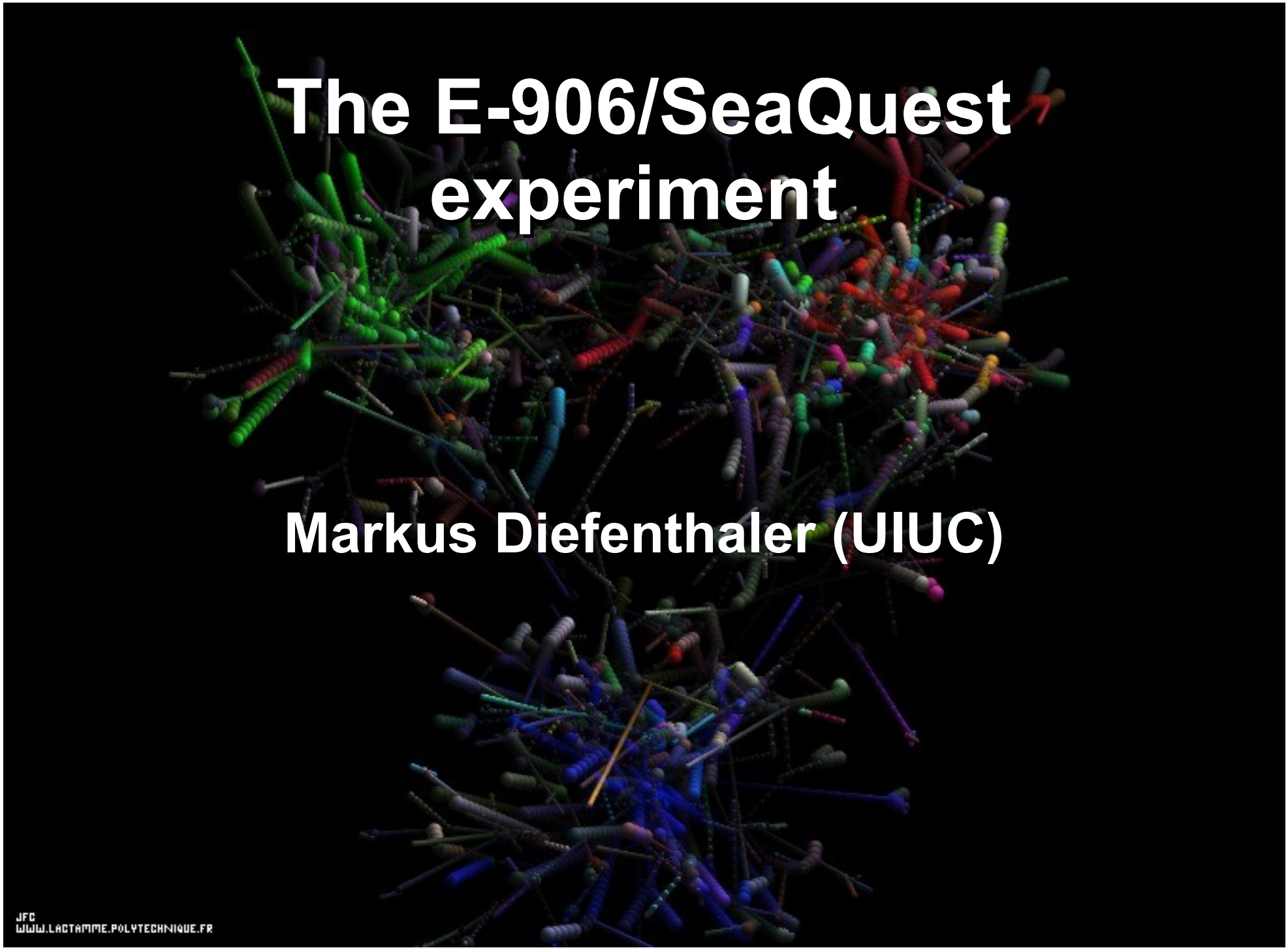
The E-906/SeaQuest experiment

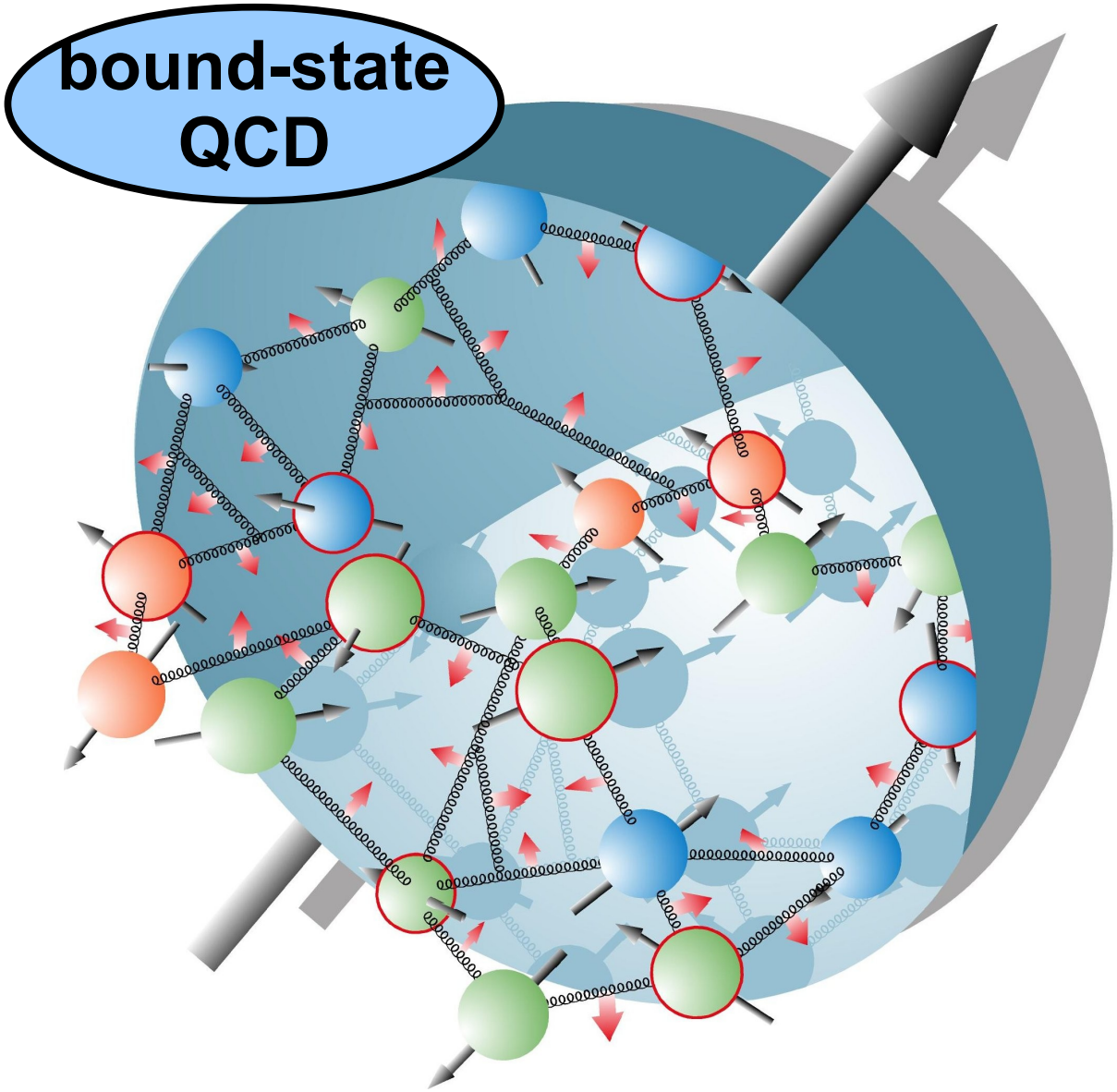
Markus Diefenthaler (UIUC)



The SeaQuest collaboration

- **Abilene Christian University:** Donald Isenhower, Tyler Hague, Rusty Towell, Shon Watson
- **Academia Sinica:** Wen-Chen Chang, Yen-Chu Chen, Shiu Shiuan-Hal, Da-Shung Su
- **Argonne National Laboratory:** John Arrington, **Donald F. Geesaman** (*co-spokesperson*), Kawtar Hafidi, Roy Holt, Harold Jackson, David Potterveld, **Paul E. Reimer** (*co-spokesperson*), Joshua Rubin
- **University of Colorado:** Ed(ward) Kinney, Joseph Katich, Po-Ju Lin
- **Fermi National Accelerator Laboratory:** Chuck Brown, Dave Christian, Jin-Yuan Wu
- **University of Illinois:** Bryan Dannowitz, Markus Diefenthaler, Bryan Kerns, Naomi C.R Makins, R. Evan McClellan, Jen-Chieh Peng
- **KEK:** Shin'ya Sawada
- **Ling-Tung University:** Ting-Hua Chang
- **Los Alamos National Laboratory:** Christine Aidala, Gerry Garvey, Mike Leitch, Han Liu, Ming Liu, Pat McGaughey, Joel Moss, Andrew Puckett
- **University of Maryland:** Betsy Beise, Kazutaka Nakahara
- **University of Michigan:** Chiranjib Dutta, Wolfgang Lorenzon, Richard Raymond, Michael Stewart
- **National Kaohsiung Normal University:** Rurngsheng Guo, Su-Yin Wang
- **University of New Mexico:** Younus Imran
- **RIKEN:** Yoshinori Fukao, Yuji Goto, Atsushi Taketani, Manabu Togawa
- **Rutgers University:** Lamiaa El Fassi, Ron Gilman, Ron Ransome, Brian Tice, Ryan Thorpe, Yawei Zhang
- **Tokyo Tech:** Shou Miyaska, Kenichi Nakano, Florian Sanftl, Toshi-Aki Shibata
- **Yamagata University:** Yoshiyuki Miyachi

The inner structure of the nucleon



Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3

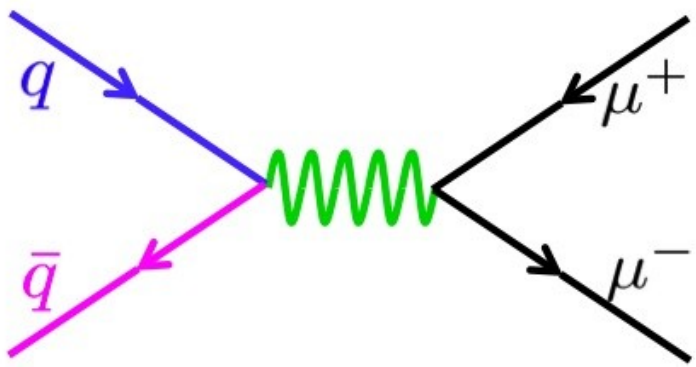
Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

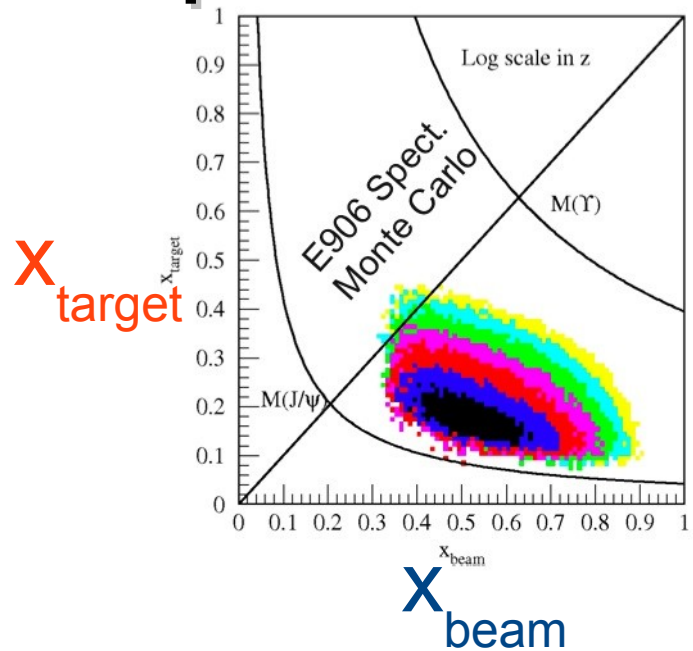
The inner structure of the nucleon

- Mathematical proof of confinement included among the seven Millennium Prize Problems in Mathematics.
- **Exploring the nonperturbative regime:**
  - **Lattice QCD:** *"Through difficult calculations of merciless precision that call upon the full power of modern computer technology, […] they have demonstrated the origin of the proton's mass [...]I believe this is one of the greatest scientific achievements of all time."* (Frank Wilczek)
  - Intense **experimental studies** of deep-inelastic scattering, electron-positron annihilation and proton-proton collisions (including **Drell-Yan scattering**).

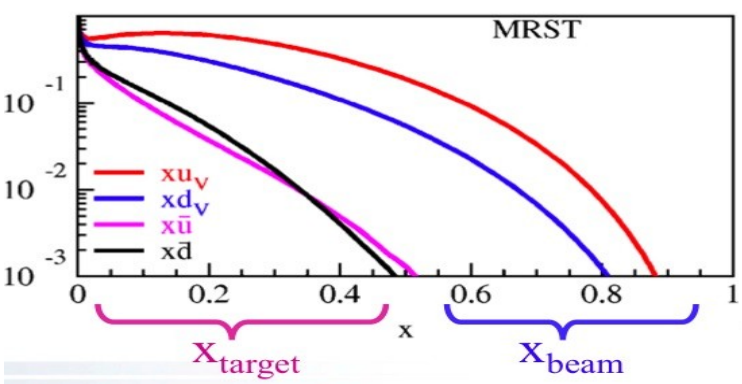
A laboratory for sea quarks

The Drell-Yan process



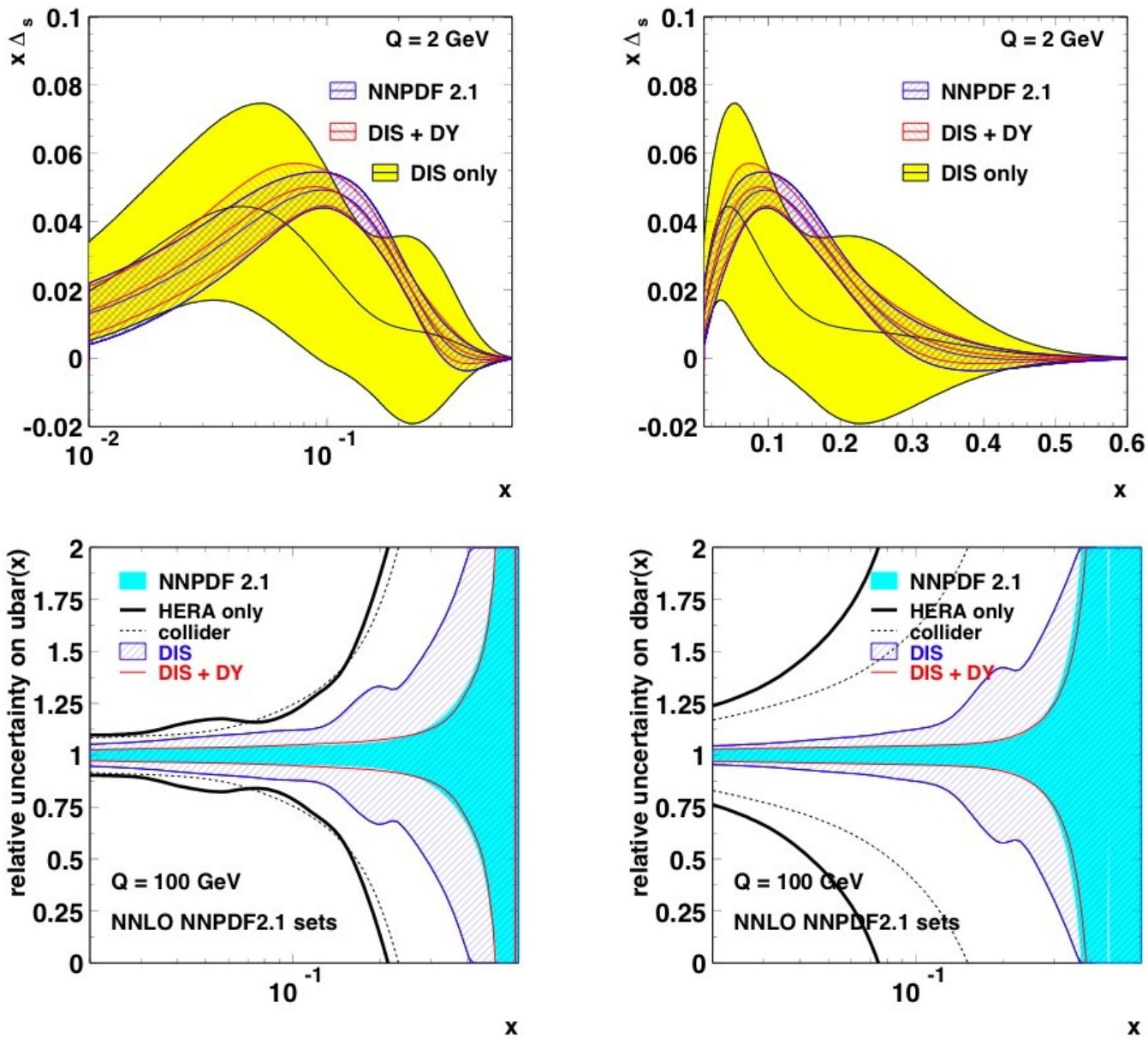


$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x_\mathrm{b}\,\mathrm{d}x_\mathrm{t}} = \frac{4\pi\alpha^2}{9x_\mathrm{b}\,x_\mathrm{t}}\frac{1}{s}\sum_q e_q^2\left[\bar{q}_\mathrm{t}(x_\mathrm{t})q_\mathrm{b}(x_\mathrm{b}) + q_\mathrm{t}(x_\mathrm{t})\bar{q}_\mathrm{b}(x_\mathrm{b})\right]$$

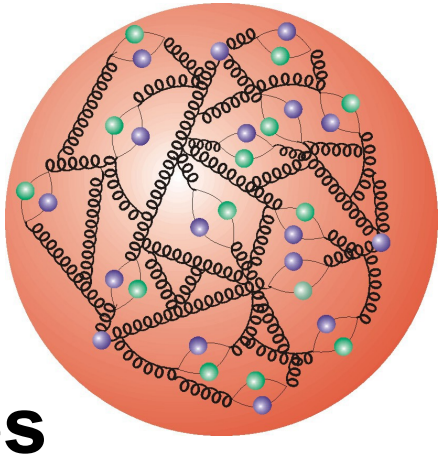


beam: valence quarks at high-x
target: sea quarks at low/intermediate-x

Unique sensitivity to sea quarks



Probing the proton sea

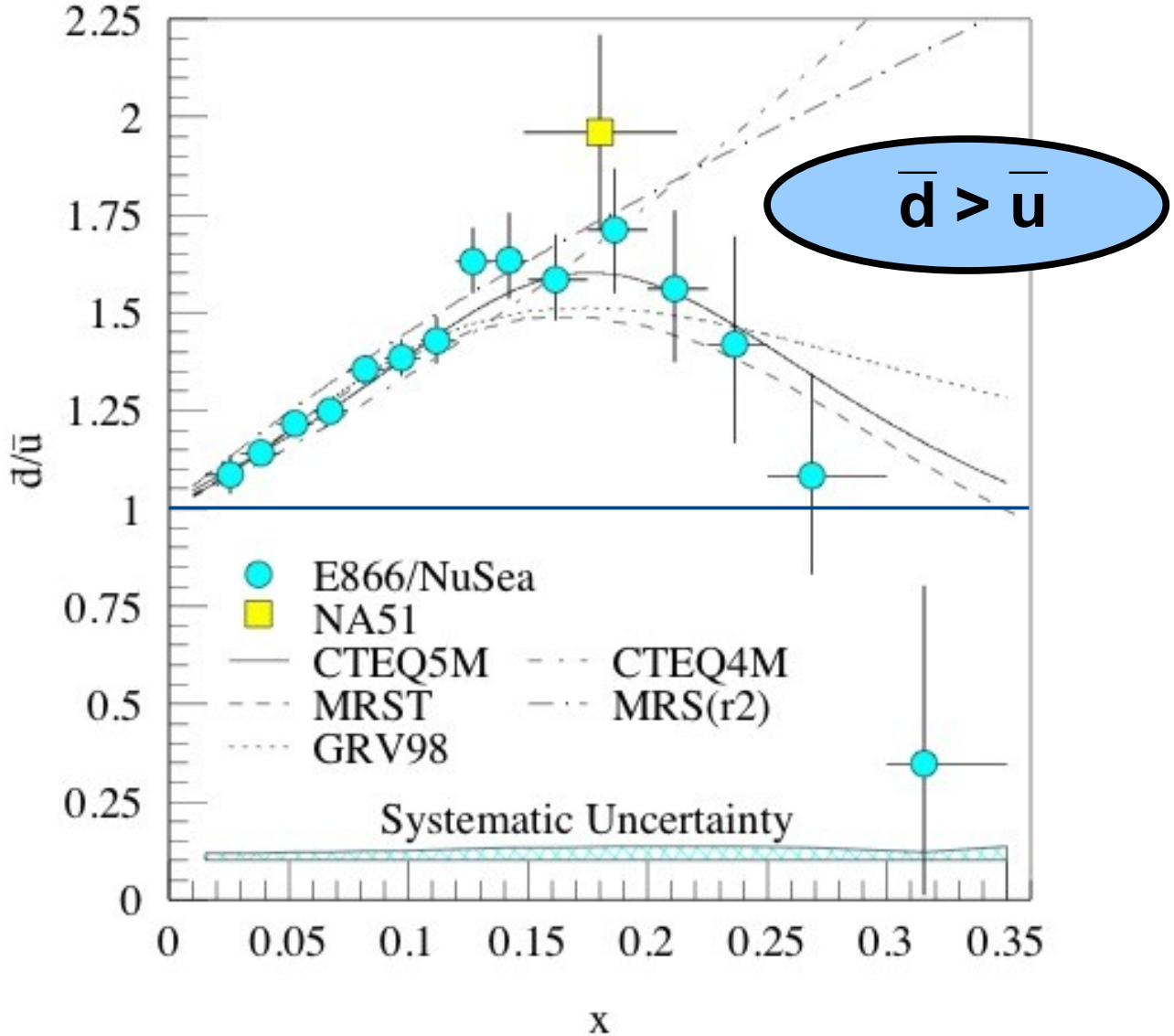


- **perturbative sea: g → q$\bar{q}$,**
  flavor-symmetric, **$\bar{u}$ = $\bar{d}$**
- **analysis of cross-section differences**
  → sensitivity to **$\bar{d}$ - $\bar{u}$** in valence region
- **measurement of cross-section ratios**

$$\left.\frac{\sigma^{pd\to\mu^+\mu^-}}{\sigma^{pp\to\mu^+\mu^-}}\right|_{x_\mathrm{b}\gg x_\mathrm{t}} \approx \frac{1}{2}\left[1+\frac{\bar{d}(x_\mathrm{t})}{\bar{u}(x_\mathrm{t})}\right]$$

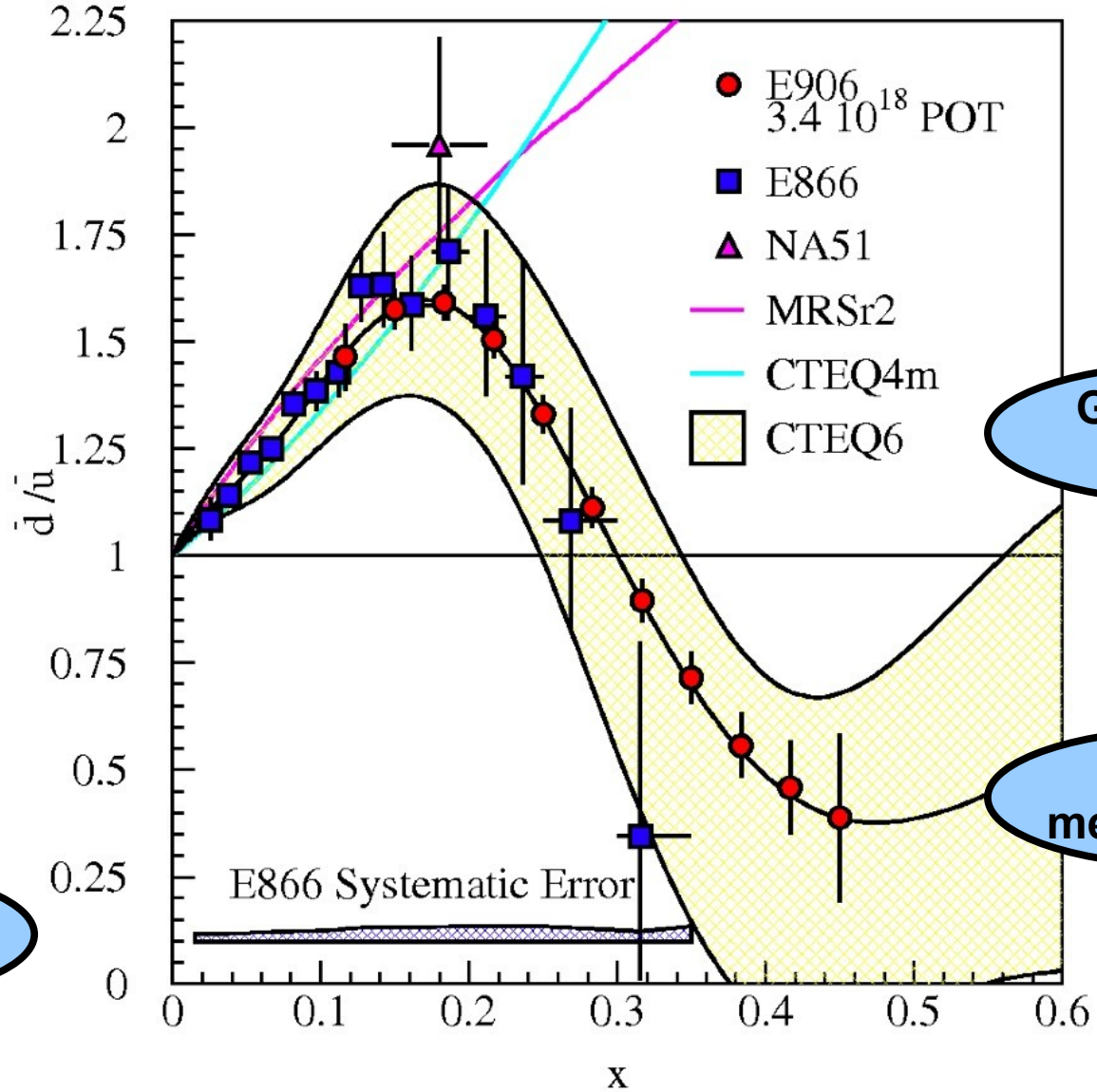
  → sensitivity to **$\bar{u}$** and **$\bar{d}$** in **proton sea**

Insights into the proton sea



alternate degrees of freedom?

SeaQuest probing the proton sea



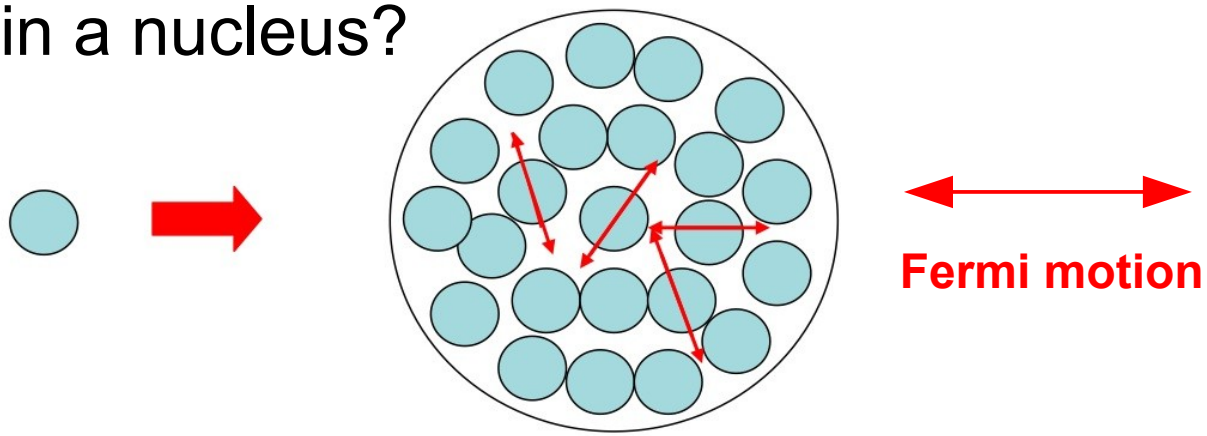
Global NLO PDF fit

extend measurement

SeaQuest: Syst. ~ 1%

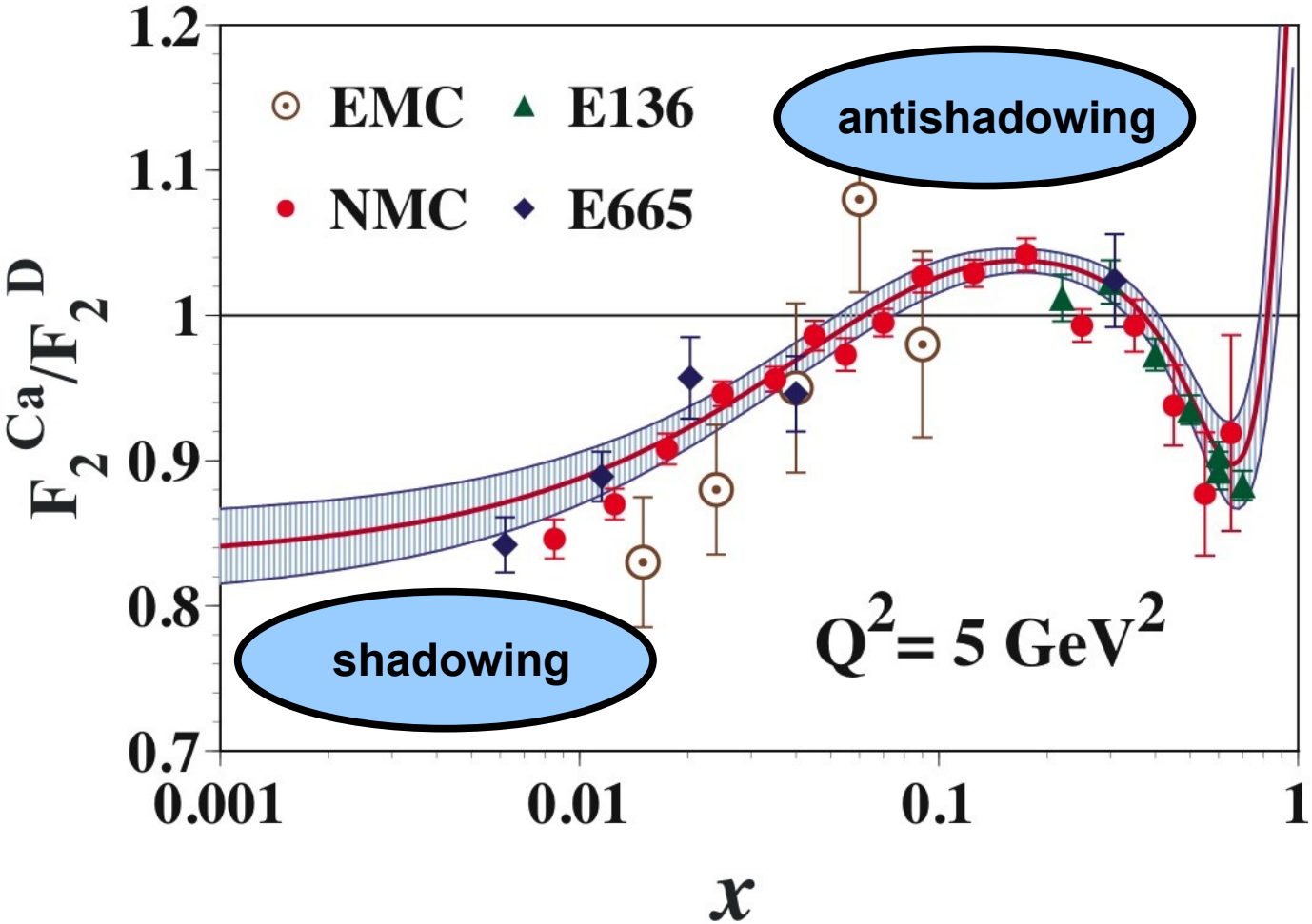
Nucleons embedded in nuclei

- Do nucleons change their internal properties when embedded in a nucleus?

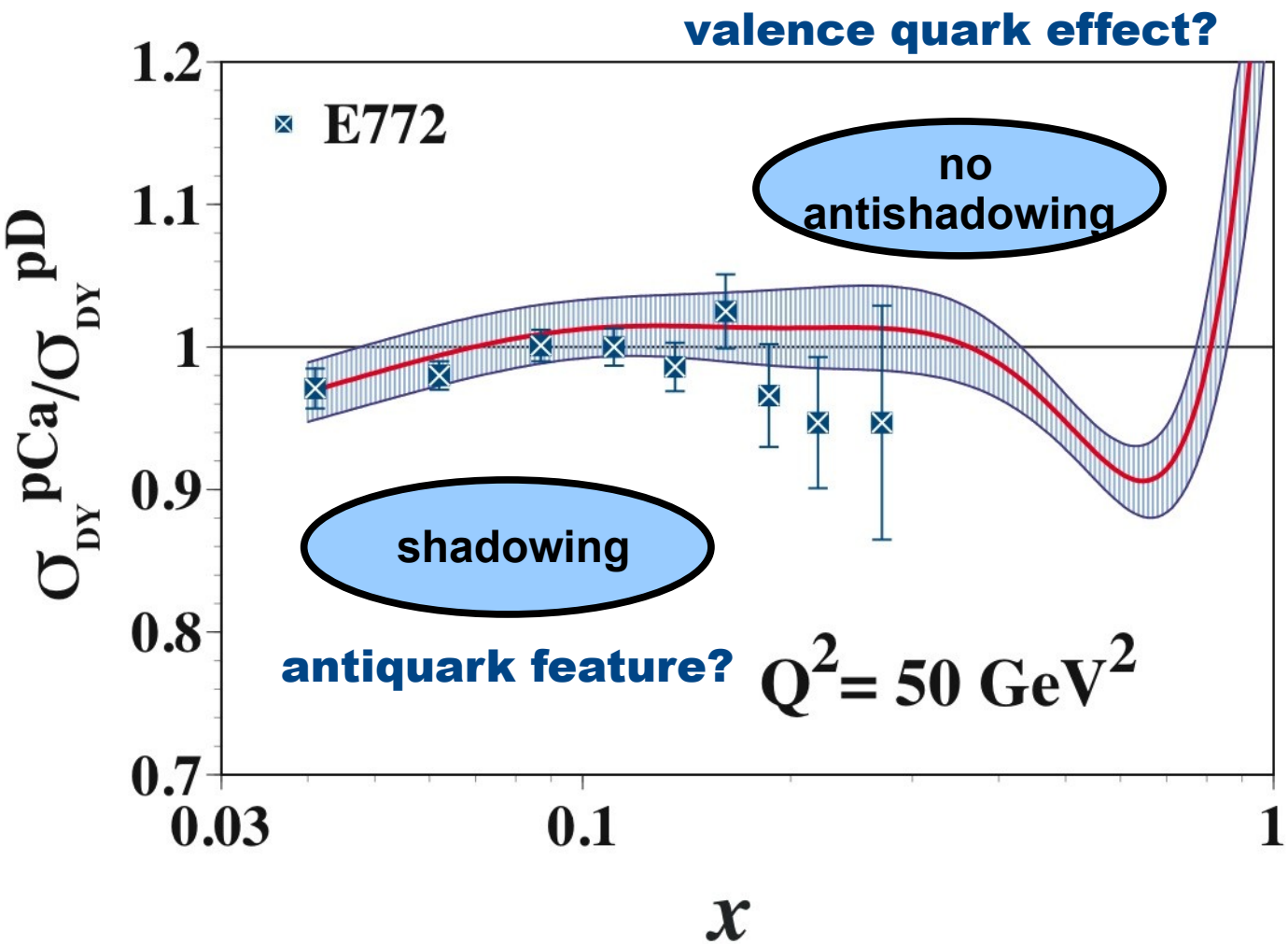


- Is confinement influenced by the nuclear medium?
- Do quarks and gluons play any role in the understanding of nuclear forces?
- Can the model of nuclear forces be replaced by a fundamental theory based on the strong interaction between quarks and gluons?

The EMC effect

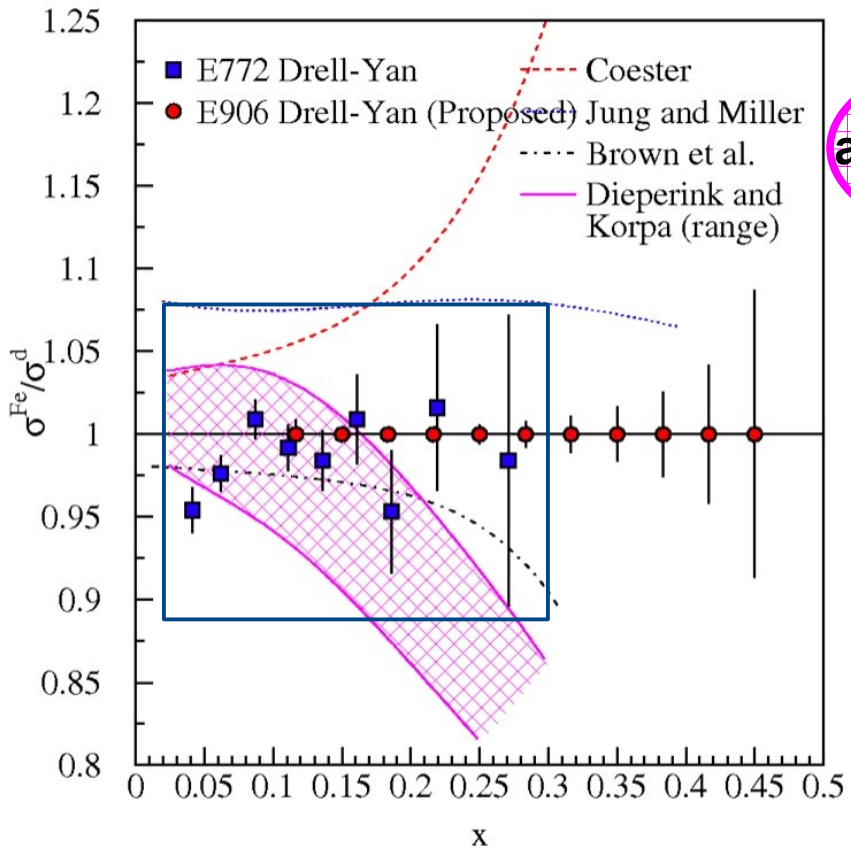


The EMC effect in Drell-Yan



The inner structure of a nucleus

- nuclear force mediated by meson exchange



no antiquak enhancement

large effects to antiquark PDF predicted as x increases

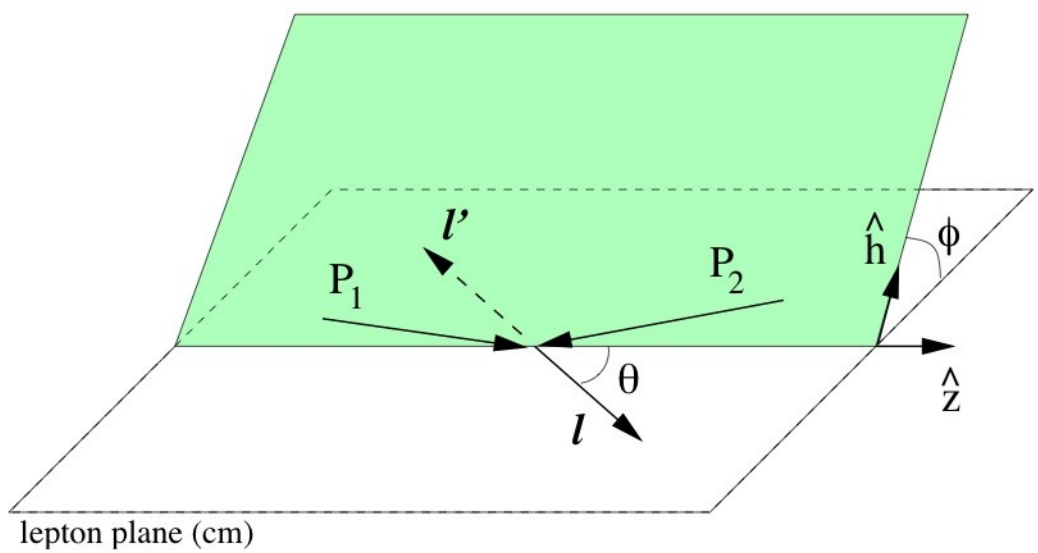
- **Where are the *nuclear* pions?**

The Lam-Tung relation

- **angular dependence** of the Drell-Yan cross-section:

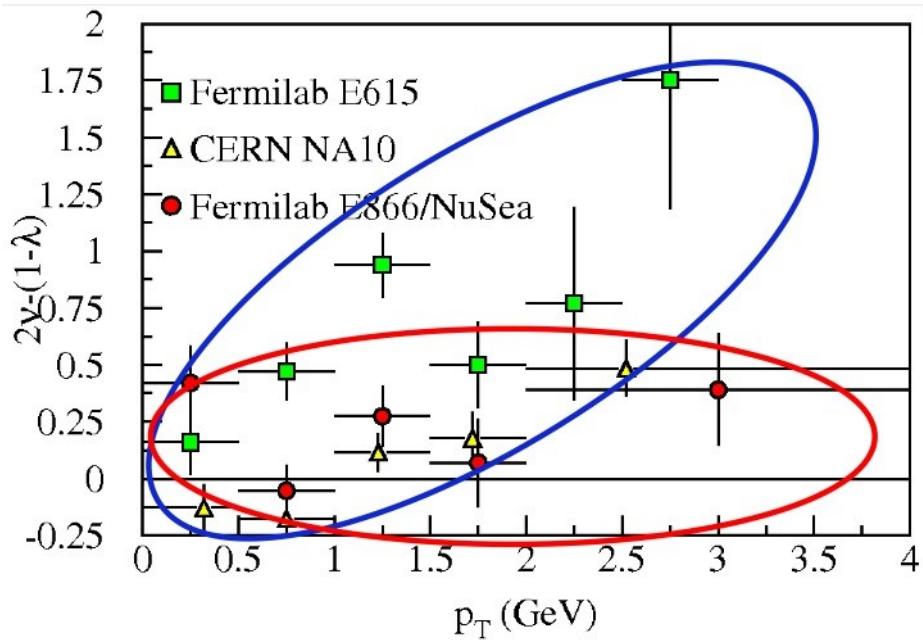
$$\frac{\mathrm{d}\,\sigma}{\mathrm{d}\,\Omega} \propto 1 + \lambda \cos(\theta)^2 + \mu \sin(2\theta)\cos(\phi) + \frac{\nu}{2}\sin(\theta)^2 \cos(2\phi)$$

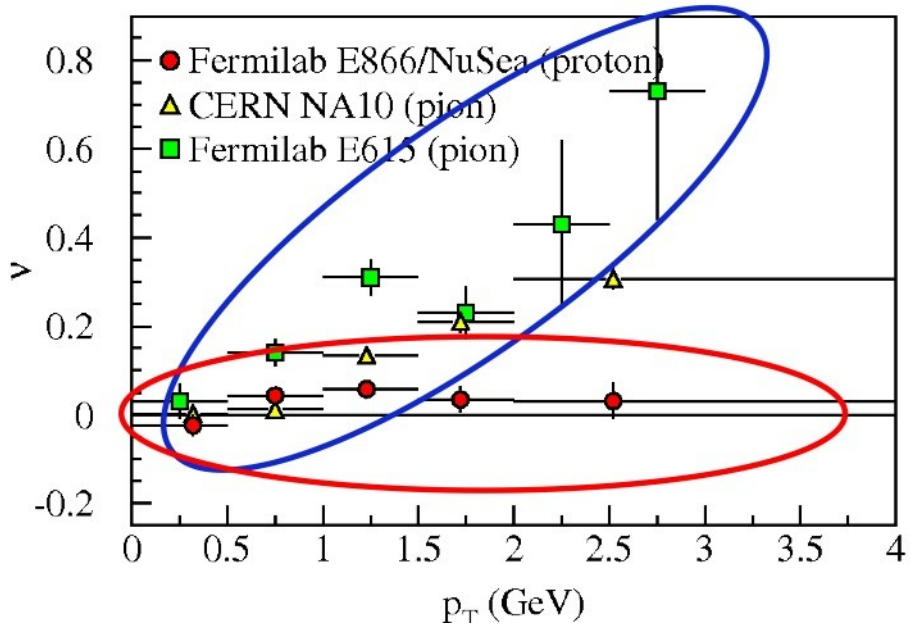
- **Lam-Tung relation:** $1 - \lambda = 2\nu$



Angular dependence

- **measurement in pion DY and proton DY:**





- **Collinear PDF:** only higher order gluon emission can generate deviations

The Boer-Mulders function

- **transverse-momentum dependent PDF:**

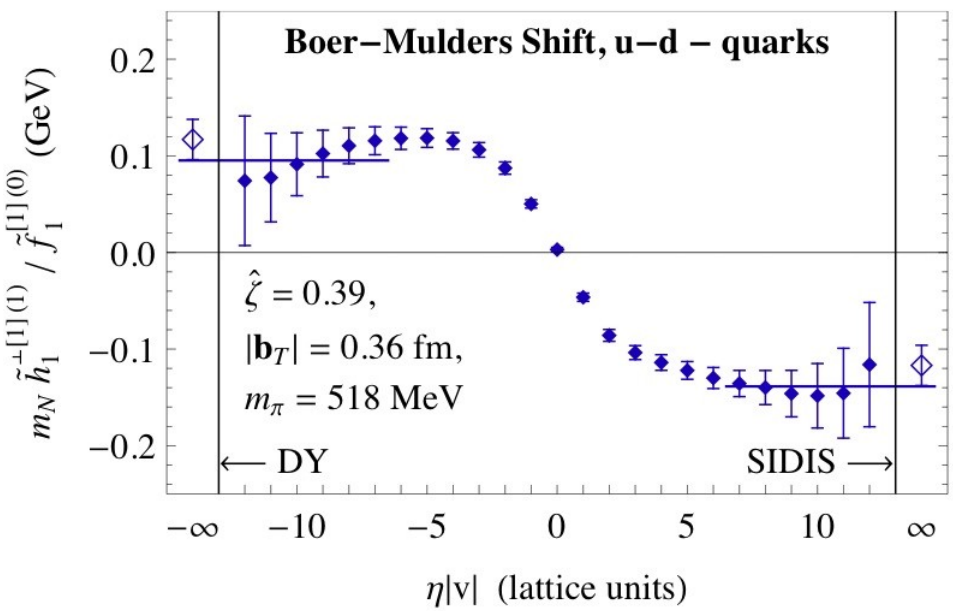
$$h_1^{\perp,q}(x,\mathbf{p}_T^2)$$ $$s_T^i \varepsilon^{ij} p_T^j \frac{1}{M}$$

- **chiral odd,** rather exotic in being **naive-time-reversal-odd**

  ↔ initial (Drell-Yan) and final state (SIDIS) interactions

  → **single-spin asymmetries**

- challenging the concept of factorization and universality



The SeaQuest mission

- **significant increase in physics reach**
- unique access to **sea quarks at high-x**
- **What is the structure of the nucleon?**
  - What is $\bar{\mathbf{d}}$ / $\bar{\mathbf{u}}$?
  - What are the origins of the sea quarks?
  - What is the high-x structure of the proton?
  - How are quark spin and orbital motion correlated?
- **What is the struture of nucleonic matter?**
  - Where are the *nuclear* pions?
  - Is antishadowing a valence effect?
- **Do colored partons lose energy in cold nuclear matter?**

The proton beam for SeaQuest

- extracted from **Fermilab Main Injector**

- 2×10^{12} protons / s for 5s spills each minute
- **120 GeV** proton beam instead of a 800 GeV proton beam (as used for E-866 / NuSea):
  - Drell-Yan cross section scales as **1/s**
  - J/Ψ decay (dominant background) scales as **s**
  - **50x** luminosity as E-866 (for same rate)

The SeaQuest target

luminosity: $3.4 \times 10^{35}/cm^2/s$

liquid hydrogen

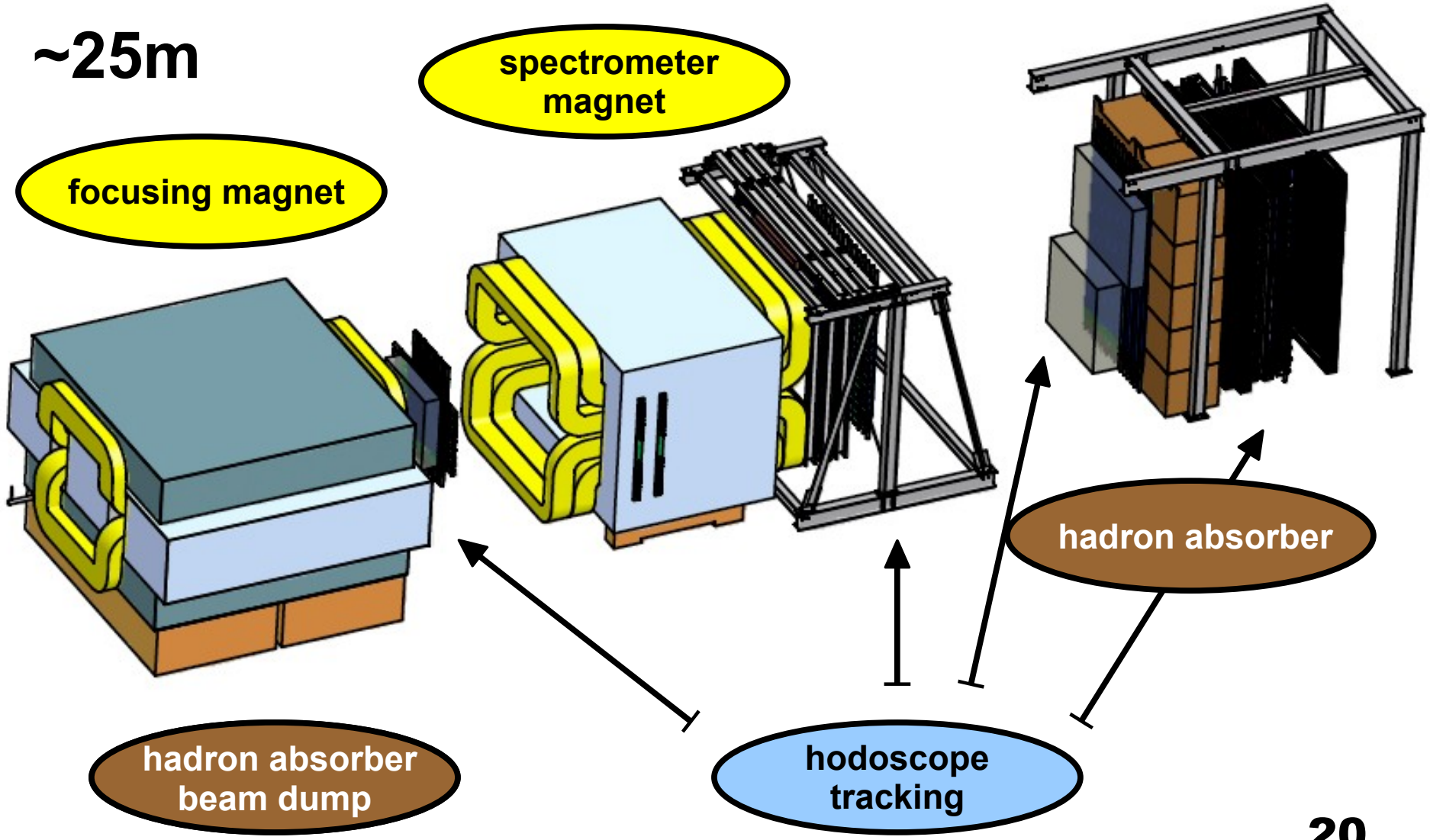
liquid deuterium

Carbon

Calcium

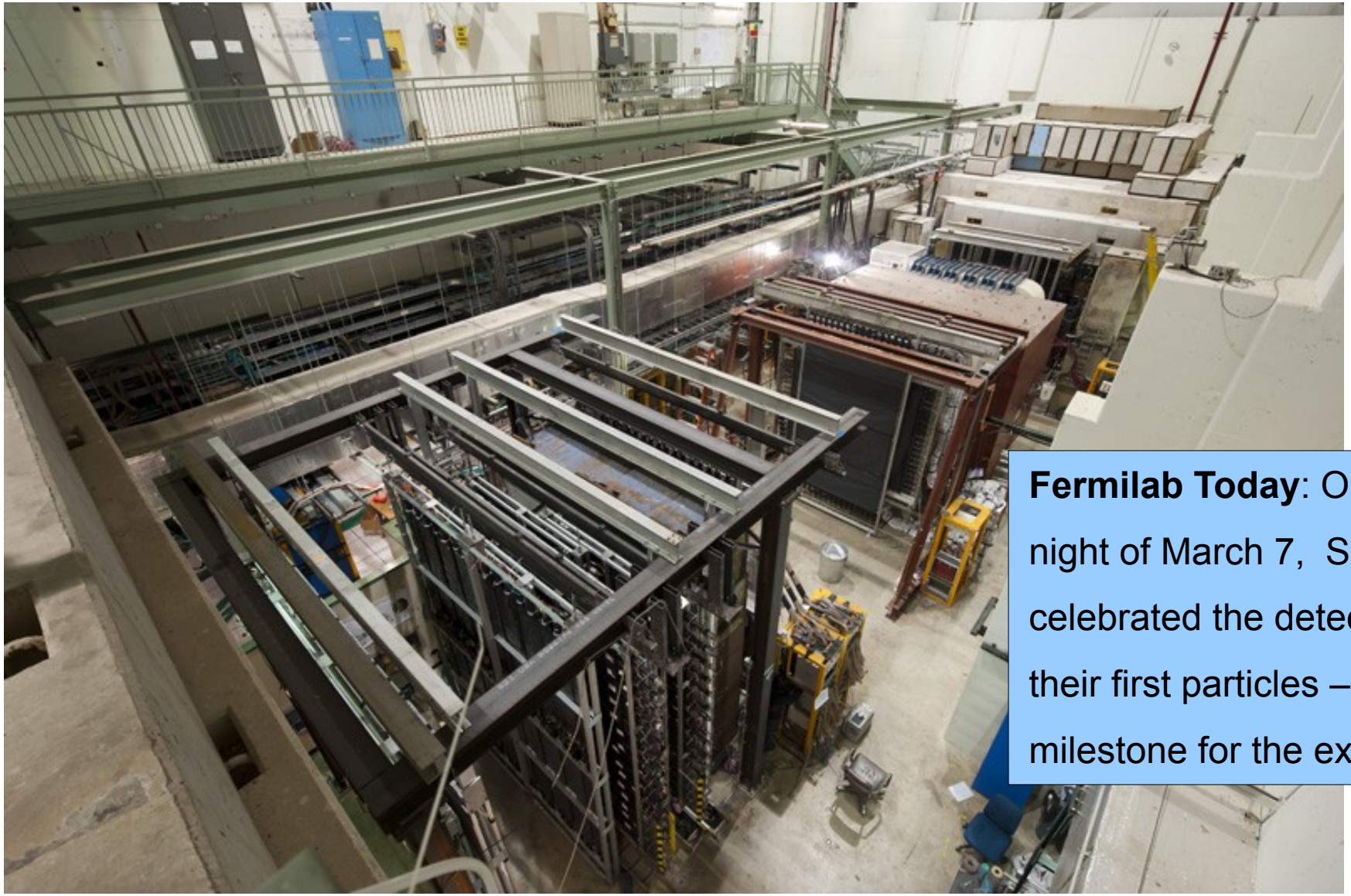
Tungsten

The SeaQuest spectrometer



Reuse and recylce

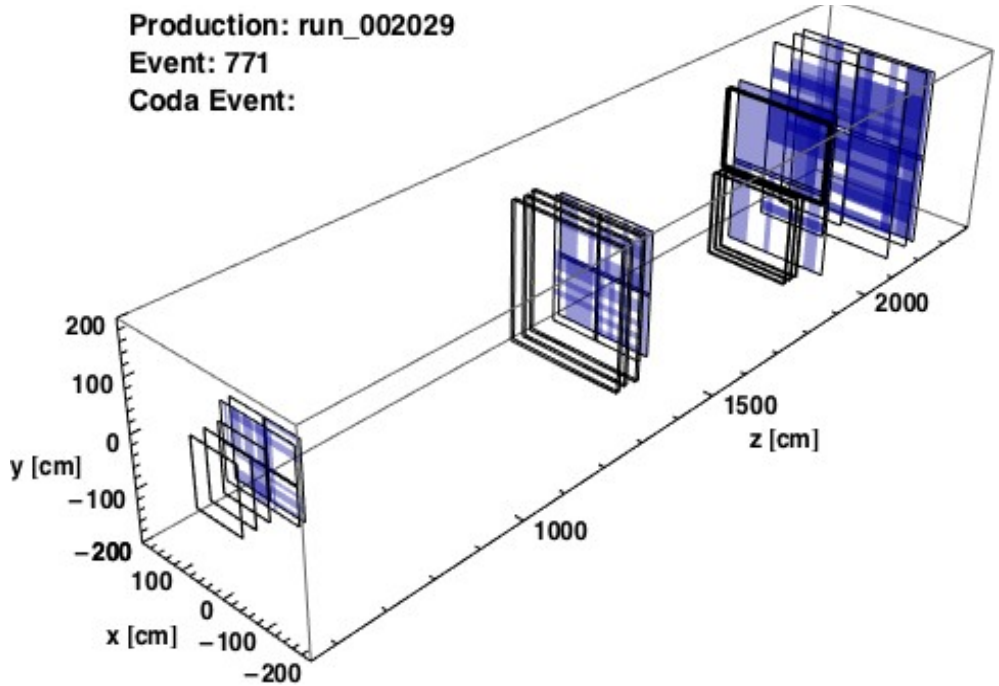
“Joy and toil as Fermilab sends first particles to SeaQuest”

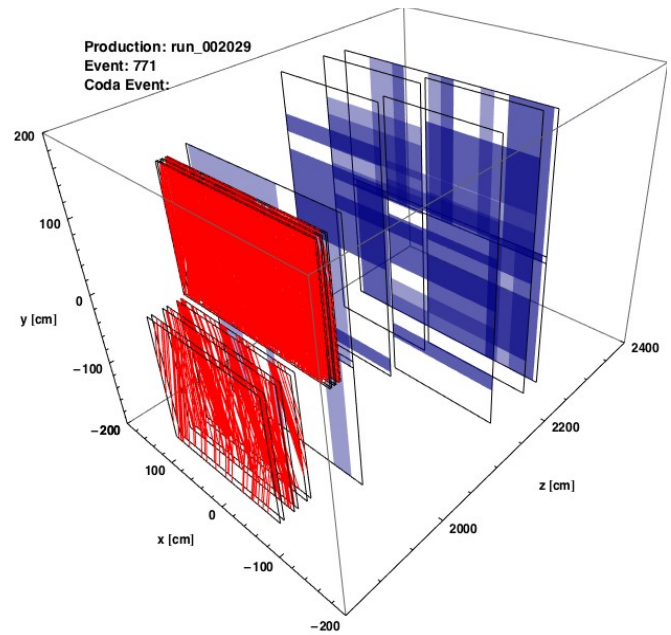


Fermilab Today: On the night of March 7, SeaQuest celebrated the detection of their first particles – a new milestone for the experiment.

Commissioning Run 2012

- Brief 2-month run after many interesting diversions
- all systems worked
- Large intensity variations within spill
  - Caused entire detector to turn "on"
  - More prominent in data with dimuon trigger than single muon trigger
- DAQ TDC firmware not quite ready
  - Lacked hardware zero suppression (zero suppression in front-end CPU)
  - Large dead times, especially with large events
- PMTs at St. 1 need better rate capabilities
- Interim St. 1 and 3- Tracking





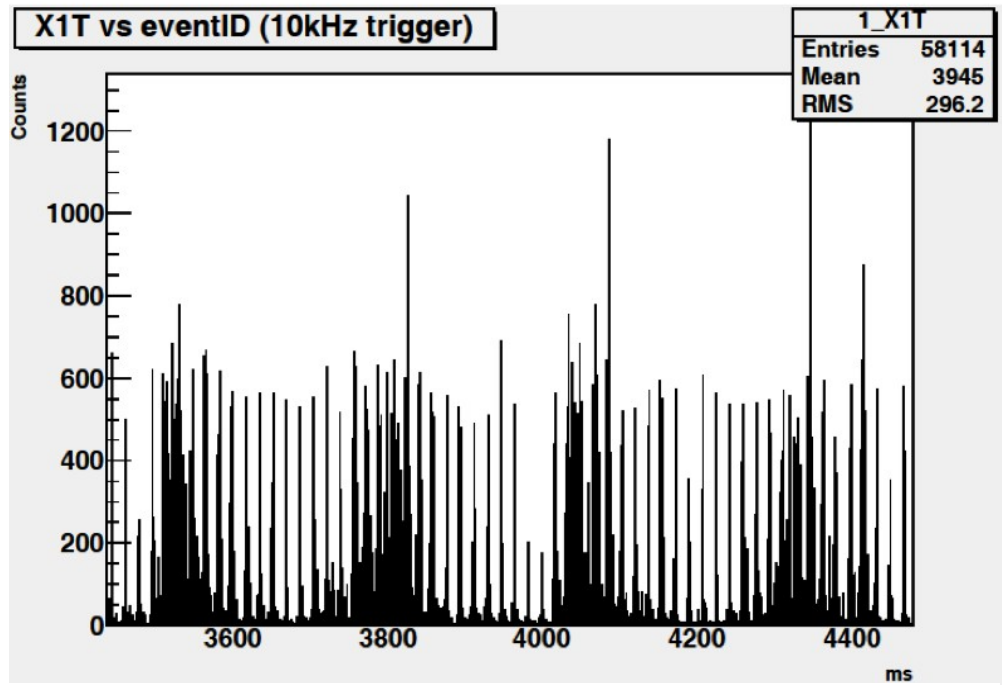
Commissioning Run

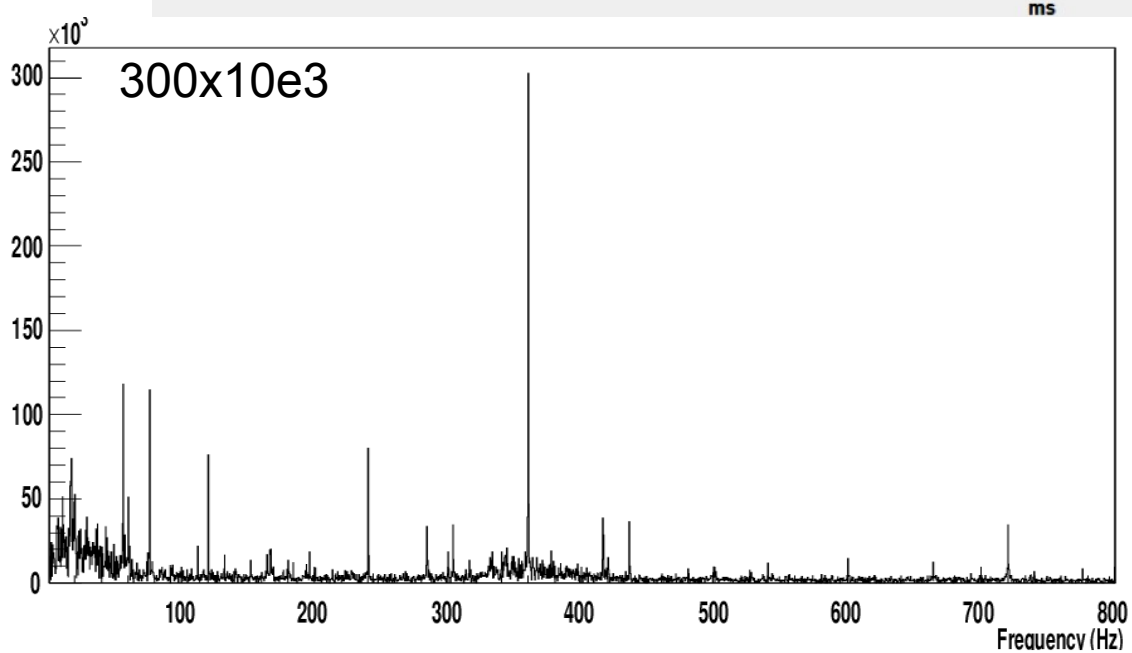
- *Average* intensity normal, measured by beamline instrumentation
- Independent 10kHz pulsed DAQ read out raw hodoscope rates
- Bins are integrated counts over 100μs (≈5000 RF buckets)
- Large variation in Instantaneous intensity, duty factor very low.
- Periodic structure— Phase locked to AC 60 Hz

Conclusion:

The MI extraction was also being commissioned.

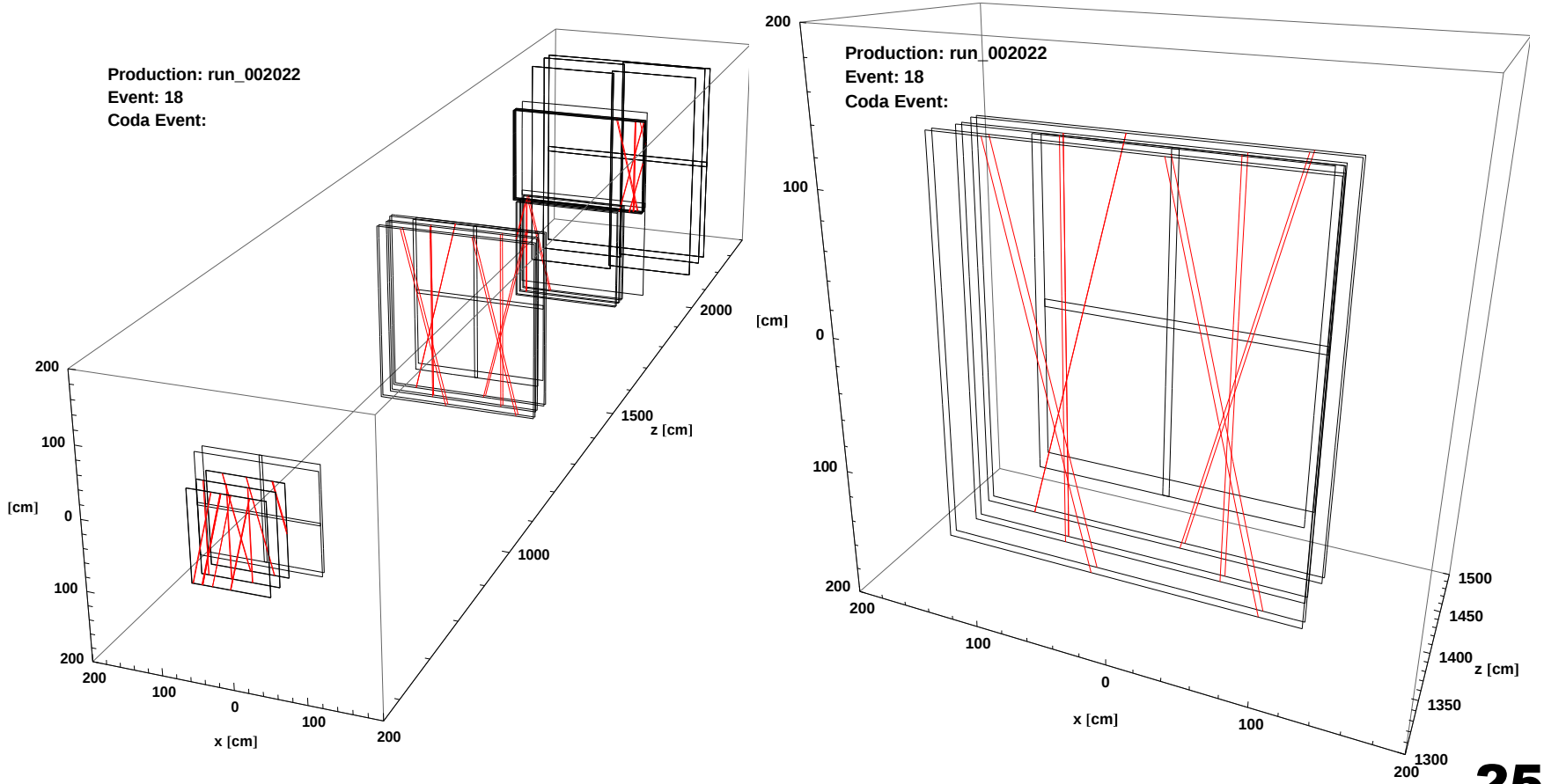
AD believes that these problems have been addressed.





"Splat" Block

- A card was developed to keep a running average of the multiplicity over a 160 ns window (8 RF buckets).
- If average multiplicity above threshold, raises a trigger veto
- Luminosity greatly reduced, but trigger suppresses windows of time with large beam intensities.



Collaboration Meeting May 17th and 18th

status review, commissioning plan,

run plan

The SeaQuest mission

unique laboratory for sea quarks at high-x

→ structure of nucleons and nucleonic matter

short commissioning run in 2012 (2 months)

→ **restart of FNAL Main Injector ~ June**

commissioning with various updates

→ **two years of data taking**

exciting extensions possible