The SeaQuest experiment at FNAL

Dr. Markus Diefenthaler (UIUC)

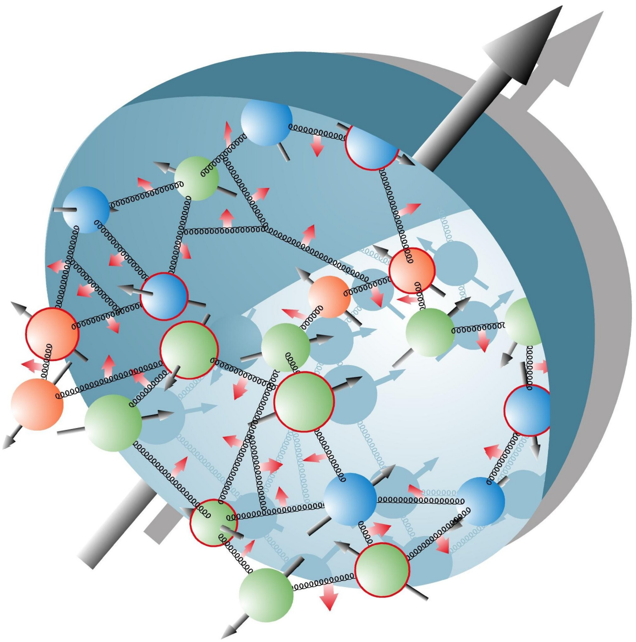
The SeaQuest collaboration

- **Abilene Christian University**: Ryan Castillo, Michael Daughertiy, Donald Isenhower, Noah Kitts, Lacey Medlock, Noah Shutty, Rusty Towell, Shon Watson, Ziao Jai Xi
- **Academia Sinica**: Wen-Chen Chang, Ting-Hua Chang, Shiu Shiuan-Hao
- **Argonne National Laboratory**: John Arrington, Donald F. Geesaman (co-spokesperson), Kawtar Hafidi, Roy Holt, Harold Jackson, David Potterveld, 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, Dhyaanesh Mullagur, R. Evan McClellan, Jen-Chieh Peng, Shivangi Prasad, Mae Hwee Teo, Mariusz Witek, Yangqiu Yin
- **KEK**: Shin'ya Sawada
- **Los Alamos National Laboratory**: Gerry Garvey, Xiaodong Jiang, Andreas Klein, David Kleinjan, Mike Leitch, Kun Liu, Ming Liu, Pat McGaughey, Joel Moss
- **University of Maryland**: Betsy Beise, Yen-Chu Chen, Kazutaka Nakahara
- **University of Michigan**: Christine Aidala, McKenzie Barber, Catherine Culkin, Vera Loggins, Wolfgang Lorenzon, Bryan Ramson, Richard Raymond, Josh(ua) Rubin, Matthew Wood
- **Mississippi State University**: Lamiaa El Fassi
- **National Kaohsiung Normal University**: Rurngsheng Guo
- **RIKEN**: Yoshinori Fukao, Yuji Goto, Atsushi Taketani, Manabu Togawa
- **Rutgers University**: Ron Gilman, Ron Ransome, Arun Tadepalli
- **Tokyo Tech**: Shou Miyaska, Kei Nagai, Kenichi Nakano, Shigeki Obata, Florian Sanftl, Toshi-Aki Shibata
- **Yamagata University**: Yuya Kudo, Yoshiyuki Miyachi, Shumpei Nara

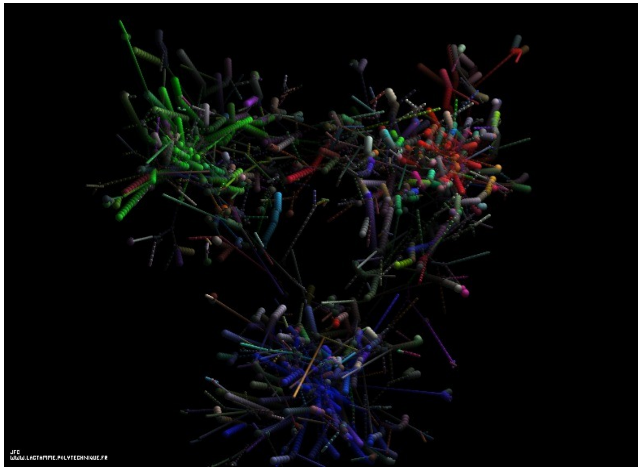
The inner structure of the nucleon

bound state of the strong interaction

relativistic quarks that exchange gluons



gluons radiate off gluons or quark antiquark pairs



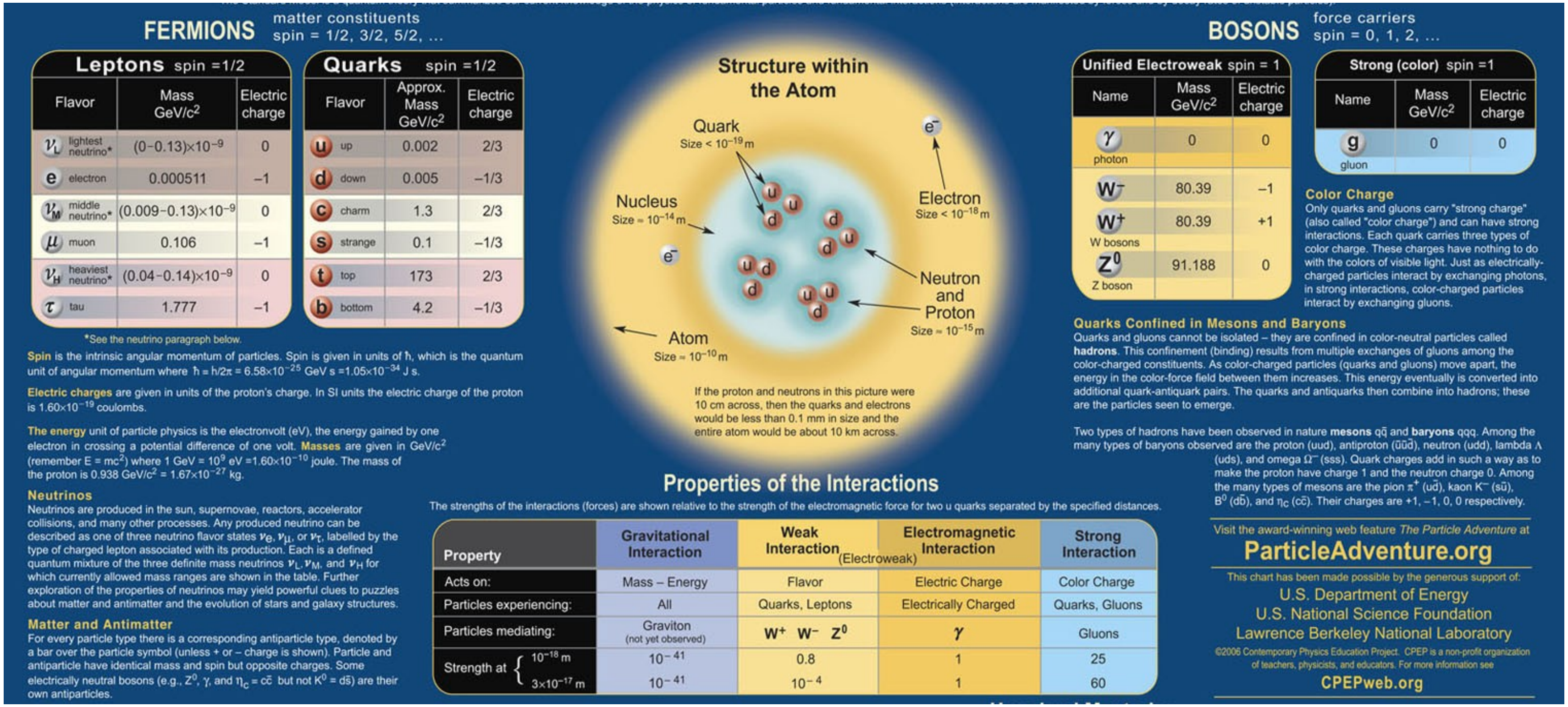
experimental investigation in Drell-Yan

unique sensitivity to antiquarks

SeaQuest – Drell-Yan experiment at FNAL

The Standard Model of Particle Physics

Fundamental interactions among fundamental (elementary) particles:

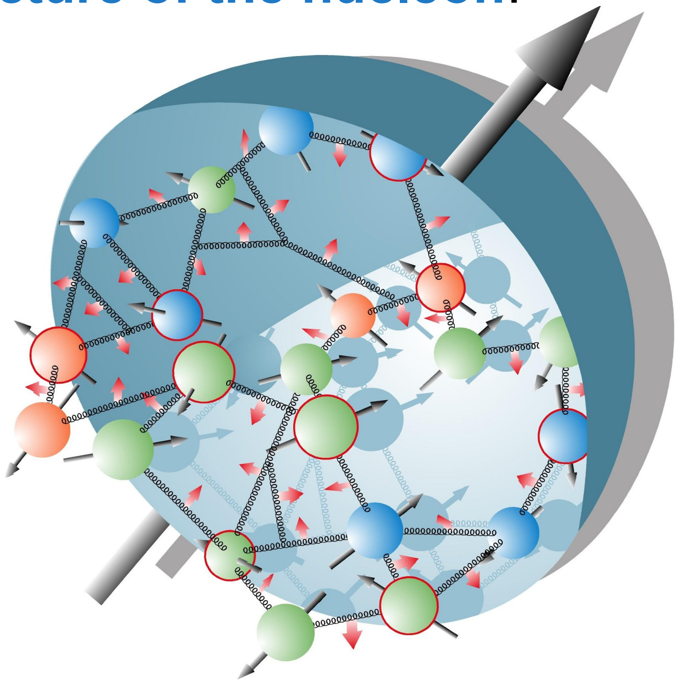


- **Higgs mechanism**: mass of an elementary particle is dynamically determined by its interaction with the Higgs particle
- **open questions**: asymmetry of matter and antimatter in the visible universe, dark matter and dark energy in the invisible universe, physics beyond the Standard Model

Physics within the standard model

- **The quark-gluon 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

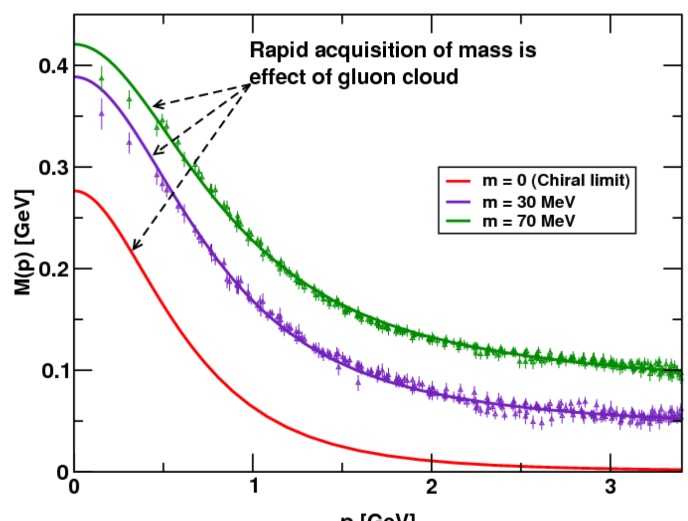


bound state of the strong interaction

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

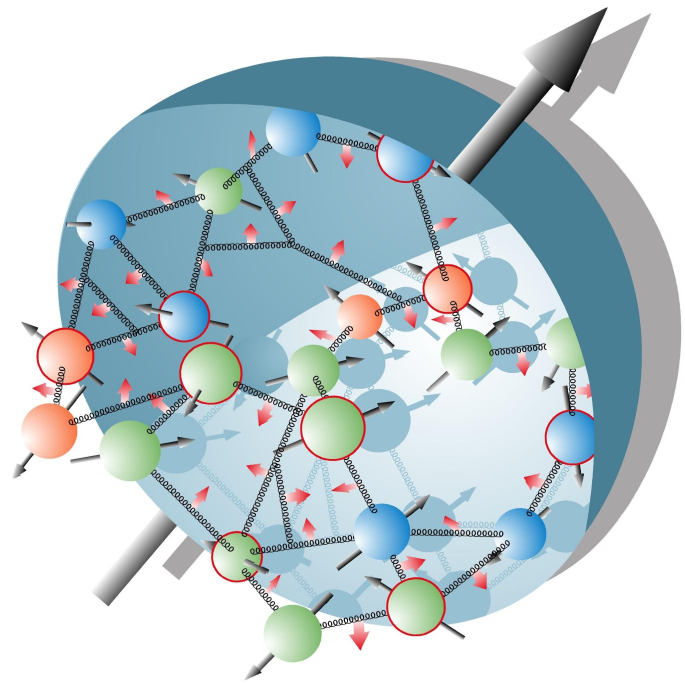
- **Nucleon mass arises from quark-gluon dynamics**:

Phys.Rev. C85 (2012) 065202



most of the mass of in the visible universe is due to the strong interaction

Properties of the nucleon



property	quarks	gluons
momentum (*)	~50%	~50%
mass	~5%	~95%
charge	valence quarks |p> = |uud> |n> = |ddu>	-
spin puzzle (*)	30%	~0%

(*) in the infinite momentum frame

Investigation of the nucleon structure

QCD - Quantum Chromodynamics

the theory of the strong interaction

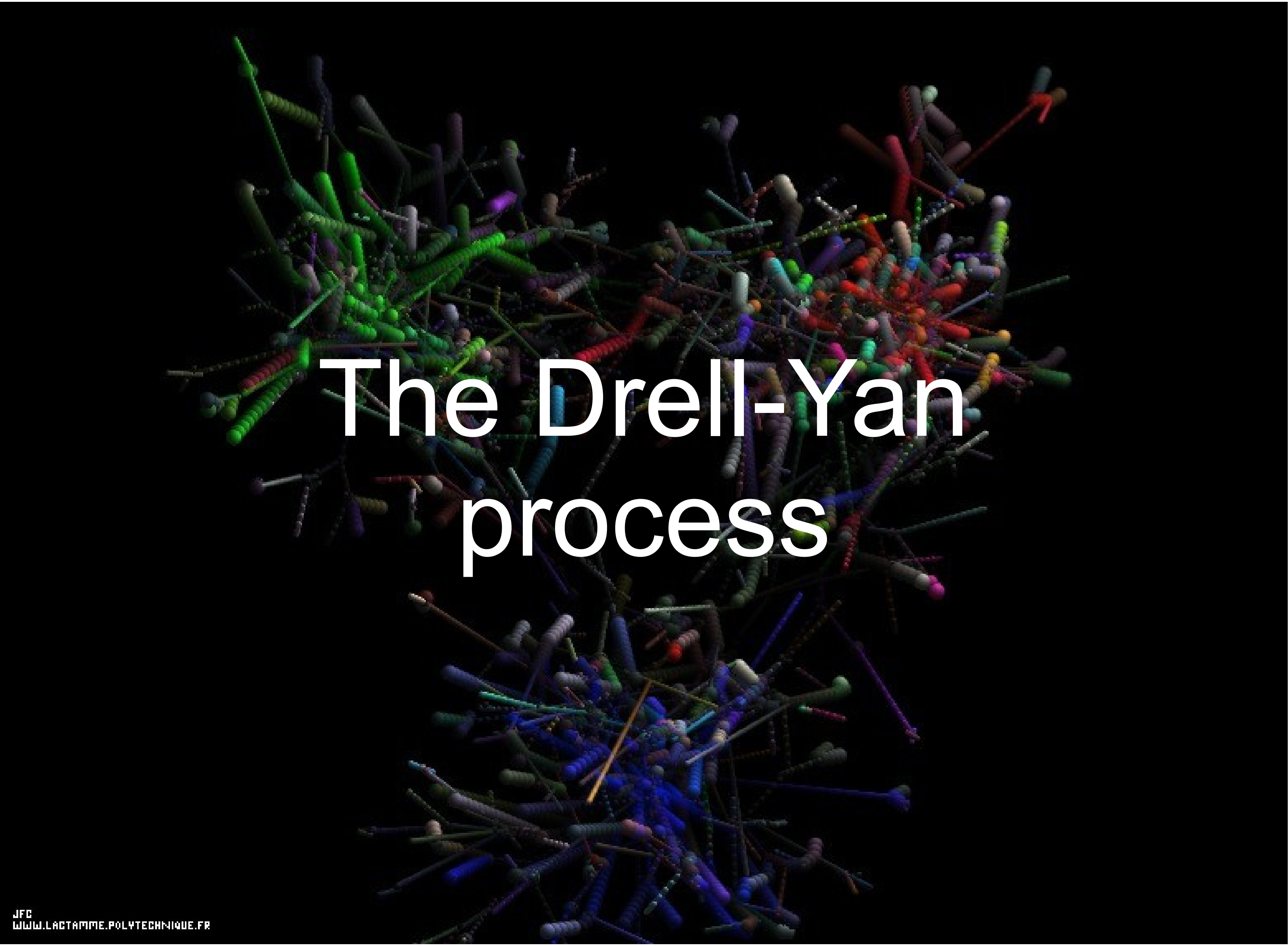
Lattice QCD

calculating observables of the strong interaction using methods of statistical physics

Experimental studies of fundamental processes

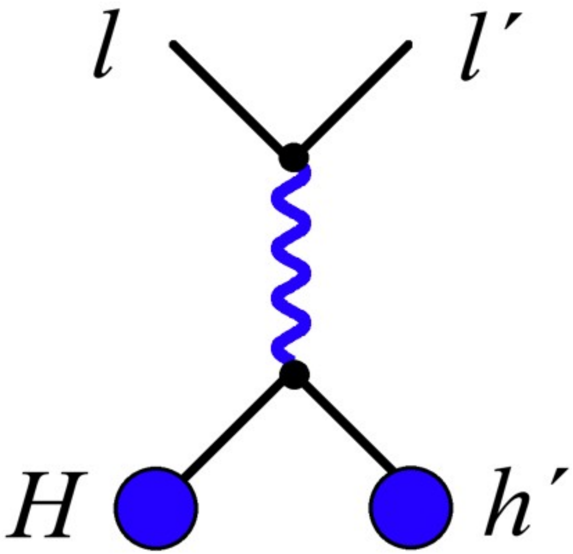
deep-inelastic scattering, electron-positron annihilation, and the Drell-Yan process

The Drell-Yan process

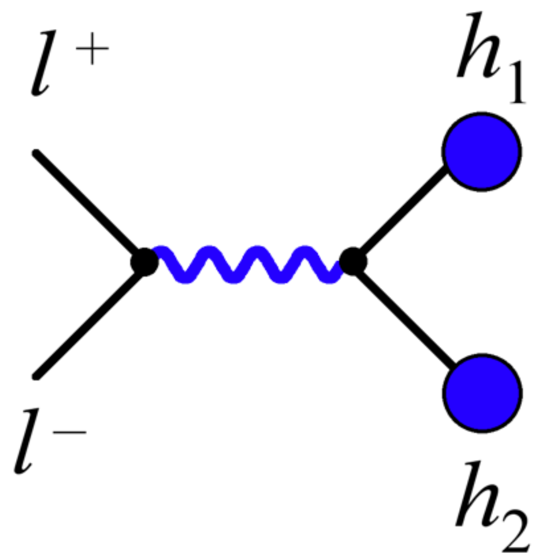


Fundamental (electro-weak) processes

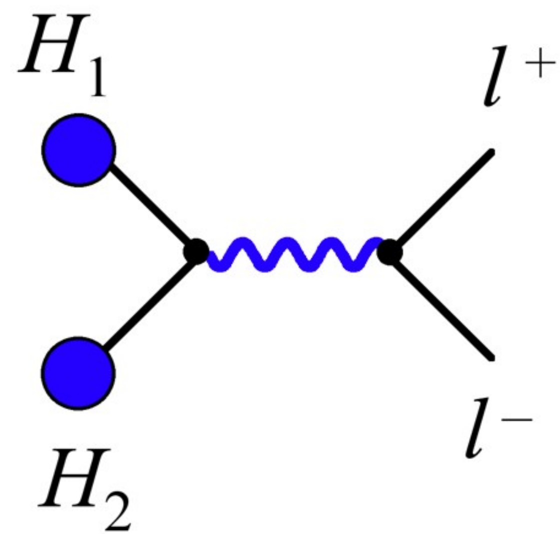
semi-inclusive DIS



e+e- annihilation



Drell-Yan



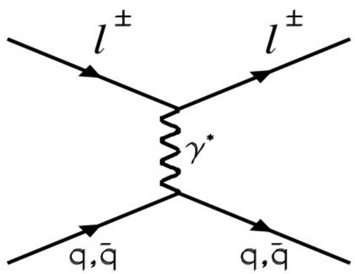
QCD factorization theorem

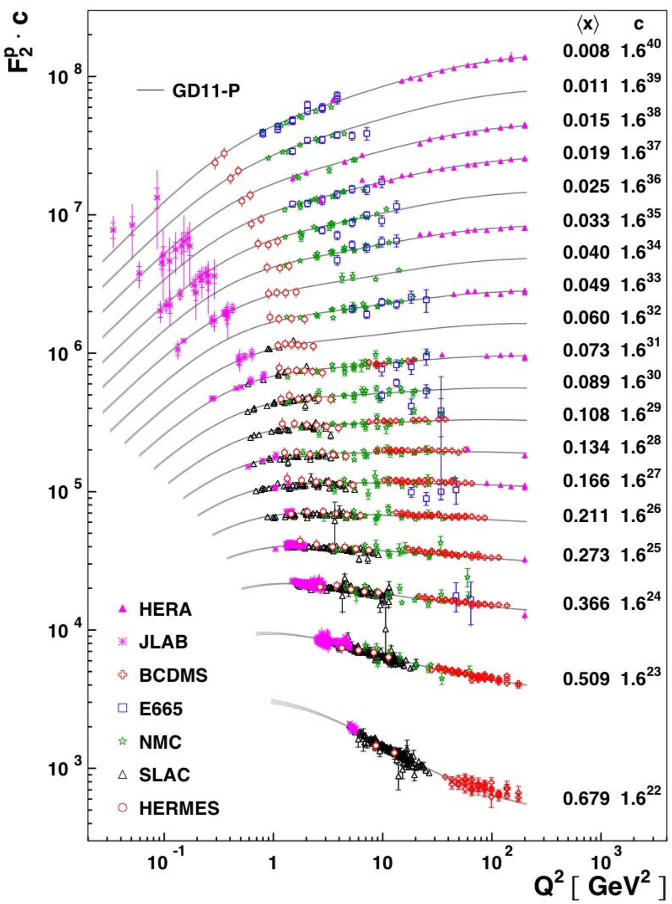
$$\sum_q e_q^2 \; \mathbf{f}_{\mathbf{q}}^{(\mathbf{H})}(x) \; \mathbf{D}_{\mathbf{q}}^{\mathbf{h}'}(z) \qquad \sum_q e_q^2 \; \mathbf{D}_{\mathbf{q}}^{\mathbf{h}_1}(z_1) \; \mathbf{D}_{\bar{\mathbf{q}}}^{\mathbf{h}_2}(z_2) \qquad \sum_q e_q^2 \; \mathbf{f}_{\mathbf{q}}^{(\mathbf{H}_1)}(x_1) \; \mathbf{f}_{\bar{\mathbf{q}}}^{(\mathbf{H}_2)}(x_2)$$

- measure all processes to disentangle **distribution** (f) and **fragmentation** (D) functions
- measure as many **hadron species** H, h as possible to disentangle **quark flavors** q

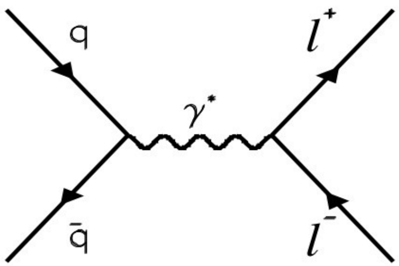
Complimentary processes

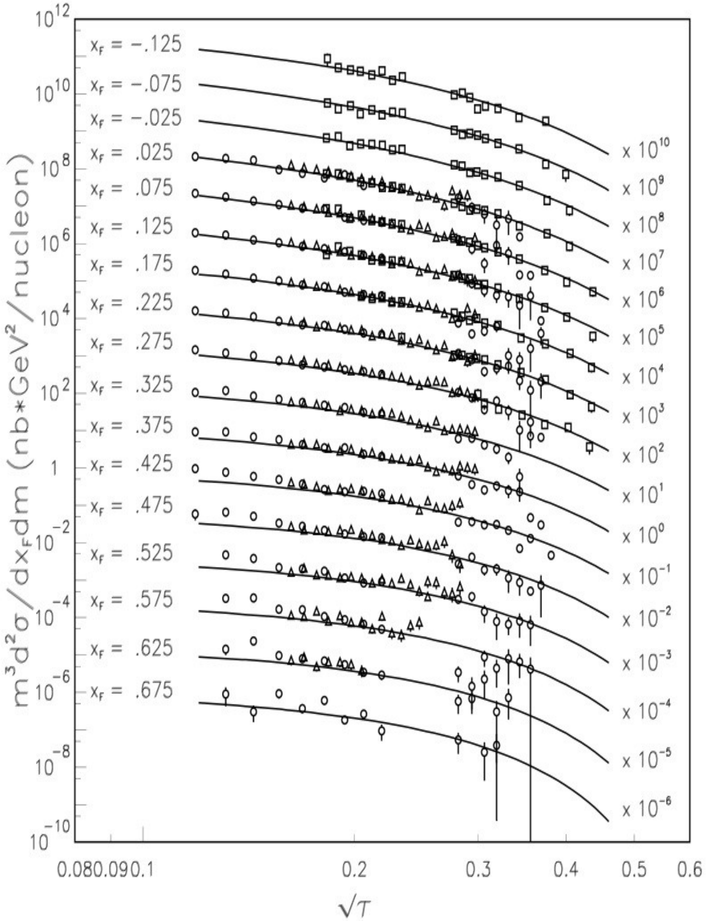
Deep-inelastic scattering





Drell-Yan scattering





The Drell-Yan process

VOLUME 25, NUMBER 21 PHYSICAL REVIEW LETTERS 23 NOVEMBER 1970

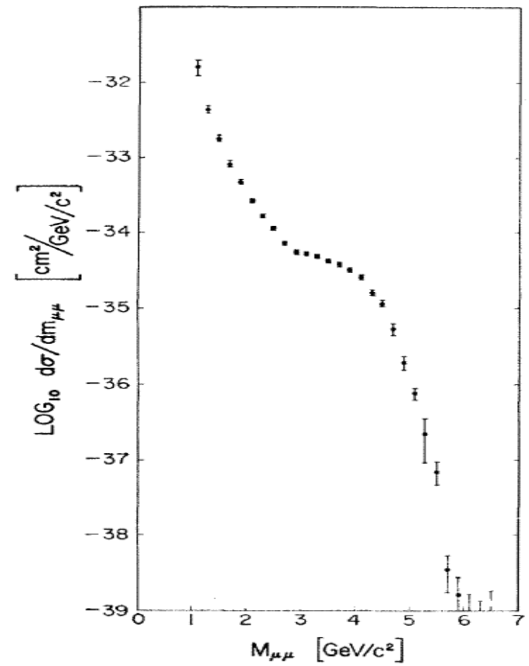
Observation of Massive Muon Pairs in Hadron Collisions*

J. H. Christenson, G. S. Hicks, L. M. Lederman, P. J. Limon, and B. G. Pope
Columbia University, New York, New York 10027, and Brookhaven National Laboratory, Upton, New York 11973

and

E. Zavattini
CERN Laboratory, Geneva, Switzerland
(Received 8 September 1970)

Muon Pairs in the mass range $1 < m_{\mu\mu} < 6.7$ GeV have been observed in collisions of high-energy protons with uranium nuclei. At an incident energy of 29 GeV, **the cross section varies smoothly as $d\sigma/dm_{\mu\mu} \approx 10^{-32} / m_{\mu\mu}^{5}$ cm² (GeV/c)$^{-2}$ and exhibits no resonant structure**. The total cross section increases by a factor of 5 as the proton energy rises from 22 to 29.5 GeV.

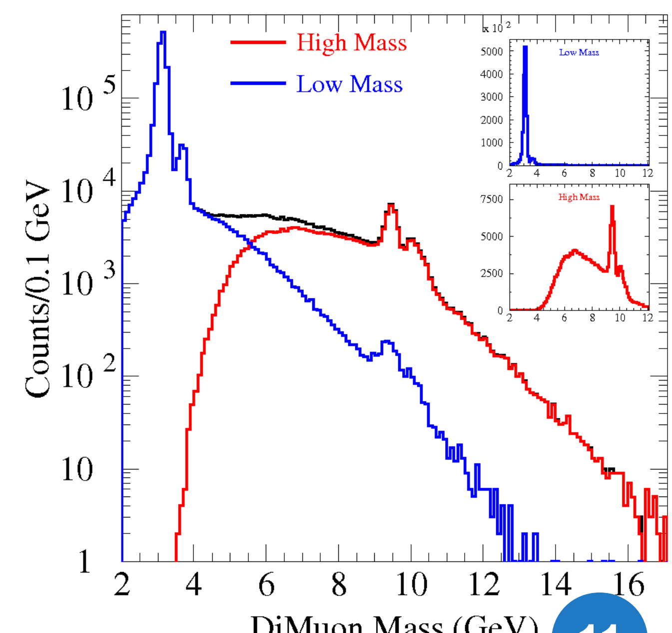


VOLUME 25, NUMBER 5 PHYSICAL REVIEW LETTERS 3 AUGUST 1970

MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES*

Sidney D. Drell and Tung-Mow Yan
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 25 May 1970)

On the basis of a parton model studied earlier we consider the production process of large-mass lepton pairs from hadron-hadron inelastic collisions in the limiting region, $s \to \infty$, Q^2/s finite, Q^2 and s being the squared invariant masses of the lepton pair and the two initial hadrons, respectively. General scaling properties and connections with deep inelastic electron scattering are discussed. In particular, a rapidly decreasing cross section as $Q^2/s \to 1$ is predicted as a consequence of the observed rapid falloff of the inelastic scattering structure function νW_2 near threshold.



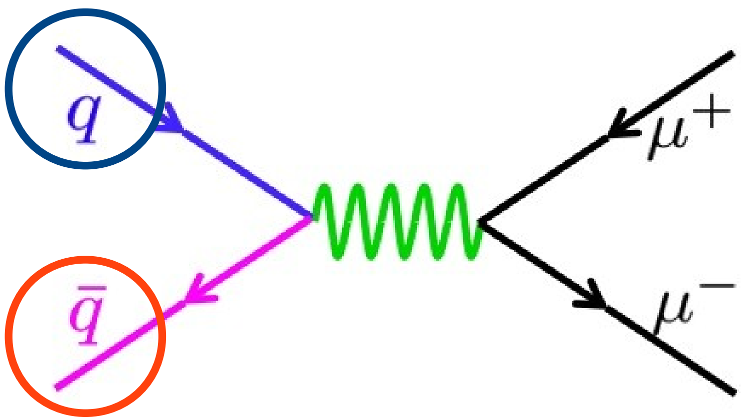
A laboratory for sea quarks

The Drell-Yan process

fixed target + forward spectrometer

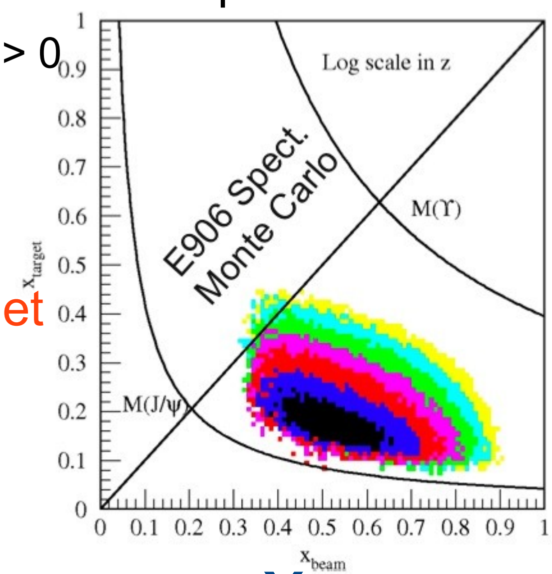
→ $x_F = x_b - x_t > 0$

beam



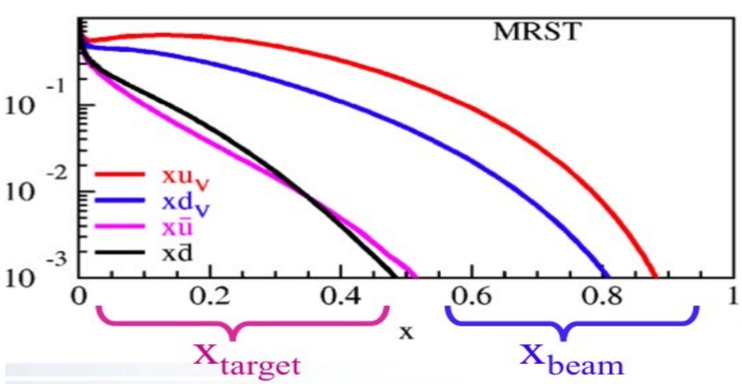
target

x_{target}

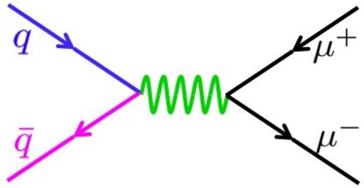


x_{beam}

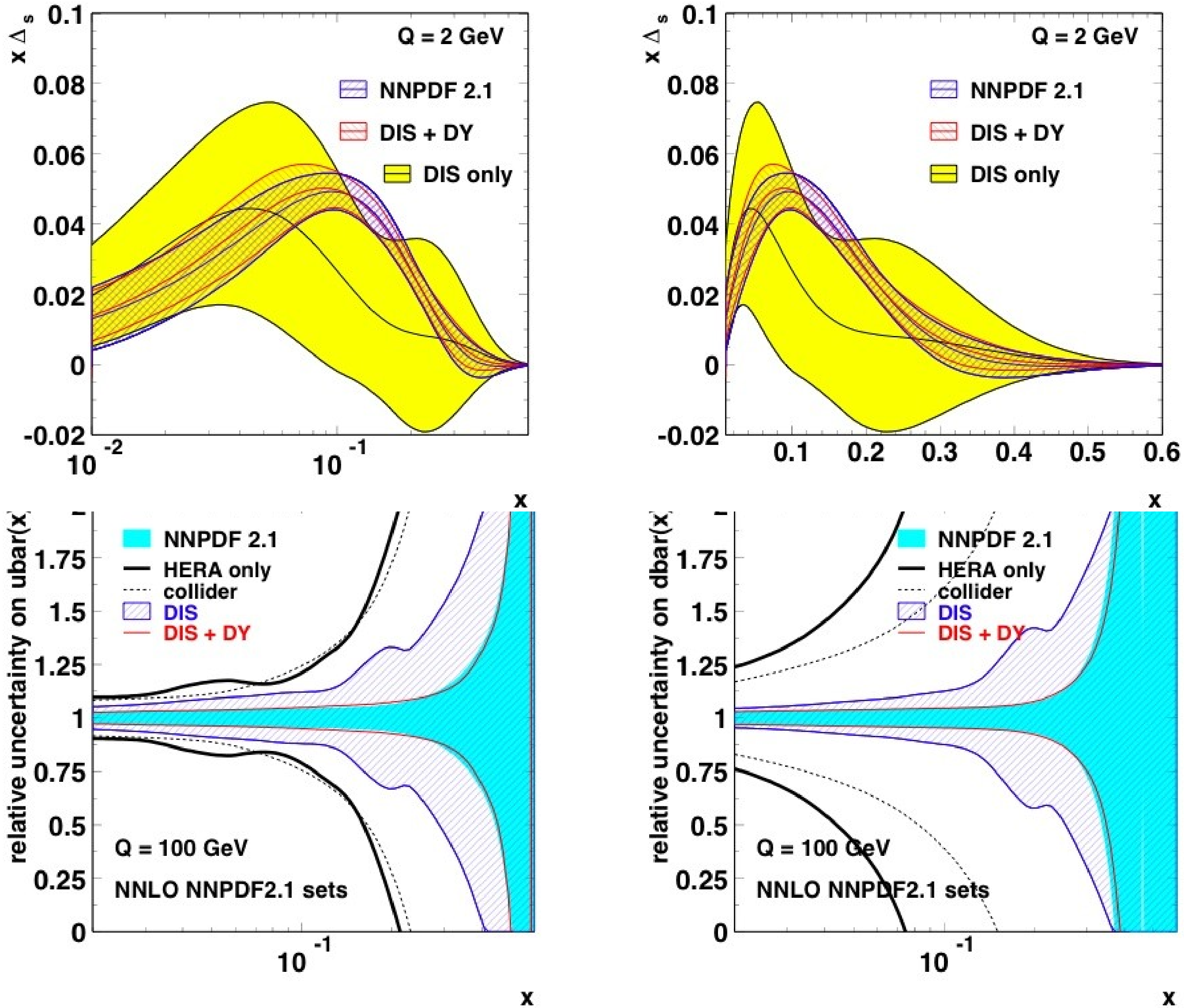
$$\frac{d^2\sigma}{dx_b\, dx_t} = \frac{4\pi\alpha^2}{9x_b\, x_t}\frac{1}{s}\sum_q e_q^2\left[\bar{q}_t(x_t)q_b(x_b) + q_t(x_t)\bar{q}_b(x_b)\right]$$



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

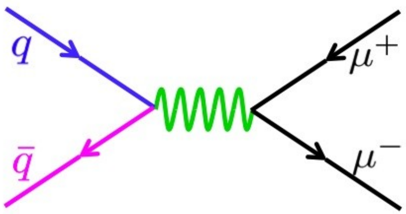


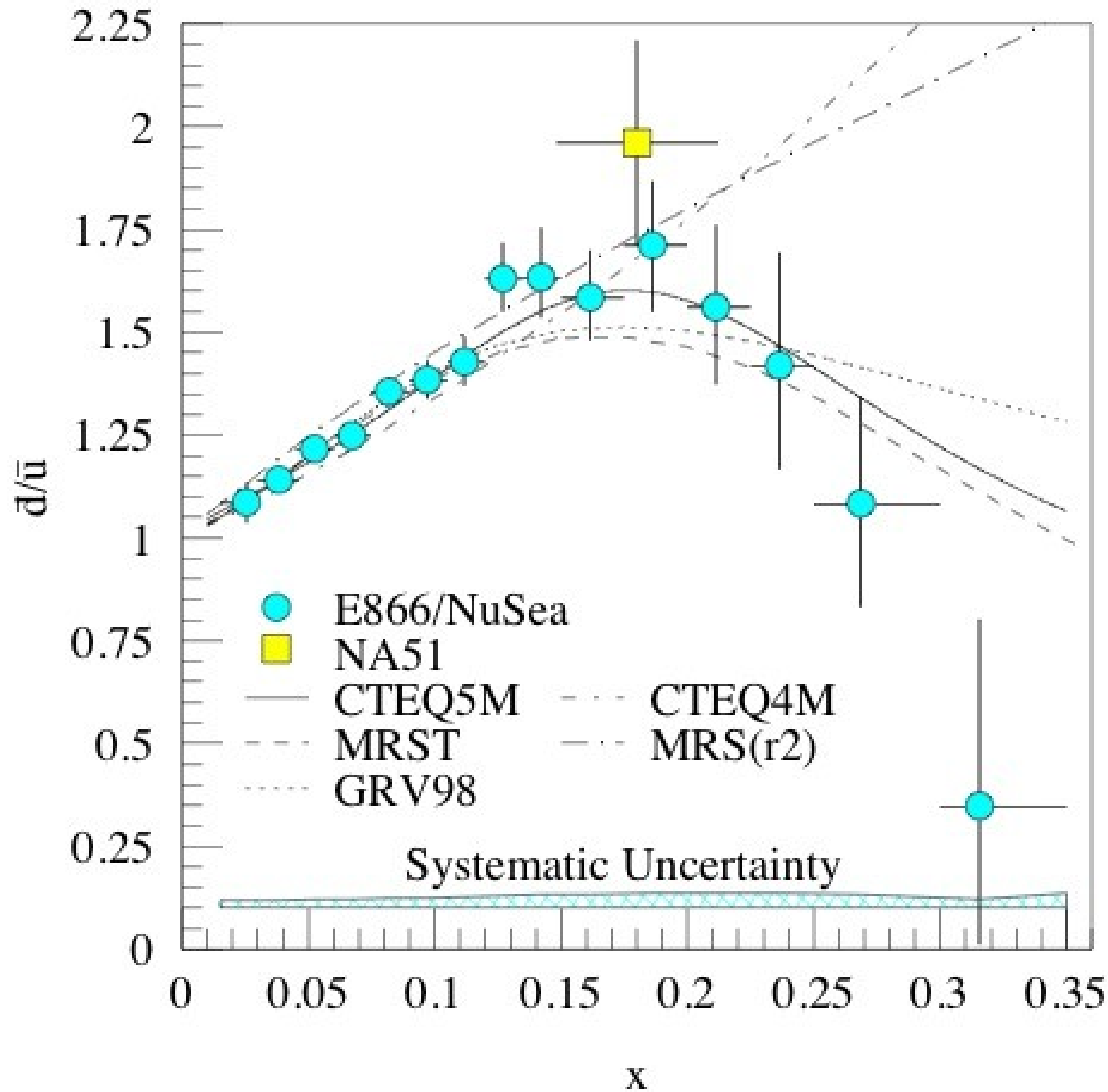
: unique sensitivity to sea quarks



The Drell-Yan Adventure

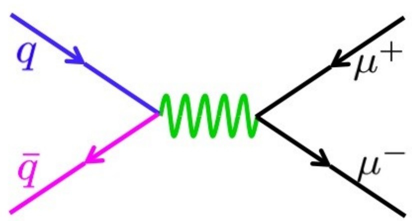
Insights into the proton sea

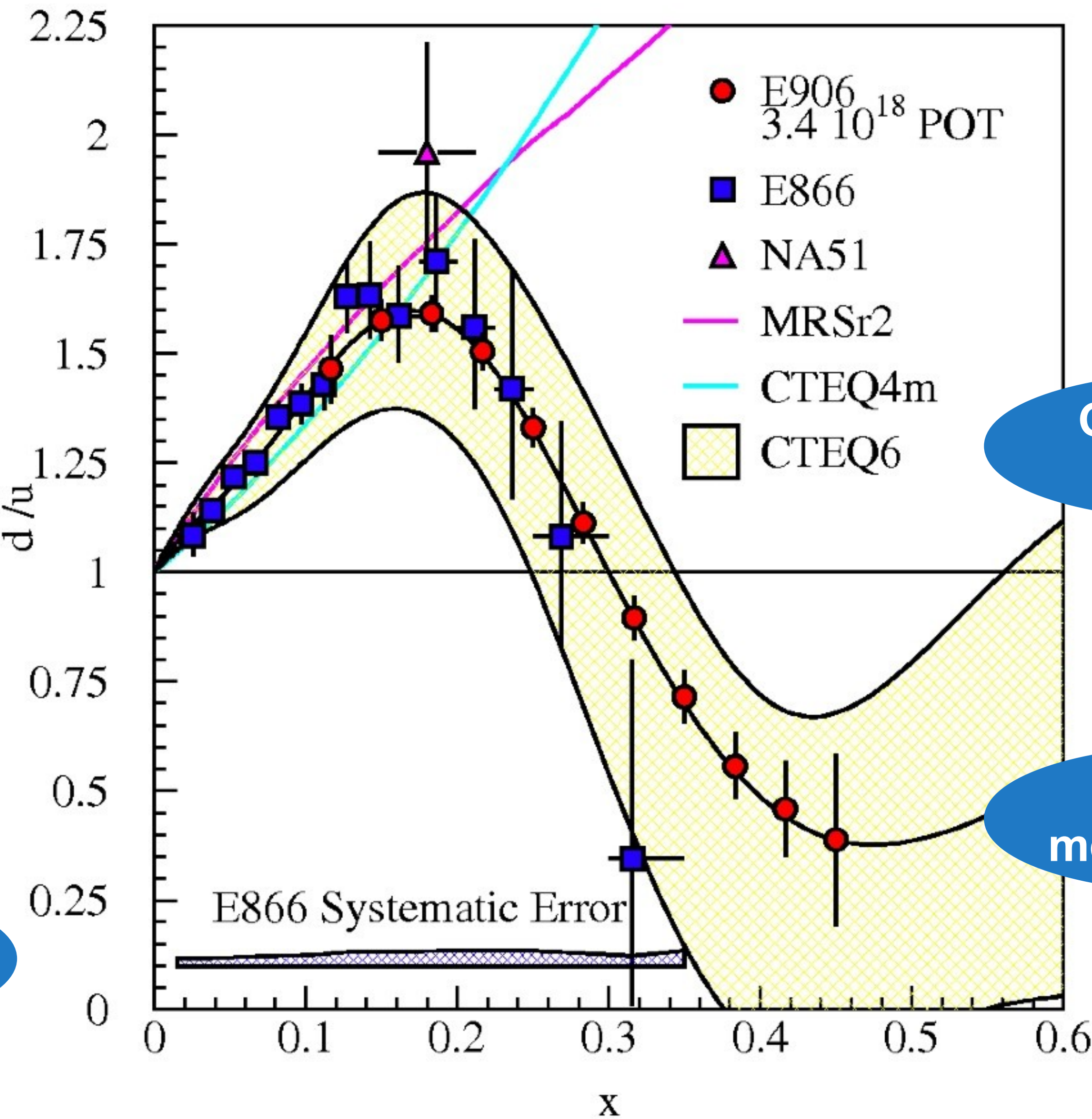




$$\left.\frac{\sigma^{pd\to\mu^+\mu^-}}{\sigma^{pp\to\mu^+\mu^-}}\right|_{x_\mathrm{b}\gg x_\mathrm{t}} \approx \frac{1}{2}\left[1+\frac{\bar{d}(x_\mathrm{t})}{\bar{u}(x_\mathrm{t})}\right]$$

SeaQuest probing the proton sea





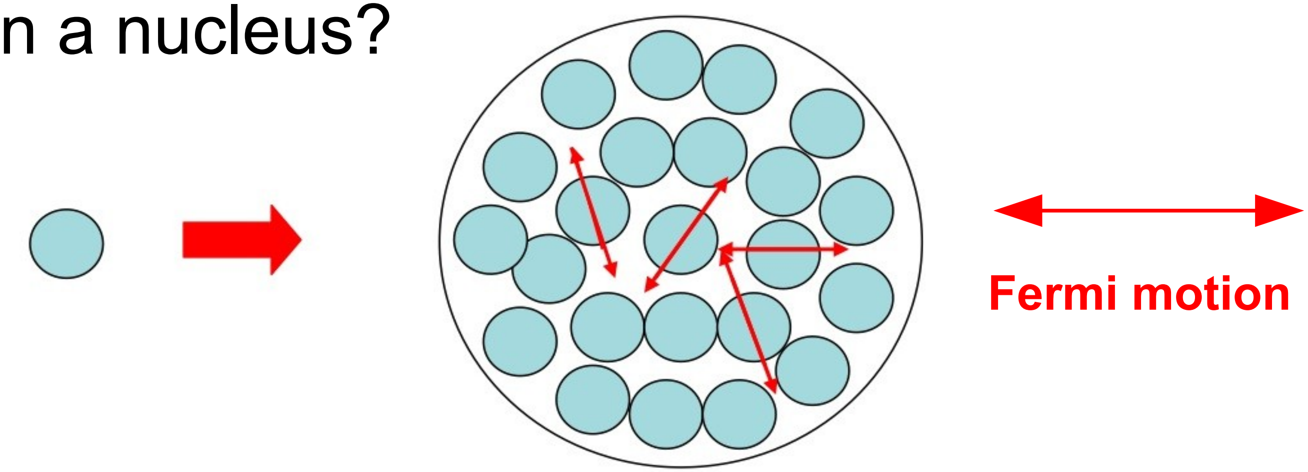
Global NLO PDF fit

extend measurement

SeaQuest: Syst. ~ 1%

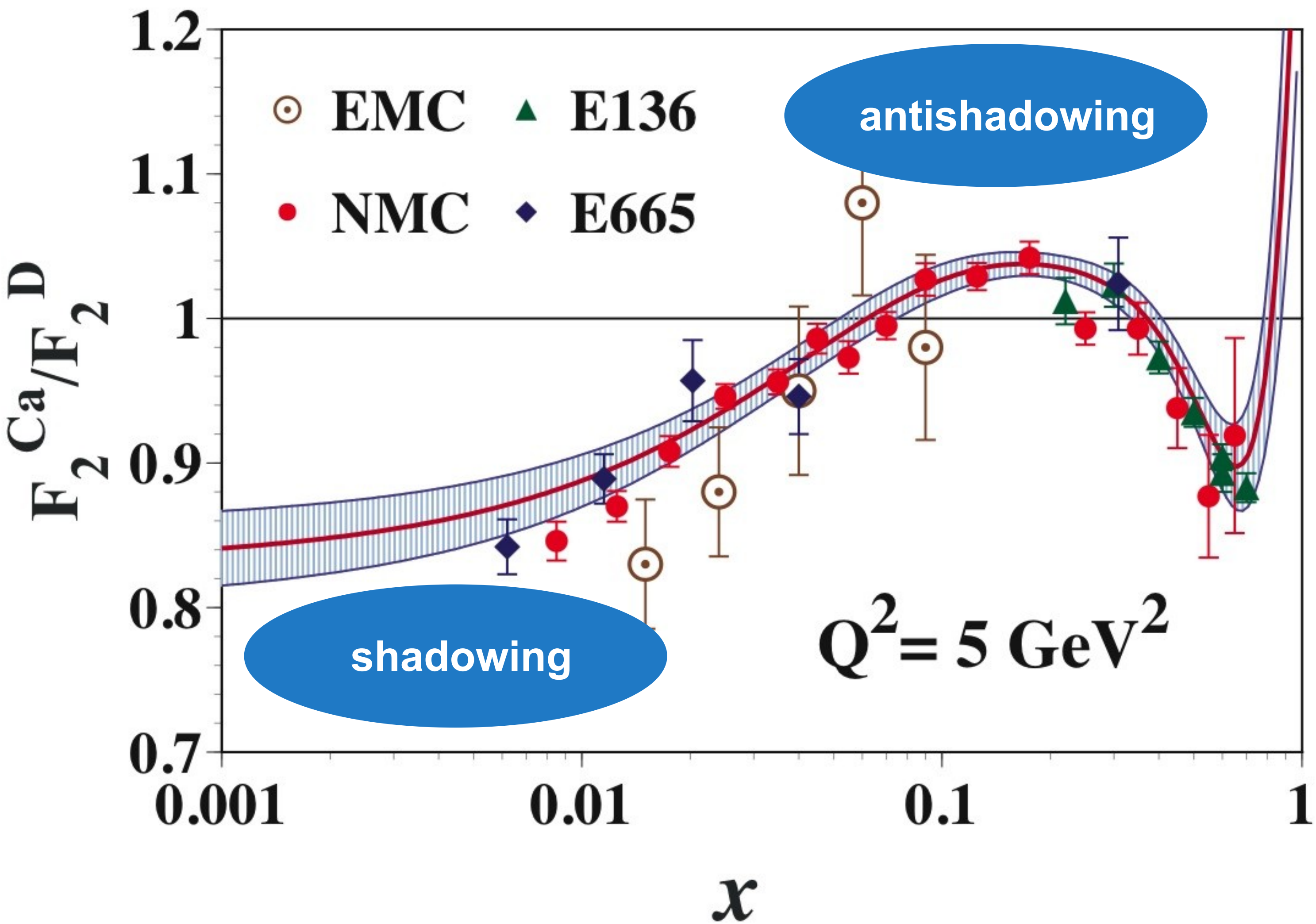
Nucleons embedded in nuclei

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



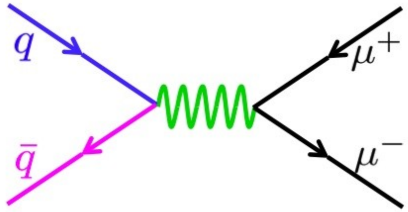
- Is confinement influenced by the nuclear medium?
- Nuclei are well-described by the strong force between protons and neutrons (and no other degrees of freedom).
- Do quarks and gluons play any role in the understanding of nuclear forces?

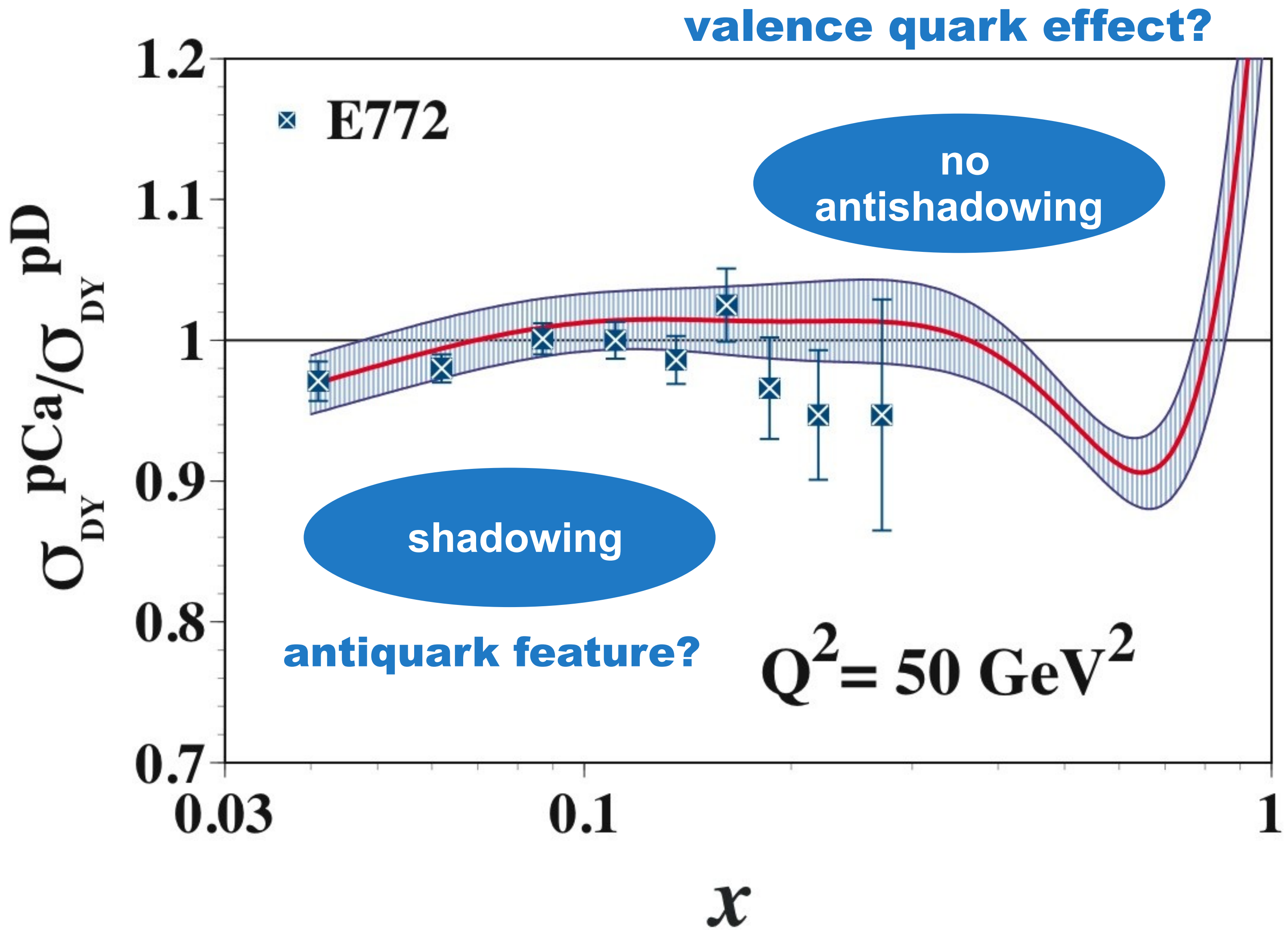
The EMC effect



New measurements required to distinguish explanations of the EMC effect (e.g., pion excess in nuclei, medium modifications of bound nucleon wave functions, short-range nucleon-nucleon correlations).

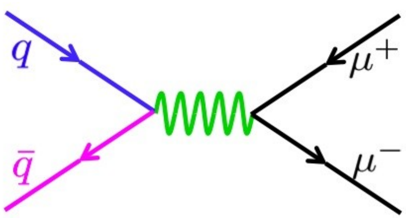
The EMC effect in

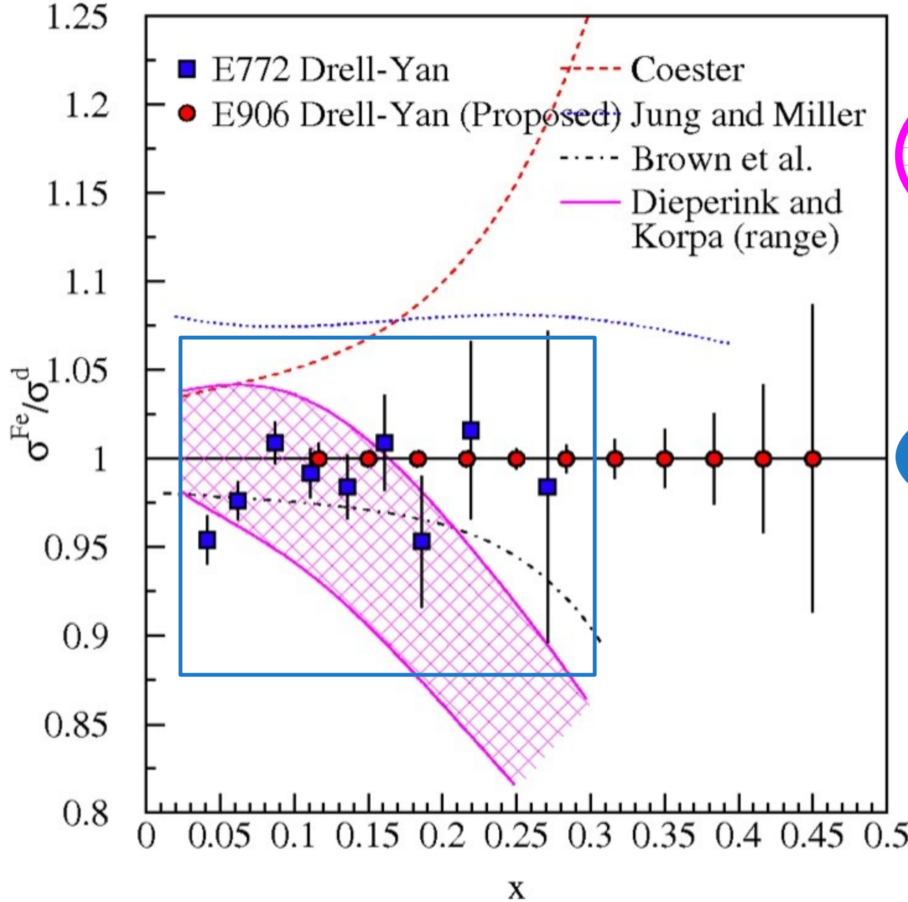




The inner structure of a nucleus

- nuclear force mediated by meson exchange





large effects to antiquark PDF predicted as x increases

no antiquak enhancement

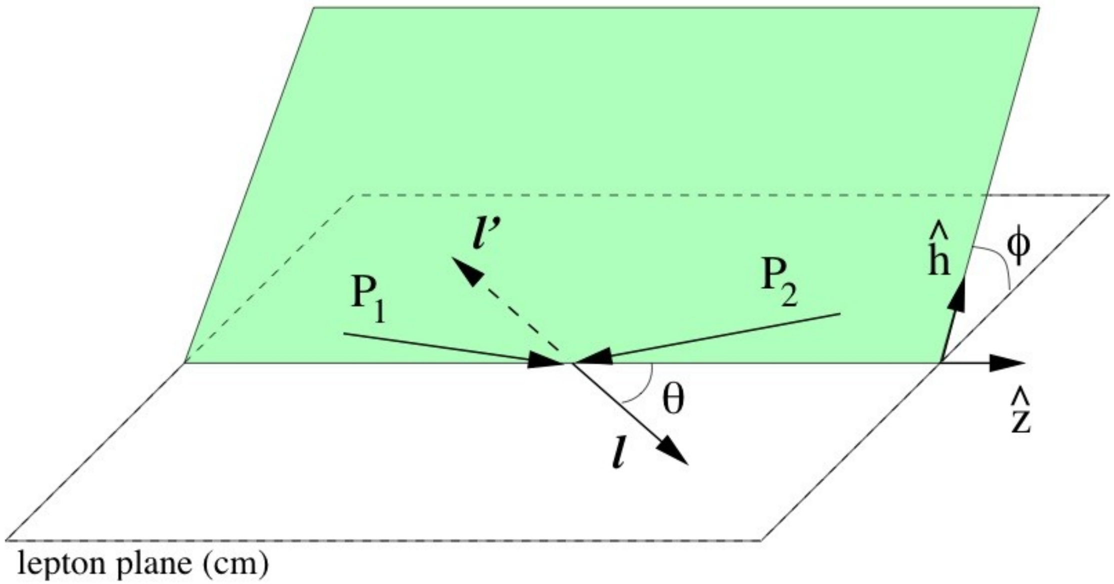
- **Where are the *nuclear* pions?**

The Lam-Tung relation

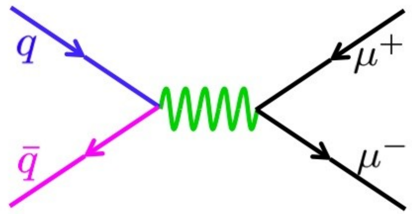
- **angular dependence** of the Drell-Yan cross-section:

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

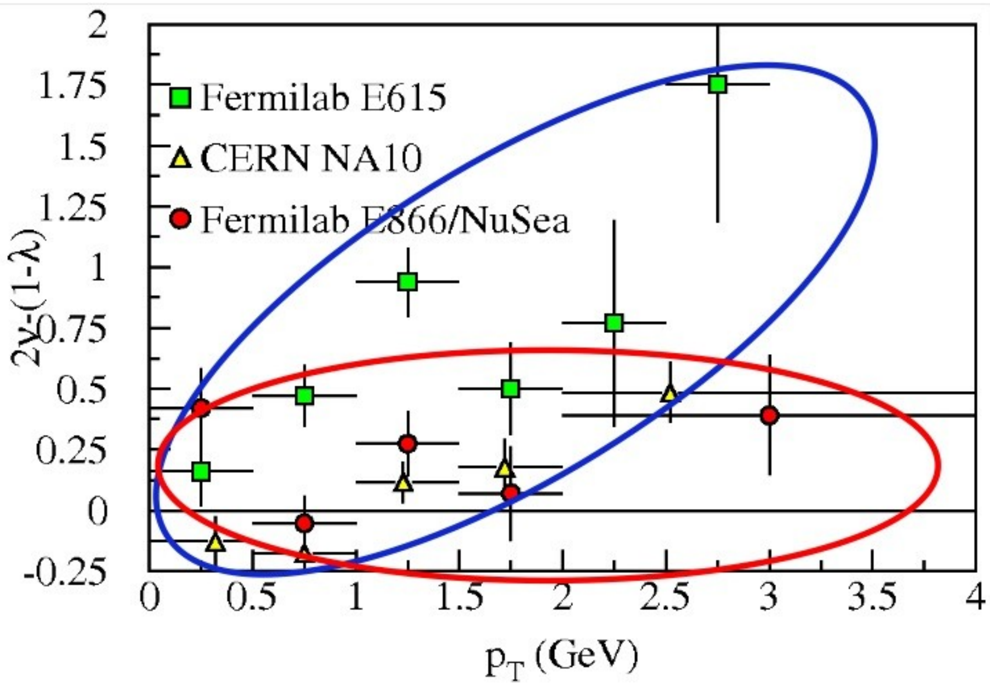
- **Lam-Tung relation**: $1 - \lambda = 2\nu$

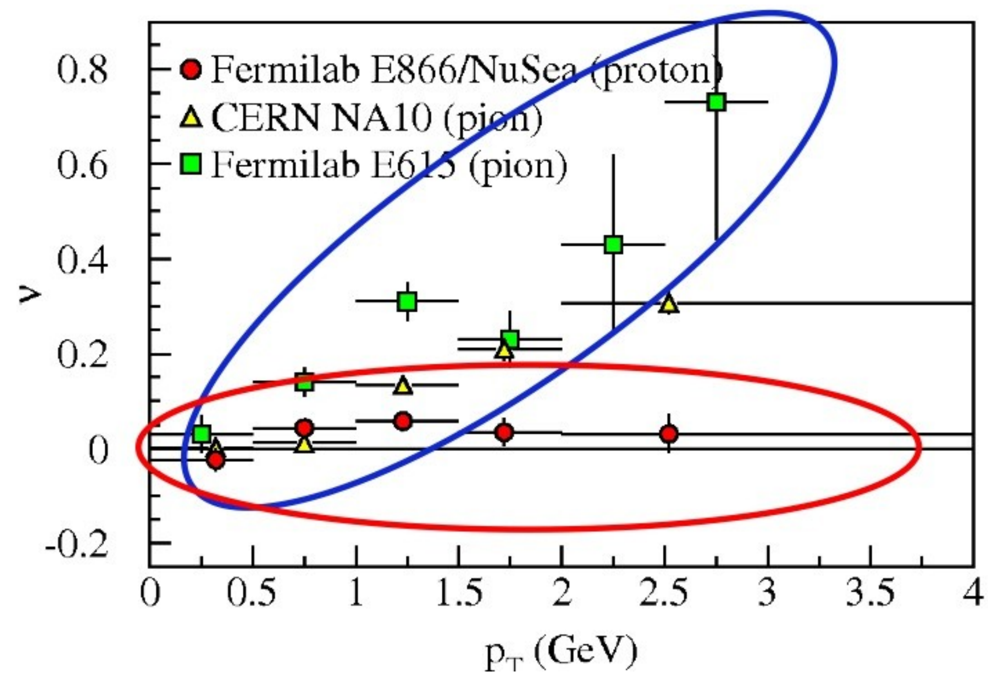


Angular dependence in



- **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**:

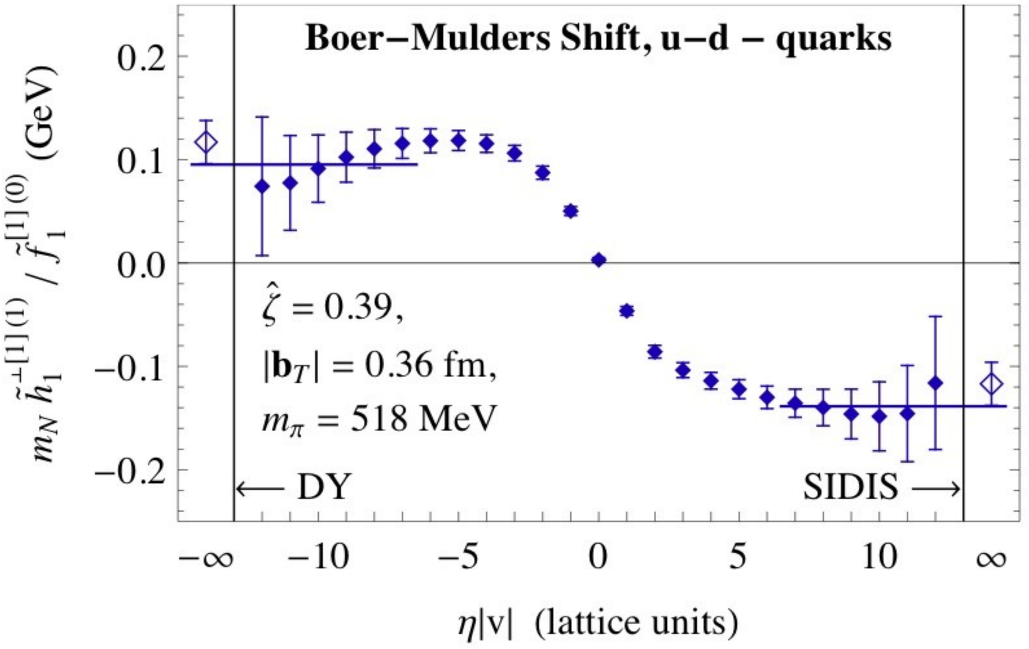
$h_1^{\perp,q}(x, \mathbf{p}_T^2)$  $-$  $s_T^i \varepsilon^{ij} p_T^j \frac{1}{M}$

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

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

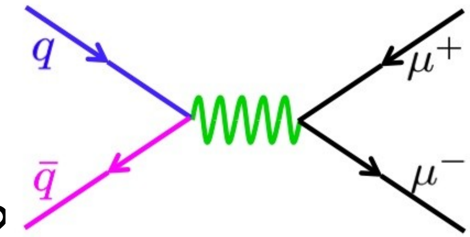
  → **single-spin asymmetries**

- challenging the concept of factorization and universality



The SeaQuest mission

- **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?



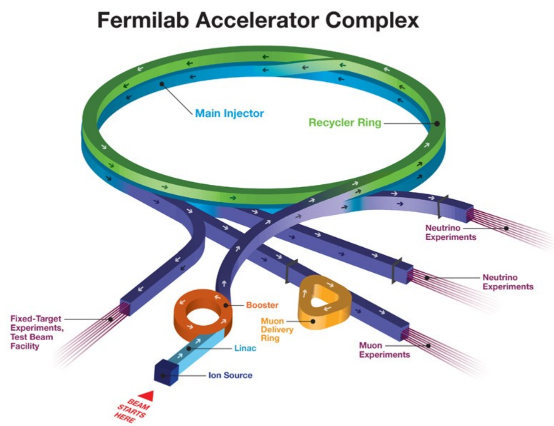
- **What is the structure of nucleonic matter?**
  - Where are the *nuclear* pions?
  - Is antishadowing a valence effect?
- **Do partons lose energy in cold nuclear matter?**
- **Do dark photons couple to a dilepton pair?**
- **Answers from SeaQuest:**
  - significant increase in physics increase
  - unique access to **sea quarks at high-x**

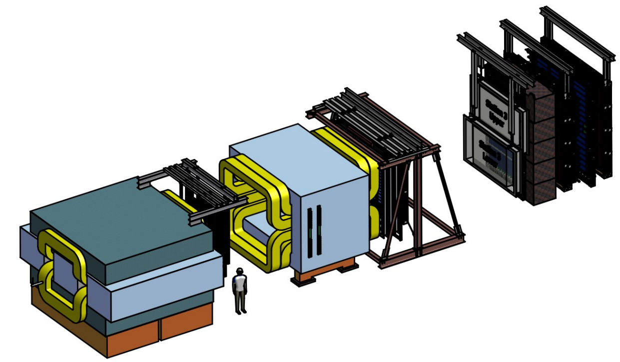
The SeaQuest experiment

Fermilab (FNAL)

The SeaQuest Experiment

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





Proton Beam

slow extraction from MI

$2x10^{12}$ 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

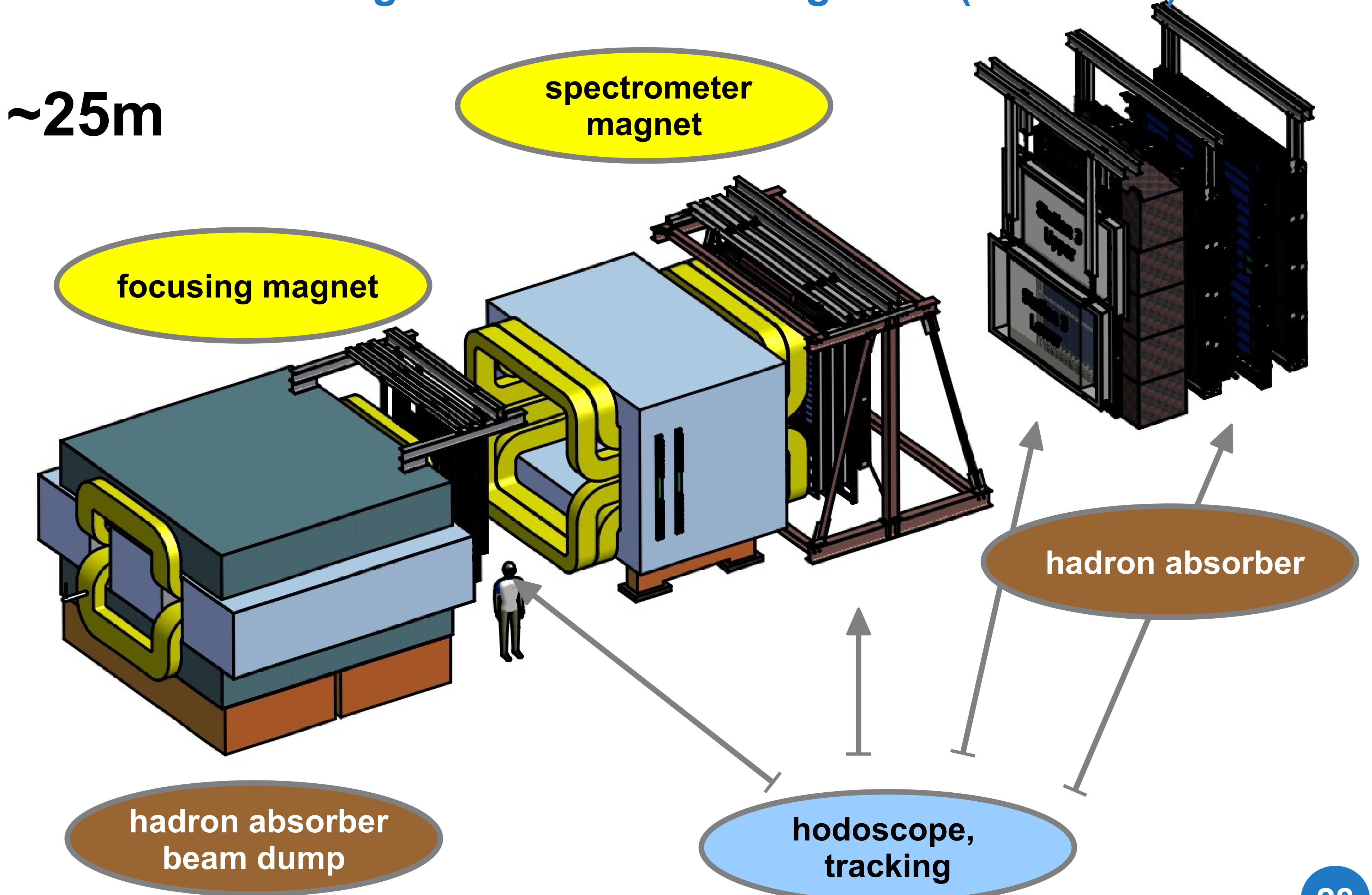
Spectrometer

reused and recycled components

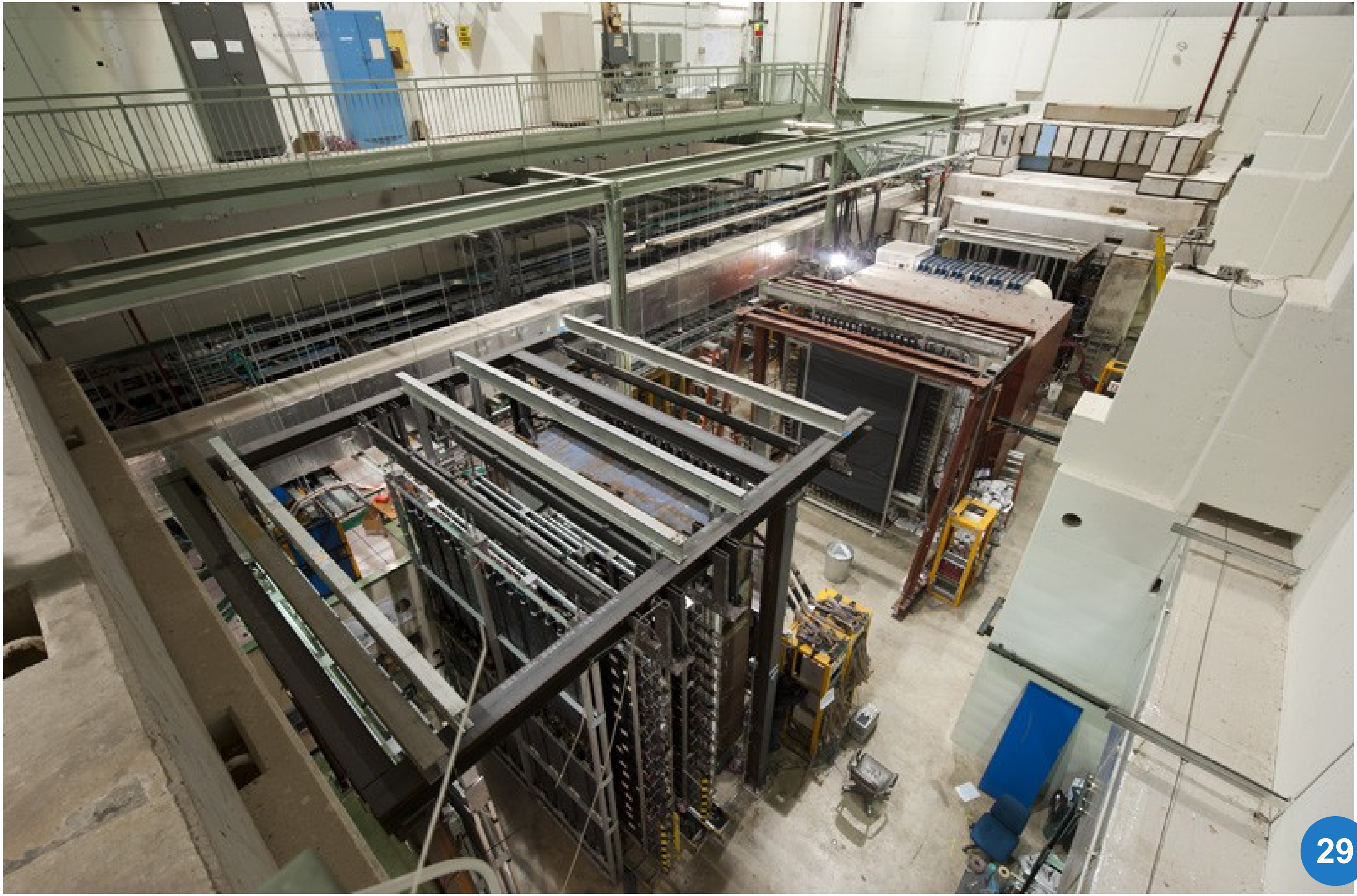
selected updates: new drift chambers, PMT bases for high-rate capability, beam diagnostics, trigger redesign, ...

The SeaQuest Spectrometer

– recording dimuon events at high rate (~ 1000 Hz)



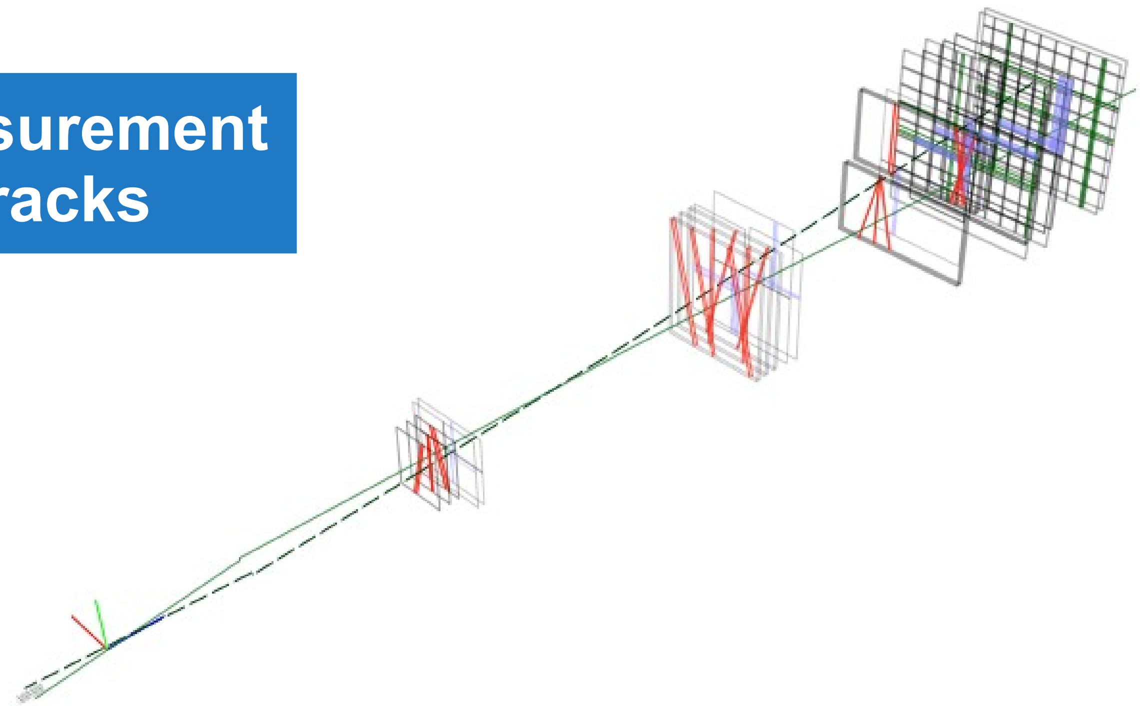
The SeaQuest spectrometer

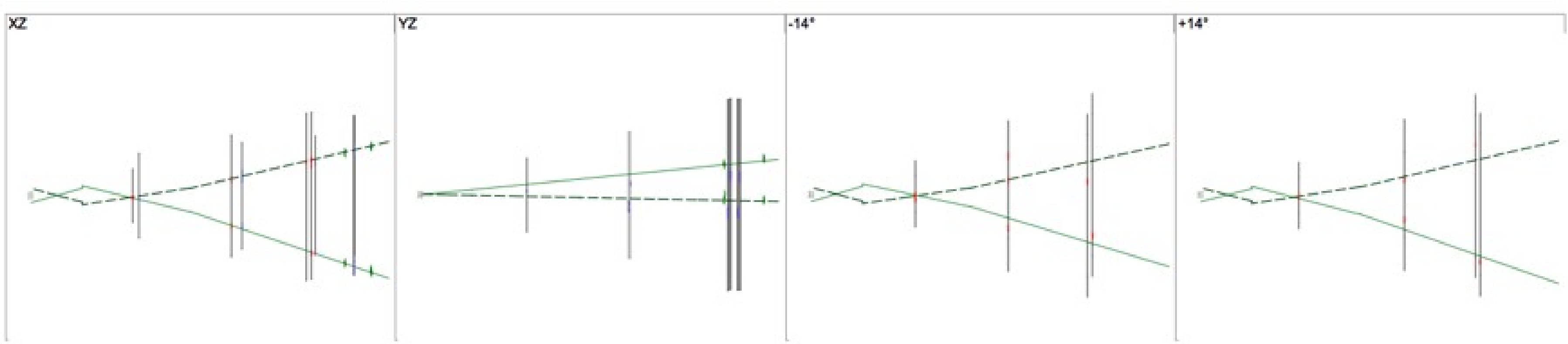


The SeaQuest spectrometer

Dimuon reconstruction

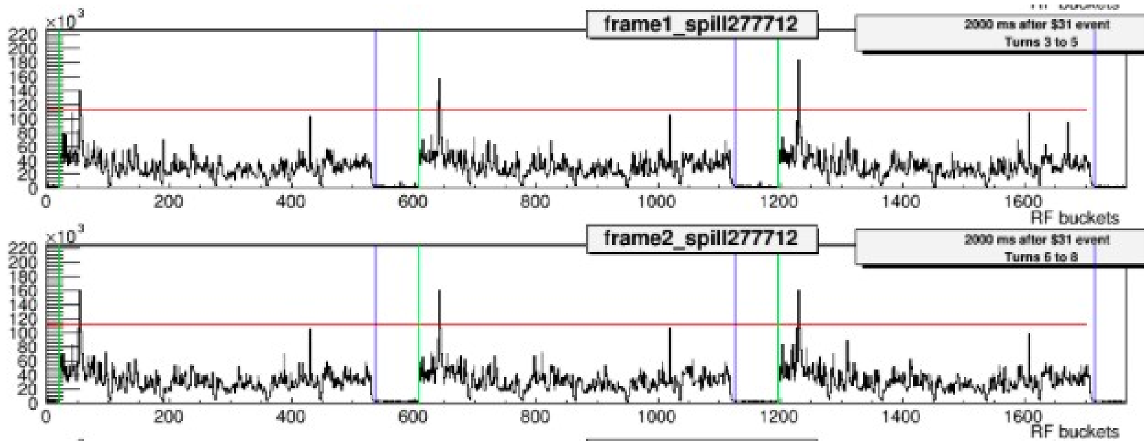
from measurement of muon tracks

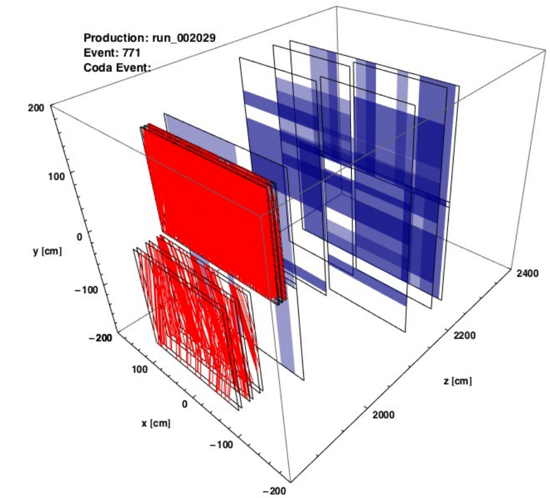




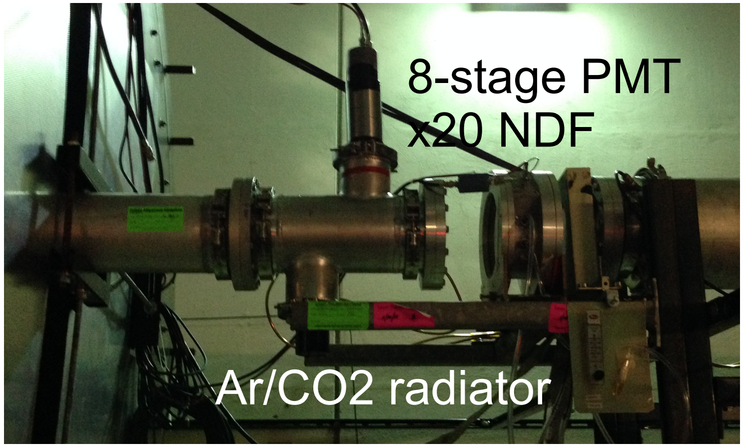
Spill Structure

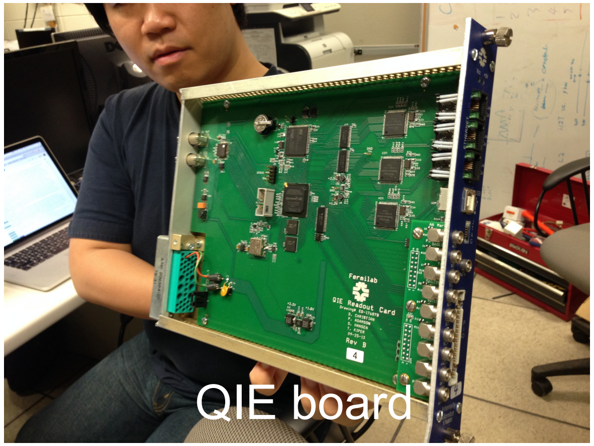
large **variations** in **instantaneous beam intensity** → high hit occupancy





beam-line Cherenkov monitor for beam diagnostics:



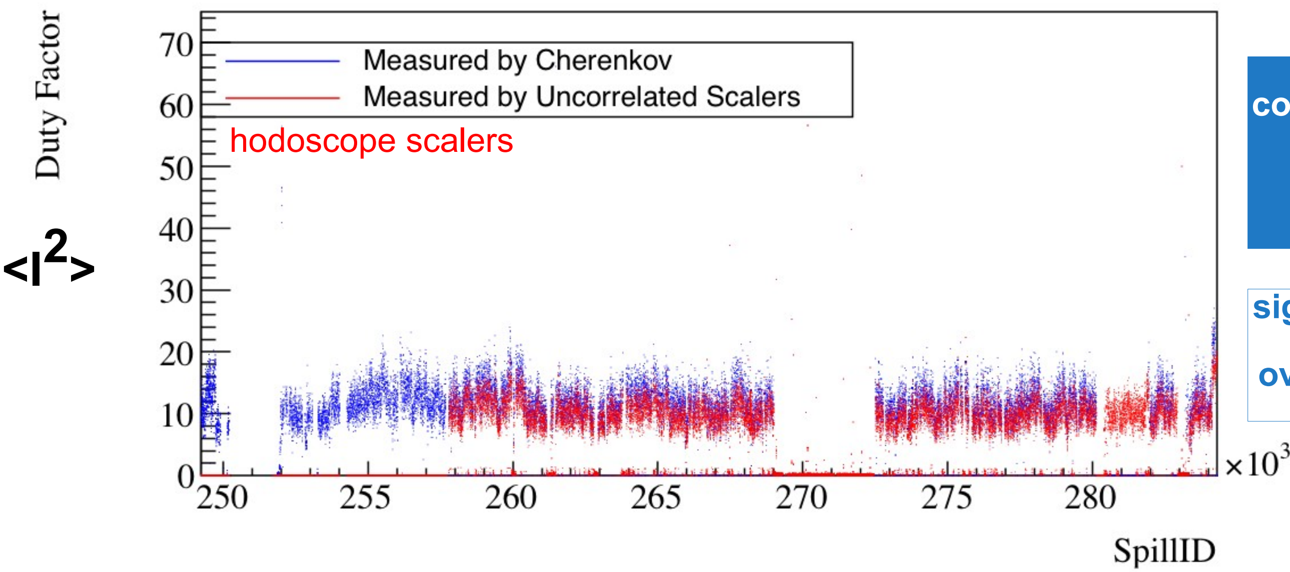


→ **beam diagnostics**: measurement of RF-bucket by RF-bucket intensity
→ **trigger inhibit**: veto on single RF buckets as a function of intensity,
½ beam inhibited due to 10x expected beam/RF-bucket

Duty Factor Measurements

– studying the uniformity of the beam

DF = <I> <I> / <I^2>

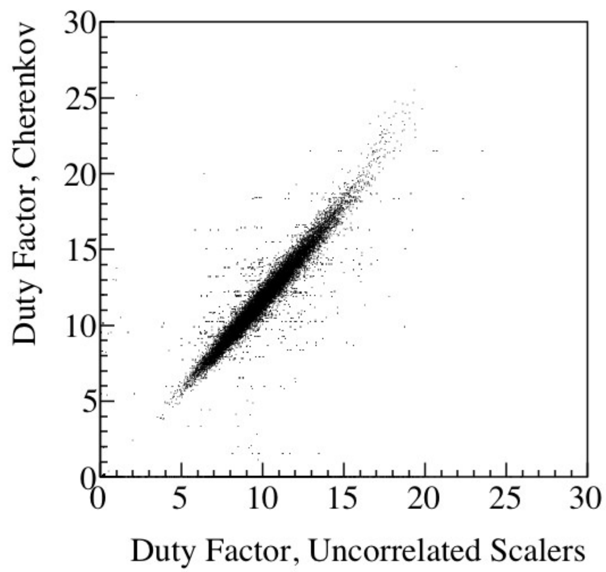


continuous effort by AD to improve DF

significant improvement over summer, DF ~ 40%

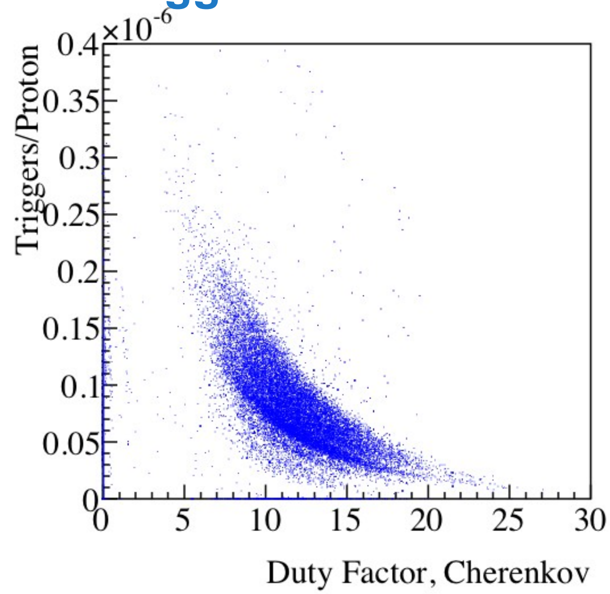
DF measurements:

affected by saturation



based on real dimuon events, affected by coincidence window and saturation

Trigger rate vs. DF:



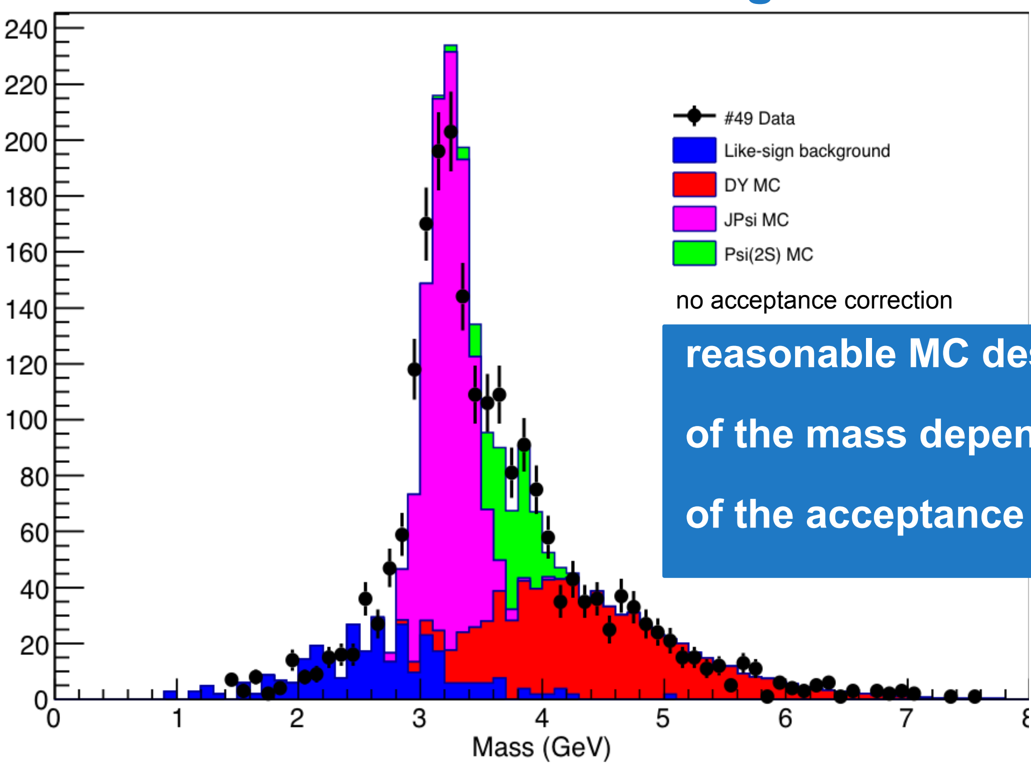
Status of the analysis

- data taking:

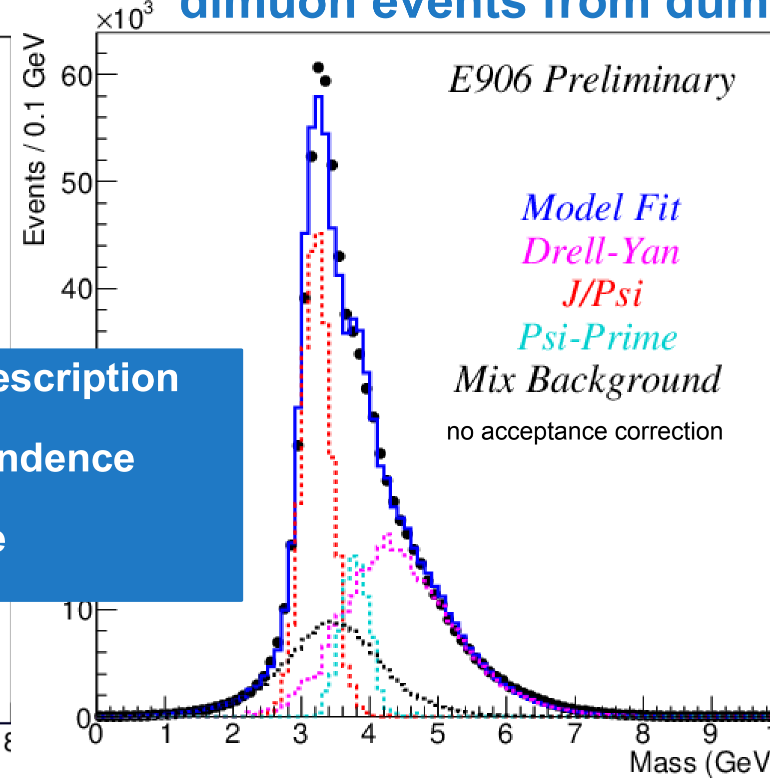
02/20	09/05	11/08 – *summer* of 2016
declared production running	fall shutdown	production running

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

dimuon events from target



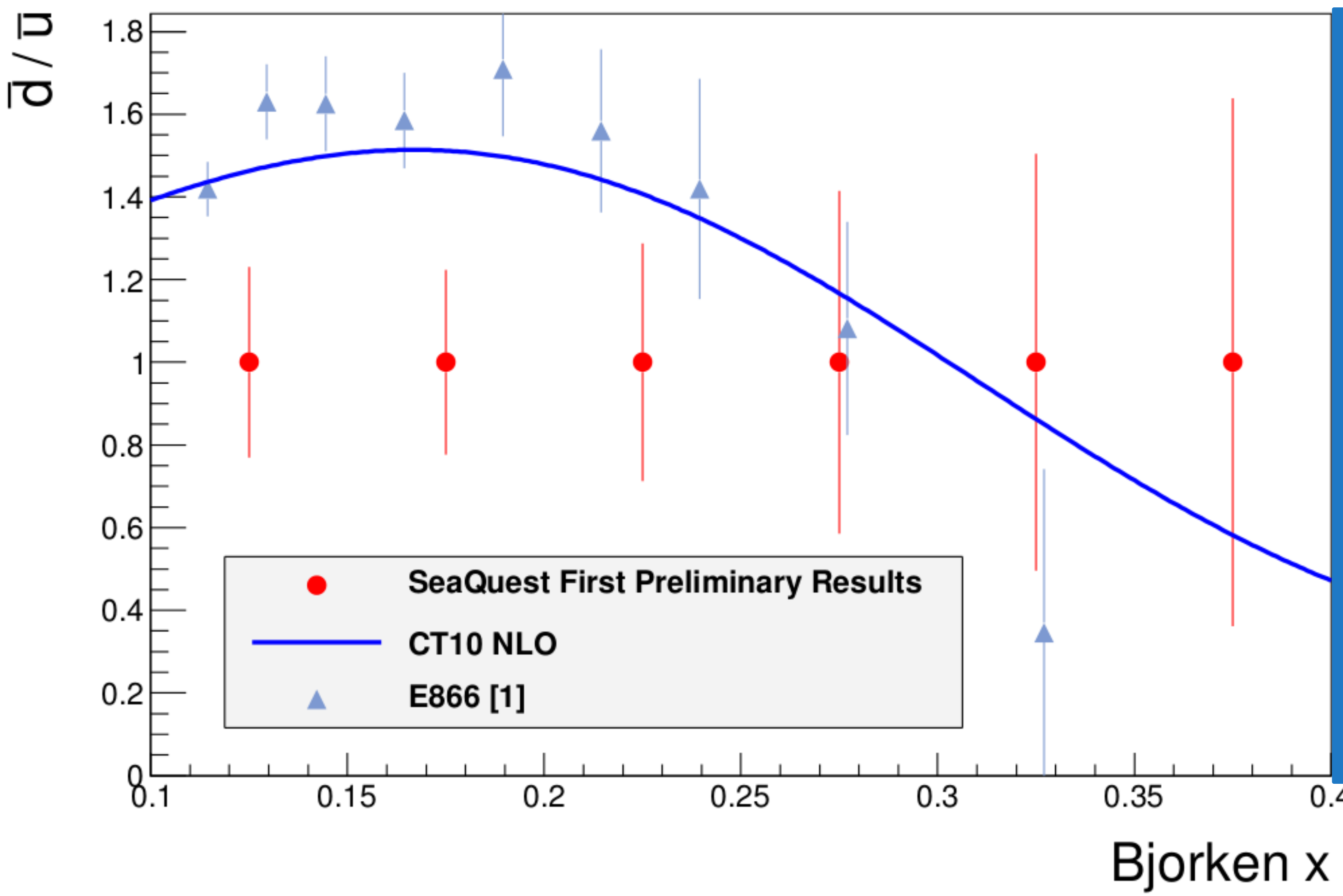
dimuon events from dump



reasonable MC description of the mass dependence of the acceptance

Upcoming results

•



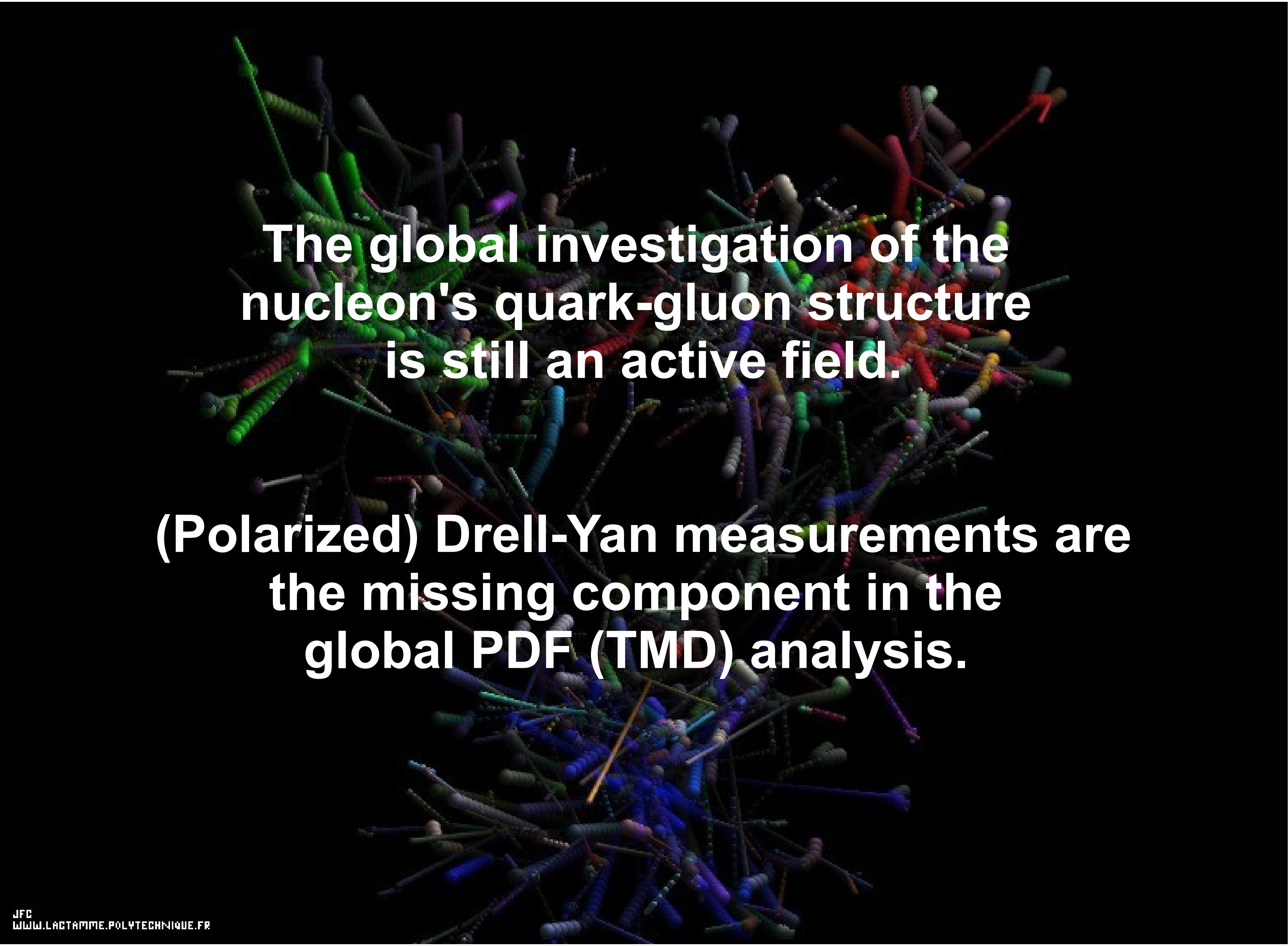
new front chamber will be installed in March and will increase physics reach to x < 0.45

5% of total luminosity

assuming 2 years of running at current luminosity

The global investigation of the nucleon's quark-gluon structure is still an active field.

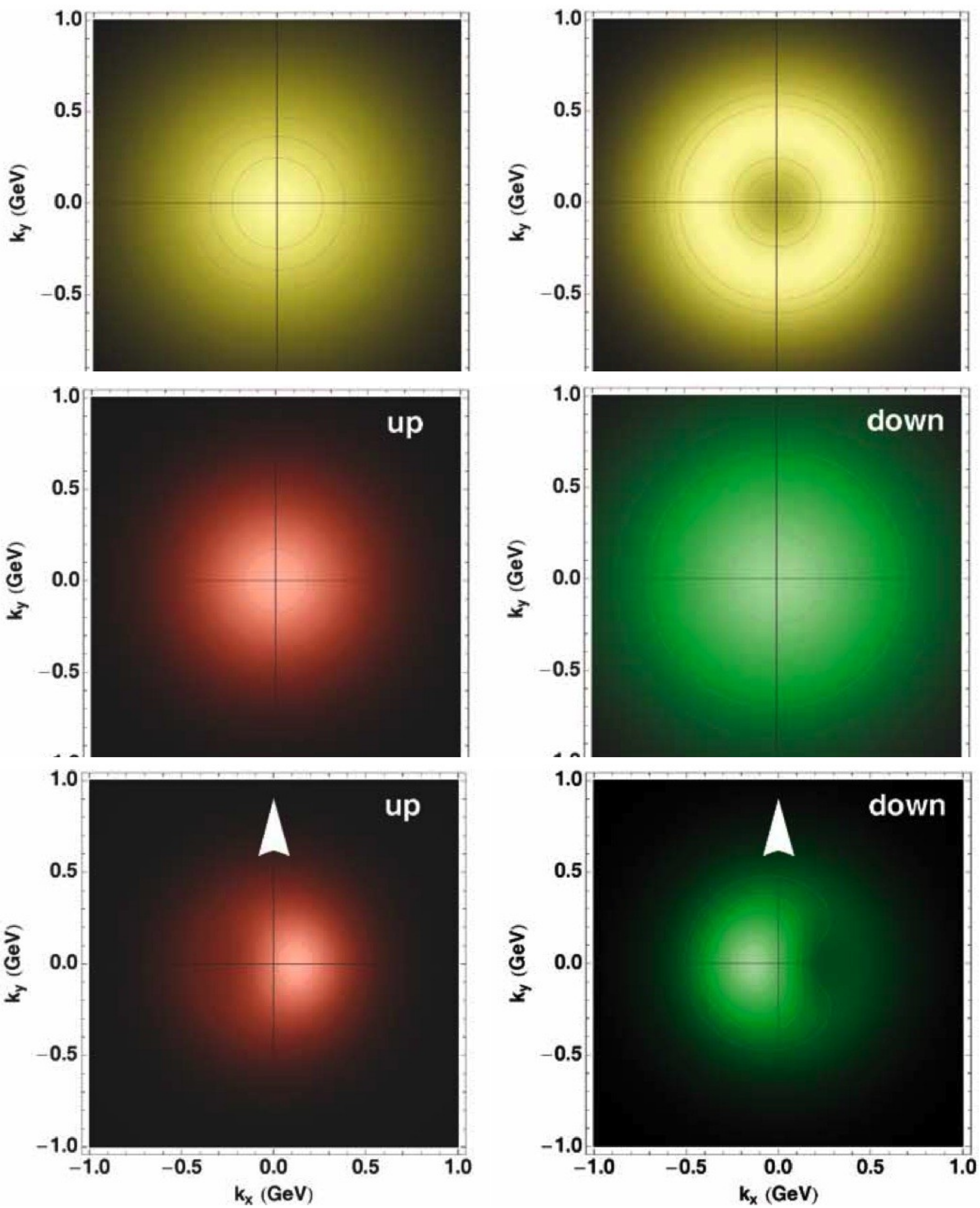
(Polarized) Drell-Yan measurements are the missing component in the global PDF (TMD) analysis.



Images of the nucleon

- **partons within the nucleon:**
  - three position coordinates
  - three momentum coordinates
  - hard probe → longitudinal direction → transverse plane
- their state can be described by **Wigner distributions:**
  - quantum phase space distribution
  - quasi-probability density (uncertainty principle, not positive definite)
  - equivalent to **parton's complete wave function**
- **projections of Wigner distributions: PDF, TMD, GPD** have probabilistic interpretation

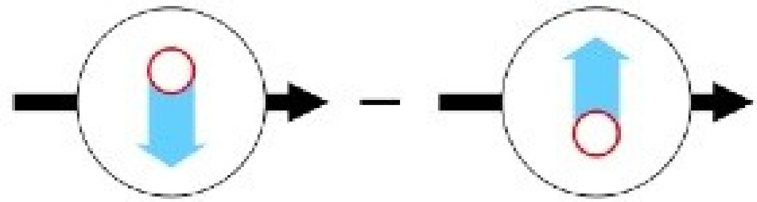
Transverse-momentum dependent PDFs (TMDs)



- **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:

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

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

↔ initial state interactions in Drell-Yan process

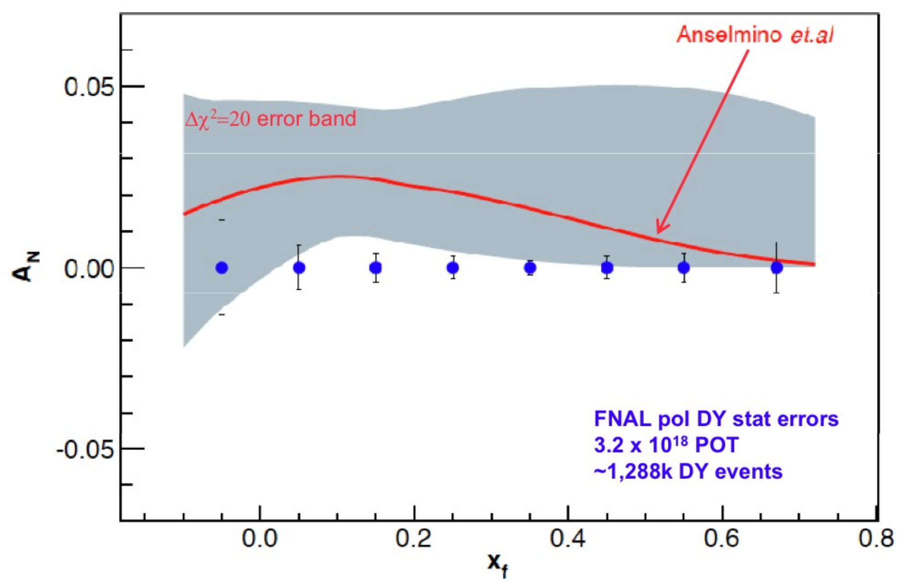
→ single-spin asymmetries:

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

- close relationship to quark orbital angular momentum
- challenging the concept of factorization and universality
  - fundamental prediction: $f_{1T}^{\perp,\mathrm{DIS}} = -f_{1T}^{\perp,\mathrm{DY}}$
  - remains to be experimentally tested
  - polarized Drell-Yan measurement required

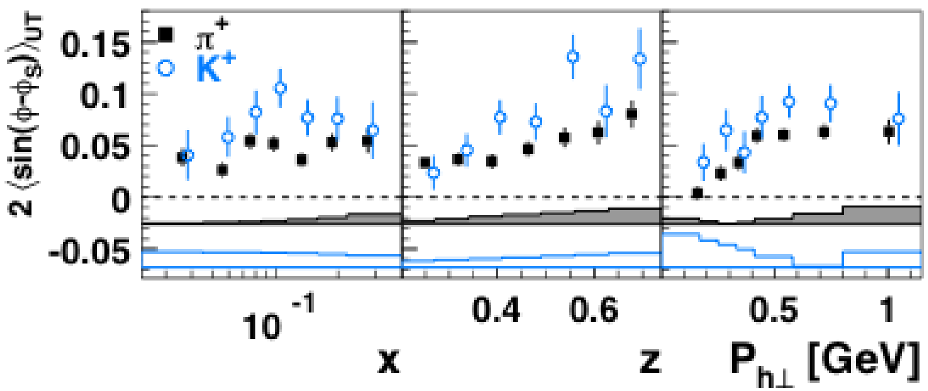
Reestablishing spin at Fermilab

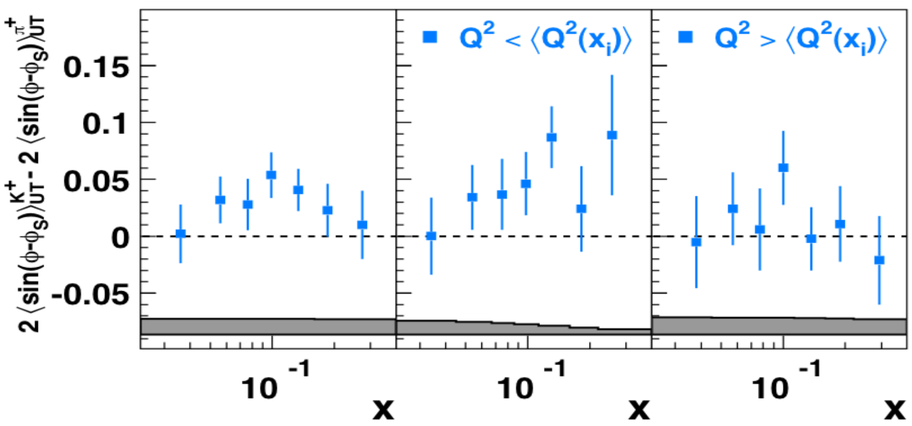
- **E-1039: SeaQuest with polarized target (approved)**
  - sensitive to Sivers TMD for sea quarks
  - hint for substantial role of sea quark Sivers effect in SIDIS data
  - LANL will provide polarized proton (NH3) target by 2015
- **E-1027: SeaQuest with polarized beam (approved)**
  - sensitive to beam valence quarks at high-x
  - large effects → sign, size, and mayhe shape of Sivers TMD

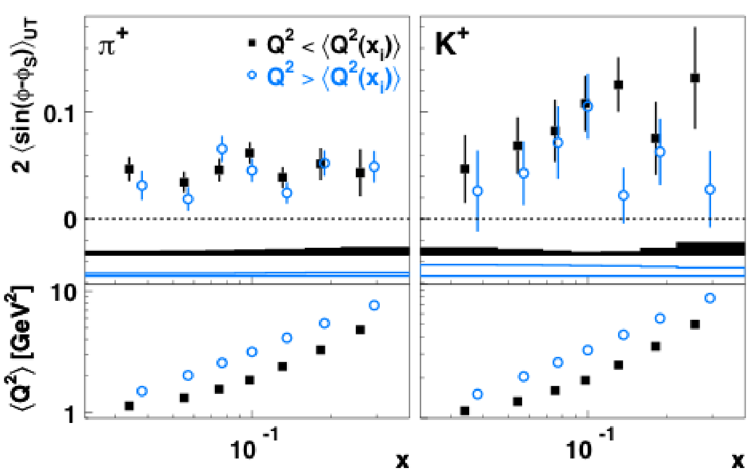


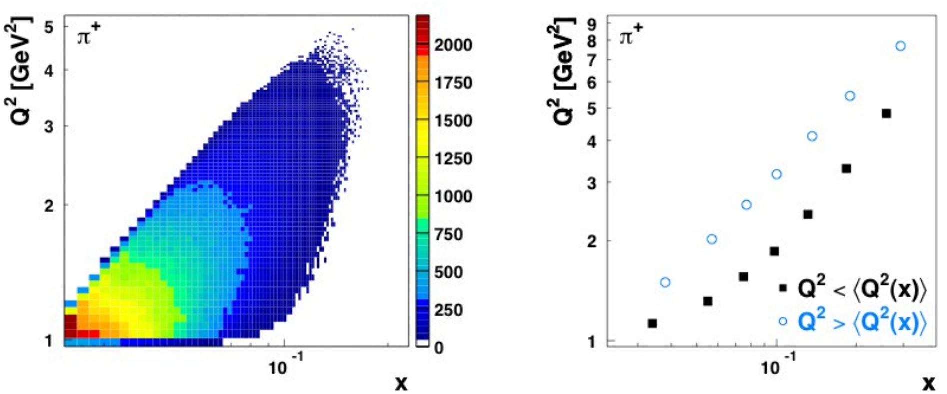
The Sivers TMD for sea quarks

HERMES measurement: $$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} \propto \ldots + S_T\left[\sin(\phi-\phi_S)\left(F_{\mathrm{UT,T}}^{\sin(\phi-\phi_S)} + \varepsilon F_{\mathrm{UT,L}}^{\sin(\phi-\phi_S)}\right) + \ldots\right] + \ldots$$









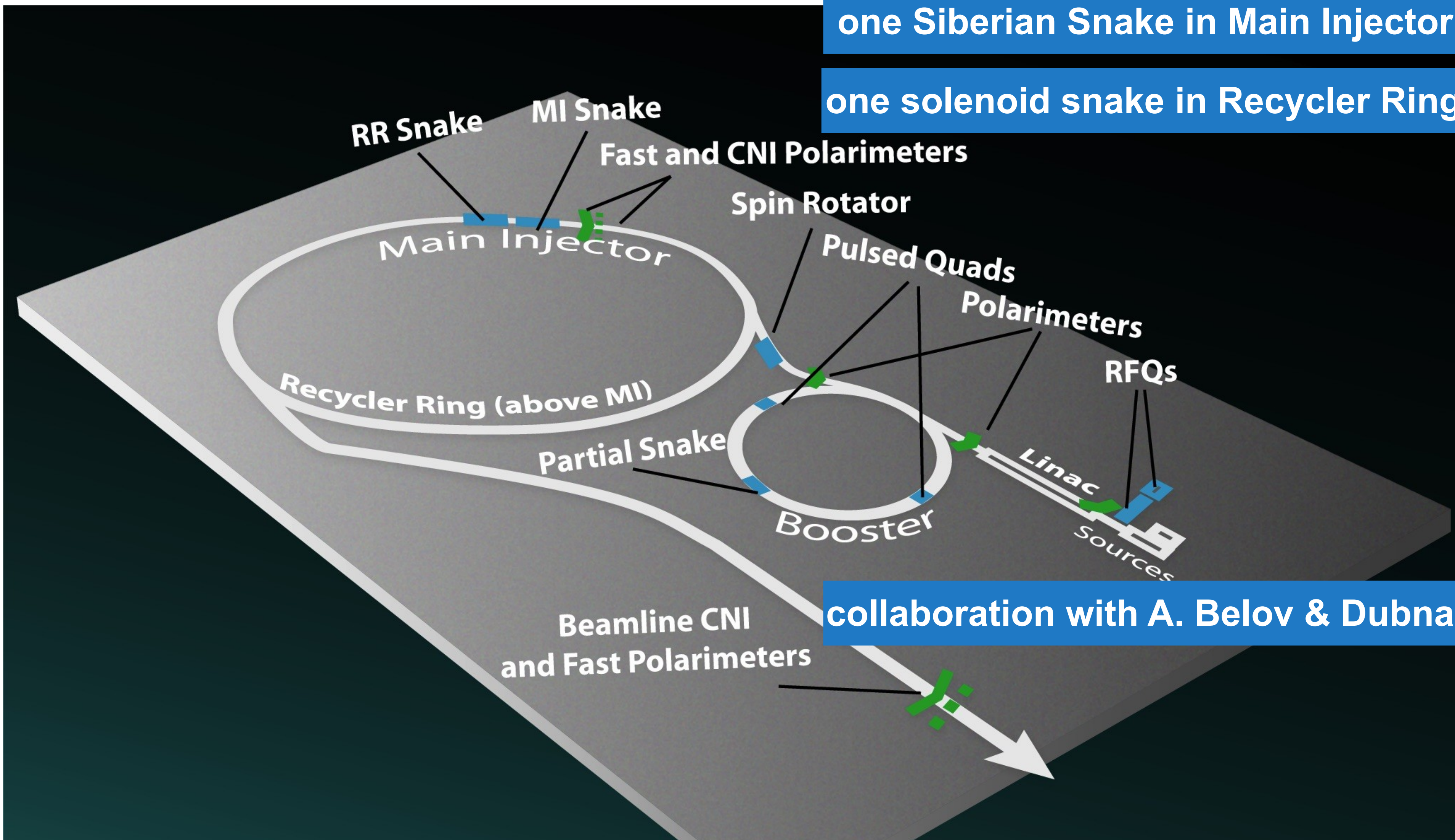
The polarized beam project

cost estimate: 10 million USD

design by SPIN@Fermi collaboration

one Siberian Snake in Main Injector

one solenoid snake in Recycler Ring



collaboration with A. Belov & Dubna

Polarized Drell-Yan experiments

	beam type	polarization beam	polarization target	favored quarks	physics goals: Sivers TMD sign change	Sivers TMD size	Sivers TMD shape	L_{sea}
COMPASS	π^-	✗	✓	valence	✓	✗	✗	✗
E-1039	proton	✗	✓	sea	✗	✓	✓	✓
E-1027	proton	✓	✗	valence	✓	✓	✓	✗
Beyond	proton	✓	✓	valence + sea	helicity, transversity, and other TMDs			

Planned Drell-Yan experiments

Experiment	Particles	Energy (GeV)	x_b or x_t	Luminosity ($cm^{-2} s^{-1}$)	$A_T^{\sin\phi_S}$	P_b or P_t (f)	rFOM#	Timeline
COMPASS (CERN)	$\pi^\pm + p^\uparrow$	160 GeV $\sqrt{s}$ = 17	x_t = 0.2 – 0.3	2 x 10^{33}	0.14	P_t = 90% f = 0.22	1.1 x 10^{-3}	2014, 2018
PANDA (GSI)	$\bar{p} + p^\uparrow$	15 GeV $\sqrt{s}$ = 5.5	x_t = 0.2 – 0.4	2 x 10^{32}	0.07	P_t = 90% f = 0.22	1.1 x 10^{-4}	>2018
PAX (GSI)	$p^\uparrow + \bar{p}$	collider $\sqrt{s}$ = 14	x_b = 0.1 – 0.9	2 x 10^{30}	0.06	P_b = 90%	2.3 x 10^{-5}	>2020?
NICA (JINR)	$p^\uparrow + p$	collider $\sqrt{s}$ = 26	x_b = 0.1 – 0.8	1 x 10^{31}	0.04	P_b = 70%	6.8 x 10^{-5}	>2018
PHENIX (RHIC)	$p^\uparrow + p^\uparrow$	collider $\sqrt{s}$ = 500	x_b = 0.05 – 0.1	2 x 10^{32}	0.06	P_b = 60%	3.6 x 10^{-4}	>2018
SeaQuest (FNAL: E-906)	p + p	120 GeV $\sqrt{s}$ = 15	x_b = 0.35 – 0.9 x_t = 0.1 – 0.45	3.4 x 10^{35}	---	---	---	2012 - 2015
Pol tgt DY‡ (FNAL: E-1039)	$p + p^\uparrow$	120 GeV $\sqrt{s}$ = 15	x_t = 0.1 – 0.45	4.4 x 10^{35}	0 – 0.2*	P_t = 88% f = 0.176	0.15	2016
Pol beam DY§ (FNAL: E-1027)	$p^\uparrow + p$	120 GeV $\sqrt{s}$ = 15	x_b = 0.35 – 0.9	2 x 10^{35}	0.04	P_b = 60%	1	2018

‡ 8 cm NH_3 target *§ L= 1 x 10^{36} $cm^{-2} s^{-1}$ (LH_2 tgt limited) / L= 2 x 10^{35} $cm^{-2} s^{-1}$ (10% of MI beam limited)*

**not constrained by SIDIS data* / # rFOM = relative lumi * P^2 * f^2 wrt E-1027 (f=1 for pol p beams)

W. Lorenzon (U-Michigan) 8/15/2014

The SeaQuest mission

unique laboratory for sea quarks at high-x

→ structure of nucleons and nucleonic matter

physics running started on February 20th

→ preliminary physics results expected soon

exciting extensions possible

→ polarized Drell-Yan measurements

→ missing piece in the global spin program

→ unique opportunity for Fermilab