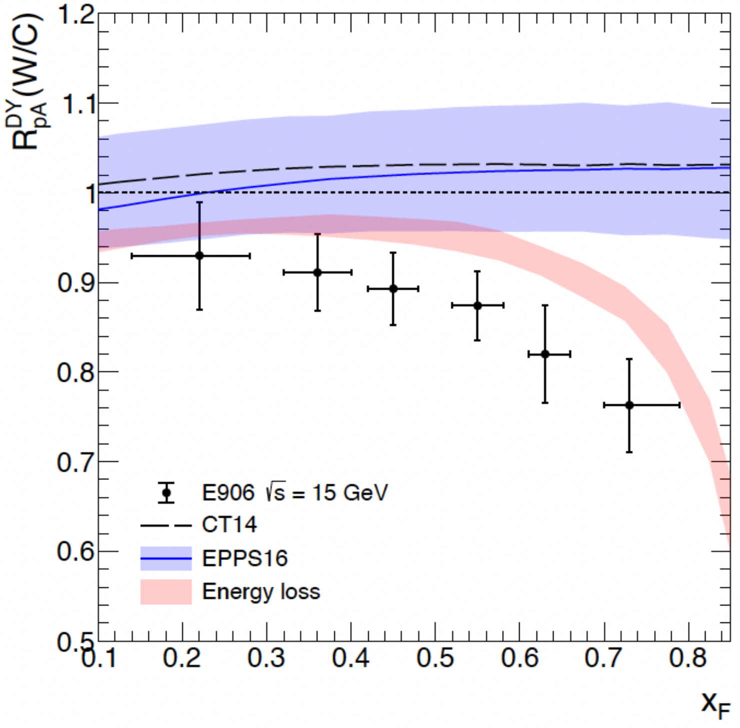



# Recent Studies

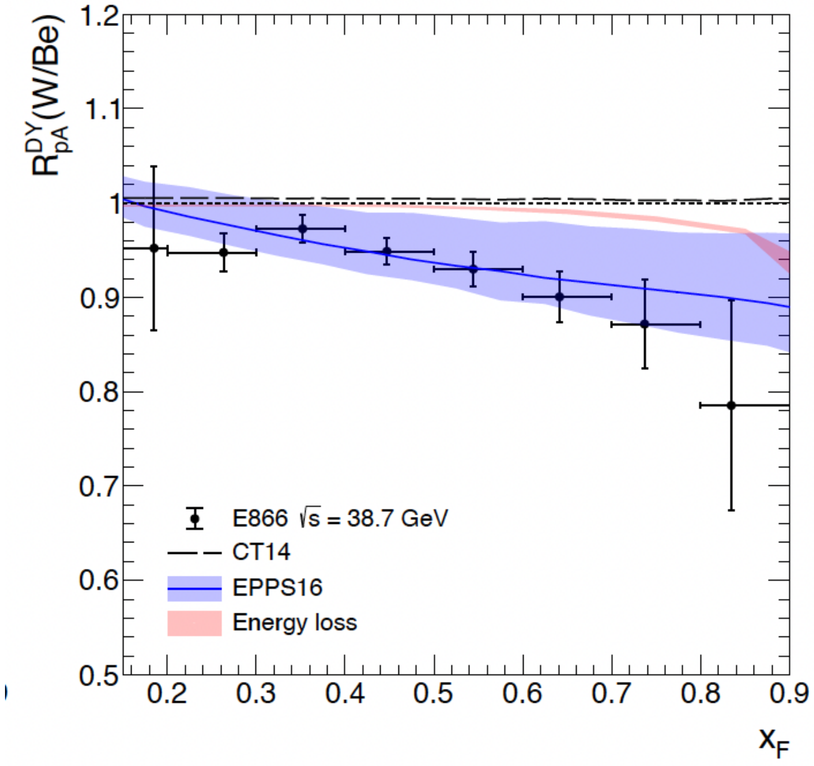
*arXiv: 1810.05120*
*François Arleo, Charles-Joseph Naïm, Stephane Platchkov*

E906 preliminary data



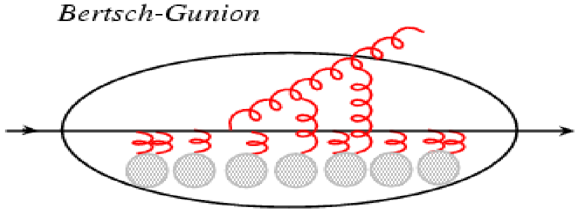




E866 DY

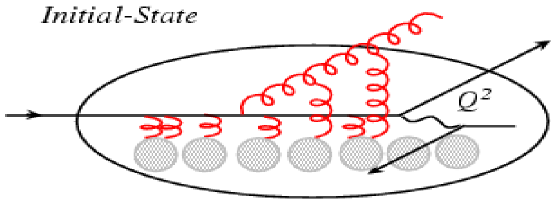



Interplay of initial state dE/dx and nPDF/shadowing

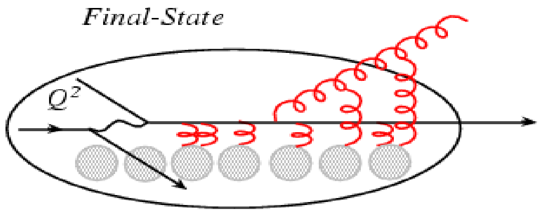
# Parton Energy Loss in p+A Collisions - initial vs final state




Ideal case: infinite volume

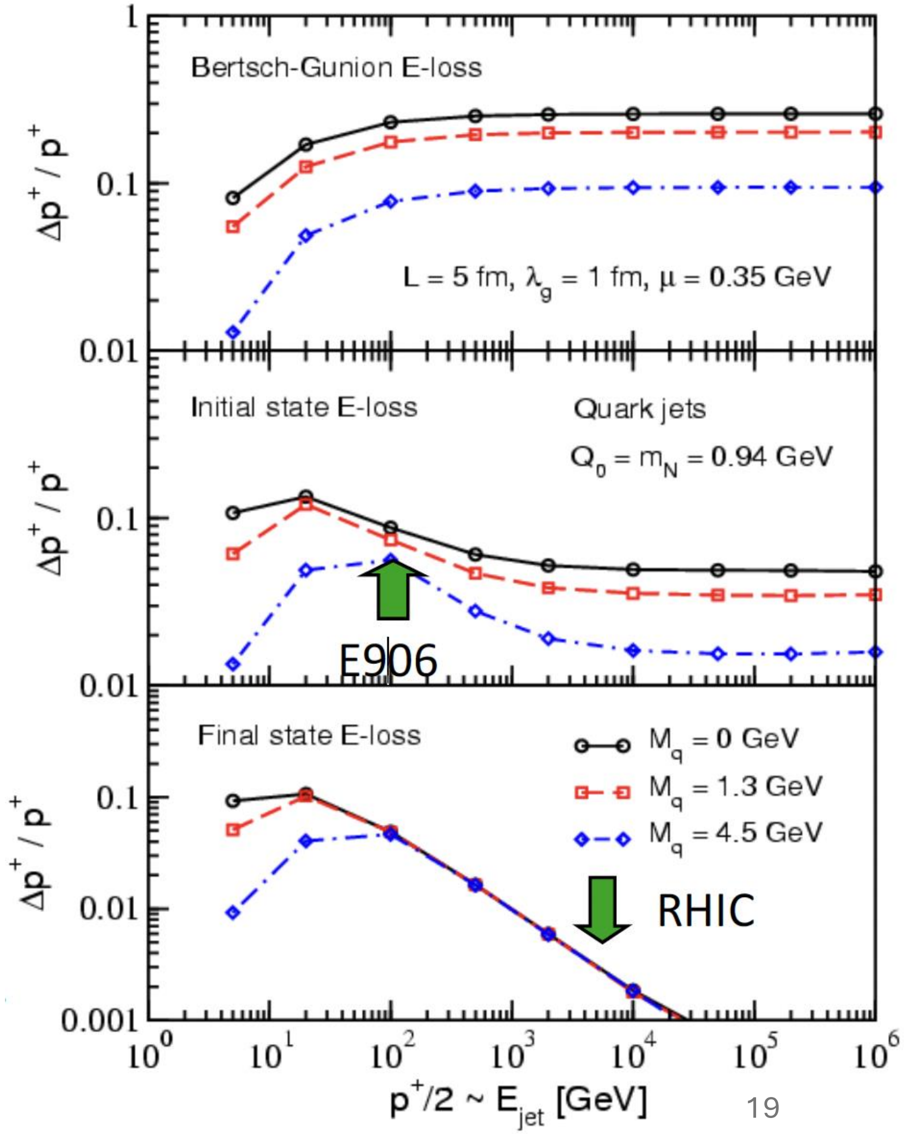



Initial state E loss:
- DY process




Final state E loss:
- SIDIS, CNM, QGP

I.Vitev PRC 75, 064906 (2007)



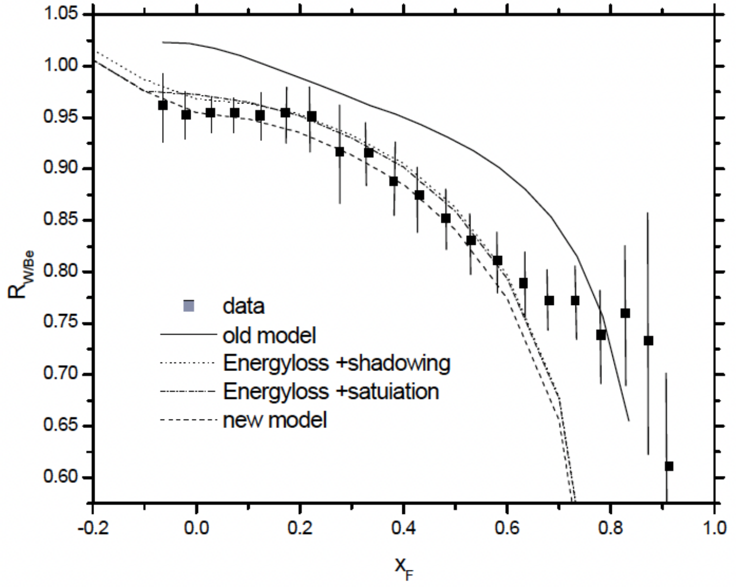

**Initial-state E-loss is large and much larger than final-state in cold nucleus, p + A or e+A**

- In Drell-Yan, we don't have final-state interactions
- In SIDIS, we don't have inital-state interactions

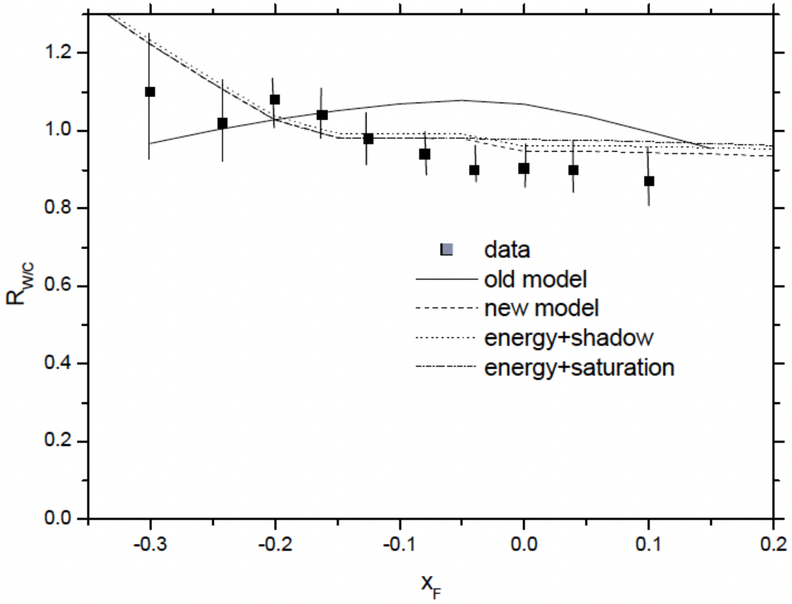
# Nuclear Effects on J/Psi Production in pA - from fixed target to collider

$$R_{pA} = \frac{1}{\langle N_{\rm coll}\rangle} \frac{d\sigma_{pA}}{dyd^2p_T} \Big/ \frac{d\sigma_{pp}}{dyd^2p_T}$$

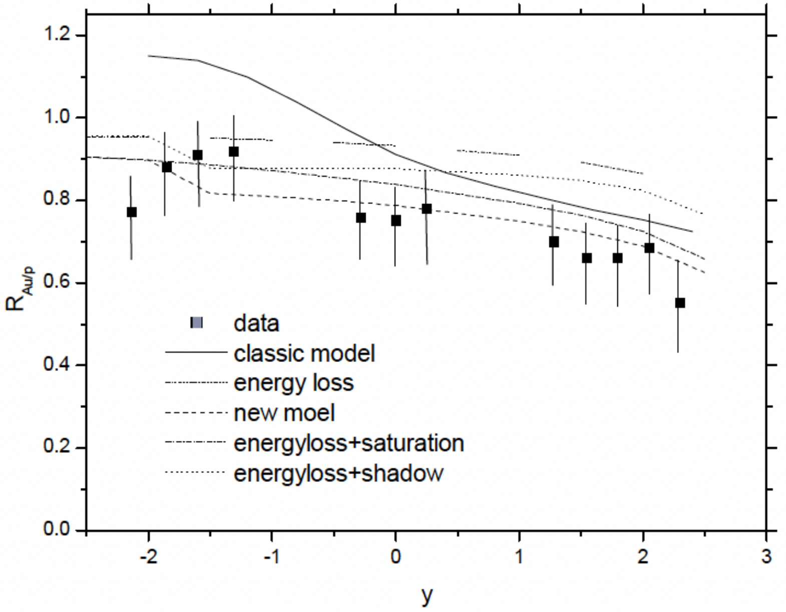
Chinese Physics C, ZF Liu (2014)




. $x_F$ distribution of $R_{W/Be}$ at E866.




$x_F$ distribution of $R_{w/c}$ R at HERA.



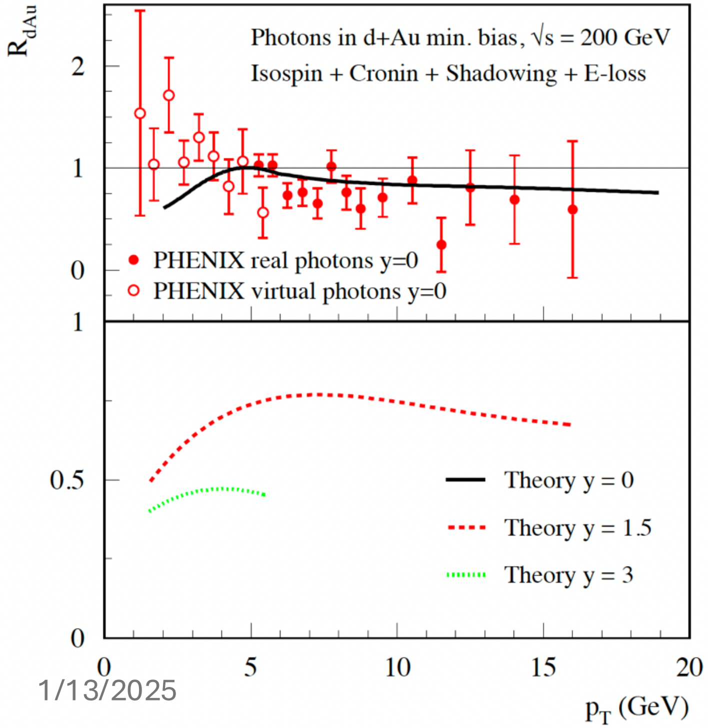

Rapidity distribution of $R_{Au/p}$ at PHENIX.

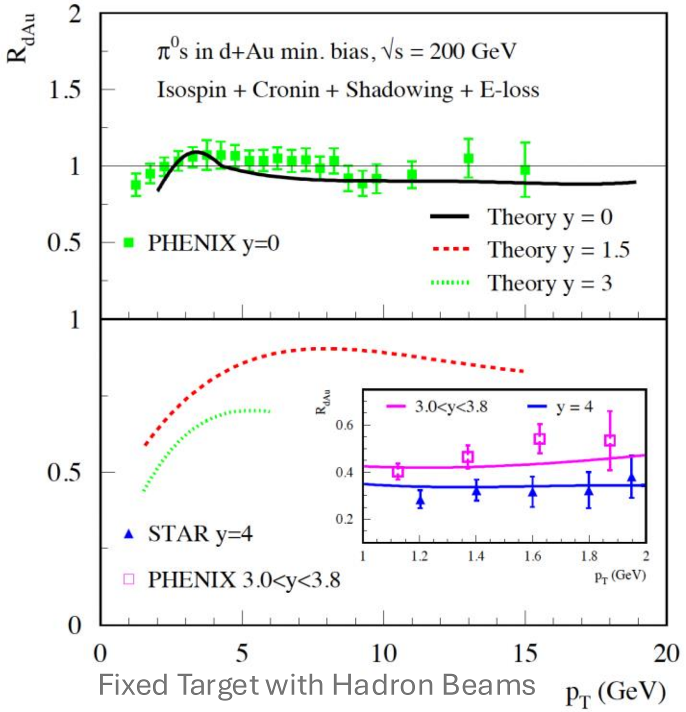
# Nuclear Effects on Particle Production:
# - from fixed target to collider

Z. B. Kang, I. Vitev, H. X. Xing, Phys. Lett. B718 (2012) 482

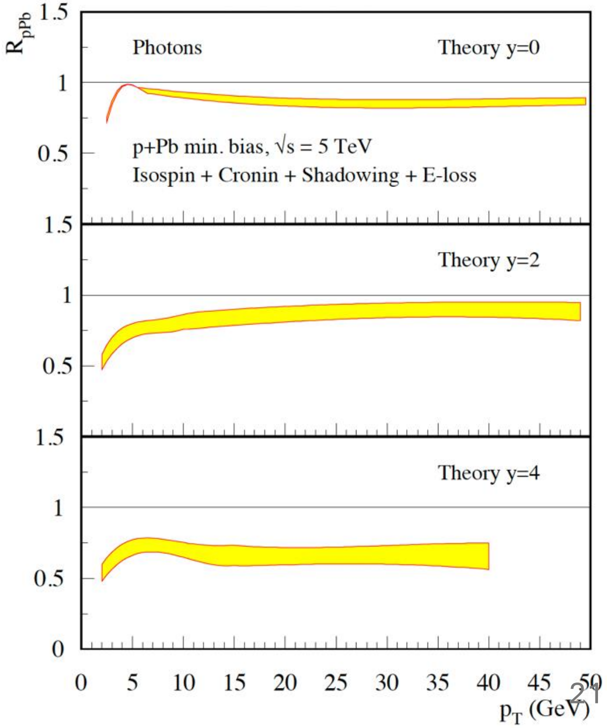
$$R_{pA} = \frac{1}{\langle N_{\rm coll} \rangle} \frac{d\sigma_{pA}}{dyd^2p_T} \bigg/ \frac{d\sigma_{pp}}{dyd^2p_T}$$

*- isospin effect, Cronin effect, cold nuclear matter energy loss and resummed QCD power corrections to the leading twist results.*

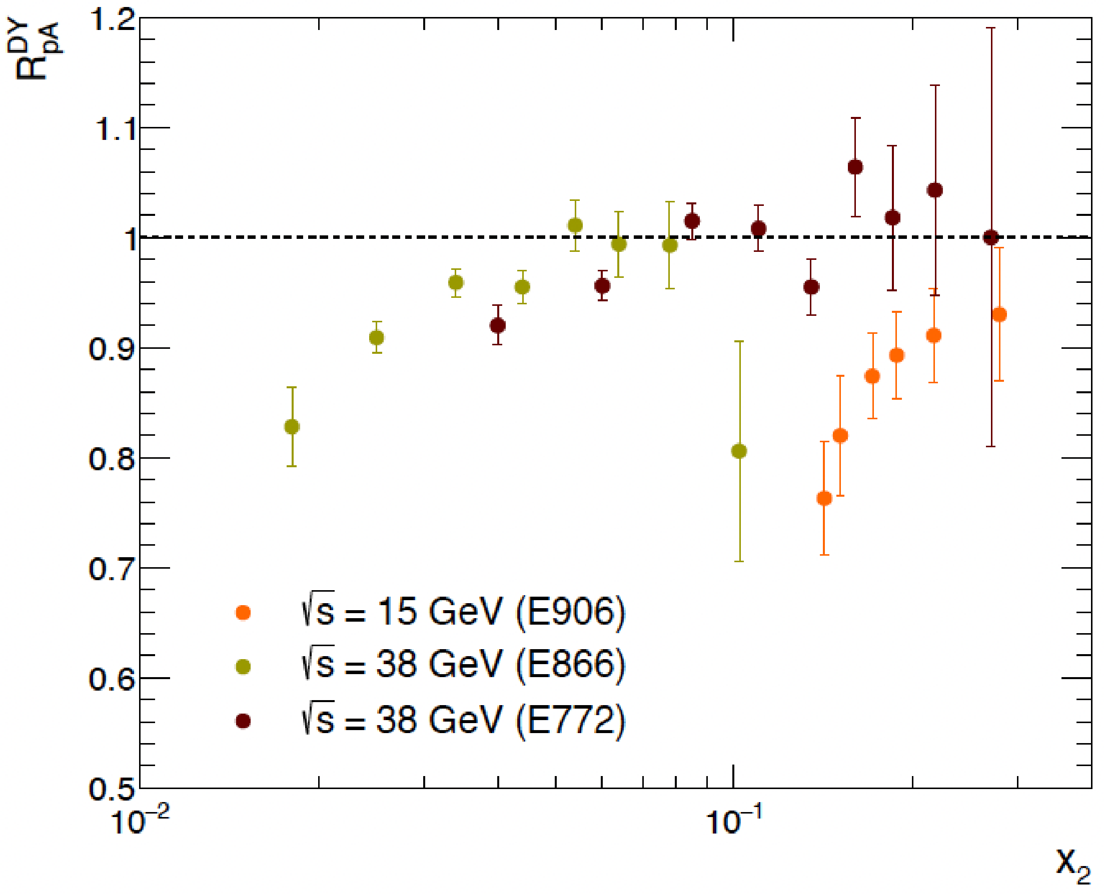


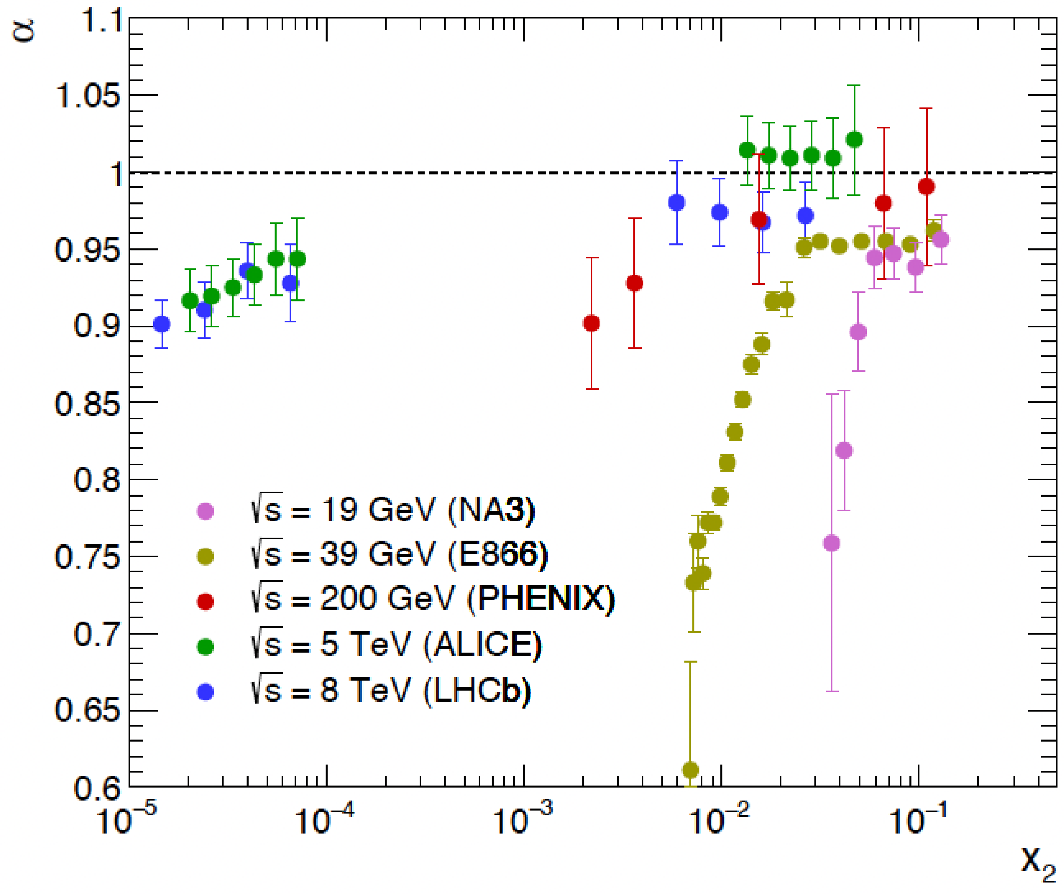




Predictions for LHC



# Nuclear Effects on DY and J/Psi Production:
# - from fixed target to collider

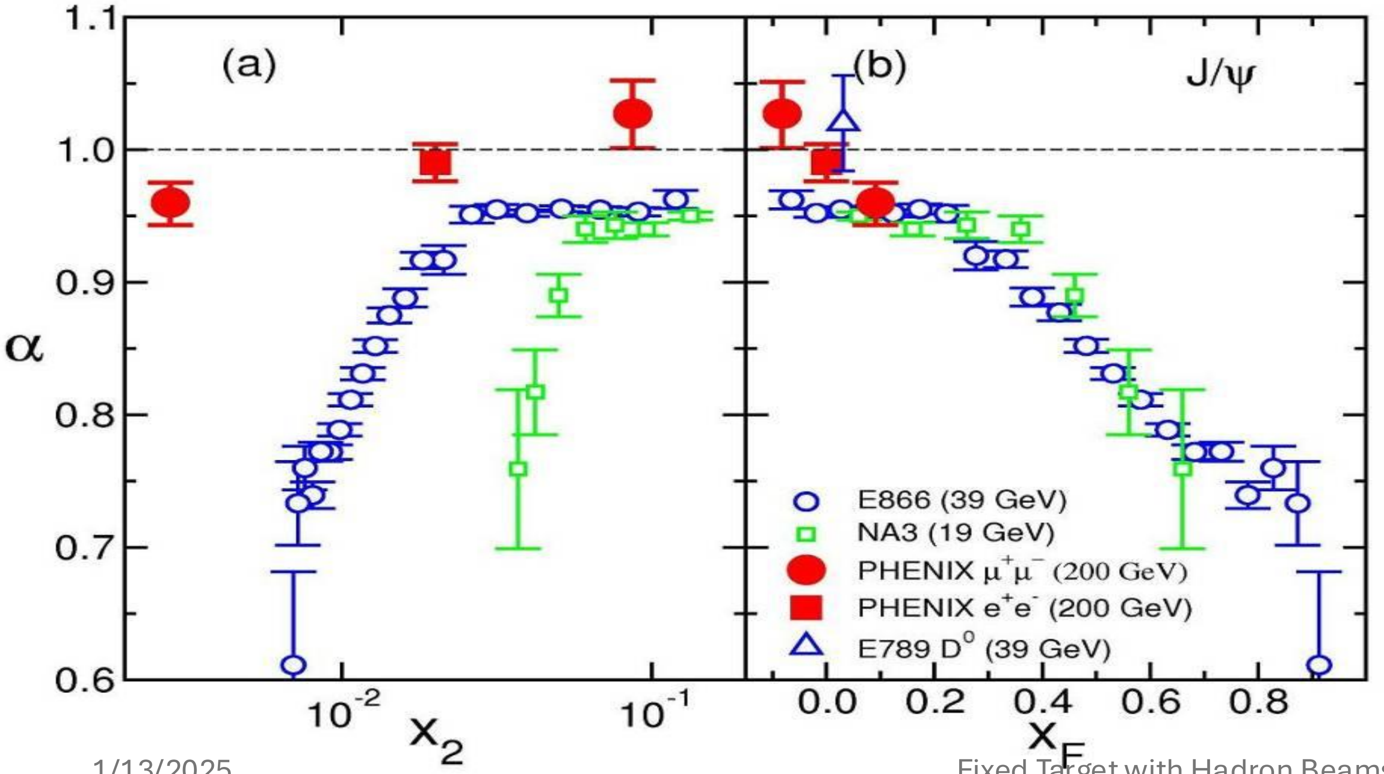


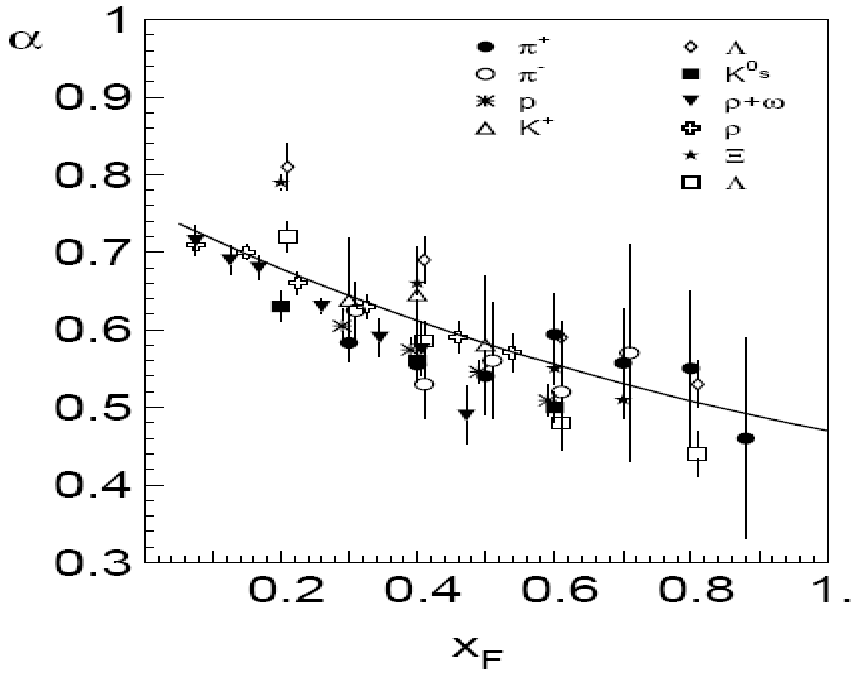



# Nuclear Effects on ***Hadron*** Production in “pA”: - initial and final state effects

$$\frac{\sigma_{pA_2}}{\sigma_{pA_1}} = \left(\frac{A_2}{A_1}\right)^{\alpha}$$

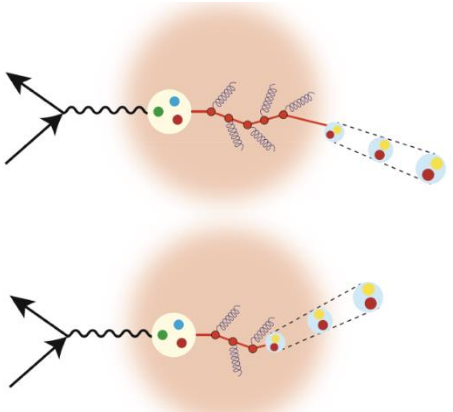
Initial state dE/dx and $X_F$ scaling ?



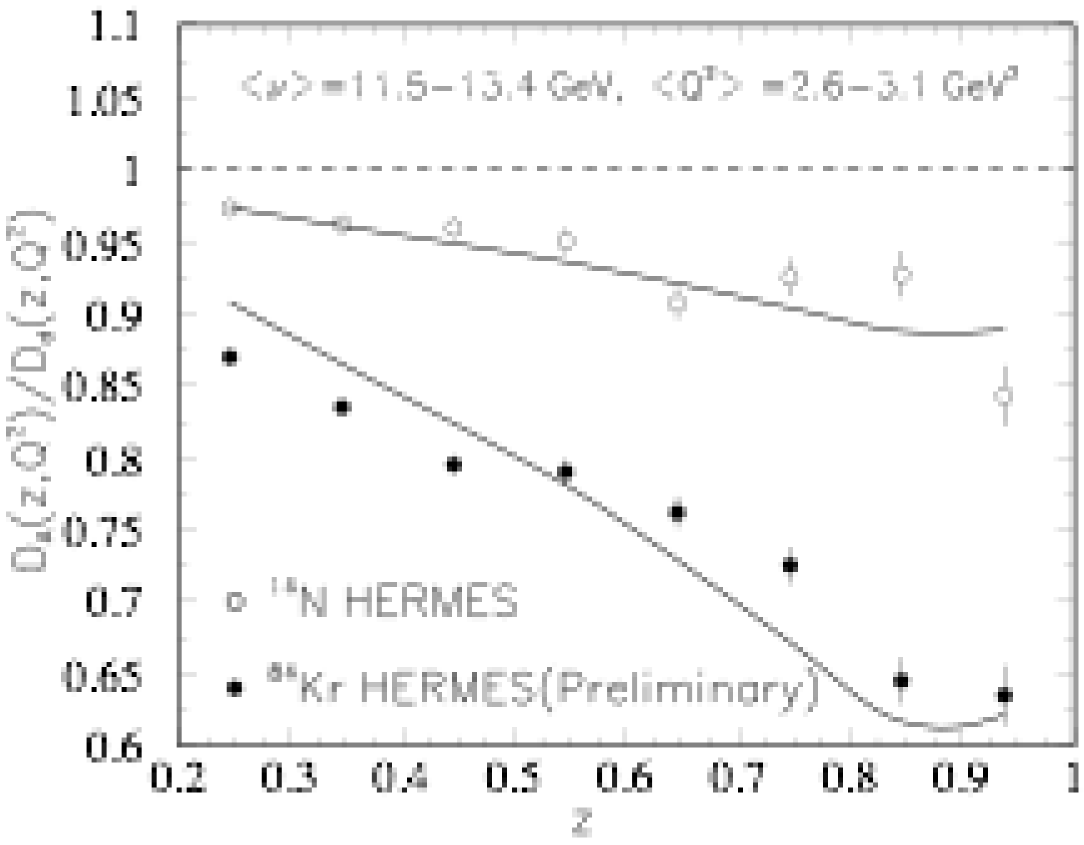
# Final State Effects – dE/dx, hadronization …

- Parton dE/dx in SIDIS
- Parton hadronization in pA
  - Poorly known at low energy
  - Energy dependence
  - Size dependence
- Hadron production in pA
  - nPDF, initial state effects also



Wang & Wang
Assume all from quark energy loss
dE/dx=0.5GeV/fm
@E =10 GeV for Au.

Wang & Wang PRL 89 (2002) 162301



# Nuclear PDF and Beyond

**nPDF: (anti)shadowing, intrinsic or process dependent?**

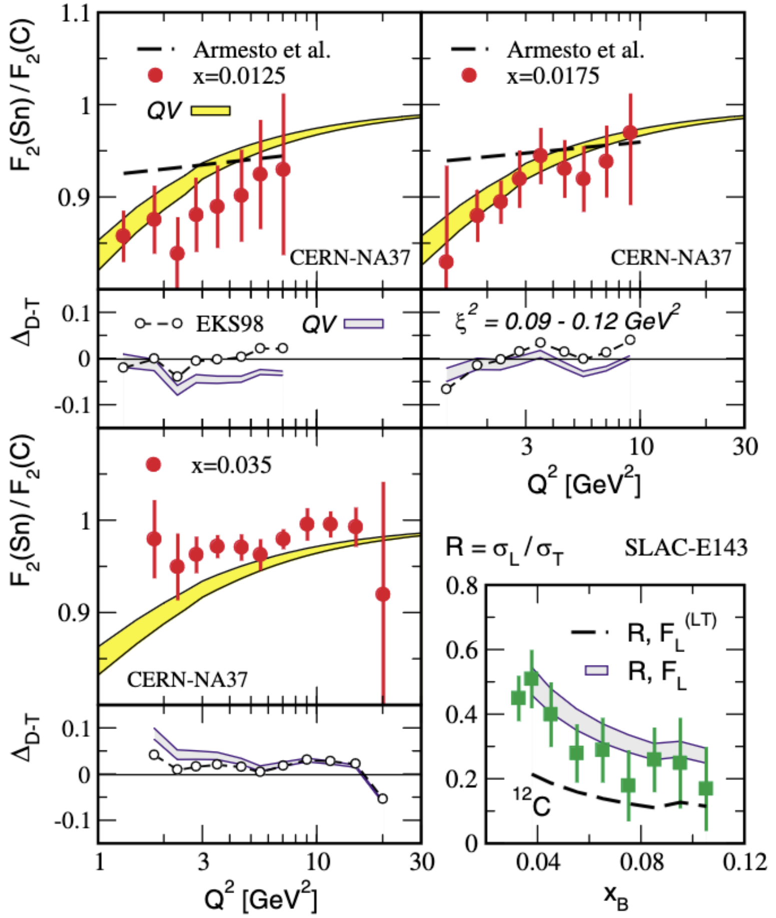
are there universal components in nPDF? How can we test them experimentally?
- Nuclear mass < sum of nucleon mass
    -> The Big question: origin of hadron mass

**Additional new observables:**
Process dependence: J/Psi or open charm vs Drell-Yan
- EIC, strong final state effects, + nPDF
- pA, initial state effects in DY, + nPDF
- pA, initial + final effects in Charm, +nPDF
-

1. Event local multiplity (activity) in the relevant phase space, enhanced multiplicity around J/Psi
2. Distinguish from general multi-parton interactions in pp, pA , high multiplicity in other phase space
3. pT broadening vs A

# Dynamic Nuclear Shadowing

J. W. Qiu, I. Vitev, Phys. Rev. Lett. 93 (2004) 262301




Power suppressed resumed coherent final state scattering of the struck parton leads to the suppression of the cross section in the small-x regio (Qiu, Vitev), effective change in x_b:

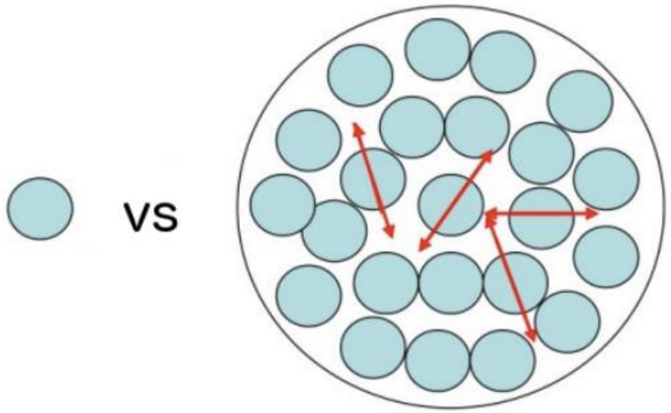
$$x_b \rightarrow x_b\left(1 + \frac{m_{dyn}^2}{Q^2}\right)$$

**Additional new observables:**

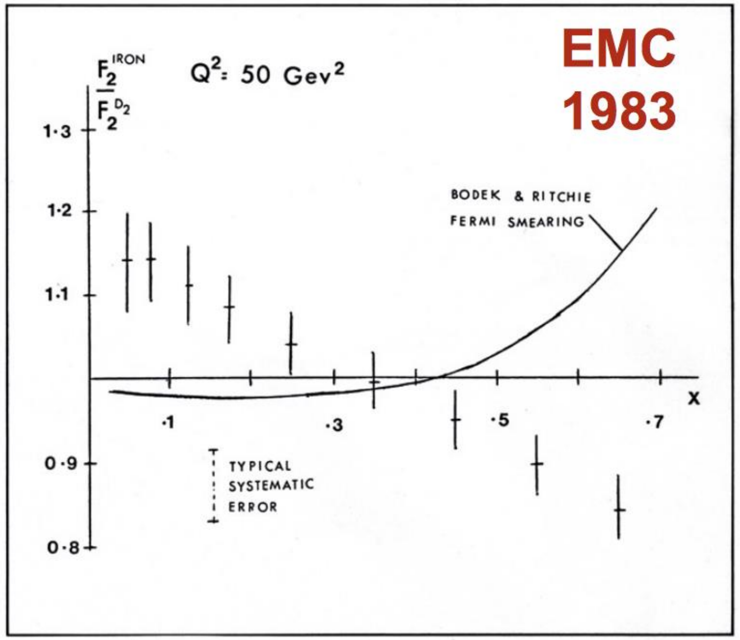
1. Event multiplity in the relevant phase space, lack of multiplicity around J/Psi
2. Distinguish from general multi-parton interactions in pp, pA , high multiplicity in other phase space
3. pT broadening vs A, and other "non-coherent" final state interactions

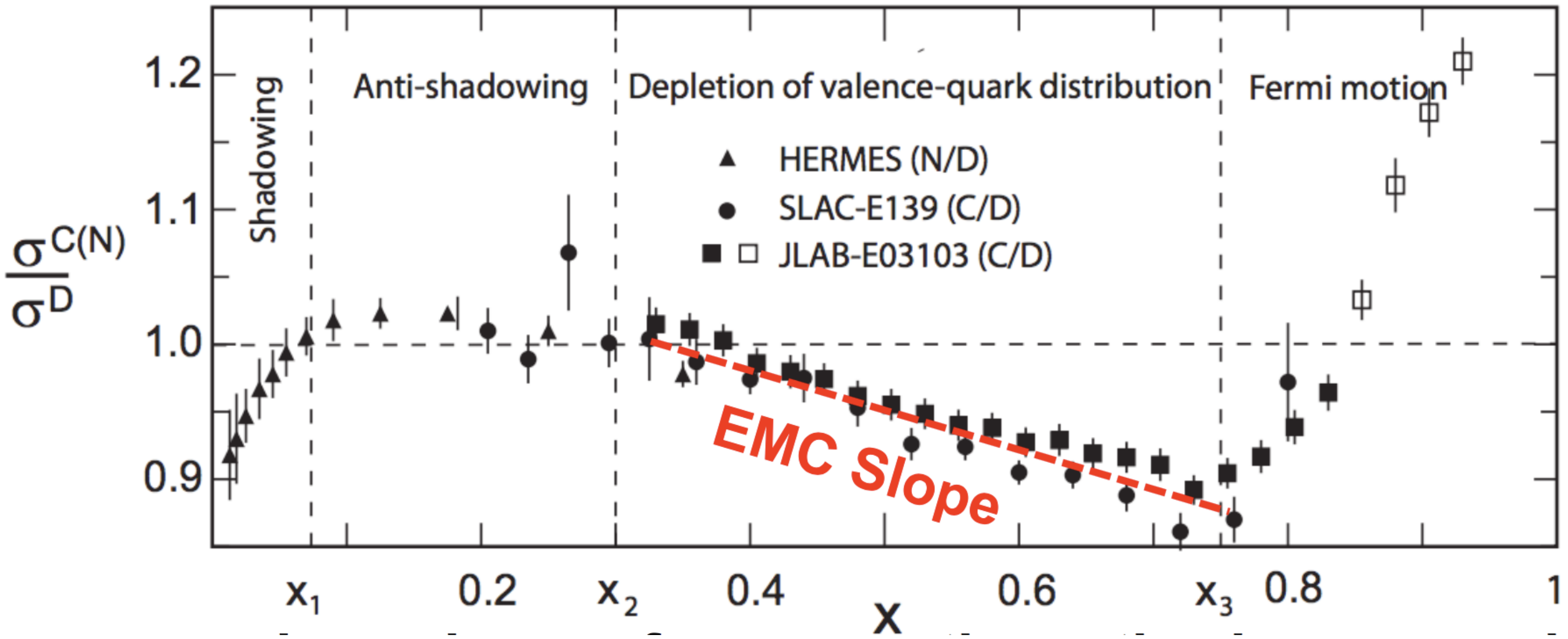
- Process dependent as it involves the final state interactions, not signific
- Different from "intrinsic" nuclear PDF modification, (anti)shadowing effects

# EMC Effects in Drell-Yan: nPDF




The interplay among these mechanisms depends on nuclear size, density, and the x-range in question. Ongoing experiments (e.g., at Jefferson Lab, Fermilab, CERN, and future EIC studies) continue to refine our quantitative understanding of **how quark and gluon distributions are modified** by nuclear matter—ultimately aiming to pin down the detailed origin of the EMC effect.



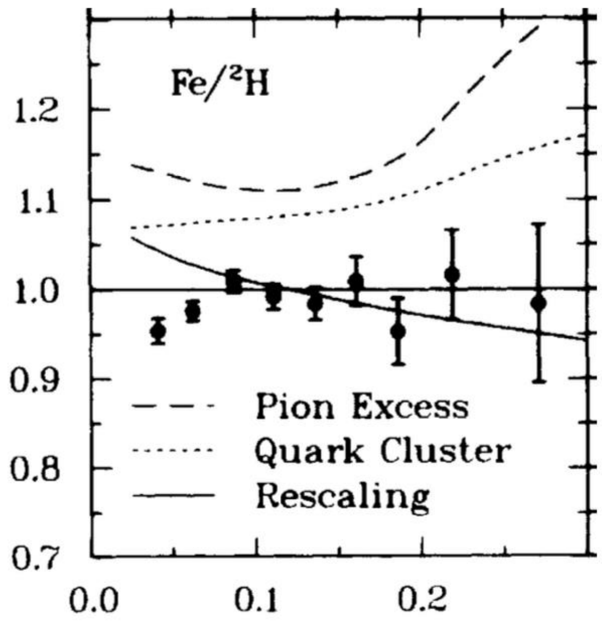

**1st observed in DIS at EMC, full understanding remains elusive ....**

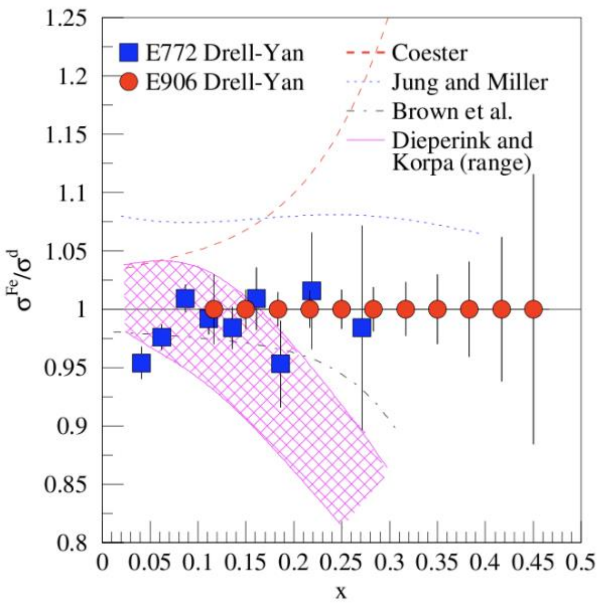
- **Short-range correlations** and **nucleon modification** provide crucial contributions around intermediate x.
- **Meson exchange** and **sea-quark effects** can become relevant at lower x.
- **Fermi motion** matters most at larger x.

D. Alde, et al., Phys. Rev. Lett. 64, 2479 (1990)

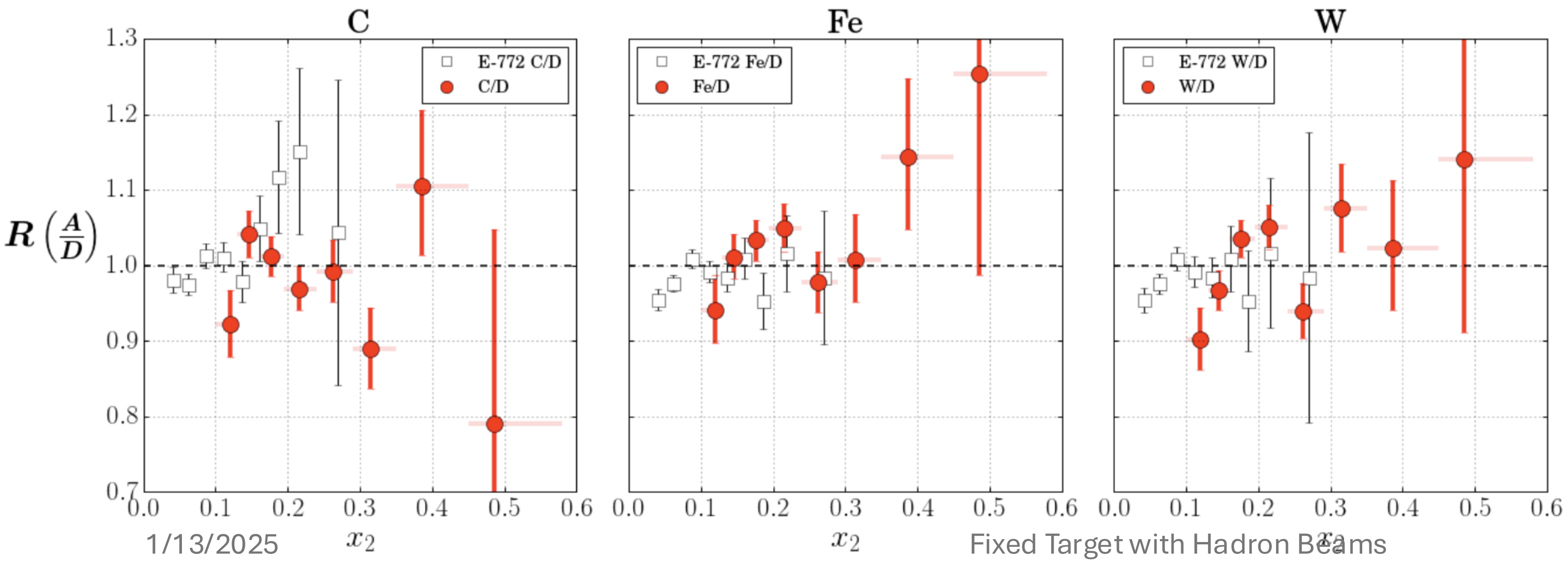
# EMC Effects in DY

- *E772 data found no anti-quark enhancement compared to the free nucleon*
- *E906 could provide good measurements …*




Fermilab E906 preliminary



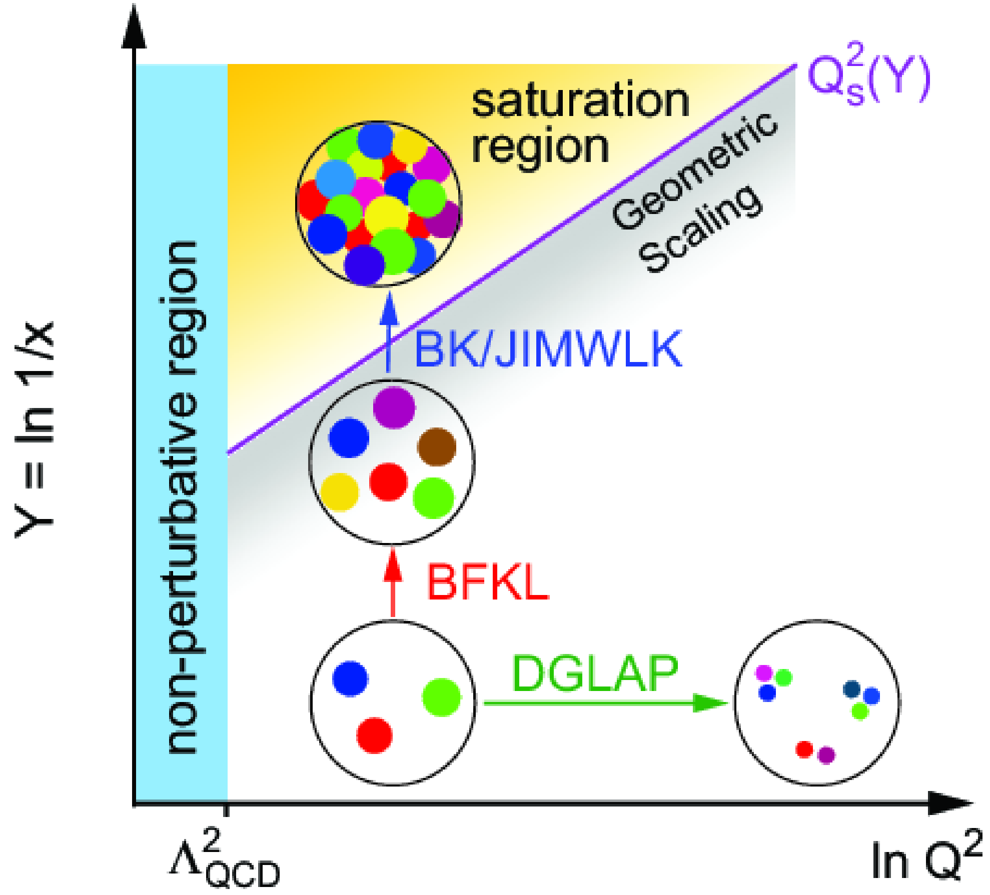

- EMC: ~ "x2" target
- dE/dx: ~ "x1" beam

# Gluon saturation in small-x

- Difficulty to access in fixed target p+A
- Very forward rapidity in collider prefered to access small-x with large $Q^2$ in p+A, LHCb, ALICE, STAR-FW…
- **High energy EIC would be an ideal place**

**Additional new observables:**

1. Event multiplity in the relevant phase space, around J/Psi
2. Distinguish from parton incoherent multiple in pp, pA , high multiplicity in other phase space
3. Strong A-dependance of Q_S



# CGC meets High-Twist

Coherent multiple parton scattering in pA : two theoretical frameworks

1. Color Glass Condensate (CGC) effective theory
2. Collinear factorization at high-twist.

https://arxiv.org/pdf/2406.01684,
Yu Fu, Zhong-Bo Kang, Farid Salazer, Xin-Nian Wang and Hongxi Xing

We perform a detailed calculation and analysis of direct photon production in proton-nucleus scattering as a concrete example to establish the matching between HT and CGC up to twist-4, including initial- and final-state interactions, as well as their interferences.

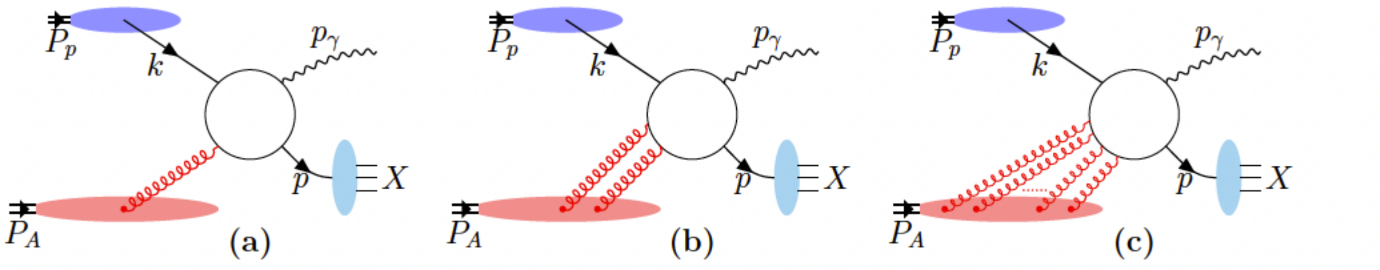



FIG. 1. Schematic diagrams for single (a), double (b), and multiple (c) scatterings for direct photon production in pA collisions, the circles represent quark-gluon(s) partonic hard interaction.

**Experimental study over a wide range of kinematic to test our understanding!**

**- Forward@LHC vs EIC**

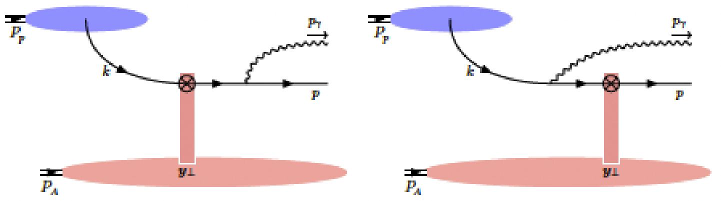


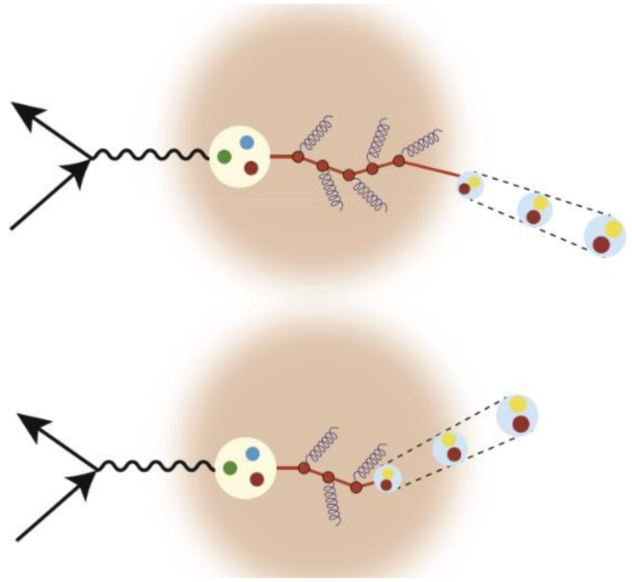
FIG. 9. Leading order diagrams for quark + photon production in proton-nucleus collisions in the CGC EFT within the hybrid factorization. The incoming collinear quark from the proton undergoes multiple eikonal scattering with the strong color field of the nucleus. The red rectangle represents the multiple scattering interaction between the quark and the nucleus.

# Looking ahead at EIC

**Opportunities:**

- Disentangle the interplay between nuclear structure and fundamental QCD processes.
  - Vary beam energy, nuclear species, and collision geometry
  - Detailed measurements of parton distribution modifications, final-state energy loss, and heavy-flavor dynamics across diverse kinematic regimes

Complementary data to pA collisions



**Goals:**

- Build a comprehensive picture of how partons behave in cold nuclear environments
- Testing QCD at its most fundamental level

# Outstanding Physics Questions and (New) Observables for Future Experiments

## The upcoming EIC, with RHIC, LHC, and fixed target FNAL, AMBER will help address the following key topics:

1. **Precise Mapping of Nuclear PDFs – QCD dynamics and hadron mass related**

   **Flavor Decomposition**: The sea-quark and gluon distributions in nuclei remain poorly constrained, especially at small x and moderate to high Q^2.

   **Saturation and Small-**x **Dynamics**: Determining whether gluon densities saturate at high energies and how that saturation manifests at different scale regimes is essential for understanding quantum chromodynamics (QCD) in dense environments.

2. **Space–Time Evolution of Parton Propagation in Cold Nuclear Matter – QCD dynamics and Effective Theory**

   **Energy Loss Mechanisms**: How partons lose energy (radiatively or via elastic scattering) without forming a hot medium is still not fully understood.

   **Hadron Formation Times**: Learning precisely when and where a scattered quark or gluon forms a hadron can differentiate initial-state vs. final-state nuclear effects.

3. **Heavy-Flavor and Quarkonium - QCD Dynamics, pQCD tool**

   **Charm and Beauty Production**: More precise measurements of open heavy-flavor hadrons (e.g., D, B mesons) can reveal how mass-dependent energy loss differs in a cold nuclear environment.

   **Quarkonium States**: Systematic studies of the entire quarkonium spectrum (e.g., psi', \chi_c, \Upsilon(1S,2S,3S)) in electron–nucleus and hadron–nucleus collisions will shed light on color neutralization and absorption mechanisms.

4. **Transverse Momentum Broadening and Spin Structure – CGC vs HT unification at overlapping small-x region**

   **Cronin Effect vs. Saturation**: Determining whether observed transverse momentum broadening arises purely from multiple scattering or if gluon saturation also plays a role at small x.

   **Spin-Dependent Effects**: Future polarized p+A collisions could illuminate how the nucleus modifies spin-dependent parton distributions.

5. **Three-Dimensional Imaging of Nuclei at the EIC - QCD dynamics and hadron mass related**

   By scattering electrons off ions at variable energy and momentum transfer, the EIC will enable tomographic imaging of quark and gluon distributions within nuclei, offering unprecedented insight into spatial and momentum correlations.

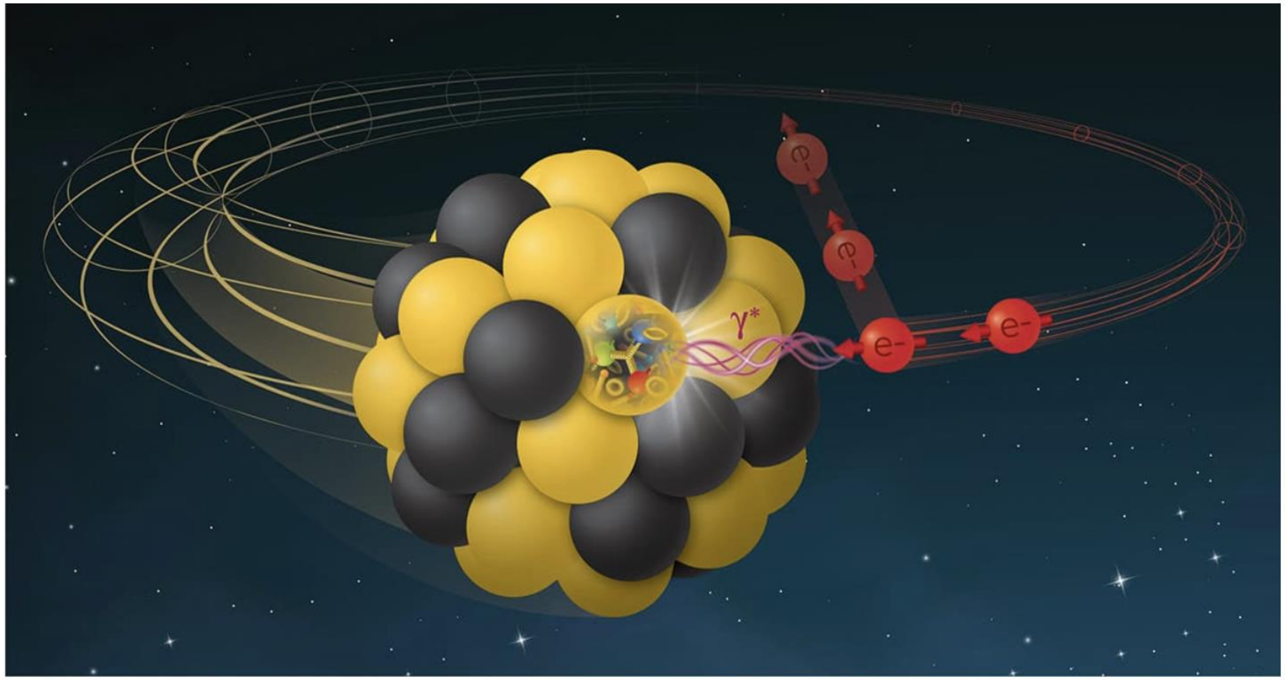
# Summary

- Proton–nucleus collisions at high energies provide a valuable testing ground for exploring how quarks and gluons behave when embedded in nuclear matter, yet in conditions less extreme than those of heavy-ion collisions where a hot, deconfined medium can form.

- Over several decades, experiments at Fermilab (fixed-target p+A), CERN (SPS, later LHC with p+Pb), and Brookhaven National Laboratory (RHIC with p+Au, d+Au, and ^3He+Au) have revealed a range of phenomena collectively known as **Cold-Nuclear-Matter (CNM) effects**.
- **EIC will provide a new playground for QCD study, complementary to pA**

The primary objectives of this workshop include **proposing a coherent, universal theoretical/ phenomenological framework** for interpreting all existing data, fostering **dialogue between theorists and experimentalists**, and **highlighting the potential of future EIC data** for advancing our understanding of Cold Nuclear Matter effects (CNM). At the conclusion of this workshop, we will identify the key CNM questions that remain unresolved, as well as the most suitable observables that can be employed to address them. An important outcome of the workshop will be **a paper summarizing these key questions and proposing ways to answer them.**

We will also provide an assessment following the Workshop on proton-nucleus collisions at the LHC at ECT* in 2013, **addressing the remaining open questions and what has been learned over the past decade**.



# Backup

# Outline

- Origin of CNM effect in pA: mostly significant in the “forward” kinematic region in experimental data
    - nPDF, universal, from global fit, leading twist pQCD factorization framework
    - CGC, gluon saturation in small-x region, non-linear corrections to QCD evolution equation in very dense gluon region
    - Parton multiple scatterings in pQCD framework, thus process dependent, DY (& direct-photon) vs J/Psi for e.g.

- Physics with fixed target with hadron beams
    - IS
    - FS

    - Based on multiple scattering of partons in nuclear matter, arising from the elastic, inelastic and coherent scacttering
    - - cold nuclear matter energy loss
    - Gluon saturation effect
    - Dynamical shadowing
    - nPDF, CNM mostly from modified nuclear PDF, universal …. Partially works for RHIC and LHCb data..

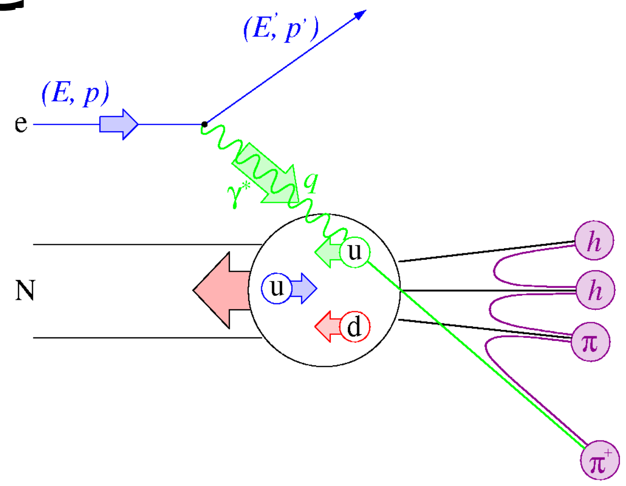
- Recent history ~30 years, FNAL, CERN, BNL (discovery of J/Psi etc.)
- Latest highlights from FNAL, CERN, RHIC/LHC?
    - FNAL - SeaQuest/SpinQuest
    - CERN - COMPASS, AMBER and others
    - HERA-B
- Big questions and EIC prospects
    - Parton hadronization
    - Physics of vacuum and confinement
    - Hadron mass

# Parton Energy Loss SIDIS @HERMES

- Out going quarks
  - HERMES A-dep Fragmentation Functions
  - Must understand nuclear–dependent fragmentation
  - Wang & Wang
    - Assume all from quark energy loss

    dE/dL=0.5GeV/fm

    @E =10 GeV for Au.




Wang & Wang PRL 89 (2002) 162301

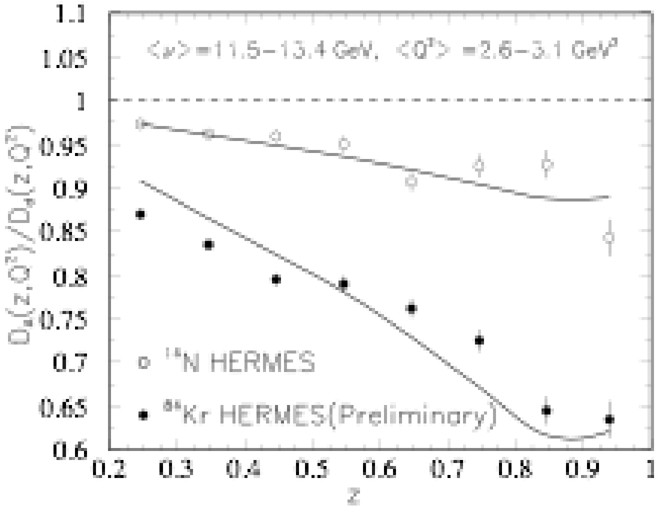
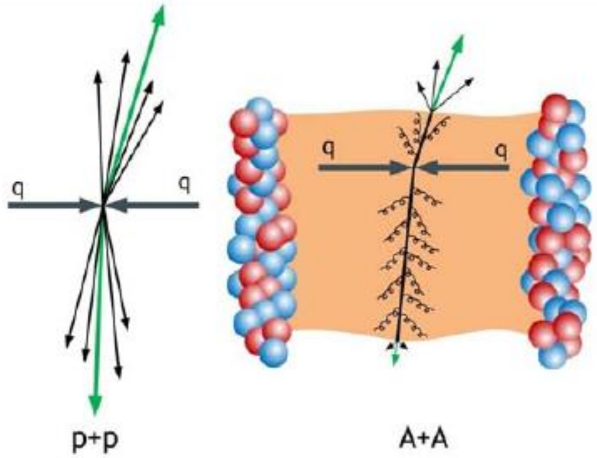
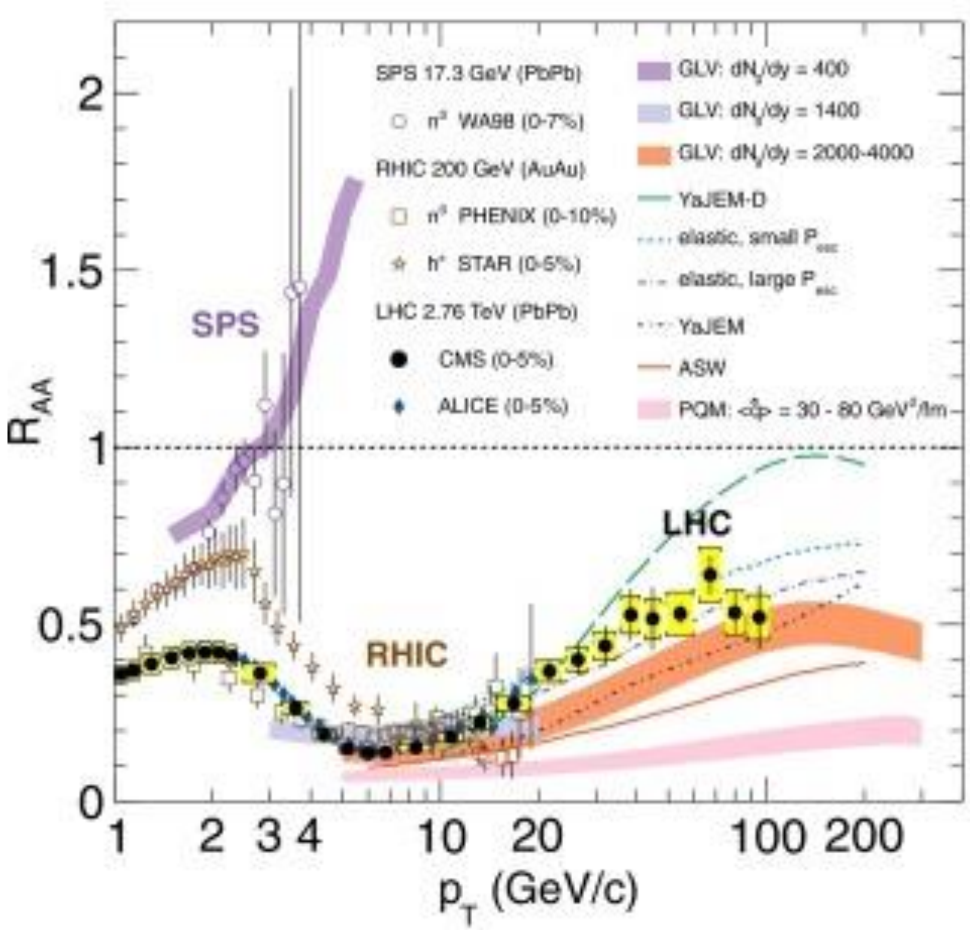



FIG. 1. Predicted nuclear modification of jet fragmentation function is compared to the HERMES data [10] on ratios of hadron distributions between $A$ and $D$ targets in DIS.

# Jet Quenching Observed @RHIC and LHC

$$R_{AA} = \frac{1}{N_{coll.}^{AA}} \frac{\sigma_{AA}}{\sigma_{pp}}$$



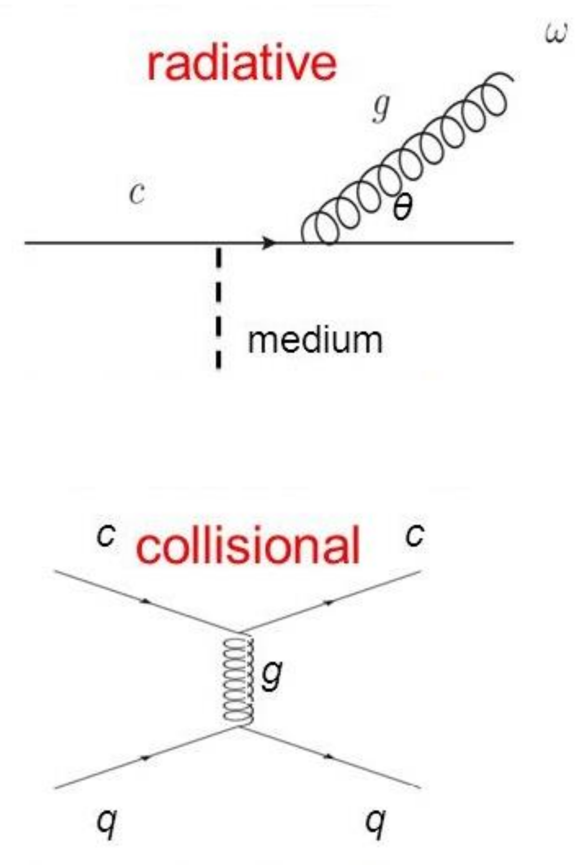

- Great progress in the last decade, but significant model dependence remains in the understanding of the physics of jet suppression and QGP properties at RHIC and LHC

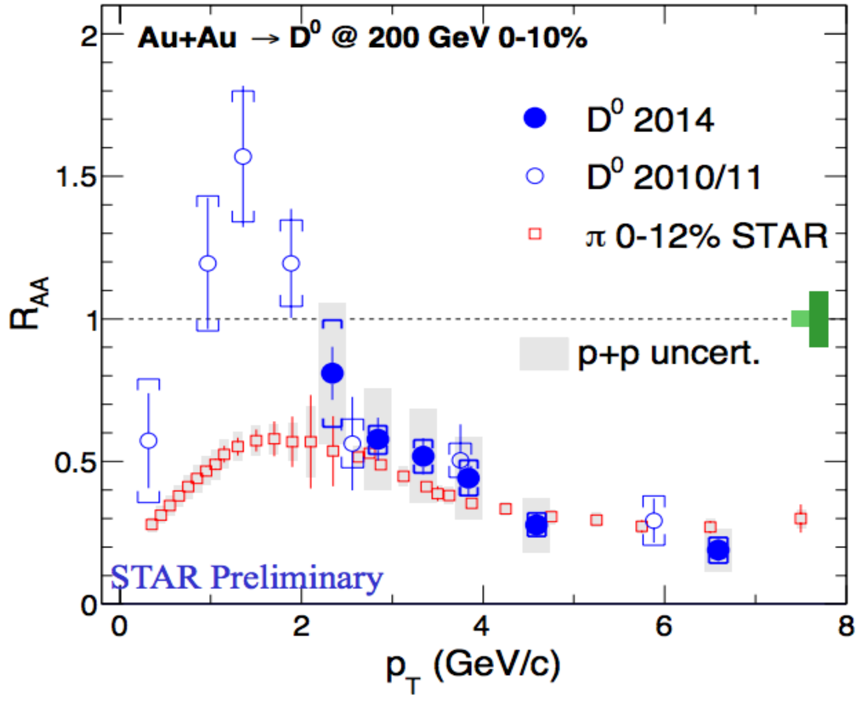
**- sPHENIX goals - understand the inner workings of QGP**

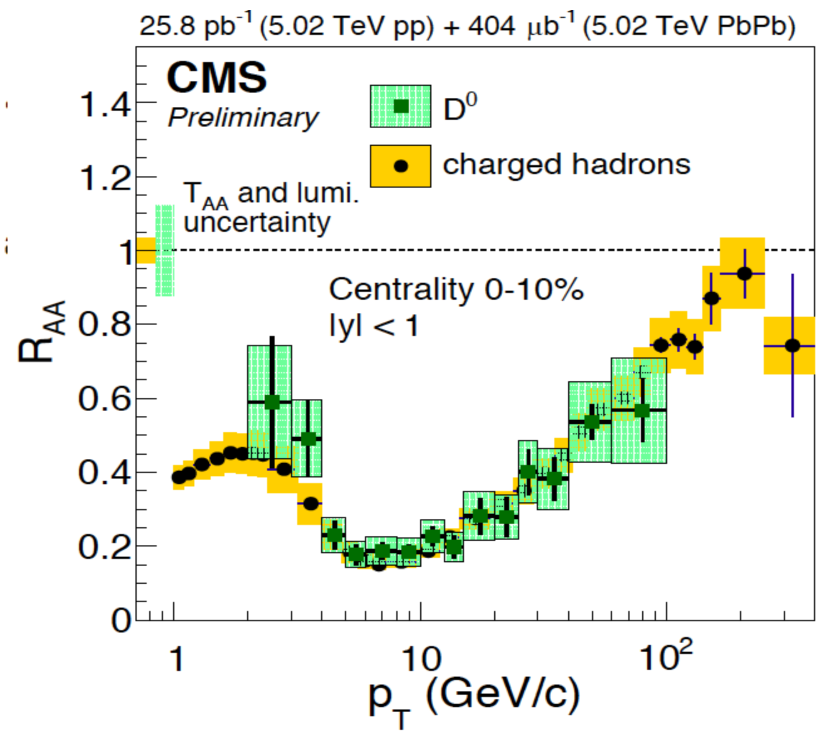
# Recent Highlight I: Charm $R_{AA}$ @RHIC and LHC

$R_{AA}$ (D-meson) ~ $R_{AA}$ (h) at high $p_T$ ~> 4 GeV/c

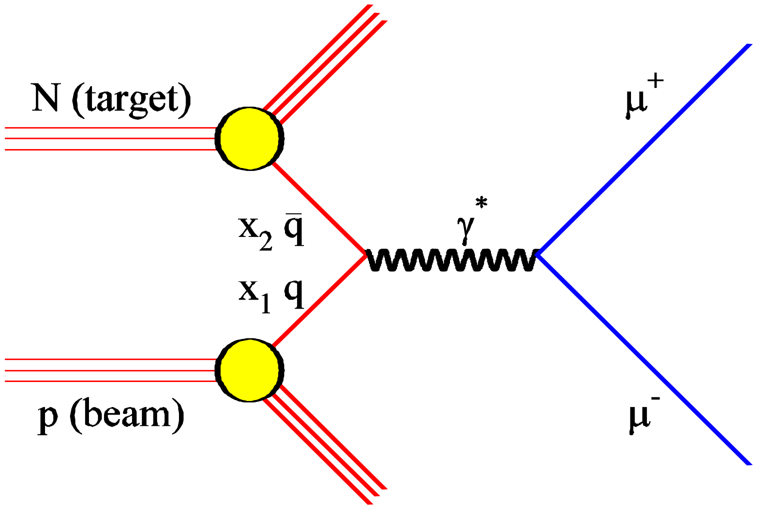
- significant suppression of charmed hadron $R_{AA}$ in central A+A collisions
- strong charm-medium interactions
- mass effects?: expected important at low pT, dead-cone, collisional effects etc.

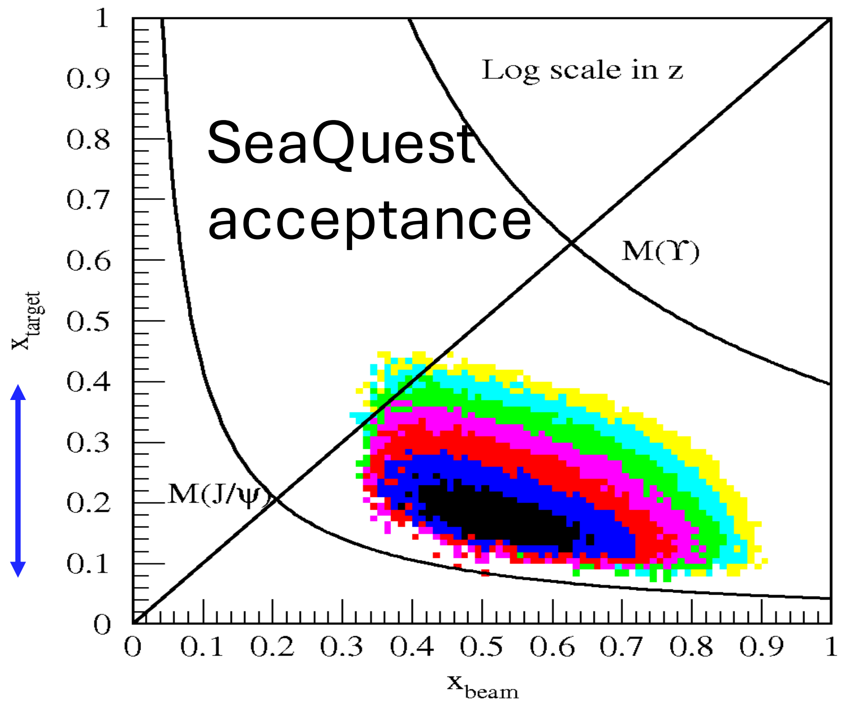


# Drell-Yan @SeaQuest – a Sea Quark Laboratory



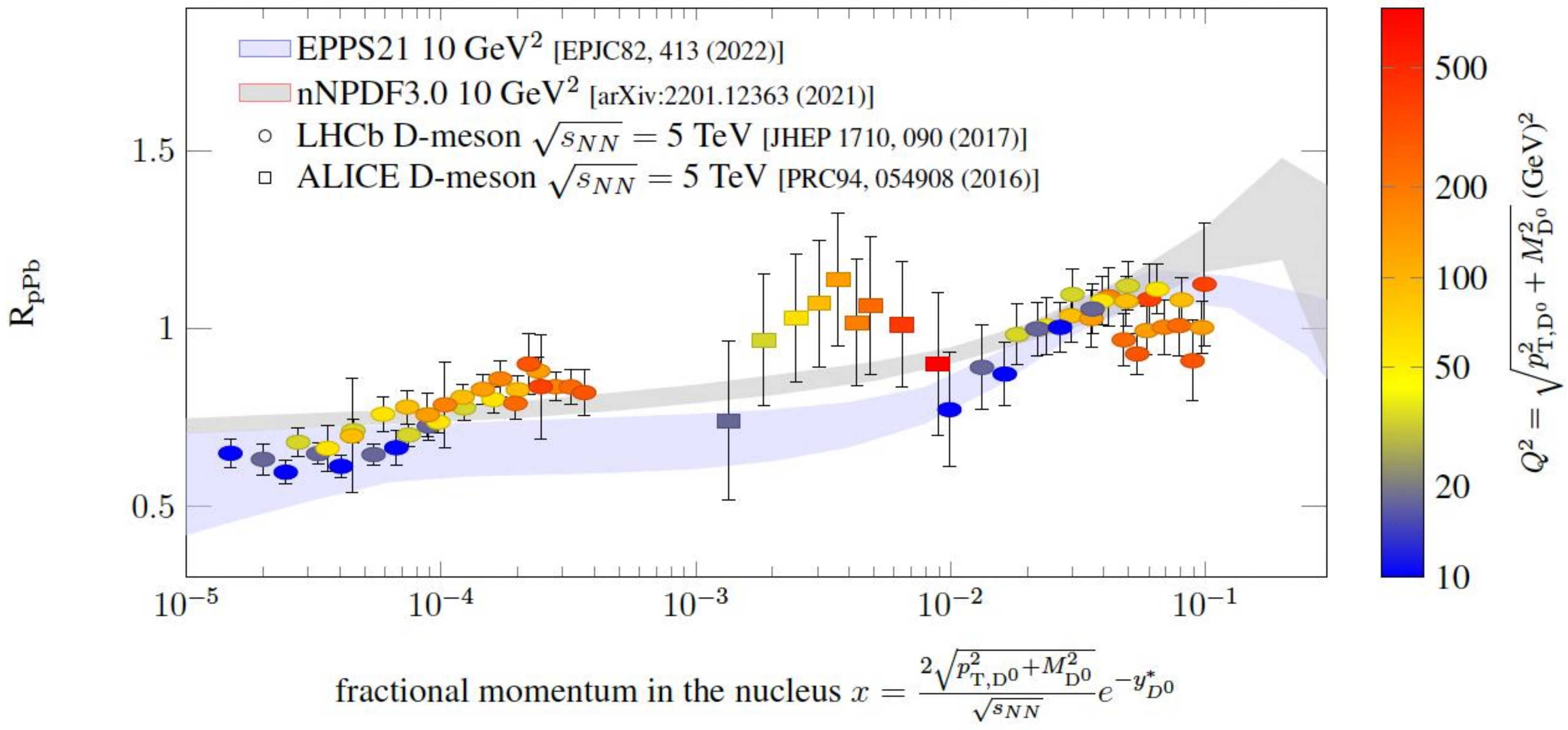




$$\frac{d^2\sigma}{dx_t dx_b} = \frac{4\pi\alpha^2}{9x_1x_2s}\sum e^2[q_b(x_b)\bar{q}_t(x_t) + \bar{q}_b(x_b)q(x_t)]$$

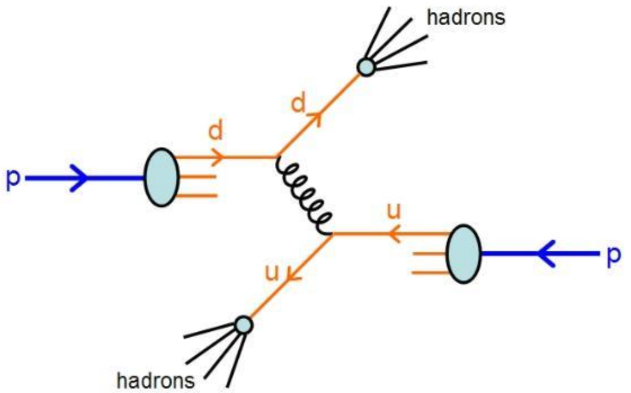
$$\approx \frac{4\pi\alpha^2}{9x_1x_2s}\sum e^2[q_b(x_b)\bar{q}_t(x_t)]$$

Kinematically favors sea-quarks from target – **a sea quark lab!**

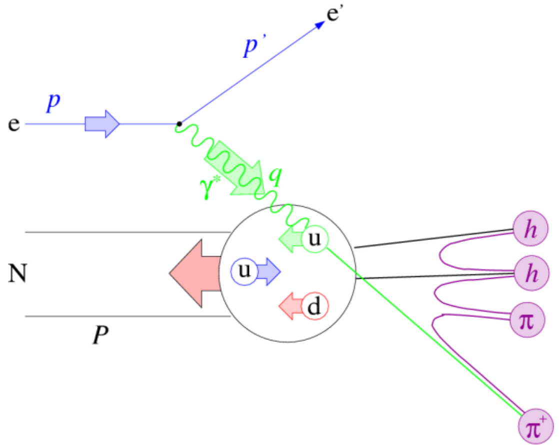
## $D^0$ $R_{pA}$ @ LHC



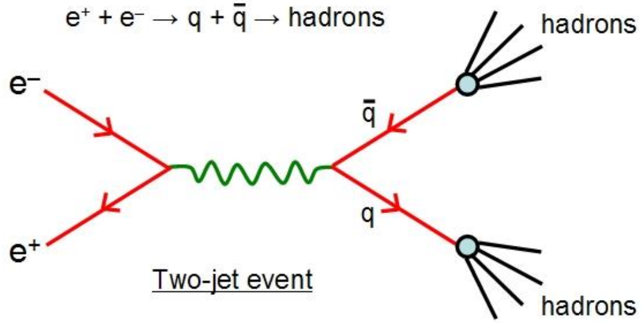
EPPS21 10 GeV² [EPJC82, 413 (2022)]
nNPDF3.0 10 GeV² [arXiv:2201.12363 (2021)]
LHCb D-meson $\sqrt{s_{NN}}$ = 5 TeV [JHEP 1710, 090 (2017)]
ALICE D-meson $\sqrt{s_{NN}}$ = 5 TeV [PRC94, 054908 (2016)]
$R_{pPb}$
1.5
1
0.5
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
fractional momentum in the nucleus $x = \frac{2\sqrt{p^2_{T,D^0}+M^2_{D^0}}}{\sqrt{s_{NN}}} e^{-y^*_{D^0}}$
500
200
100
50
20
10
$Q^2 = \sqrt{p^2_{T,D^0} + M^2_{D^0}}$ (GeV)²

hadrons
d
d
p
u
u
p
hadrons

e'
p'
e
p
γ*
q
N
u
u
d
P
h
h
π
π+

e⁺ + e⁻ → q + q̄ → hadrons
e⁻
e⁺
q̄
q
hadrons
hadrons
Two-jet event

# Initial State Effects – pT Broadening & "Cronin Effect"
# - Q: pT broadening in e+A?

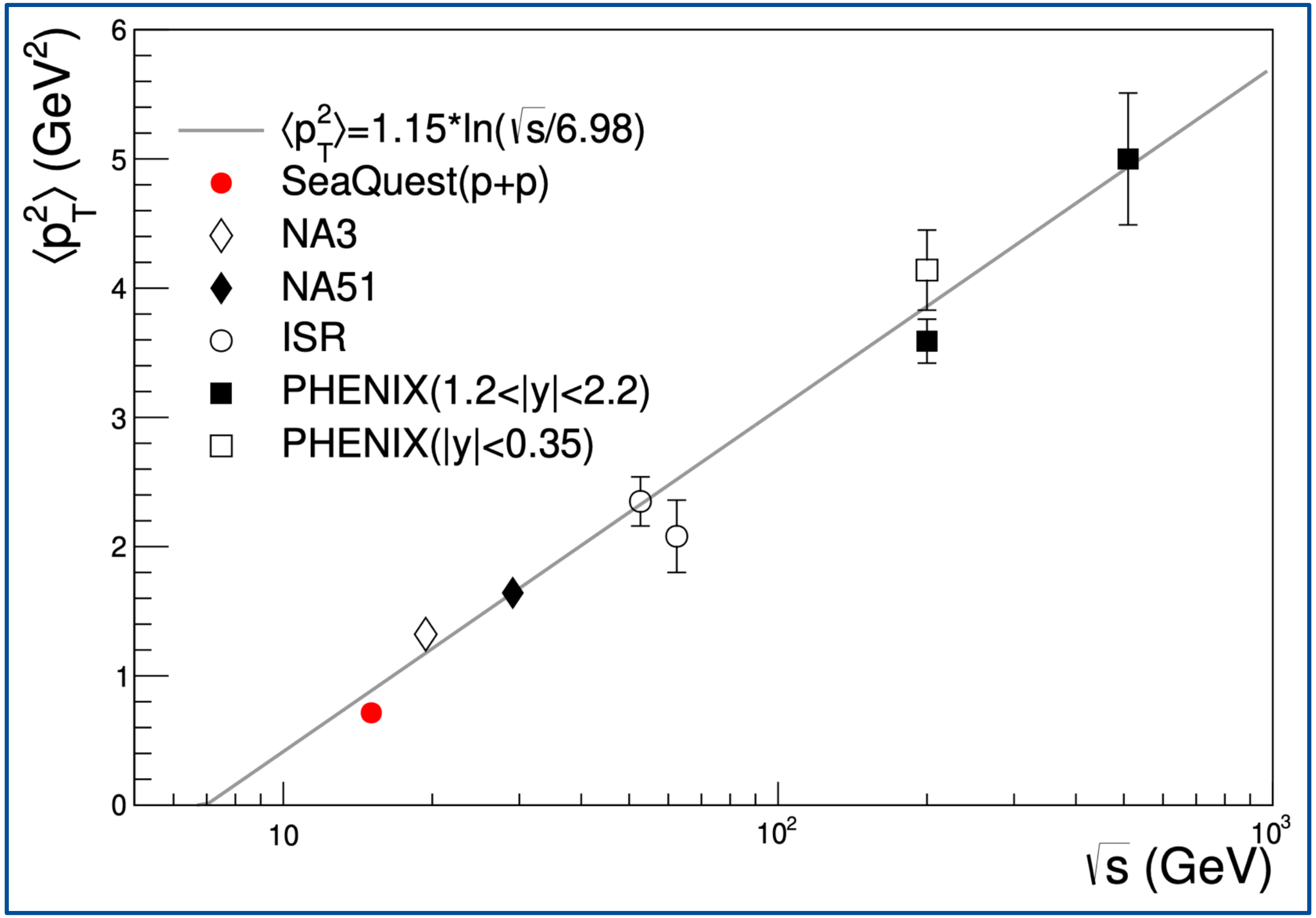
- Extracted $\langle P_T^2 \rangle$ compared with results from other experiments across a range of $\sqrt{S}$
- Increasing logarithmically against $\sqrt{S}$

$$\left\langle p_T^2 \right\rangle = a \ln\left(\sqrt{s}/b\right)$$

$$a = (1.150 \pm 0.043)\,\mathrm{GeV}^2$$

$$b = (6.98 \pm 0.37)\,\mathrm{GeV}$$

- Variation from rapidity range is expected and previously observed in fixed target experiments at Fermilab in 1980's

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