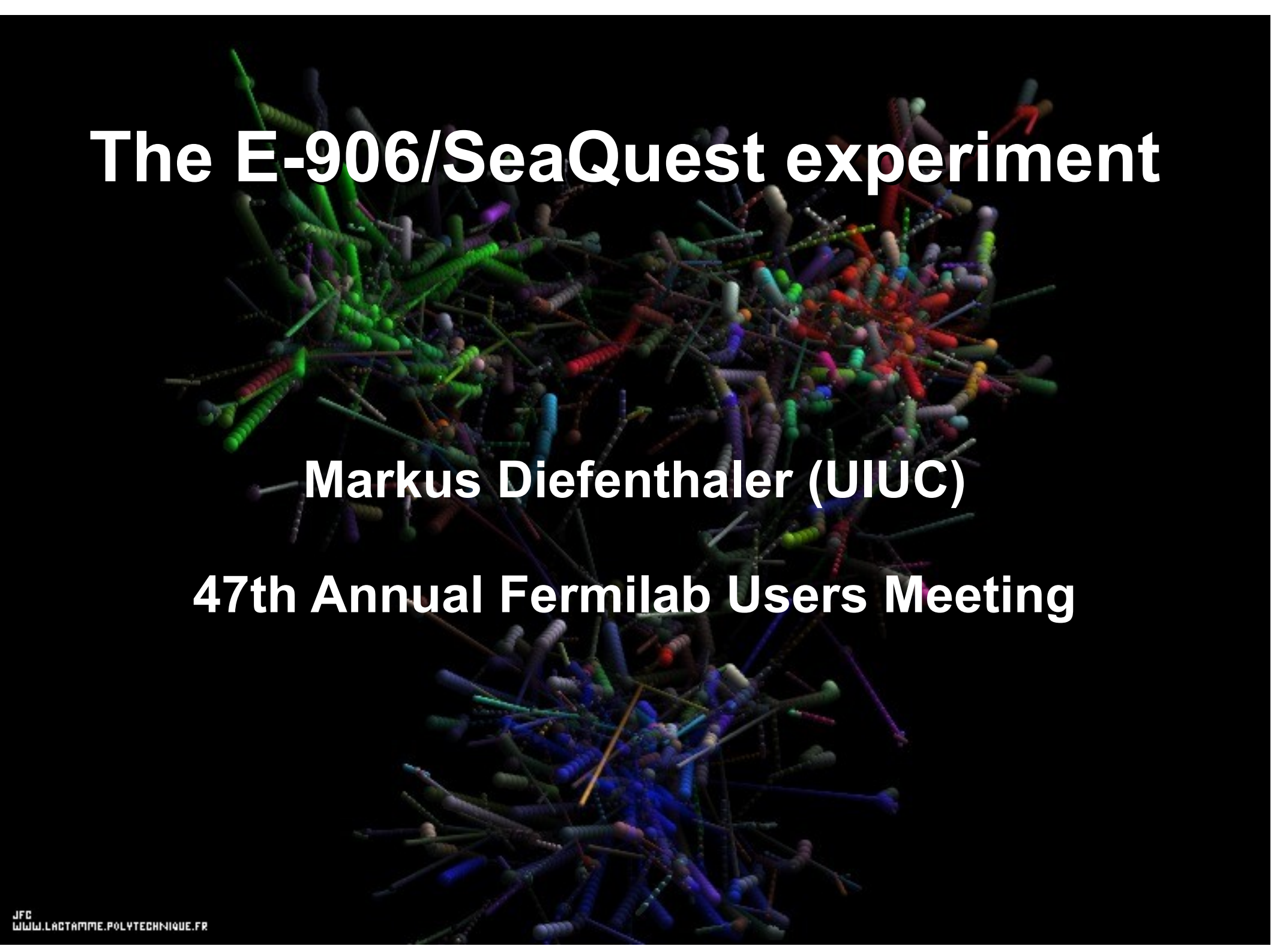
The E-906/SeaQuest experiment



Markus Diefenthaler (UIUC)

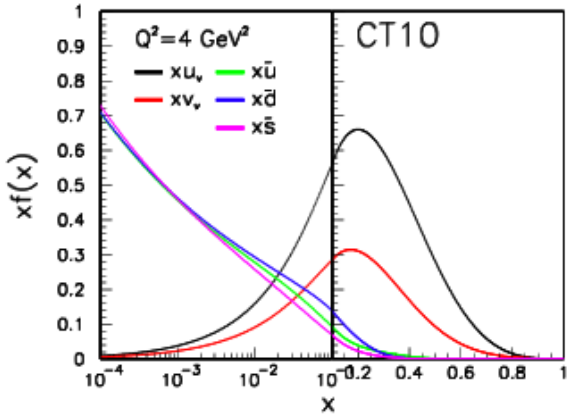
47th Annual Fermilab Users Meeting

The SeaQuest collaboration

- **Abilene Christian University**: Ryan Castillo, Michael Daughertiy, 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 Shiuan-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(ua) Rubin
- **National Kaohsiung Normal University**: Rurngsheng Guo
- **RIKEN**: Yuji Goto
- **Rutgers University**: Ron Gilman, Ron Ransome, Arun Tadepalli
- **Tokyo Tech**: Shou Miyaska, Kei Nagai, Kenichi Nakano, Toshi-Aki Shibata
- **Yamagata University**: Yuya Kudo, Yoshiyuki Miyachi

Acknowledgment

The inner structure of the nucleon



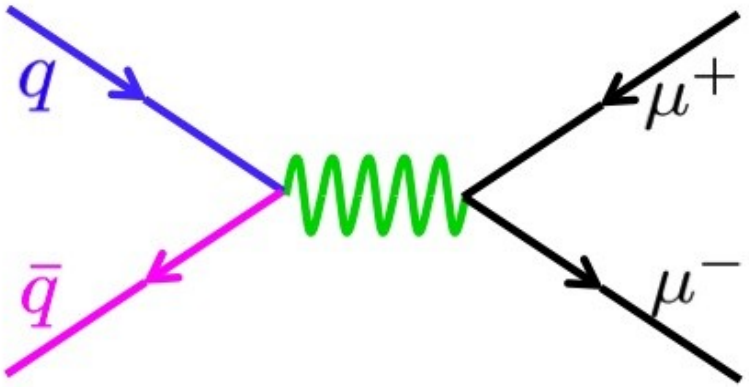
origin of the nucleon spin

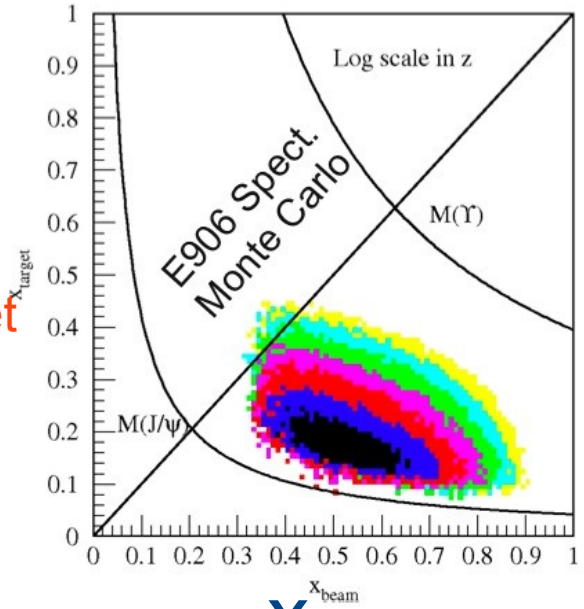
origin of nucleon sea

nucleons in nuclei

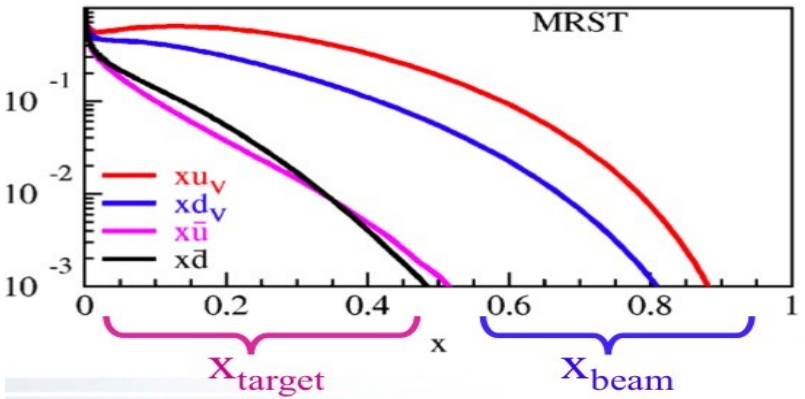
A laboratory for sea quarks

The Drell-Yan process



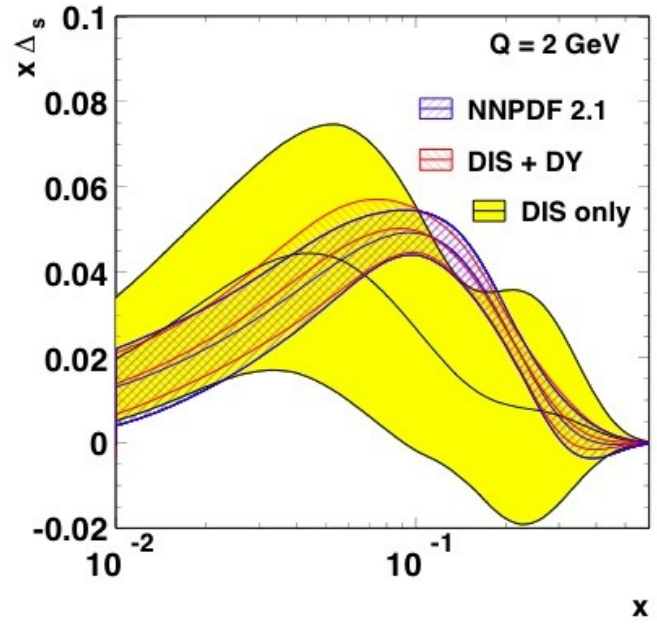


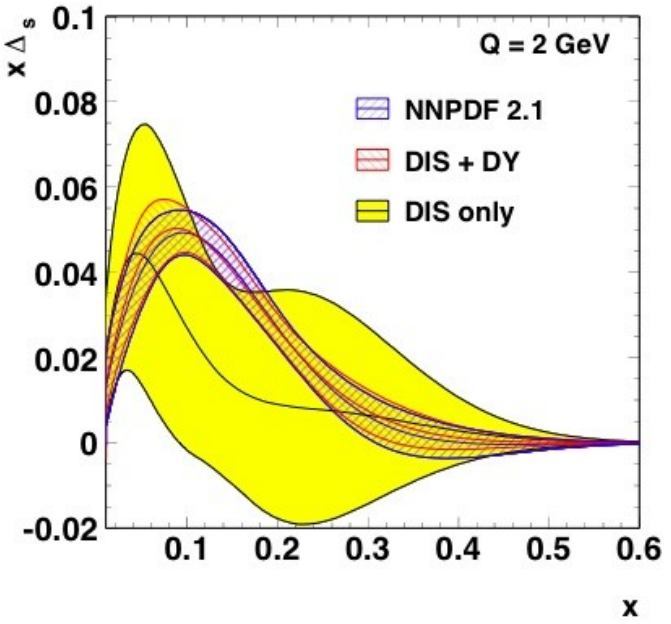
$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x_\mathrm{b}\,\mathrm{d}x_\mathrm{t}} = \frac{4\pi\alpha^2}{9x_\mathrm{b}\,x_\mathrm{t}}\frac{1}{s}\sum_q e_q^2\left[\bar{q}_\mathrm{t}(x_\mathrm{t})q_\mathrm{b}(x_\mathrm{b}) + q_\mathrm{t}(x_\mathrm{t})\bar{q}_\mathrm{b}(x_\mathrm{b})\right]$$

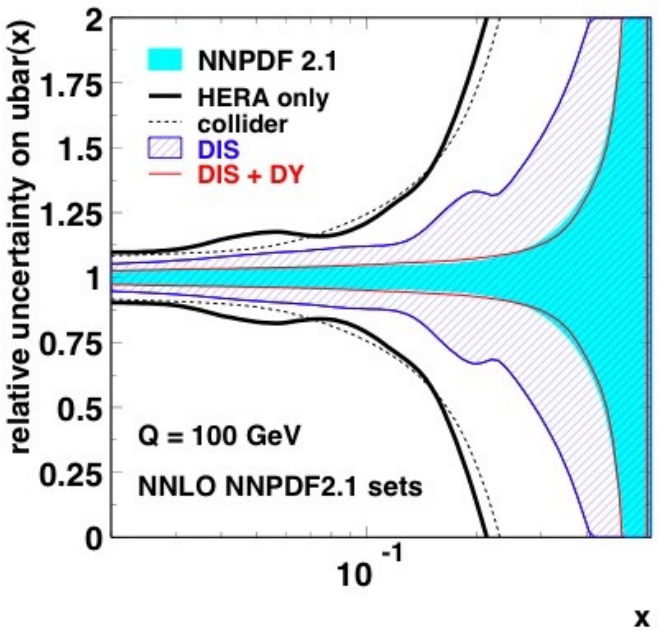


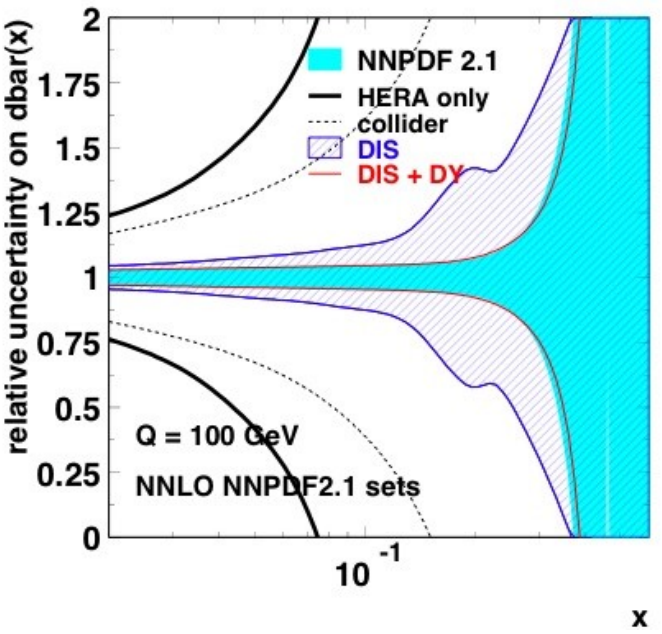
beam: valence quarks at high-x
target: sea quarks at low/intermediate-x

Unique sensitivity to sea quarks

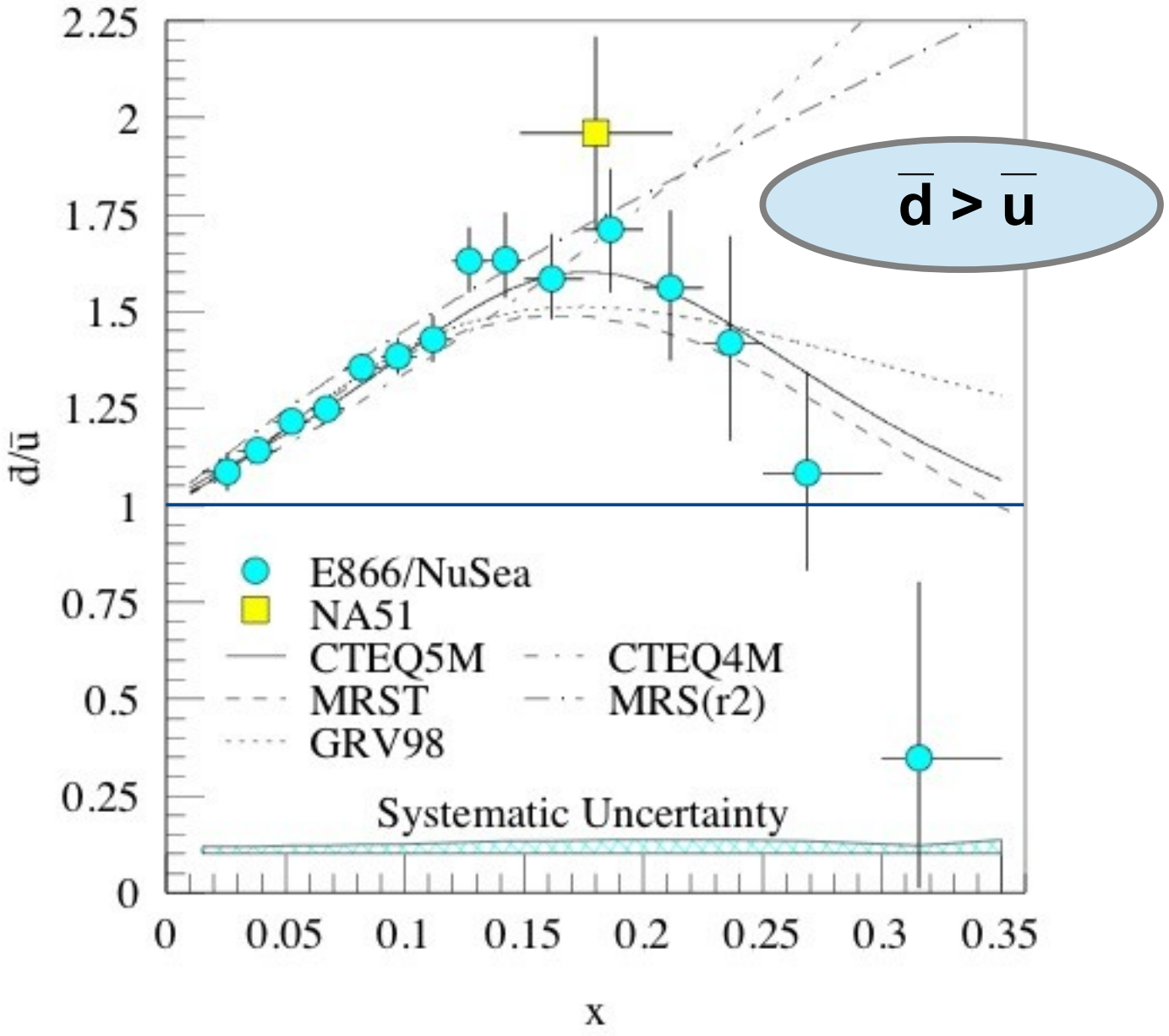






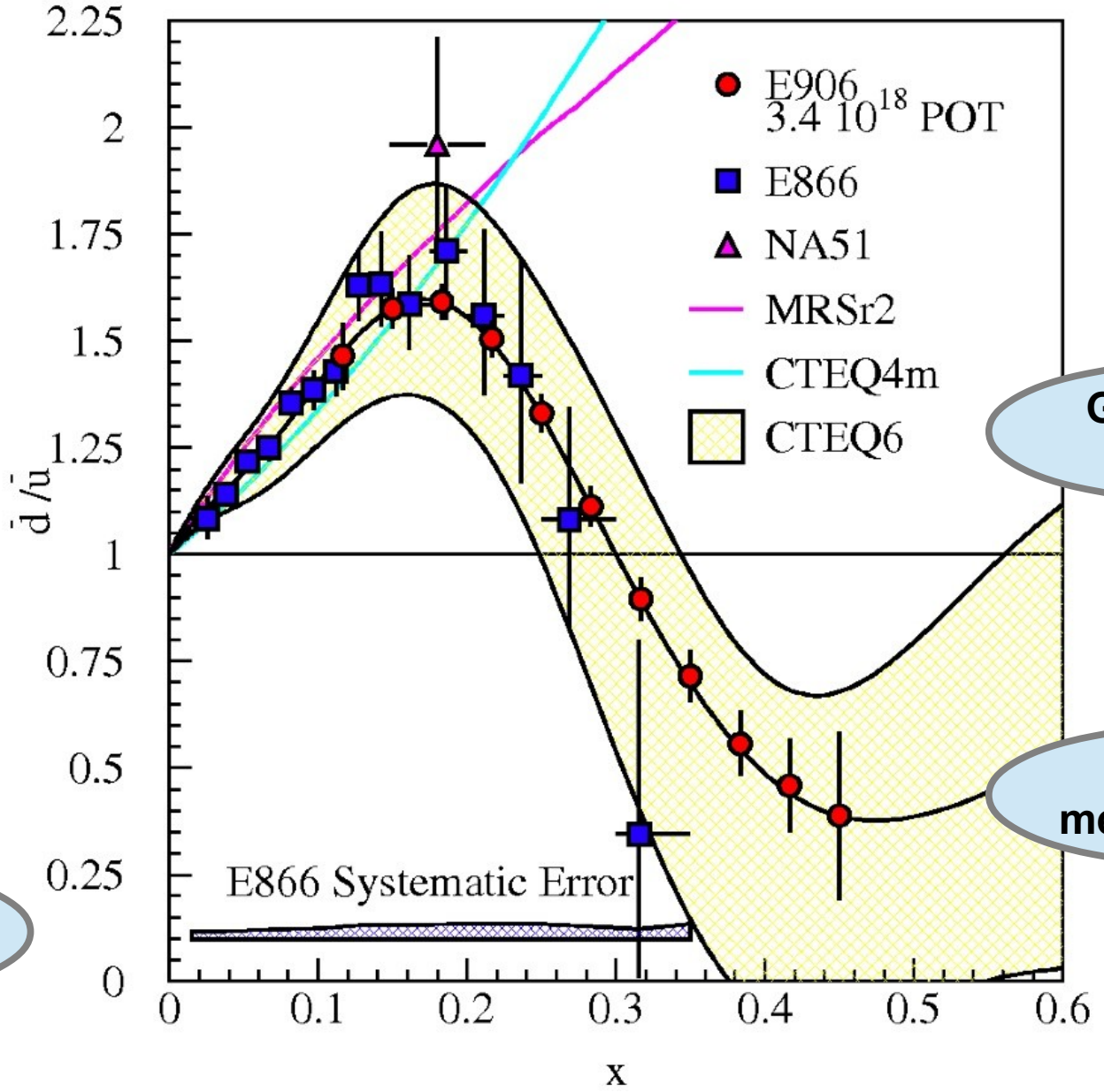


Insights into the proton sea



alternate degrees of freedom?

SeaQuest probing the proton sea



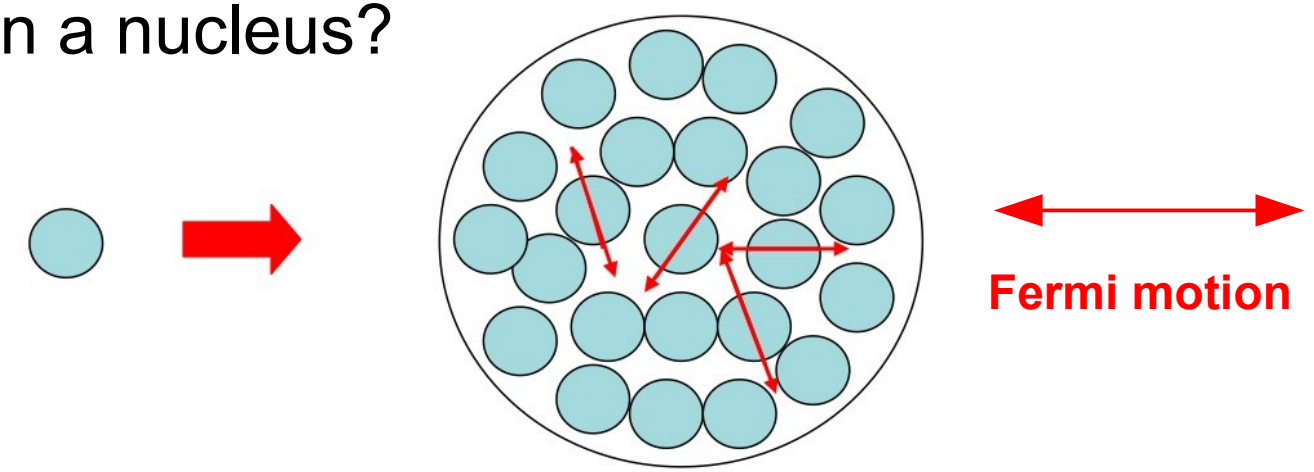
Global NLO PDF fit

extend measurement

SeaQuest: Syst. ~ 1%

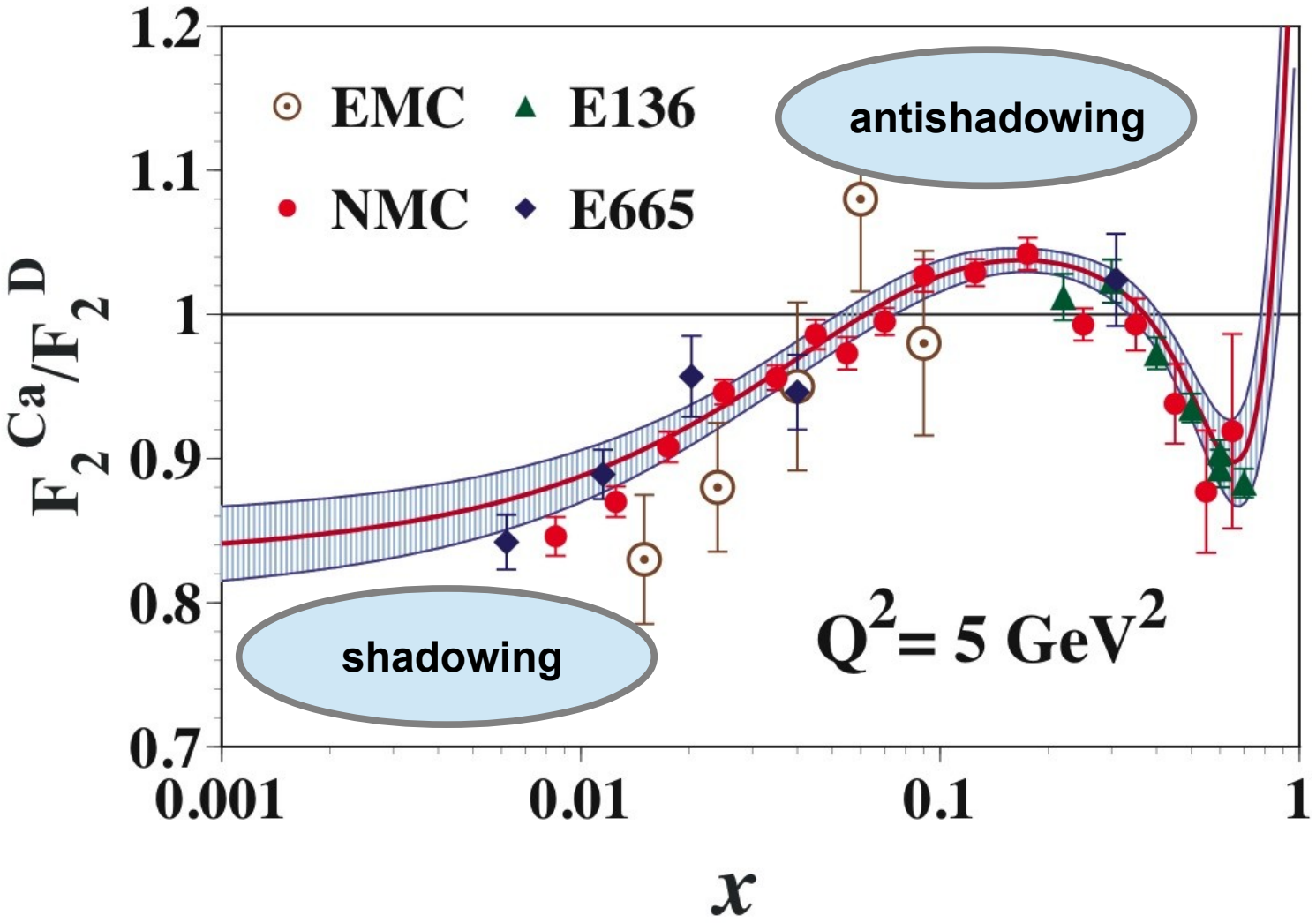
Nucleons embedded in nuclei

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

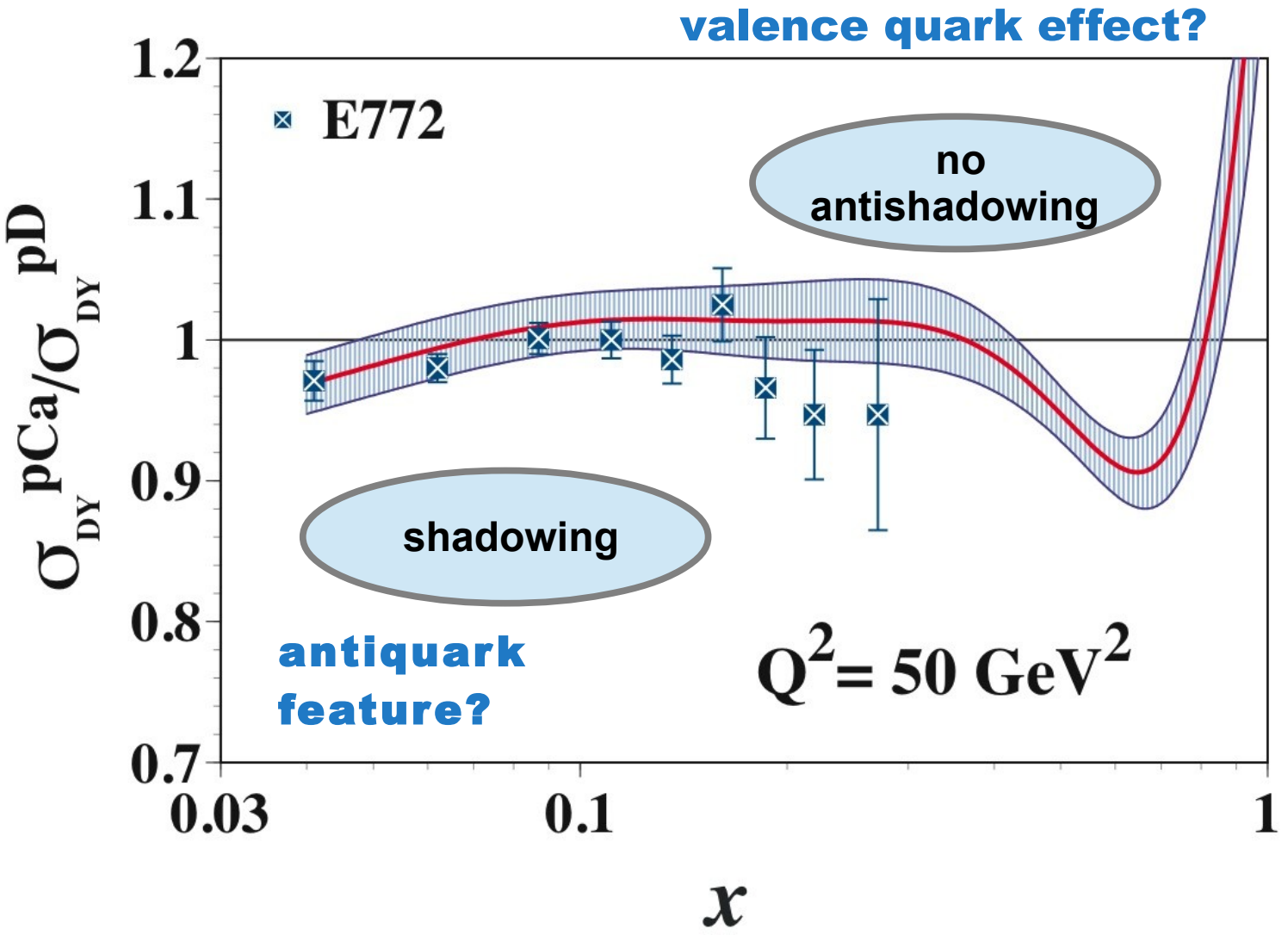


- Is confinement influenced by the nuclear medium?
- Do quarks and gluons play any role in the understanding of nuclear forces?
- Can the model of nuclear forces be replaced by a fundamental theory based on the strong interaction between quarks and gluons?

The EMC effect

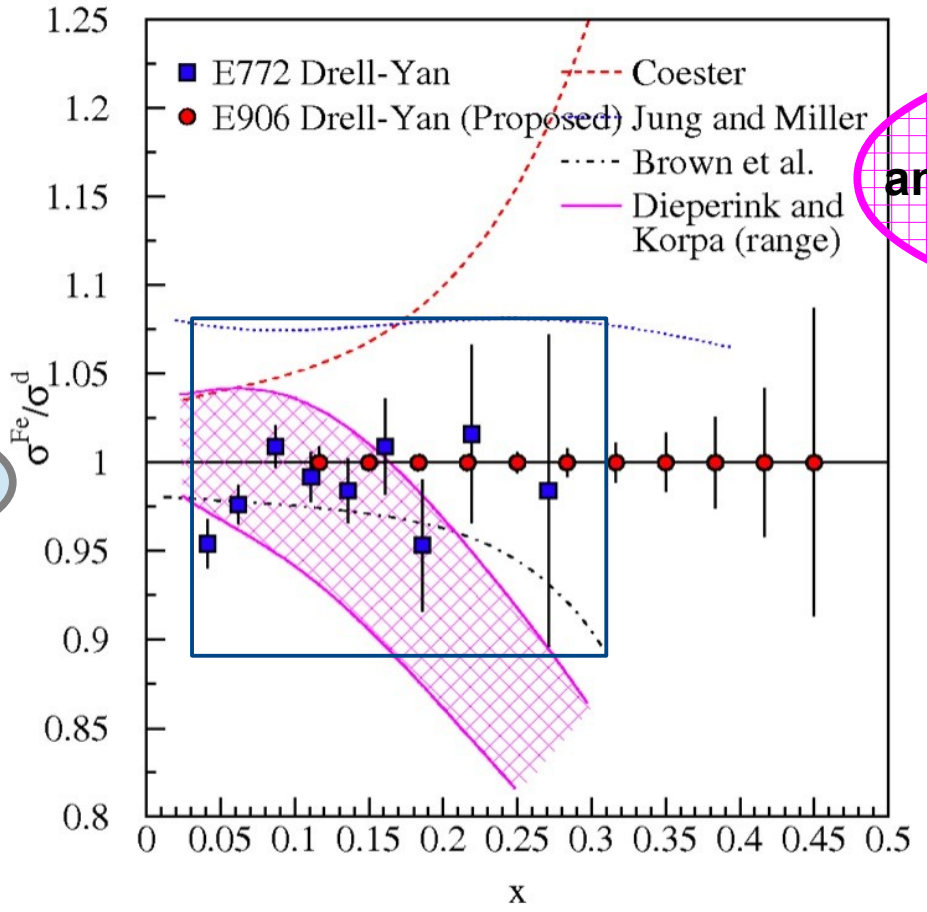


The EMC effect in Drell-Yan



The inner structure of a nucleus

- nuclear force mediated by meson exchange



large effects to antiquark PDF predicted as x increases

no antiquak enhancement

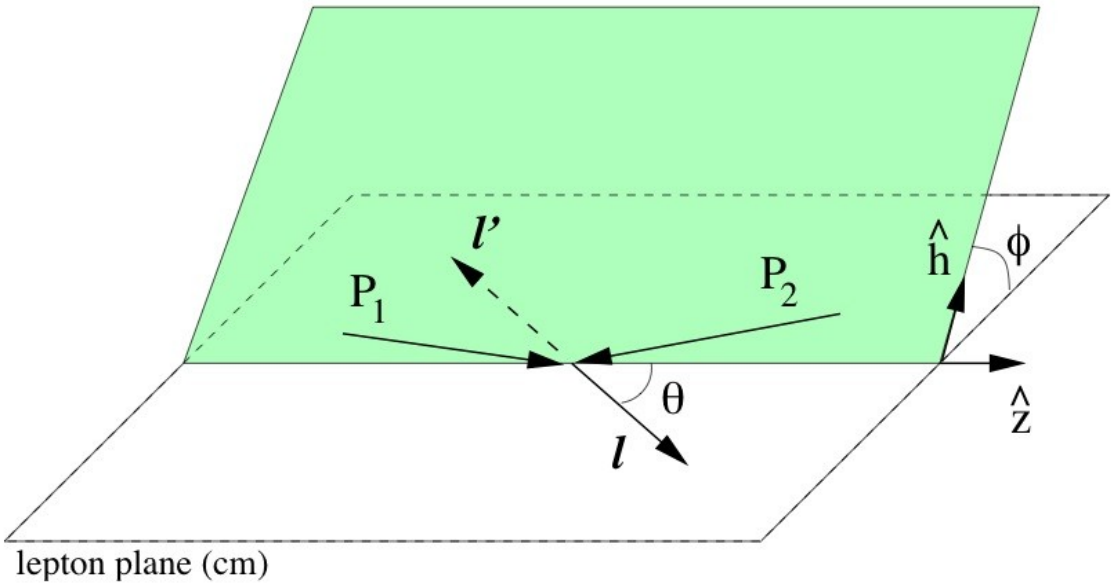
- **Where are the *nuclear* pions?**

The Lam-Tung relation

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

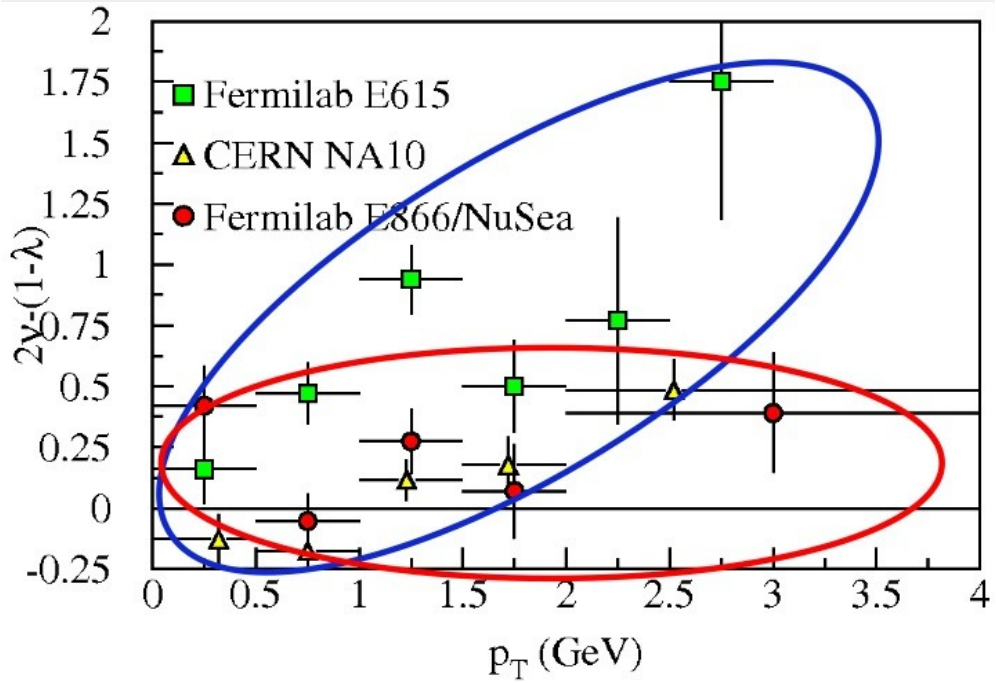
$$\frac{\mathrm{d}\,\sigma}{\mathrm{d}\,\Omega} \propto 1 + \lambda \cos(\theta)^2 + \mu \sin(2\theta)\cos(\phi) + \frac{\nu}{2}\sin(\theta)^2 \cos(2\phi)$$

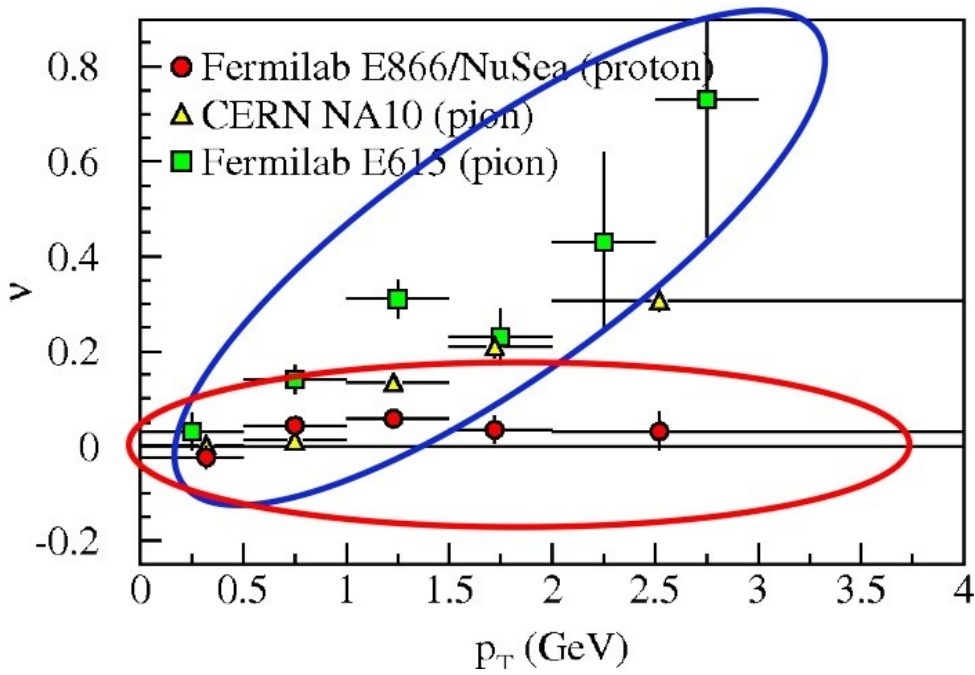
- **Lam-Tung relation:** $1 - \lambda = 2\nu$



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:**

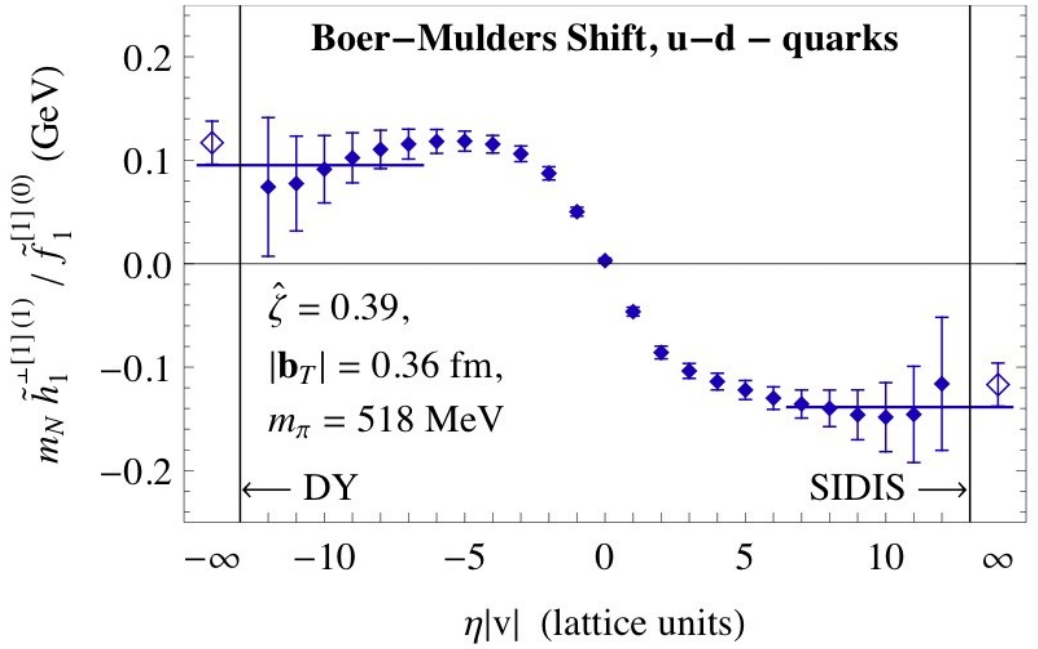
$h_1^{\perp,q}(x,\mathbf{p}_T^2)$ $-$ $s_T^i \varepsilon^{ij} p_T^j \frac{1}{M}$

- **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

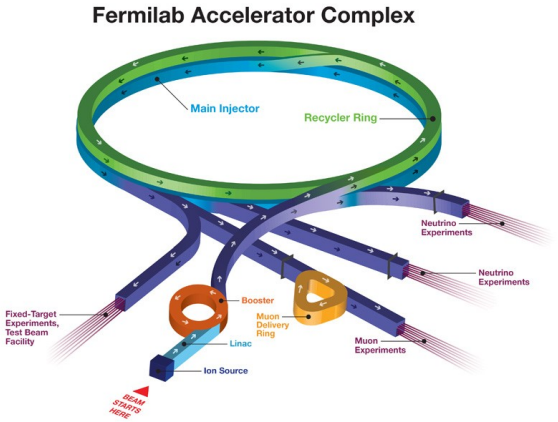


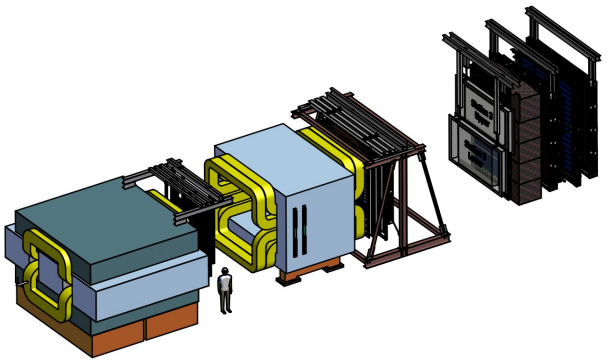
The SeaQuest mission

- **significant increase in physics reach**
- unique access to **sea quarks at high-x**
- **What is the structure of the nucleon?**
  - What is $\bar{d}$ / $\bar{u}$?
  - 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 struture 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:

H_2, D_2

solid state targets:

C, Fe, W

empty flask, no target

moves between spills

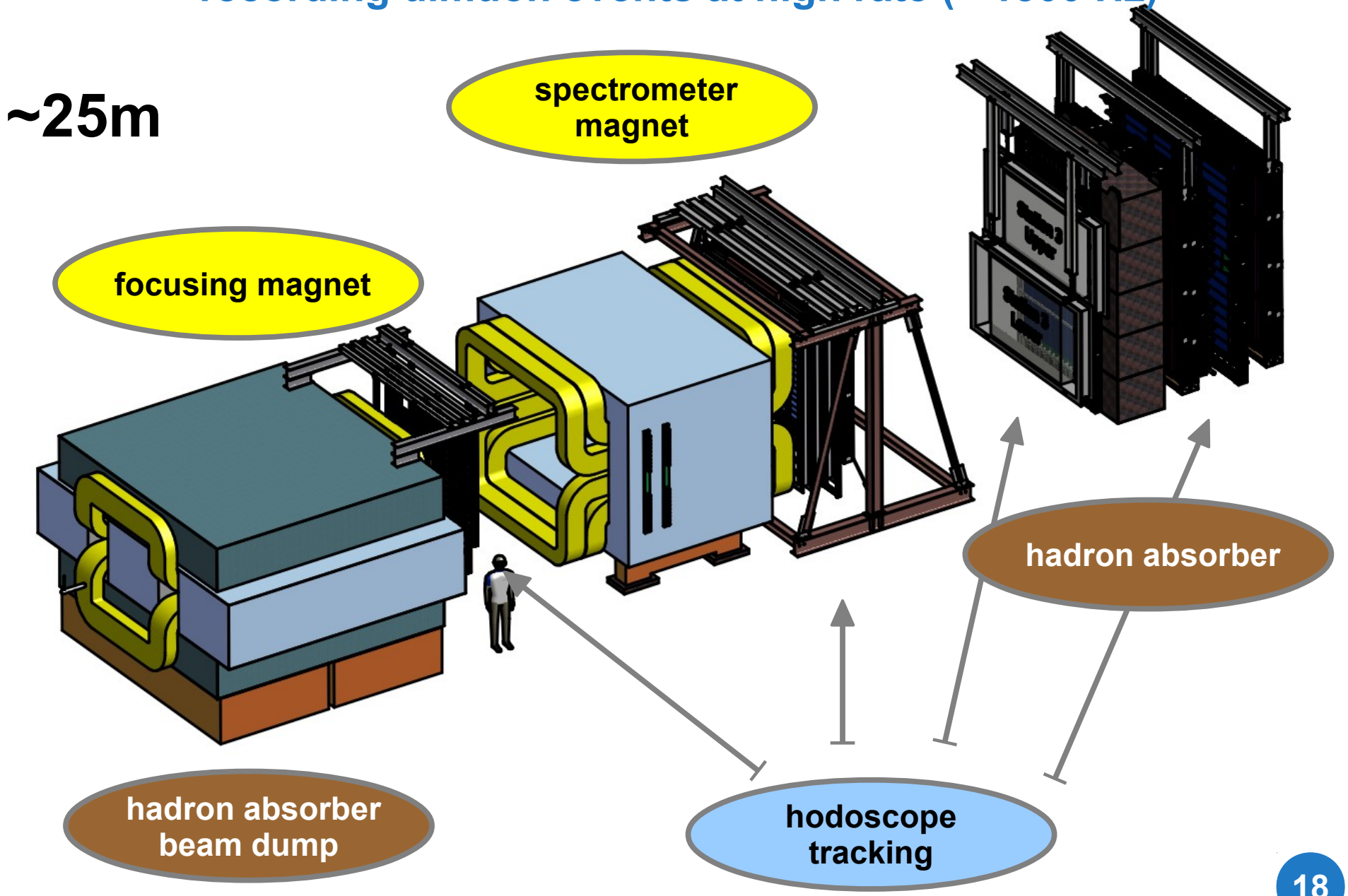
Spectrometer

reused and recycled components

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

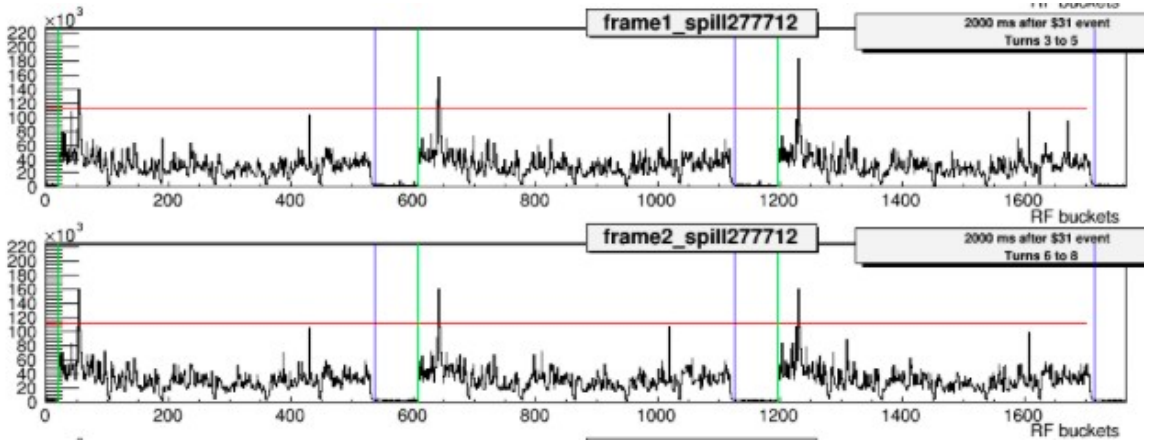
The SeaQuest Spectrometer

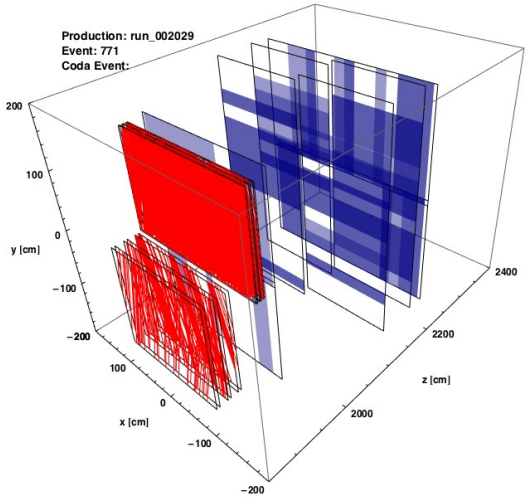
– recording dimuon events at high rate (~ 1500 Hz)



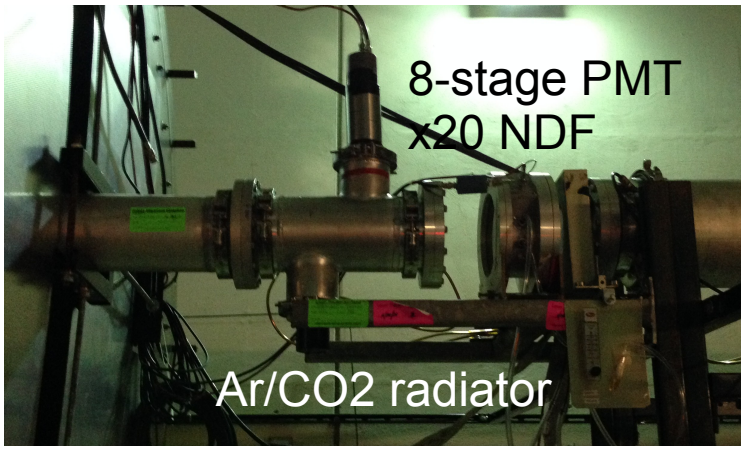
Spill Structure

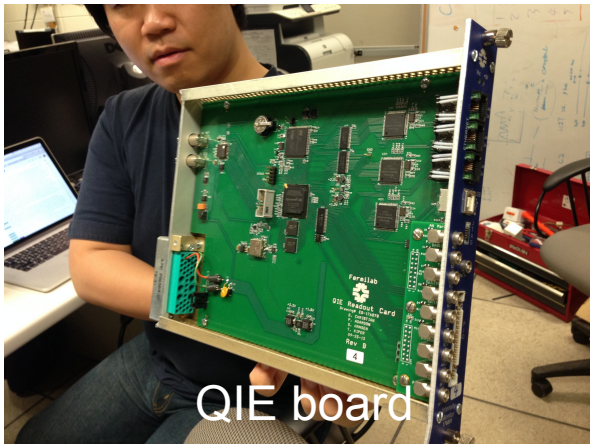
large **variations** in **instantaneous beam intensity** → high hit occupancy





beam-line Cherenkov monitor for beam diagnostics:



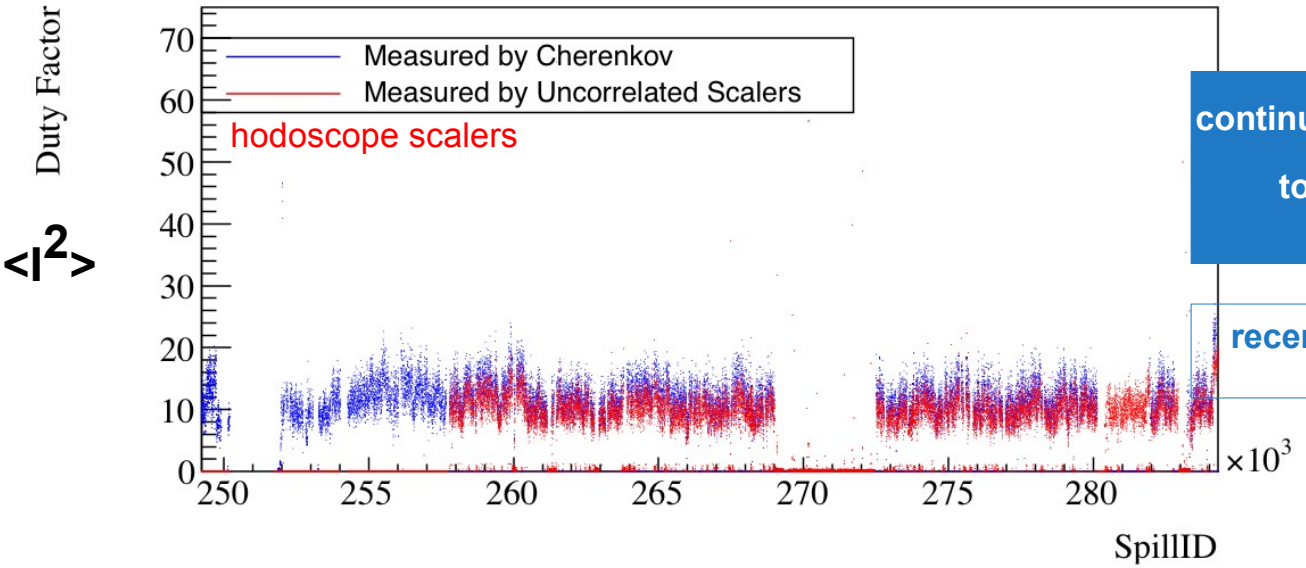


→ **beam diagnostics**: measurement of RF-bucket by RF-bucket intensity
→ **trigger inhibit**: veto on single RF buckets as a function of intensity,
½ beam inhibited due to 10x expected beam/RF-bucket

Duty Factor Measurements

– studying the uniformity of the beam

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

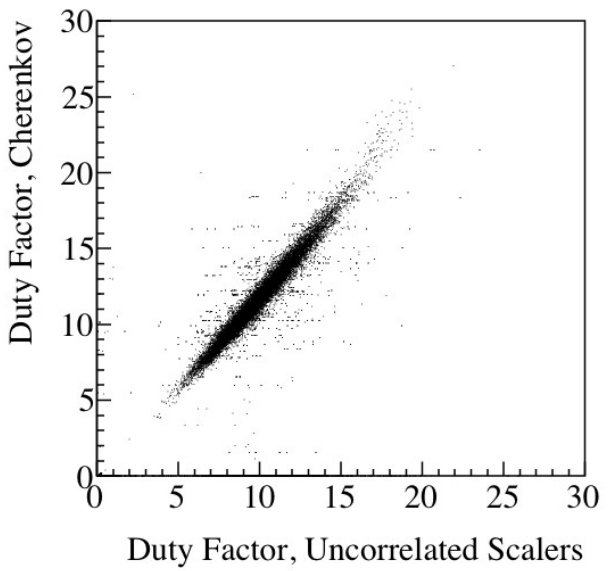


continuous effort by AD to improve DF

recent improvement

DF measurements:

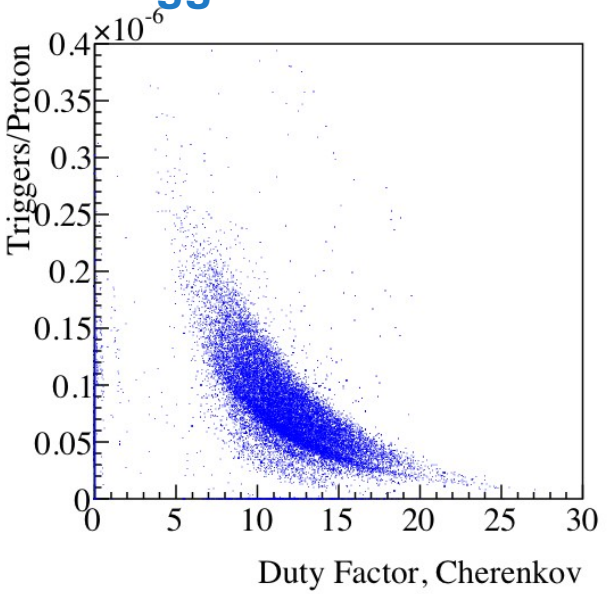
affected by saturation



based on real dimuon events,

affected by coincidence window and saturation

Trigger rate vs. DF:

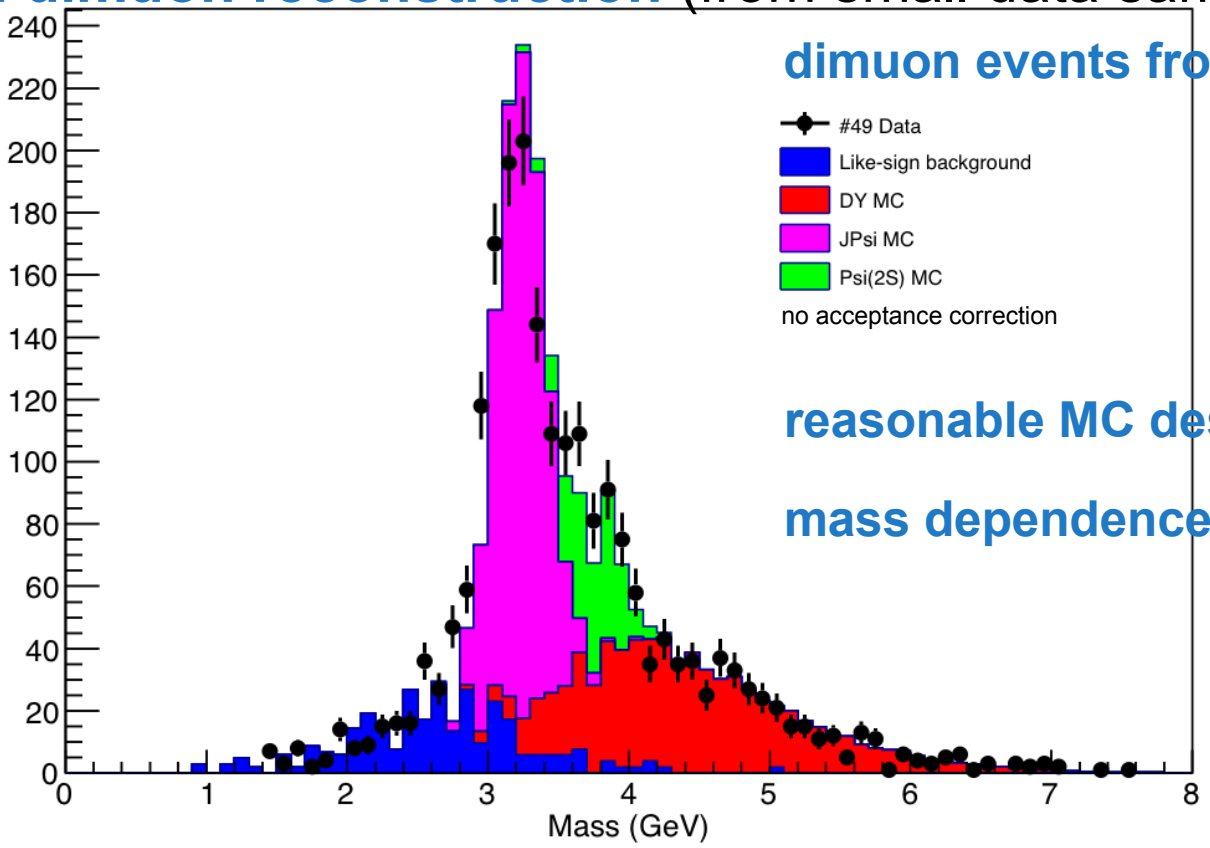


Status of the Analysis

- data taking:

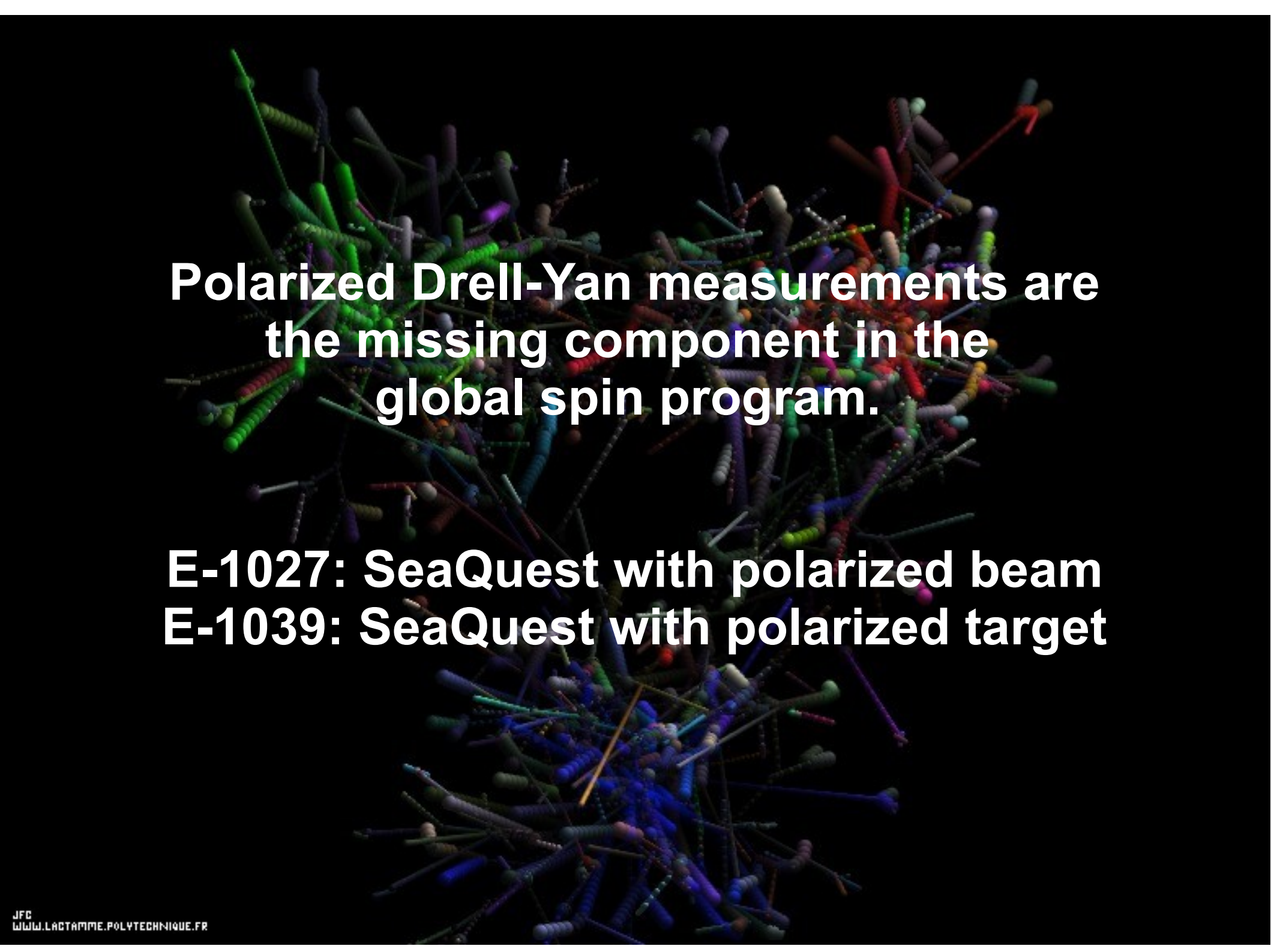
02/20	09/05	after fall shutdown
start of physics run	fall shutdown	continue physics run

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

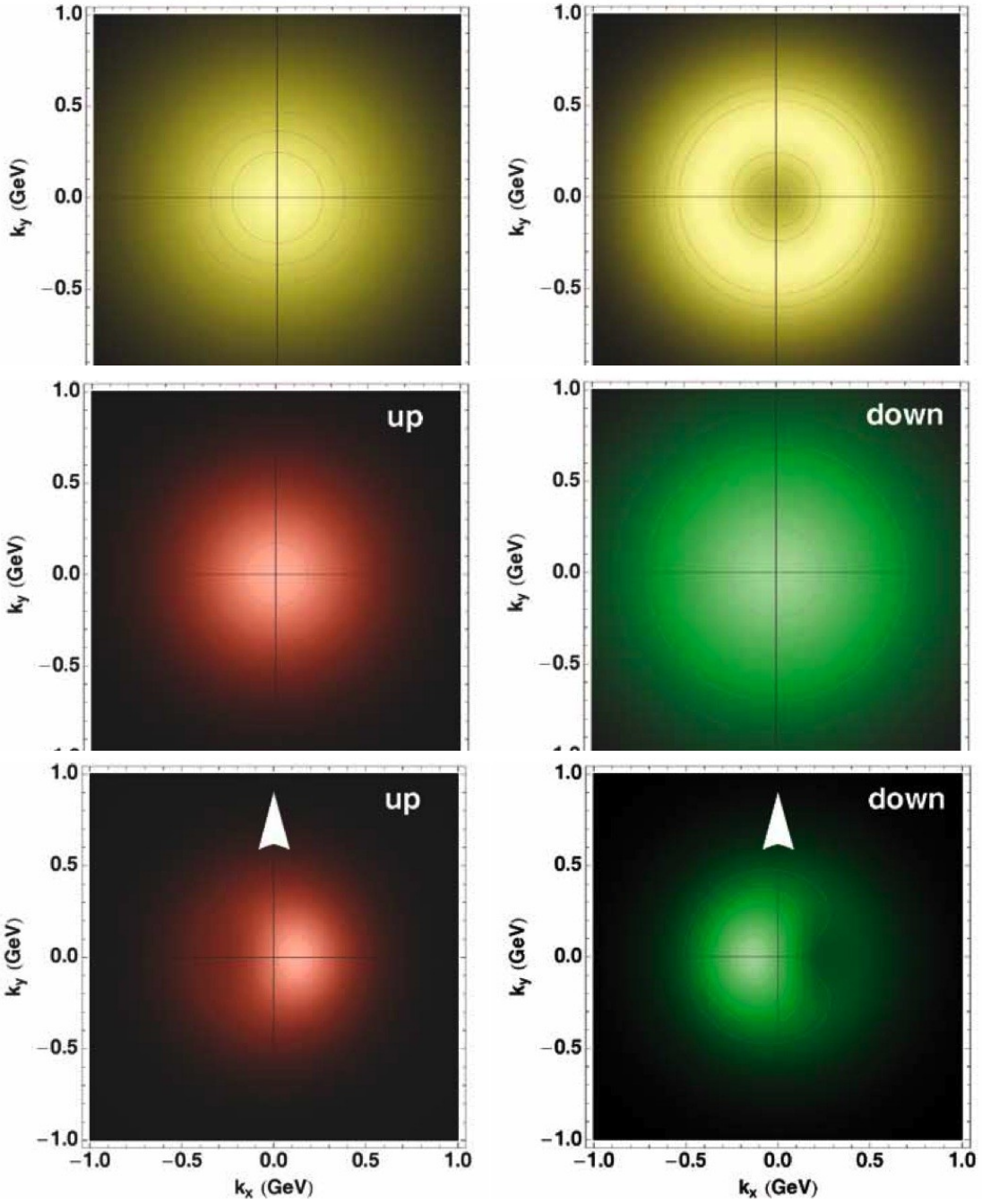


dimuon events from target (not dump)

reasonable MC description of the mass dependence of the acceptance


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
JFC
WWW.LACTAMME.POLYTECHNIQUE.FR

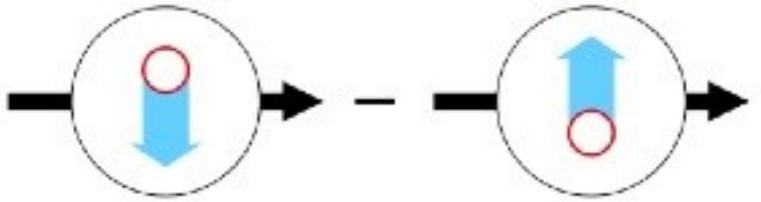
Transverse-momentum dependent PDFs (TMDs)



- **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:**

$f_{1T}^{\perp,q}\left(x,\mathbf{p}_T^2\right)$ 

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

  ↔ initial state interactions in Drell-Yan process

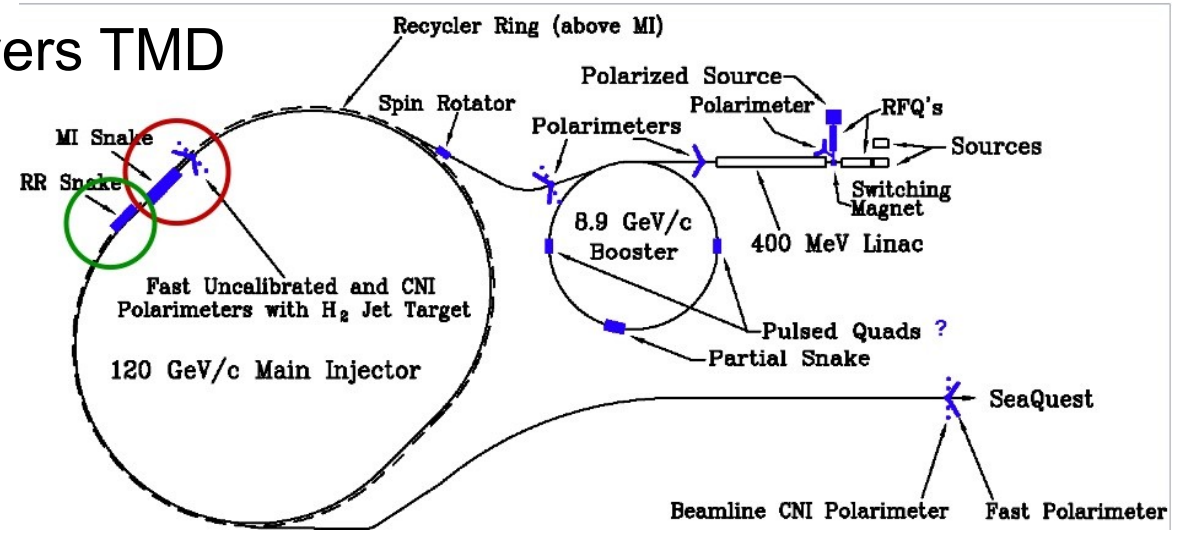
  → **single-spin asymmetries**:

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

- close **relationship to quark orbital angular momentum**
- challenging the concept of factorization and universality
  - **fundamental QCD prediction**: $f_{1T}^{\perp,\mathrm{DIS}} = -f_{1T}^{\perp,\mathrm{DY}}$
  - 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 → 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
  - 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 possible

→ polarized Drell-Yan measurements

→ missing piece in the global spin program

→ unique opportunity for Fermilab