

The E-906/SeaQuest experiment at Fermilab

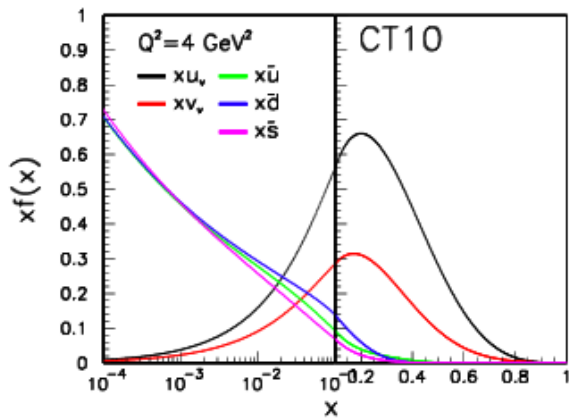
Dr. Markus Diefenthaler (UIUC)

Particles and Nuclei International Conference 2014

The SeaQuest collaboration

- **Abilene Christian University:** Ryan Castillo, Michael Daugherty, Donald Isenhower, Noah Kitts, Lacey Medlock, Rusty Towell, Shon Watson, Ziao Jai Xi
- **Academia Sinica:** Wen-Chen Chang, Yen-Chu Chen, Ting-Hua Chang, Shiu Shiu-Hao
- **Argonne National Laboratory:** John Arrington, Donald F. Geesaman (co-spokesperson), Kawtar Hafidi, Roy Holt, Paul E. Reimer (co-spokesperson), Brian Tice
- **University of Colorado:** Ed(ward) Kinney, Joseph Katich, Po-Ju Lin
- **Fermi National Accelerator Laboratory:** Chuck Brown, Dave Christian, Su-Yin Wang, Jin-Yuan Wu
- **University of Illinois:** Bryan Dannowitz, Markus Diefenthaler, Bryan Kerns, Hao Li, Naomi C.R. Makins, R. Evan McClellan, Jen-Chieh Peng, Shivangi Prasad, Mae Hwee Teo, Yangqiu Yin
- **KEK:** Shin'ya Sawada
- **Los Alamos National Laboratory:** Gerry Garvey, Andreas Klein, Mike Leitch, Kun Liu, Ming Liu, Pat McGaughey
- **University of Maryland:** Betsy Beise, Kazutaka Nakahara
- **University of Michigan:** Christine Aidala, Wolfgang Lorenzon, Bryan Ramson, Richard Raymond, Josh(u) Rubin
- **National Kaohsiung Normal University:** Rurngsheng Guo
- **RIKEN:** Yuji Goto
- **Rutgers University:** Ron Gilman, Ron Ransome, Arun Tadeipalli
- **Tokyo Tech:** Shou Miyaska, Kei Nagai, Kenichi Nakano, Toshi-Aki Shibata
- **Yamagata University:** Yuya Kudo, Yoshiyuki Miyachi

The inner structure of the nucleon



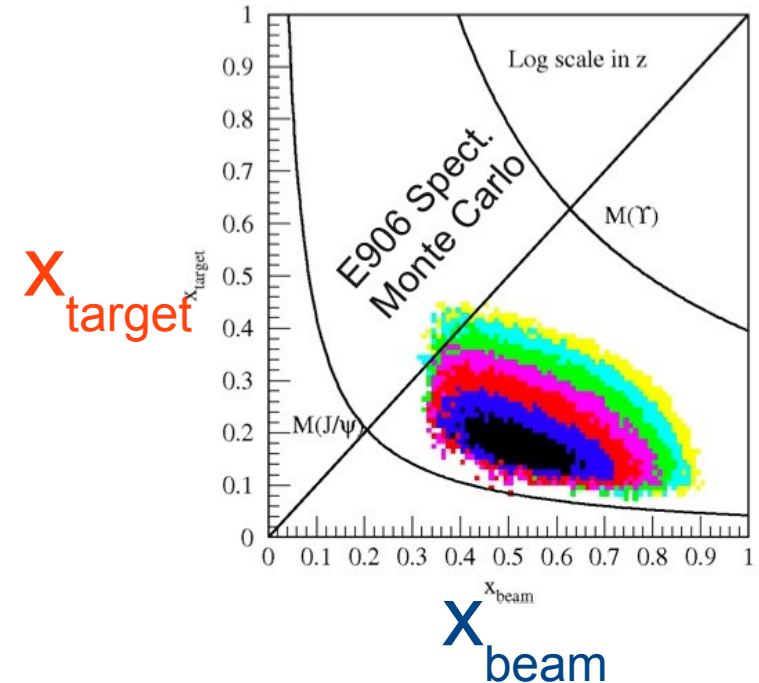
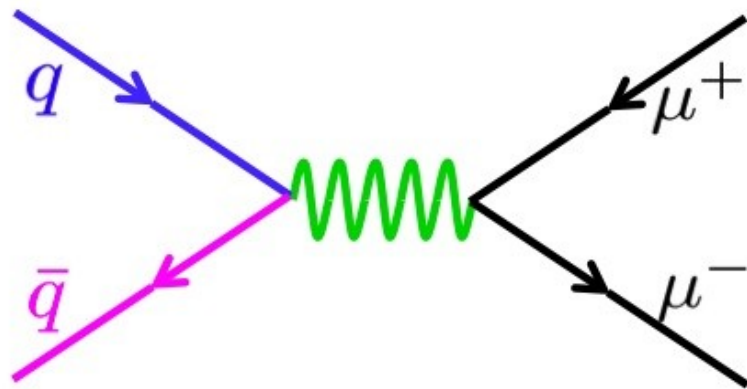
origin of the
nucleon spin

origin of
nucleon sea

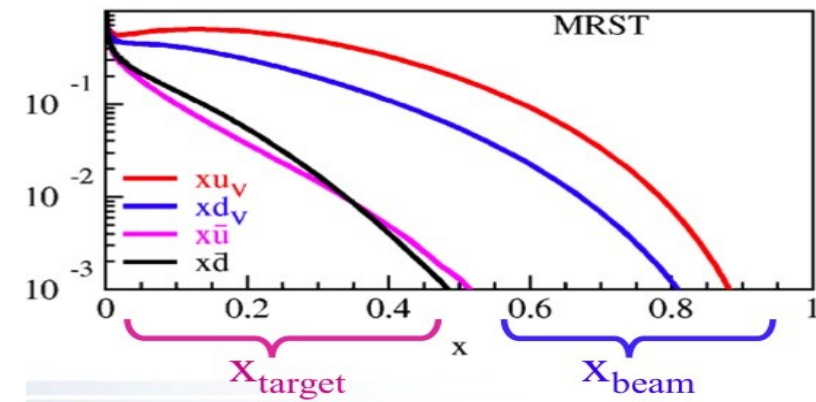
nucleons in
nuclei

A laboratory for sea quarks

The Drell-Yan process

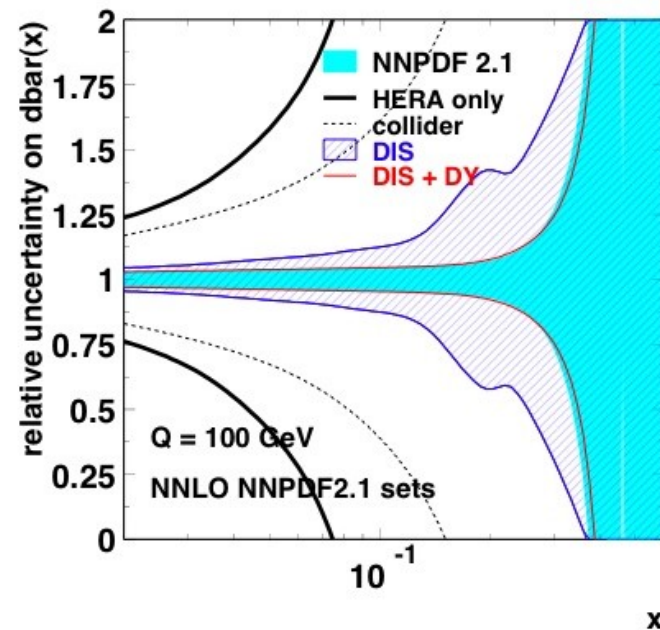
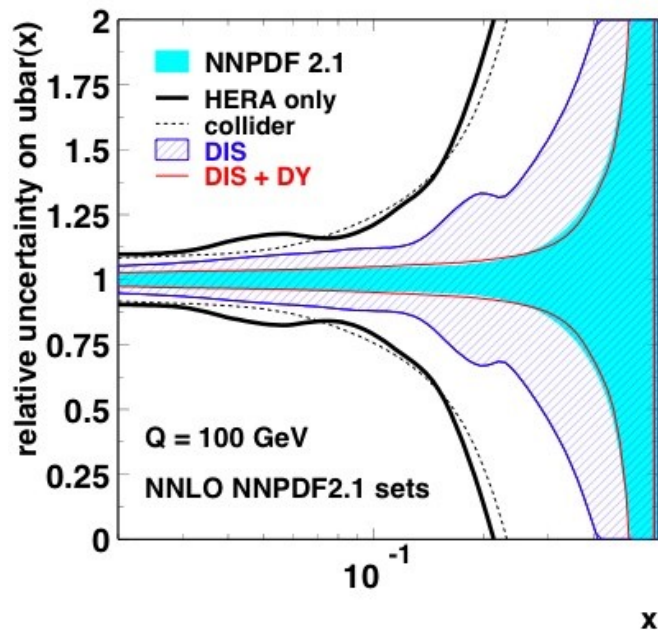
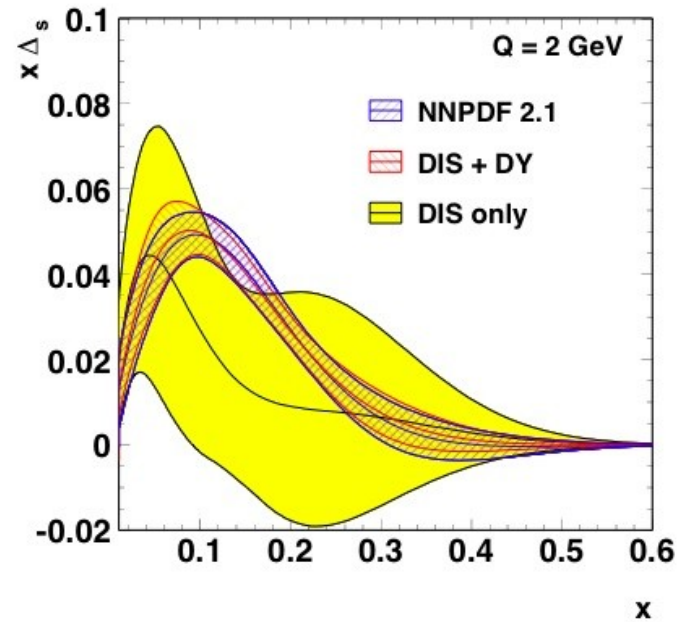
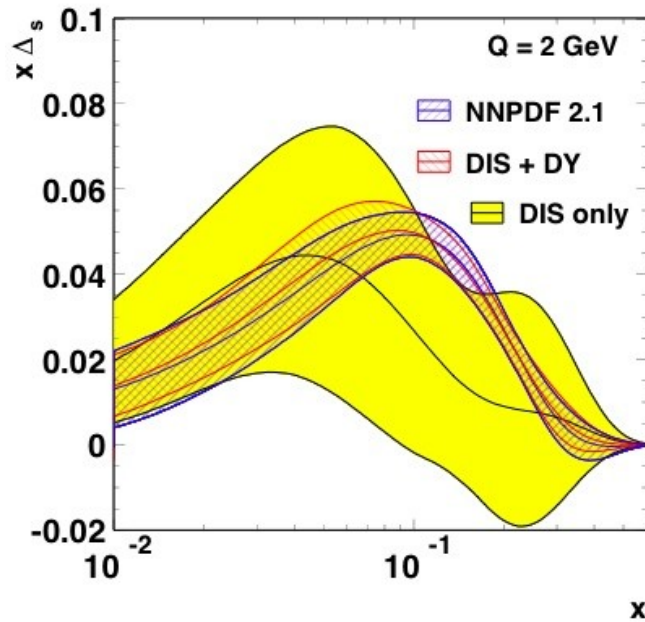


$$\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{9x_b x_t} \frac{1}{s} \sum_q e_q^2 [\bar{q}_t(x_t)q_b(x_b) + q_t(x_t)\bar{q}_b(x_b)]$$

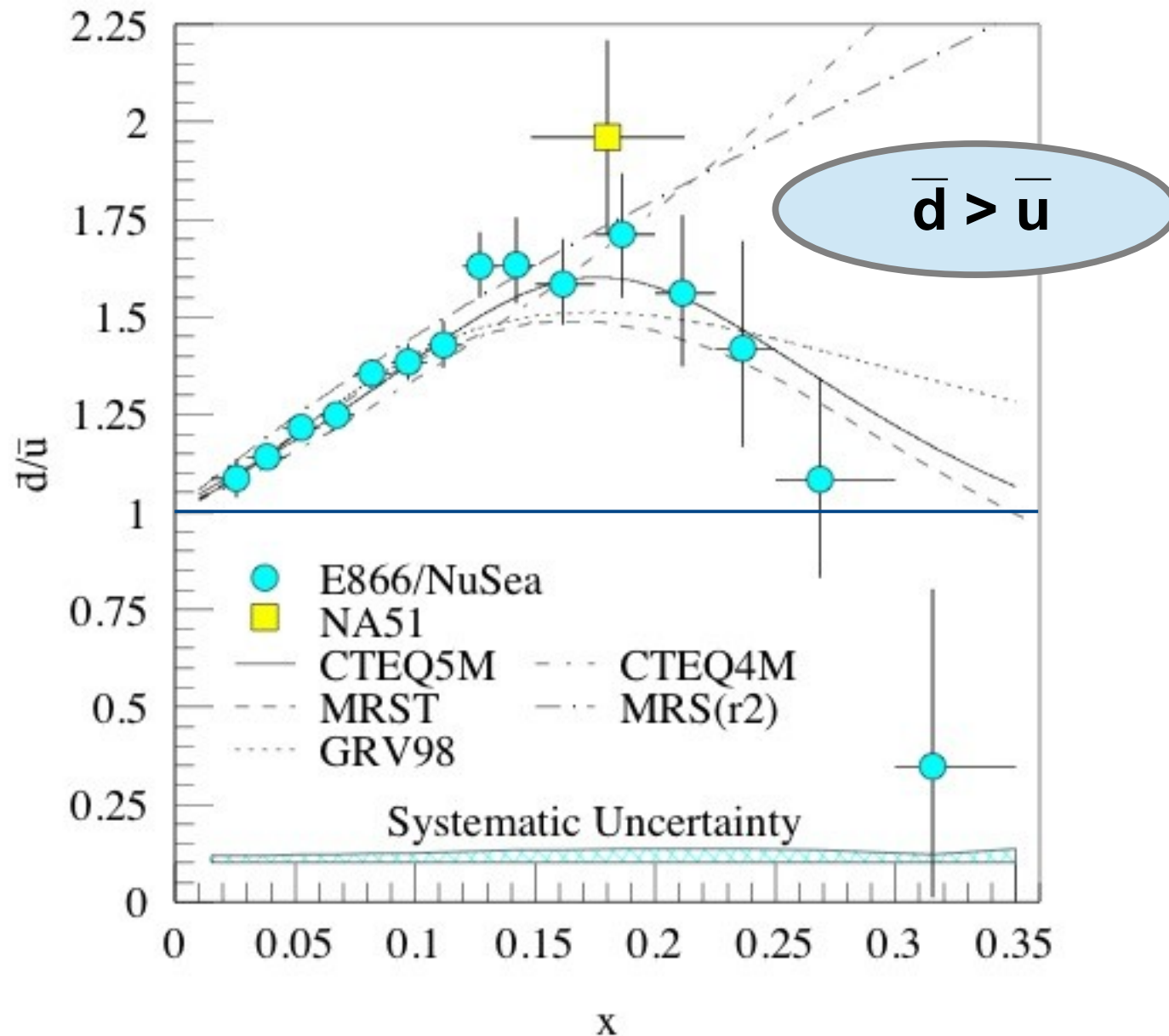


beam: valence quarks at high- x
target: sea quarks at low/intermediate- x

Unique sensitivity to sea quarks

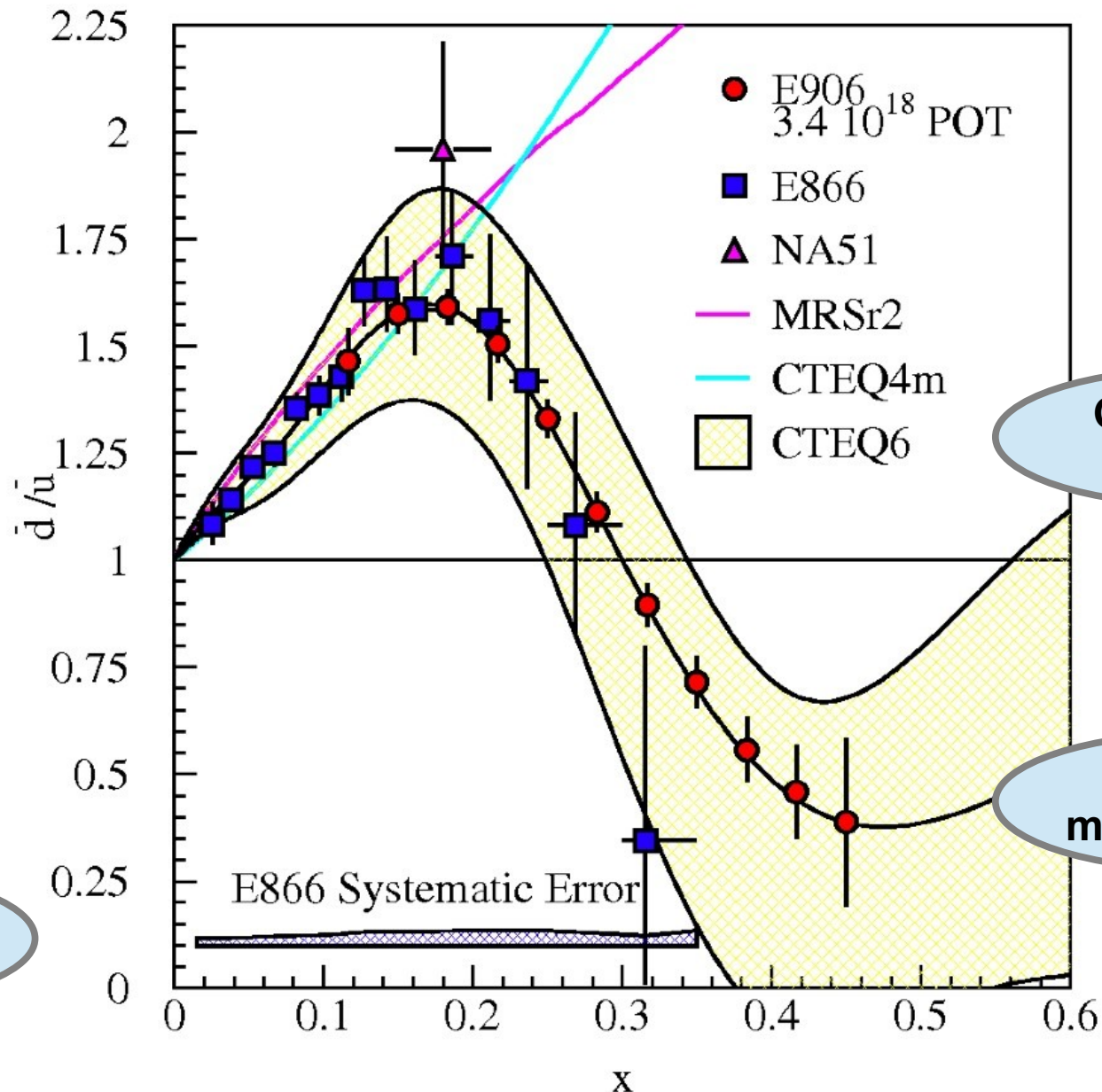


Insights into the proton sea



alternate degrees of freedom?

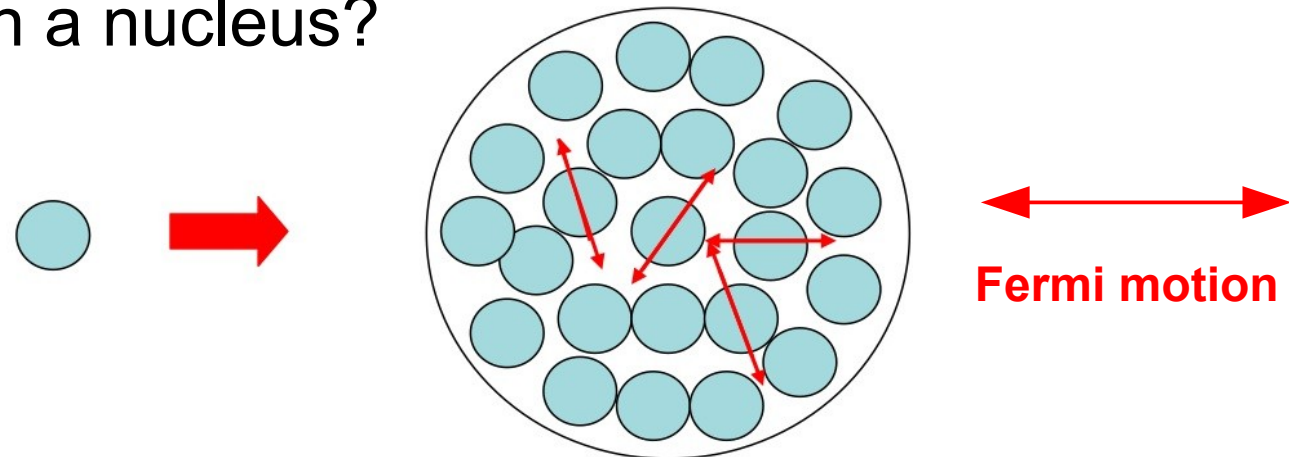
SeaQuest probing the proton sea



SeaQuest:
Syst. $\sim 1\%$

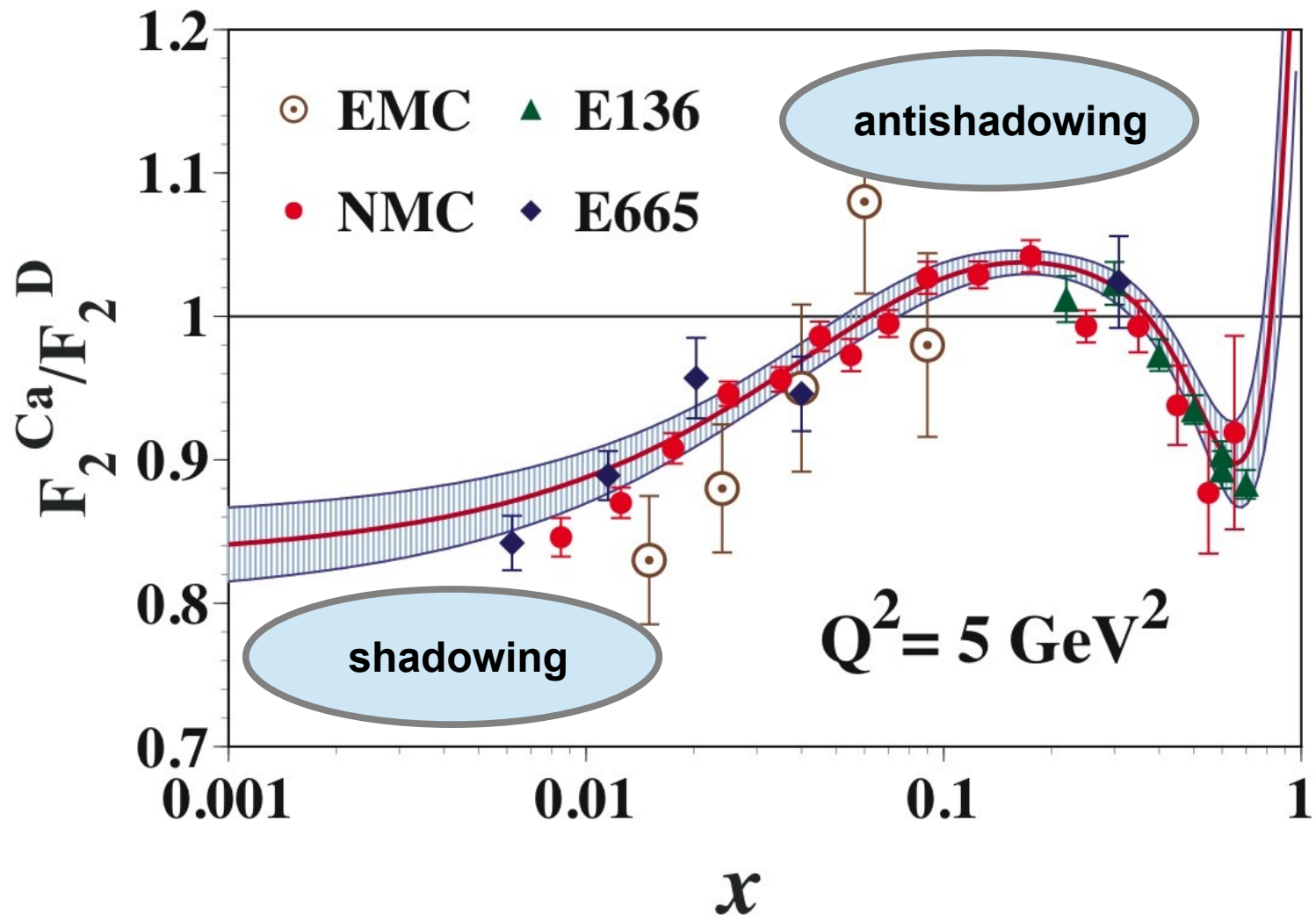
Nucleons embedded in nuclei

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

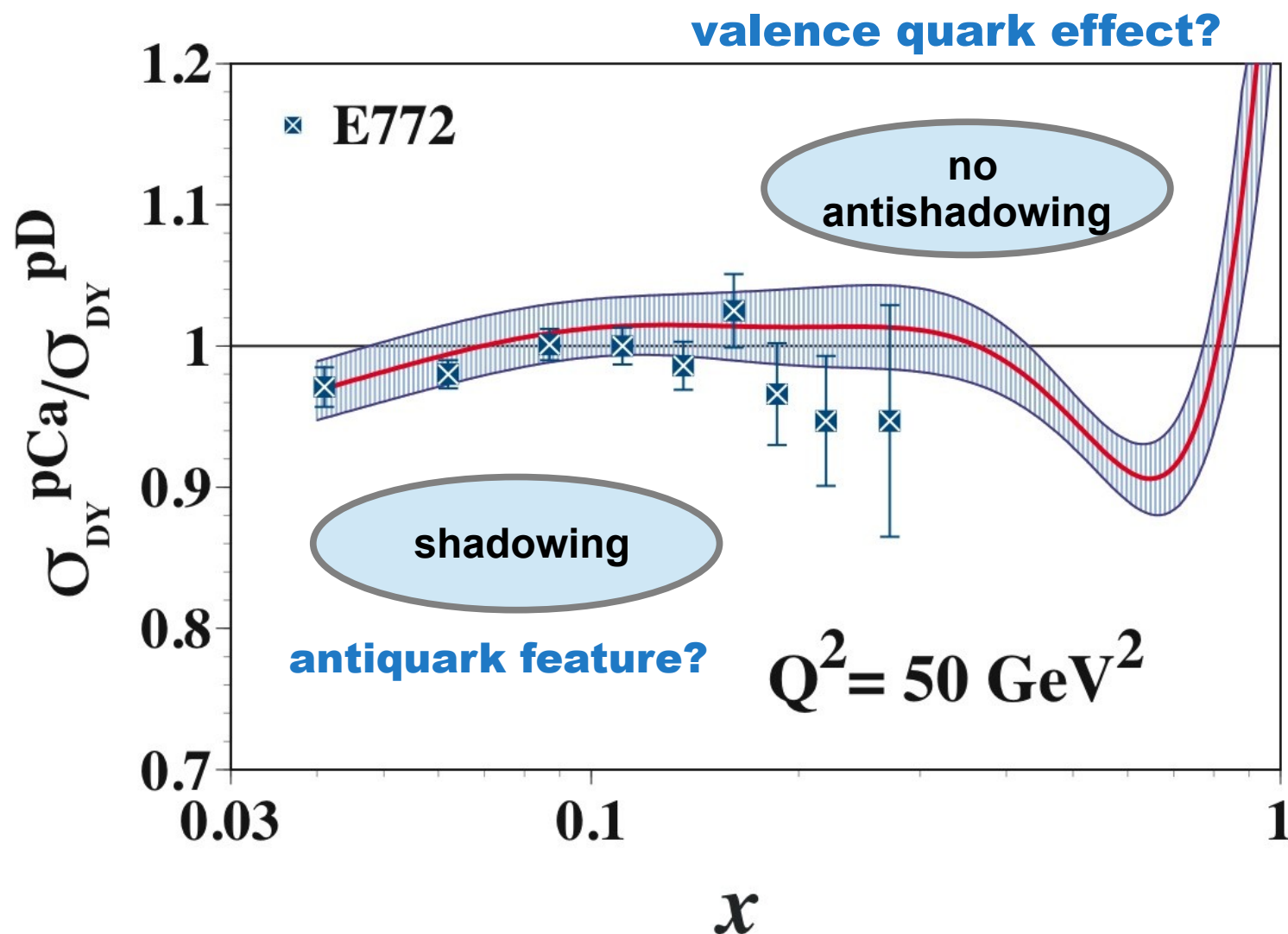


- Is confinement influenced by the nuclear medium?
- Do quarks and gluons play any role in the understanding of nuclear forces?
- Can the model of nuclear forces be replaced by a fundamental theory based on the strong interaction between quarks and gluons?

The EMC effect

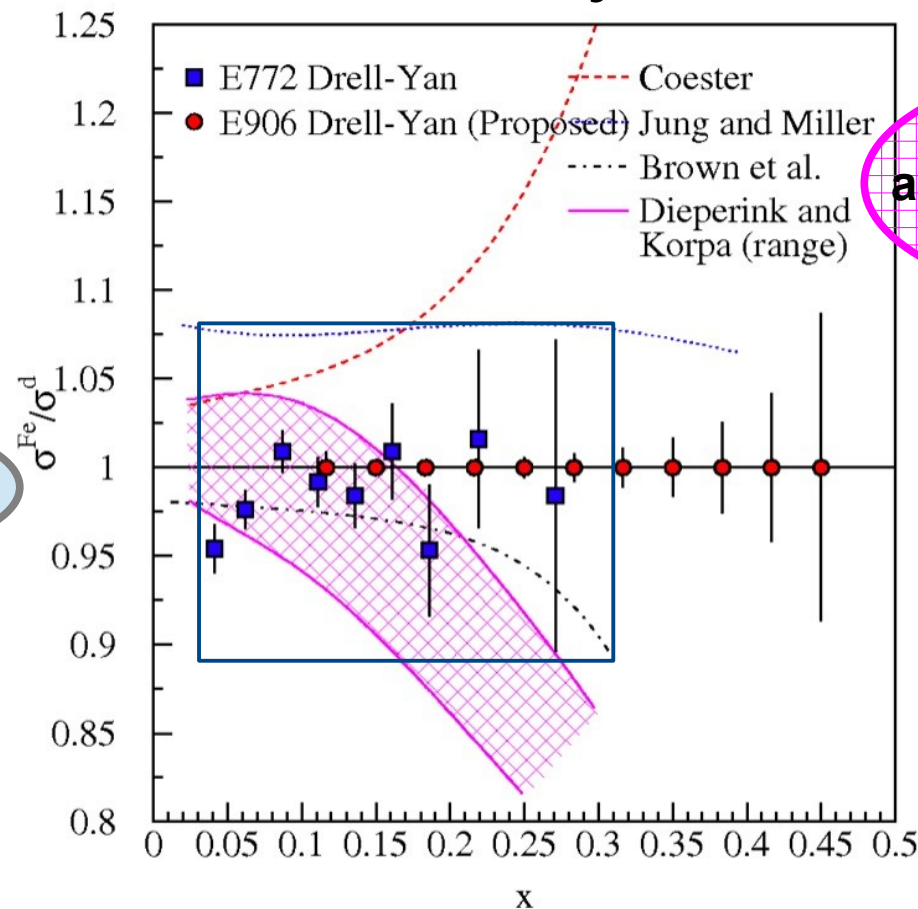


The EMC effect in Drell-Yan



The inner structure of a nucleus

- nuclear force mediated by meson exchange



large effects to antiquark PDF predicted as x increases

no antiquark enhancement

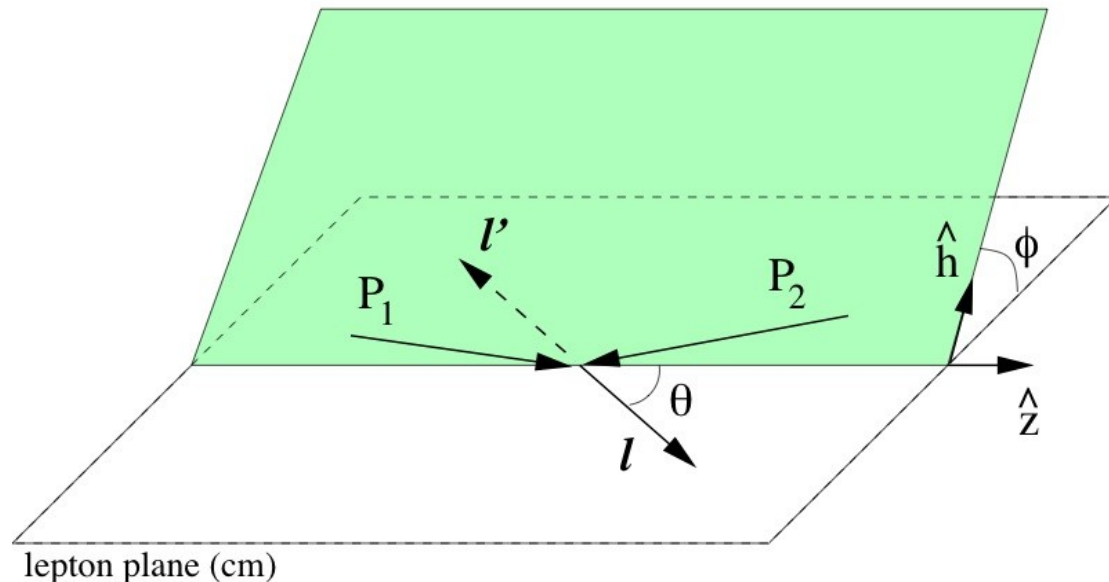
- Where are the *nuclear* pions?

The Lam-Tung relation

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

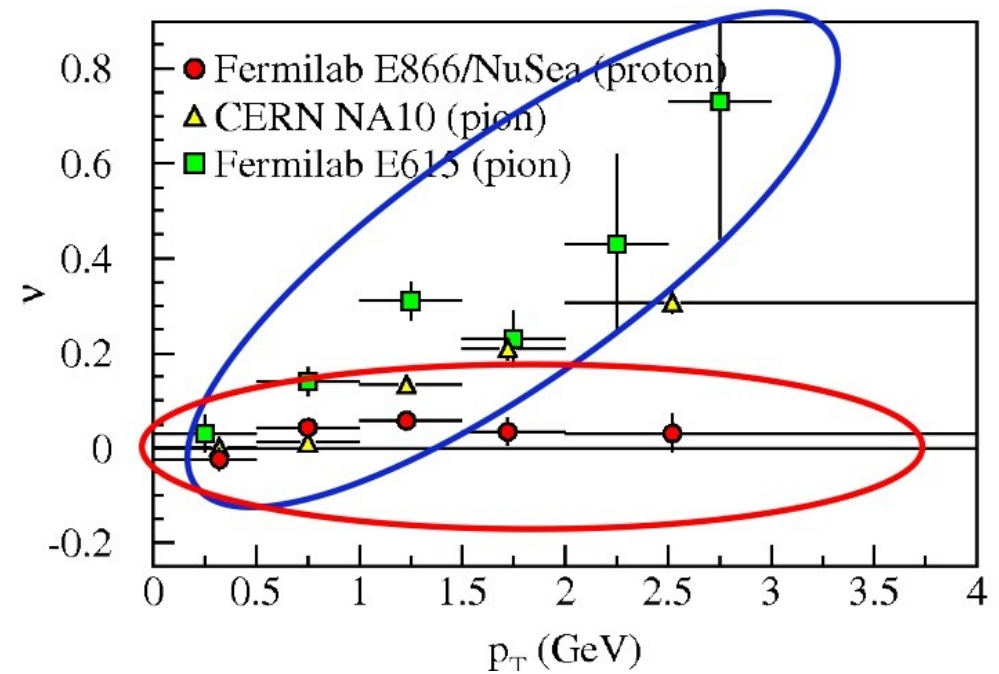
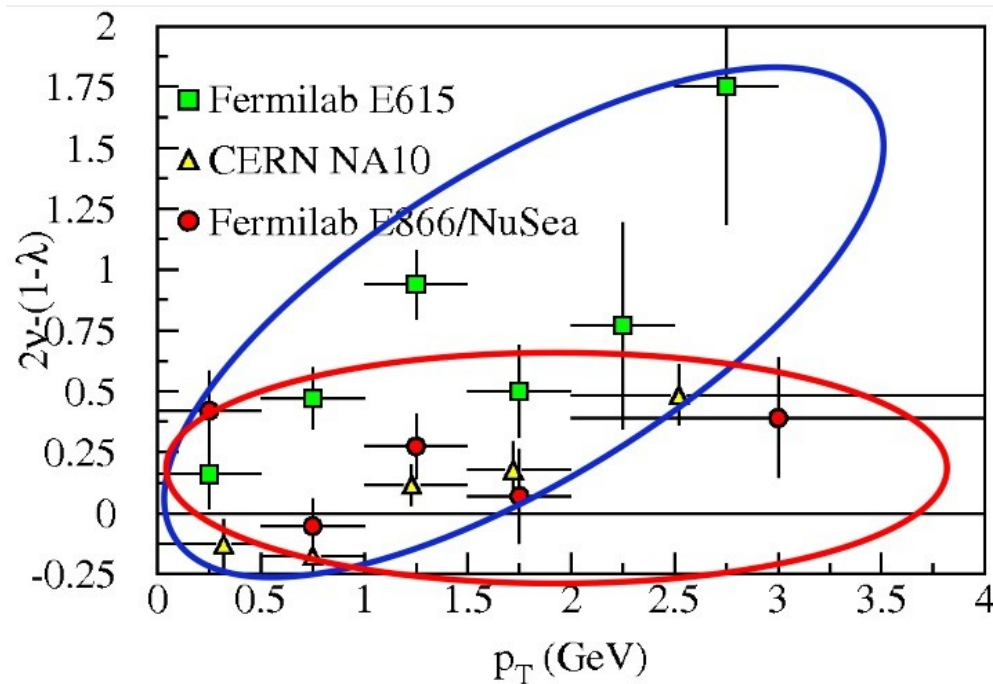
$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2(\theta) + \mu \sin(2\theta) \cos(\phi) + \frac{\nu}{2} \sin^2(\theta) \cos(2\phi)$$

- 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:

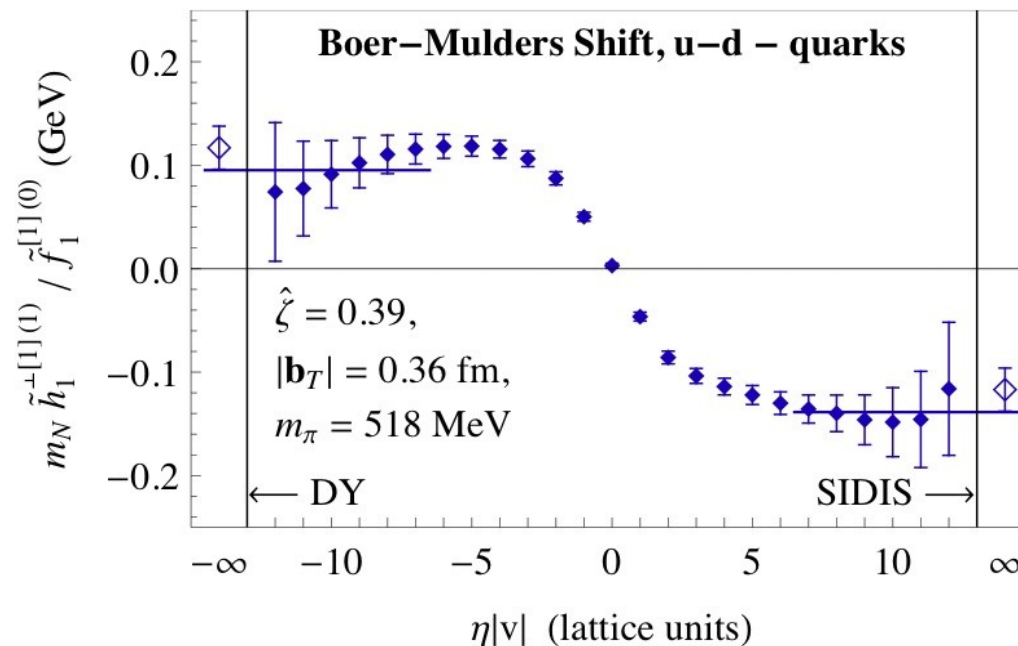
$$h_1^{\perp,q}(x, \mathbf{p}_T^2) \quad \begin{array}{c} \text{red circle with right arrow} \\ \text{blue circle with down arrow} \end{array} - \begin{array}{c} \text{blue circle with up arrow} \\ \text{red circle with right arrow} \end{array} \quad s_T^i \varepsilon^{ij} p_T^j \frac{1}{M}$$

- 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

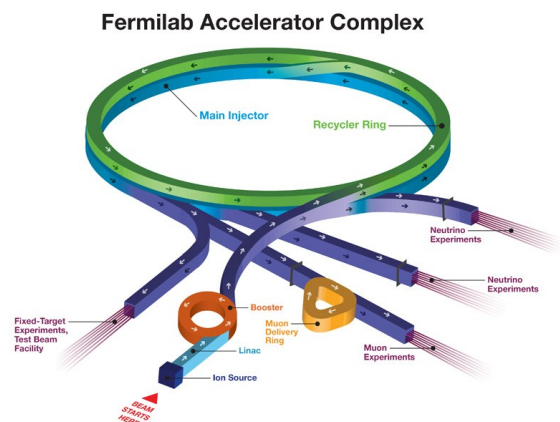


The SeaQuest mission

- significant increase in physics reach
- unique access to sea quarks at high- x
- **What is the structure of the nucleon?**
 - What is \bar{d} / \bar{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 structure of nucleonic matter?**
 - Where are the *nuclear* pions?
 - Is antishadowing a valence effect?
- **Do colored partons lose energy in cold nuclear matter?**

The SeaQuest Experiment

– continuing a series of high-mass dilepton experiments at FNAL



Proton Beam

slow extraction from MI

2×10^{12} protons / s for ~4s
spills each minute

beam energy: E-866: 800
GeV → E-906: **120 GeV**

→ 50x luminosity as E-866
(for same spectrometer rate)



Target Table

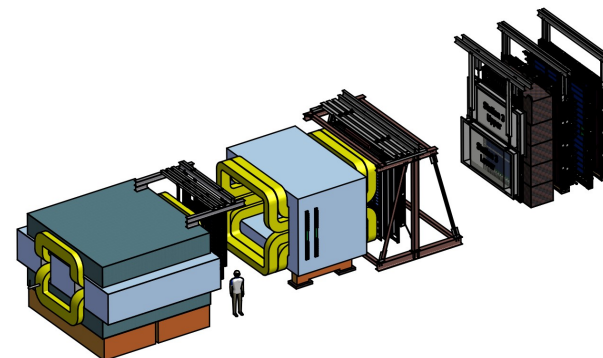
liquid target flasks:

H₂, D₂

solid state targets:

C, Fe, W

empty flask, no target
moves between spills



Spectrometer

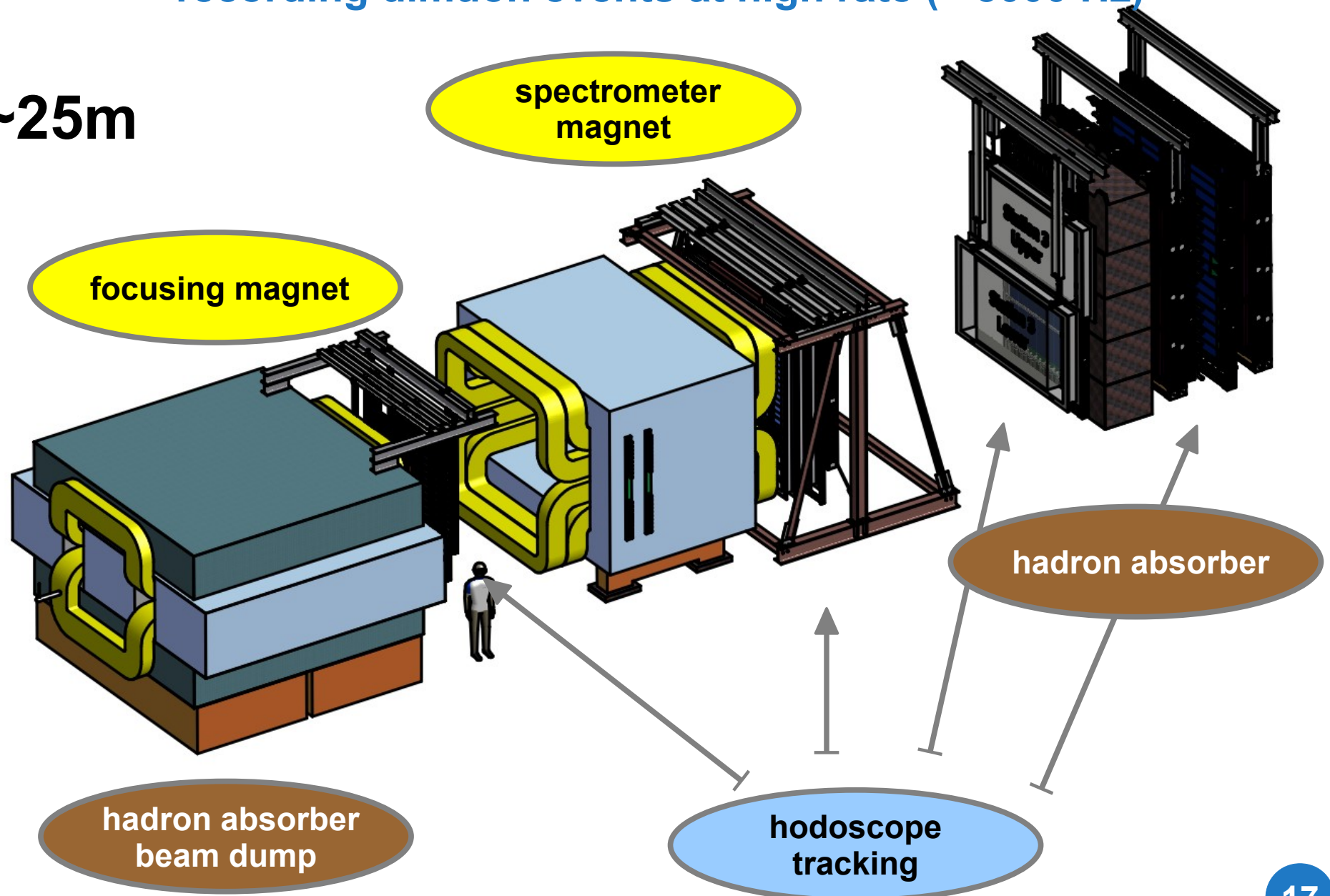
reused and recycled
components

selected updates: new drift
chambers, PMT bases for
high-rate capability, beam
diagnostics, ...

The SeaQuest Spectrometer

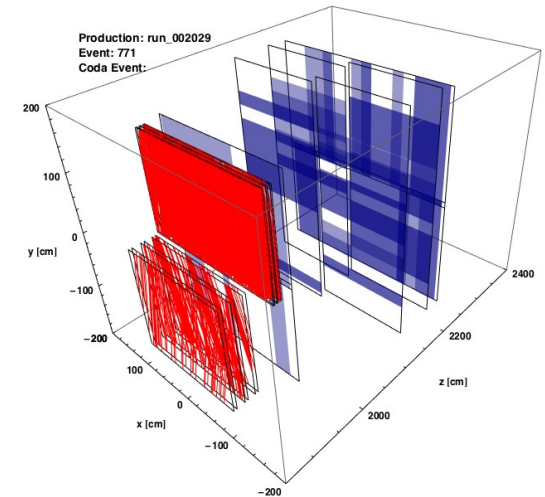
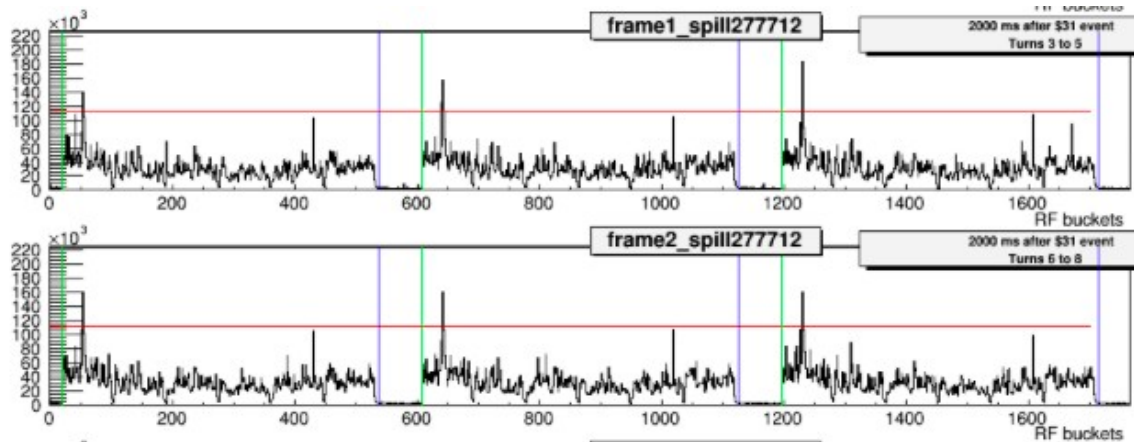
– recording dimuon events at high rate (~ 5000 Hz)

$\sim 25\text{m}$

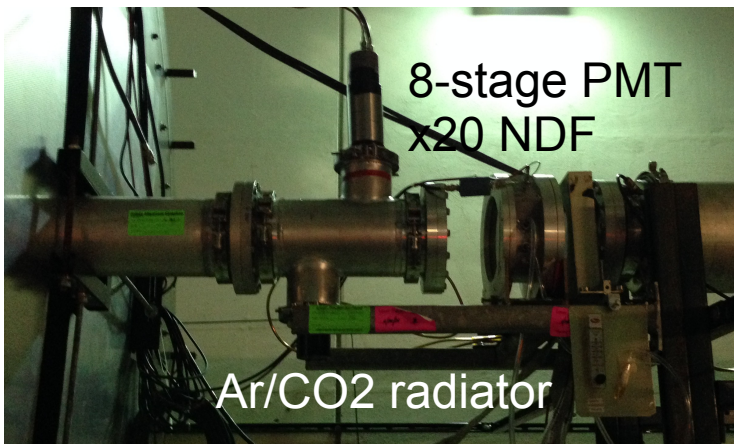


Spill Structure

large **variations** in **instantaneous beam intensity** → high hit occupancy



beam-line Cherenkov monitor for beam diagnostics:

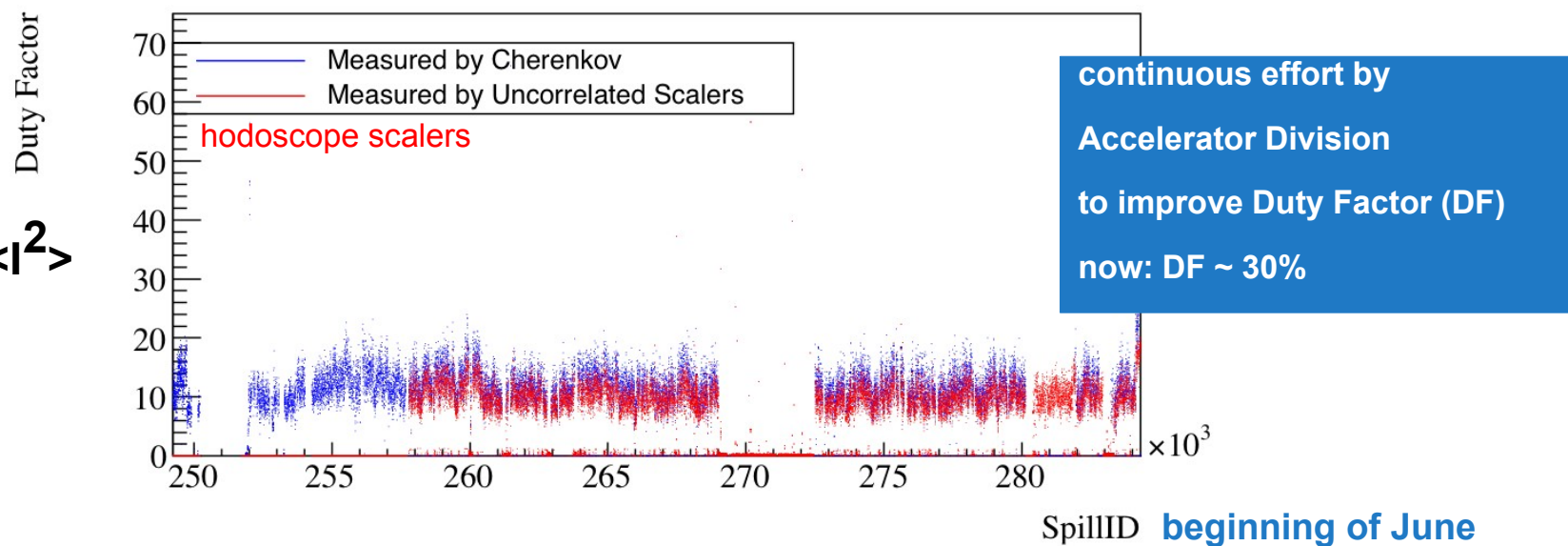


- **beam diagnostics**: measurement of RF-bucket by RF-bucket intensity
- **trigger inhibit**: veto on single RF buckets as a function of intensity,
1/2 beam inhibited due to 10x expected beam/RF-bucket

Duty Factor Measurements

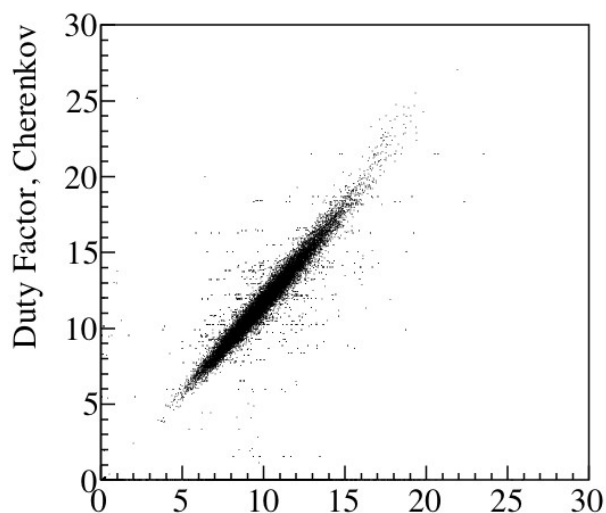
– studying the uniformity of the beam

$$DF = \langle I \rangle^2 / \langle I^2 \rangle$$



DF measurements:

affected by saturation

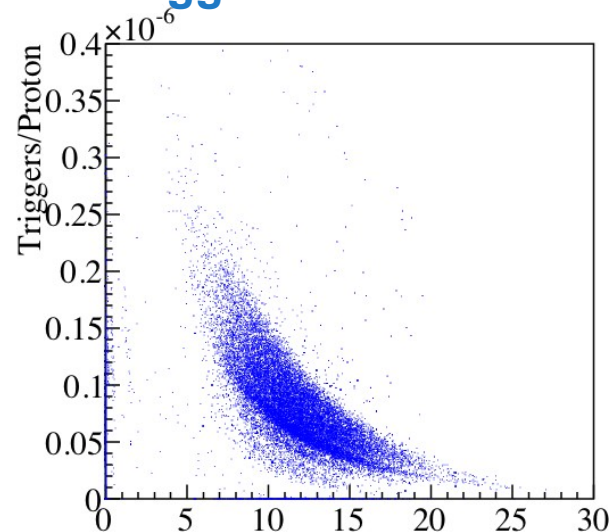


Duty Factor, Uncorrelated Scalers

based on real dimuon events,

affected by coincidence window and saturation

Trigger rate vs. DF:



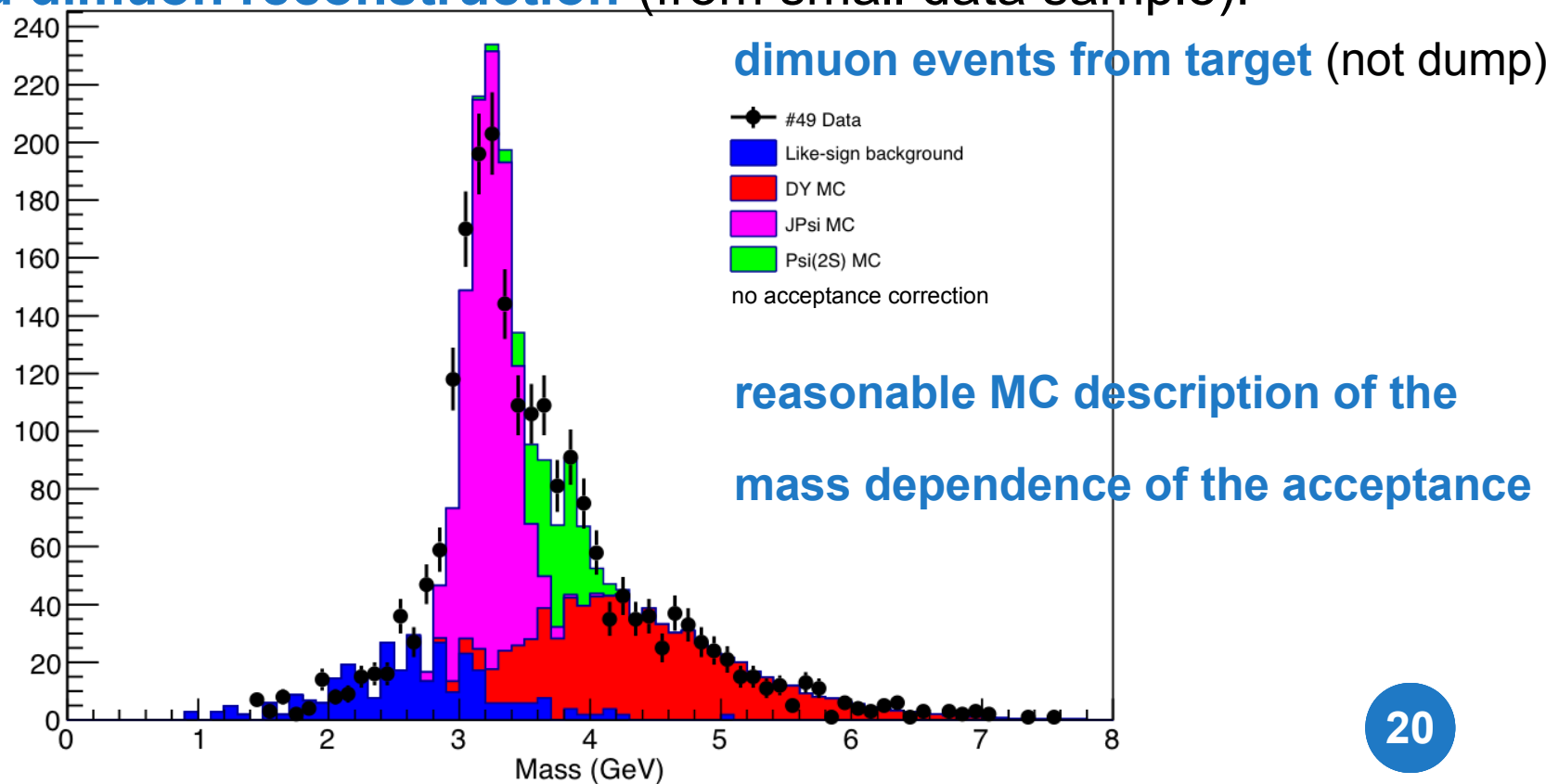
Duty Factor, Cherenkov

Status of the Analysis

- data taking:

02/20	09/05	after fall shutdown
start of physics run	fall shutdown	continue physics run

- presentation of first preliminary physics results at DNP 2014
- track and dimuon reconstruction** (from small data sample):

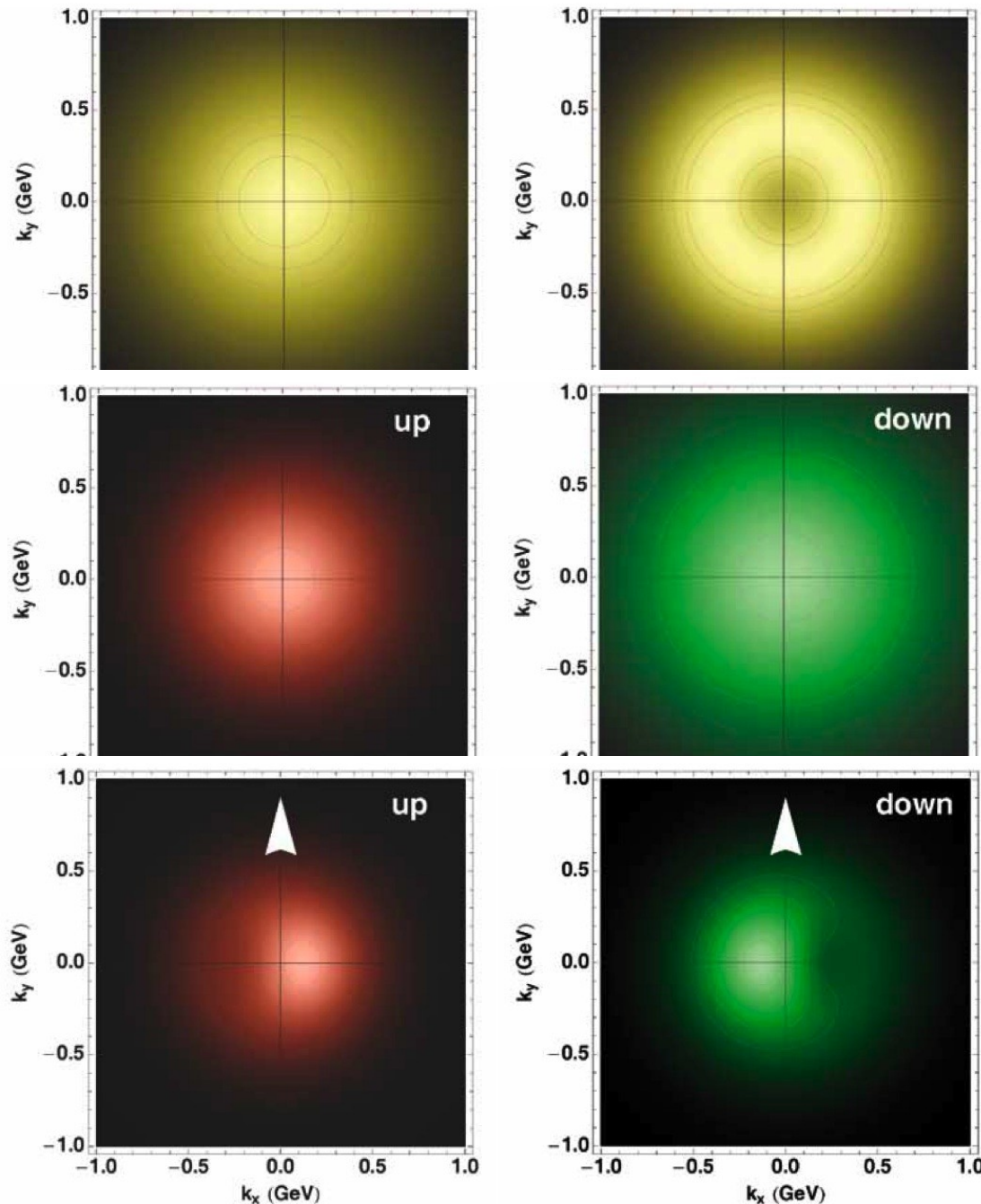




**Polarized Drell-Yan measurements are
the missing component in the
global spin program.**

**E-1027: SeaQuest with polarized beam
E-1039: SeaQuest with polarized target**

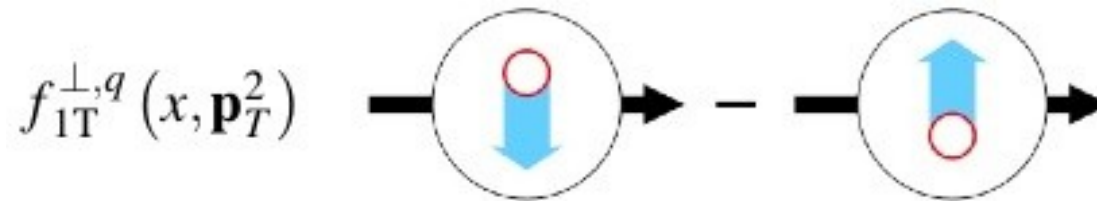
Transverse-momentum dependent PDFs (TMDs)



- 3D-densities in momentum space
- Gaussian distributions with a width of ~ 0.6 GeV
- **flavor dependence**: d-quark TMDs are larger than u-quark TMDs
- **transversely polarized nucleon**:
 - u-quarks (d-quarks) moving preferentially to the right (left)
 - TMDs are distorted in opposite ways for u and d-quarks

The Sivers TMD

- observed in semi-inclusive DIS measurements off transversely polarized proton target:



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

↔ initial state interactions in Drell-Yan process

→ **single-spin asymmetries**:

$$A_N^{\text{DY}} \sim f_{1T}^{\perp,q}(x_b) \otimes f_1^{\bar{q}}(x_t)$$

- close **relationship to quark orbital angular momentum**
- challenging the concept of factorization and universality

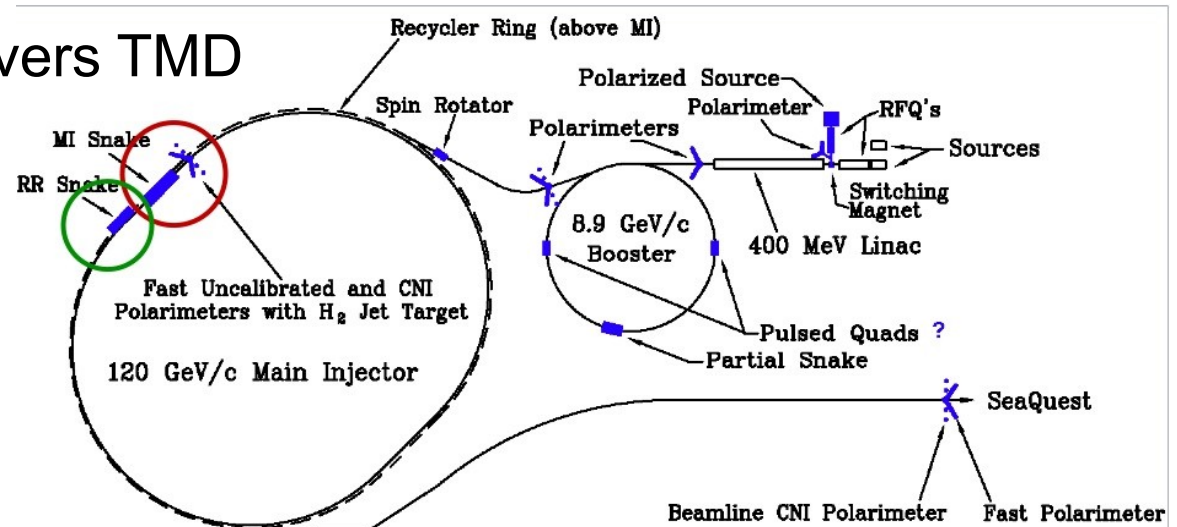
- fundamental QCD prediction:** $f_{1T}^{\perp,\text{DIS}} = -f_{1T}^{\perp,\text{DY}}$

- remains to be experimentally tested

- polarized Drell-Yan measurement required**

Reestablishing spin at Fermilab

- **E-1027: SeaQuest with polarized beam**
 - sensitive to beam valence quarks at high- x
 - large effects \rightarrow size / shape of Sivers TMD
 - verify sign change of Sivers TMD



- **E-1039: SeaQuest with polarized target**
 - sensitive to Sivers TMD for sea quarks
 - hint for substantial role of sea quark Sivers effect in SIDIS data
 - theoretical studies suggest sizable Sivers TMD for sea quarks
 - LANL will provide polarized proton (NH₃) target by 2015

The SeaQuest mission

unique laboratory for sea quarks at high- x

→ structure of nucleons and nucleonic matter

physics running started on February 20th

→ first preliminary physics results expected in fall

exciting extensions approved

→ polarized Drell-Yan measurements

→ missing piece in the global spin program