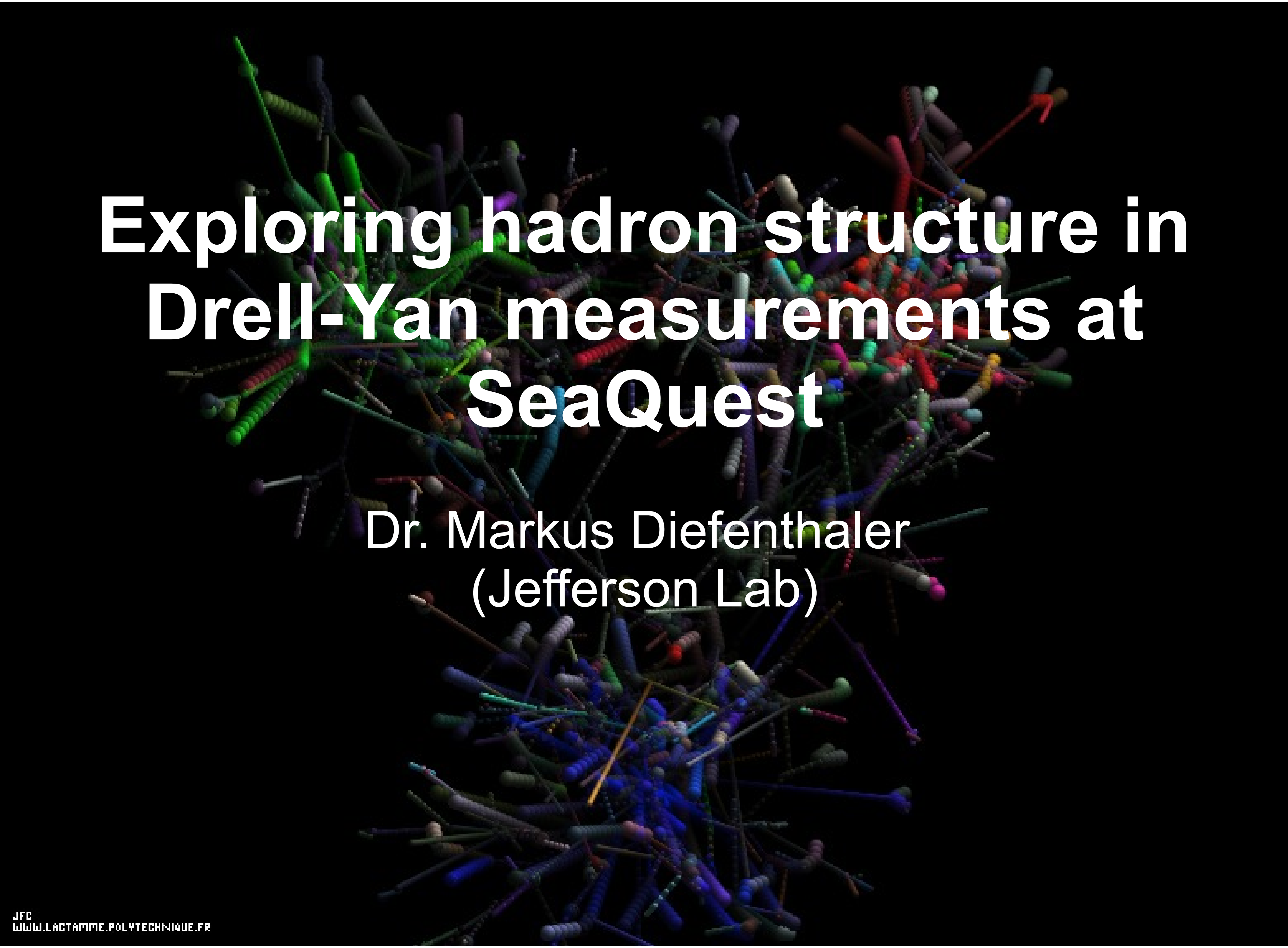
Exploring hadron structure in Drell-Yan measurements at SeaQuest

Dr. Markus Diefenthaler
(Jefferson Lab)



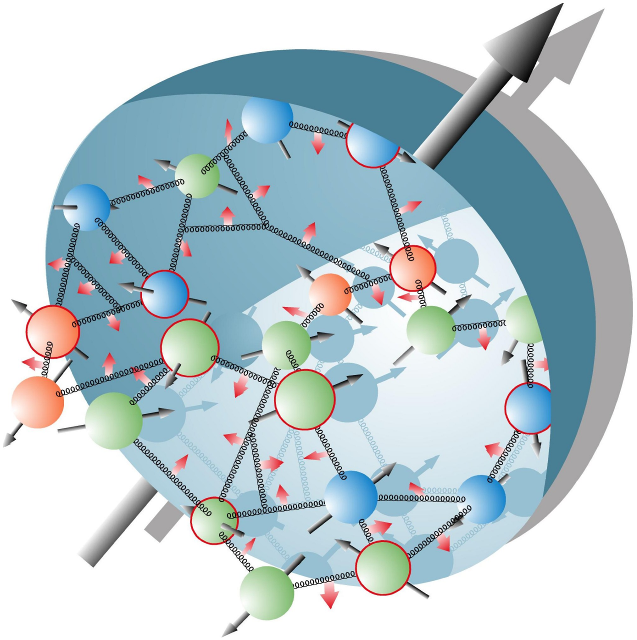
The SeaQuest collaboration

- **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, Shiu Shiuan-Hao
- **Argonne National Laboratory**: John Arrington, Donald F. Geesaman (co-spokesperson), Roy Holt, Michelle Mesquita de Medeiros, Bardia Nadim, Harold Jackson, Paul E. Reimer (co-spokesperson)
- **University of Colorado**: Ed(ward) Kinney, Po-Ju Lin
- **Fermi National Accelerator Laboratory**: Chuck Brown, Dave Christian, Su-Yin Wang, Jin-Yuan Wu
- **University of Illinois**: Bryan Dannowitz, Markus Diefenthaler (now at Jefferson Lab), 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
- **University of Michigan**: Christine Aidala, McKenzie Barber, Catherine Culkin, Wolfgang Lorenzon, Bryan Ramson, Richard Raymond, Josh(ua) Rubin, Matthew Wood
- **Mississippi State University**: Lamiaa El Fassi
- **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, Shigeki Obata, Toshi-Aki Shibata
- **Yamagata University**: Yuya Kudo, Yoshiyuki Miyachi, Shumpei Nara

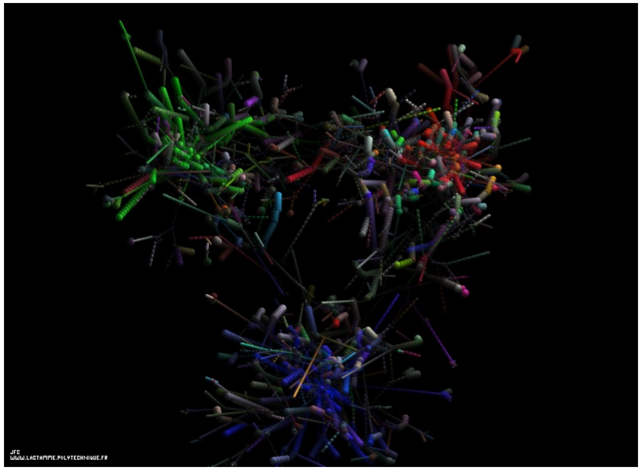
The inner structure of the nucleon

bound state of the strong interaction

relativistic quarks that exchange gluons



gluons radiate off gluons or quark antiquark pairs



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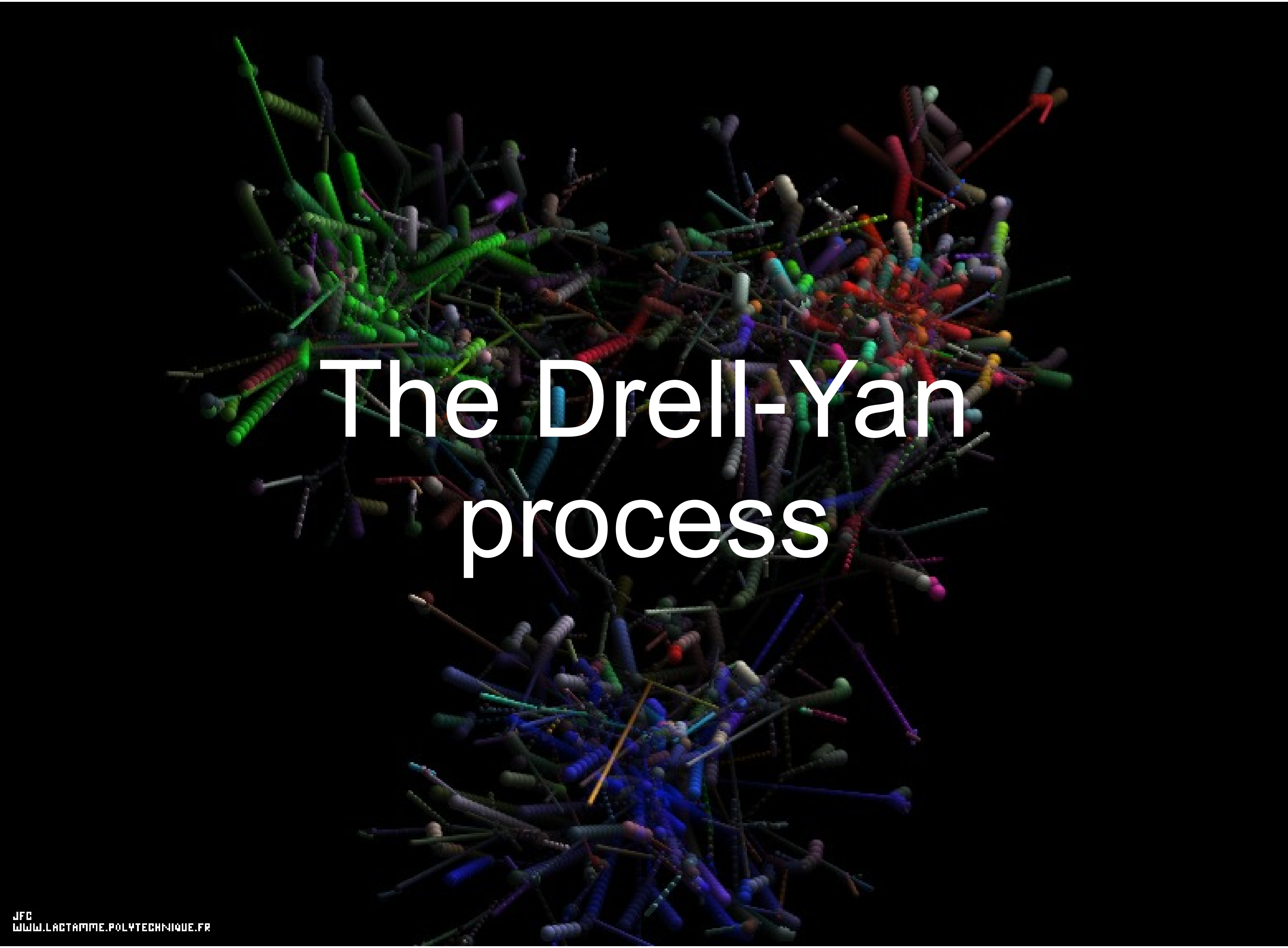
experimental investigation in Drell-Yan

unique sensitivity to antiquarks

SeaQuest – Drell-Yan experiment at FNAL



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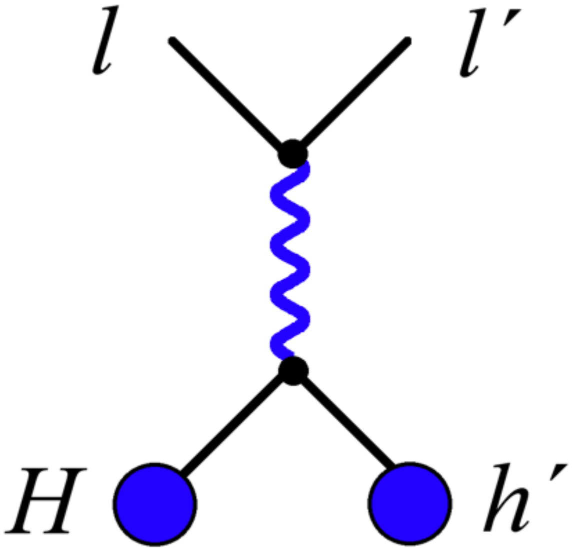
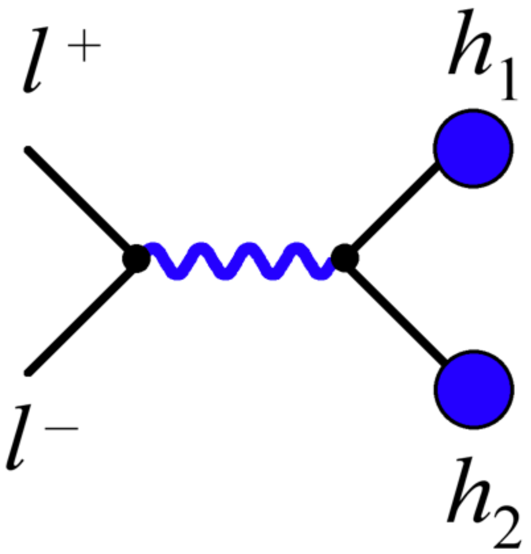
The Drell-Yan process

Fundamental (electro-weak) processes

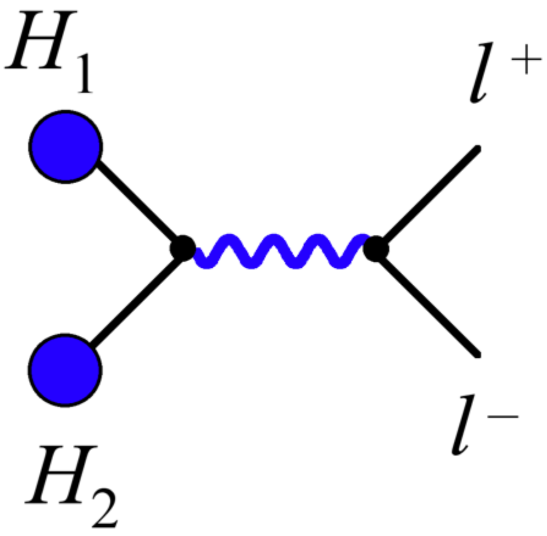
semi-inclusive DIS



e+e- annihilation



Drell-Yan

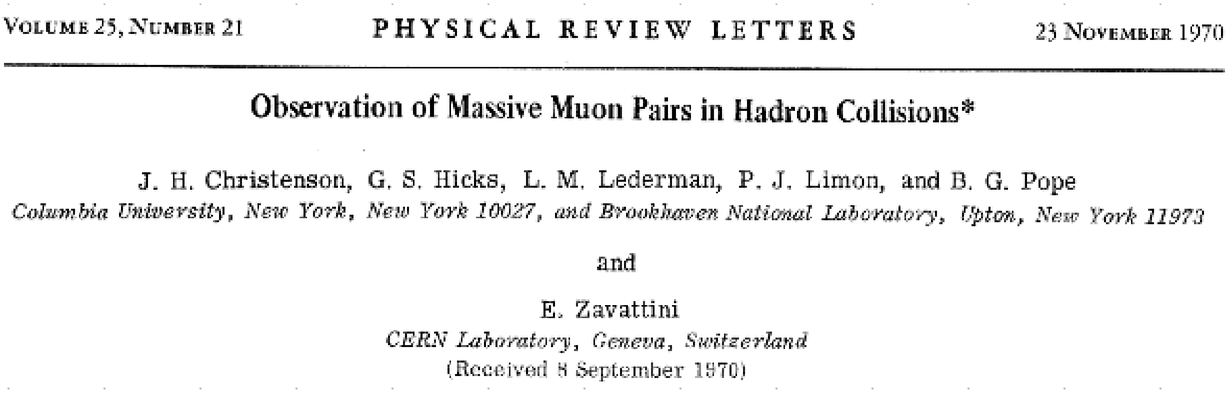


QCD factorization theorem

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

- 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

The Drell-Yan process



VOLUME 25, NUMBER 21 PHYSICAL REVIEW LETTERS 23 NOVEMBER 1970

Observation of Massive Muon Pairs in Hadron Collisions*

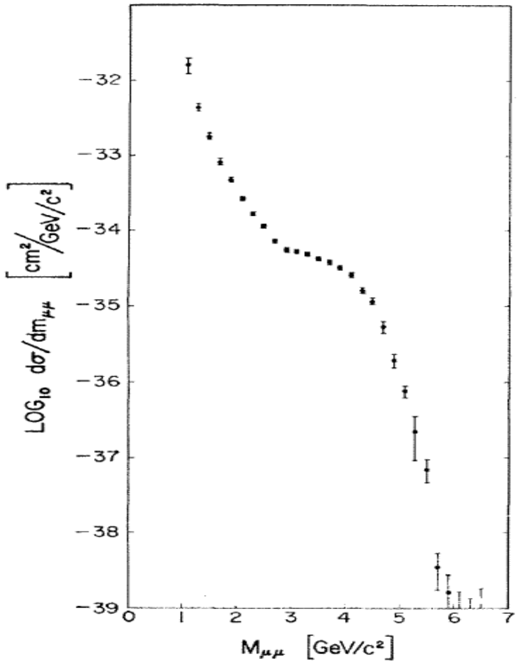
J. H. Christenson, G. S. Hicks, L. M. Lederman, P. J. Limon, and B. G. Pope
Columbia University, New York, New York 10027, and Brookhaven National Laboratory, Upton, New York 11973

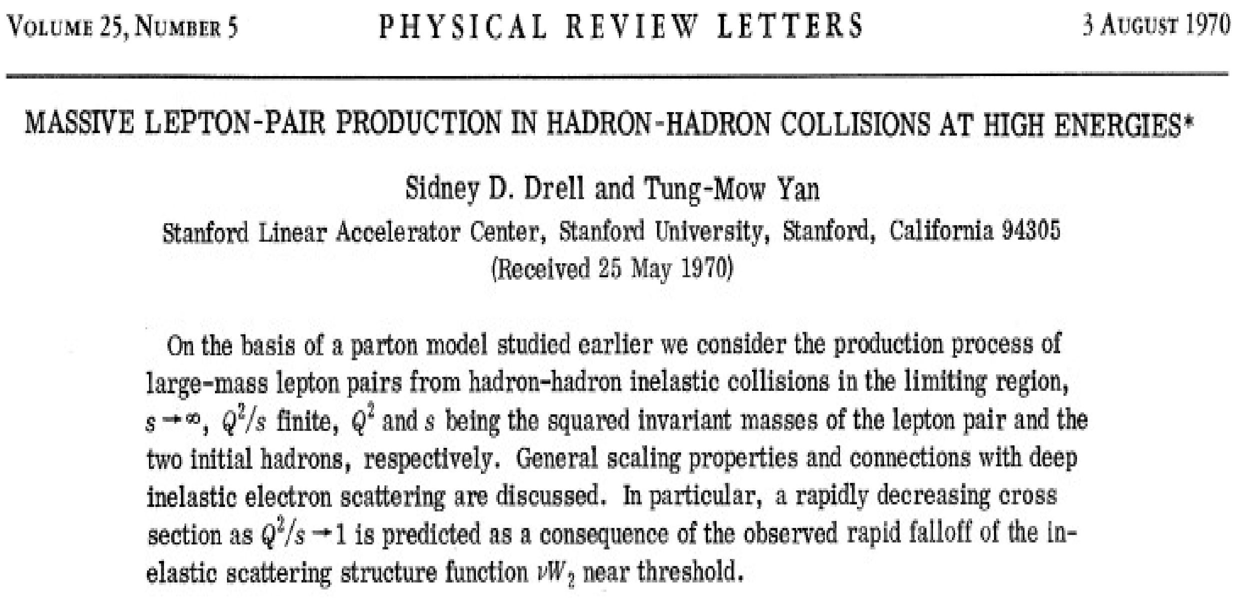
and

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.





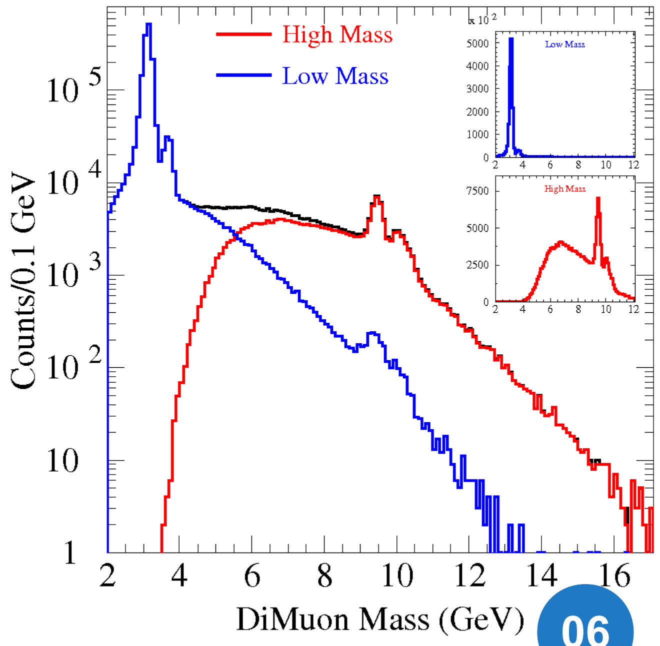
VOLUME 25, NUMBER 5 PHYSICAL REVIEW LETTERS 3 AUGUST 1970

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

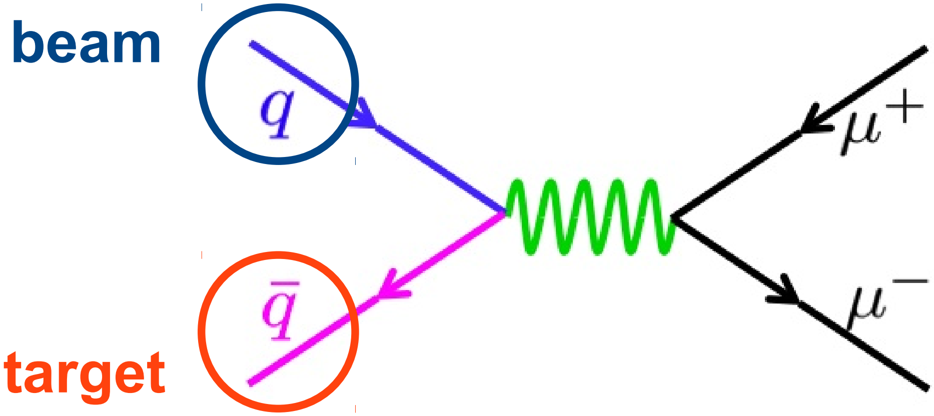
(Received 25 May 1970)

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.



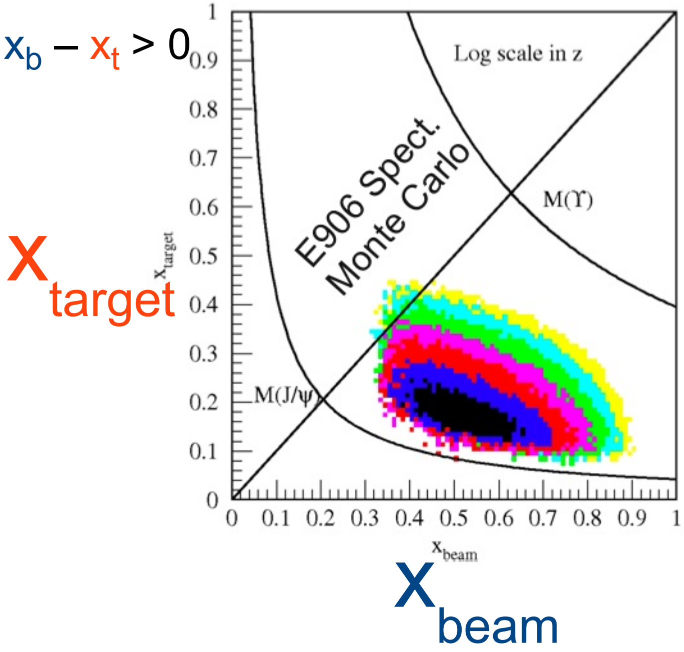
A laboratory for sea quarks

The Drell-Yan process

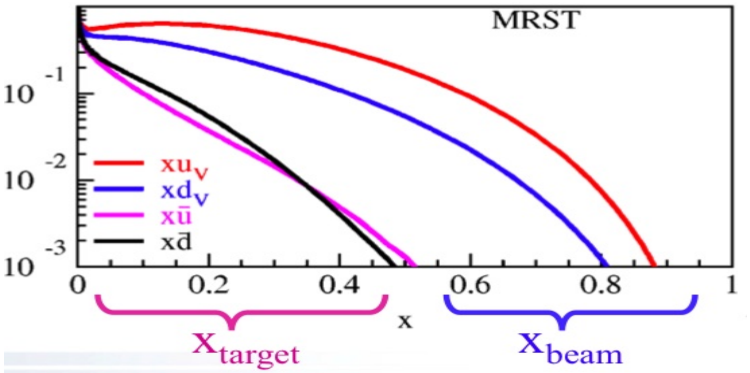


fixed target + forward spectrometer

→ $x_F = x_b - x_t > 0$



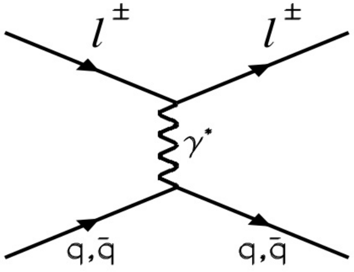
$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x_{\mathrm{b}}\,\mathrm{d}x_{\mathrm{t}}} = \frac{4\pi\alpha^2}{9x_{\mathrm{b}}\,x_{\mathrm{t}}}\frac{1}{s}\sum_q e_q^2\left[\bar{q}_{\mathrm{t}}(x_{\mathrm{t}})q_{\mathrm{b}}(x_{\mathrm{b}}) + q_{\mathrm{t}}(x_{\mathrm{t}})\bar{q}_{\mathrm{b}}(x_{\mathrm{b}})\right]$$

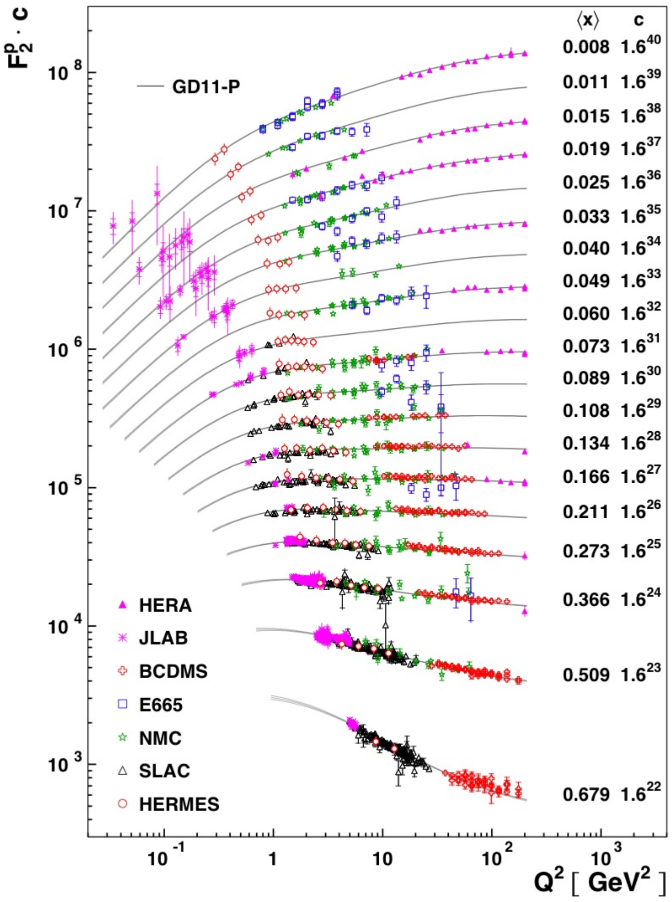


beam: valence quarks at high-x
target: sea quarks at intermediate-x

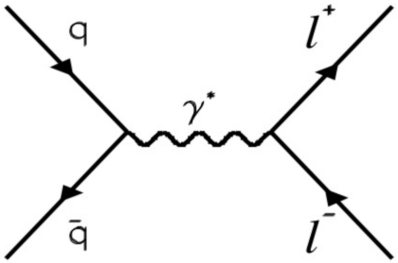
Complementary processes

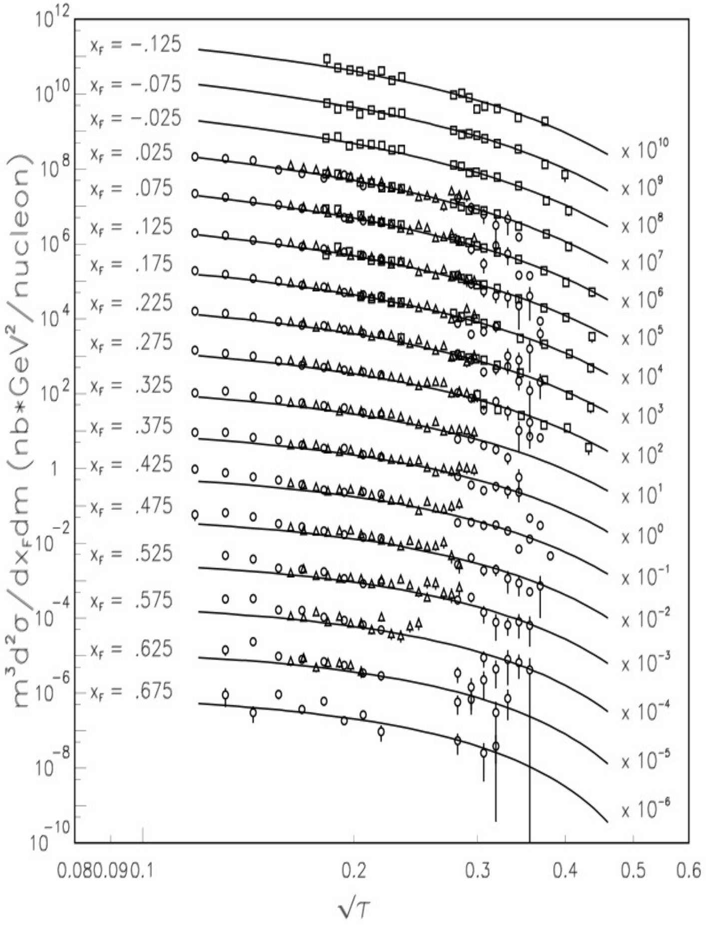
Deep-inelastic scattering

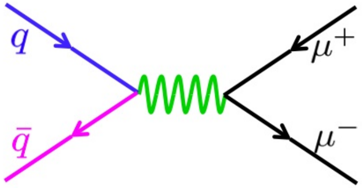




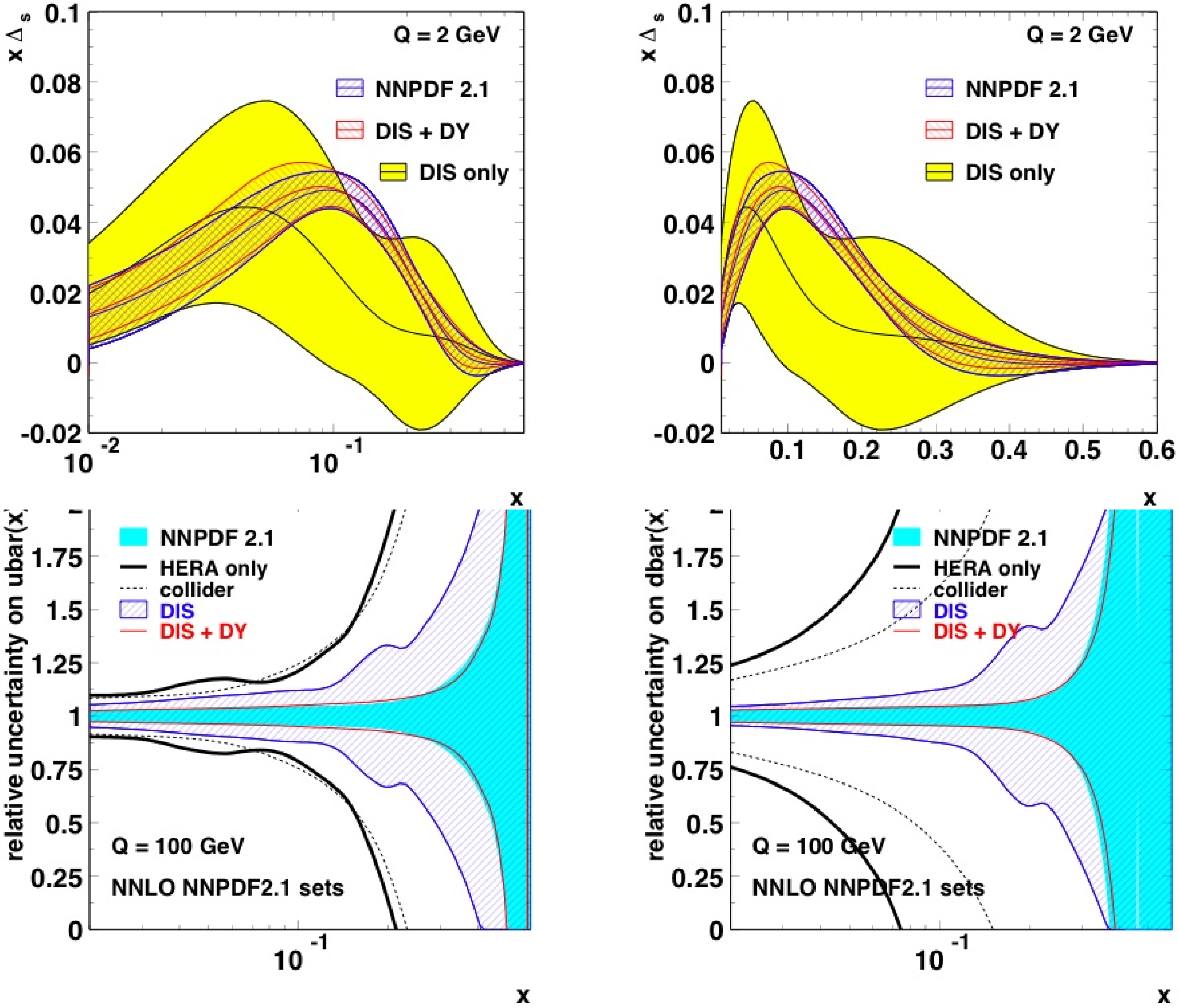
Drell-Yan scattering

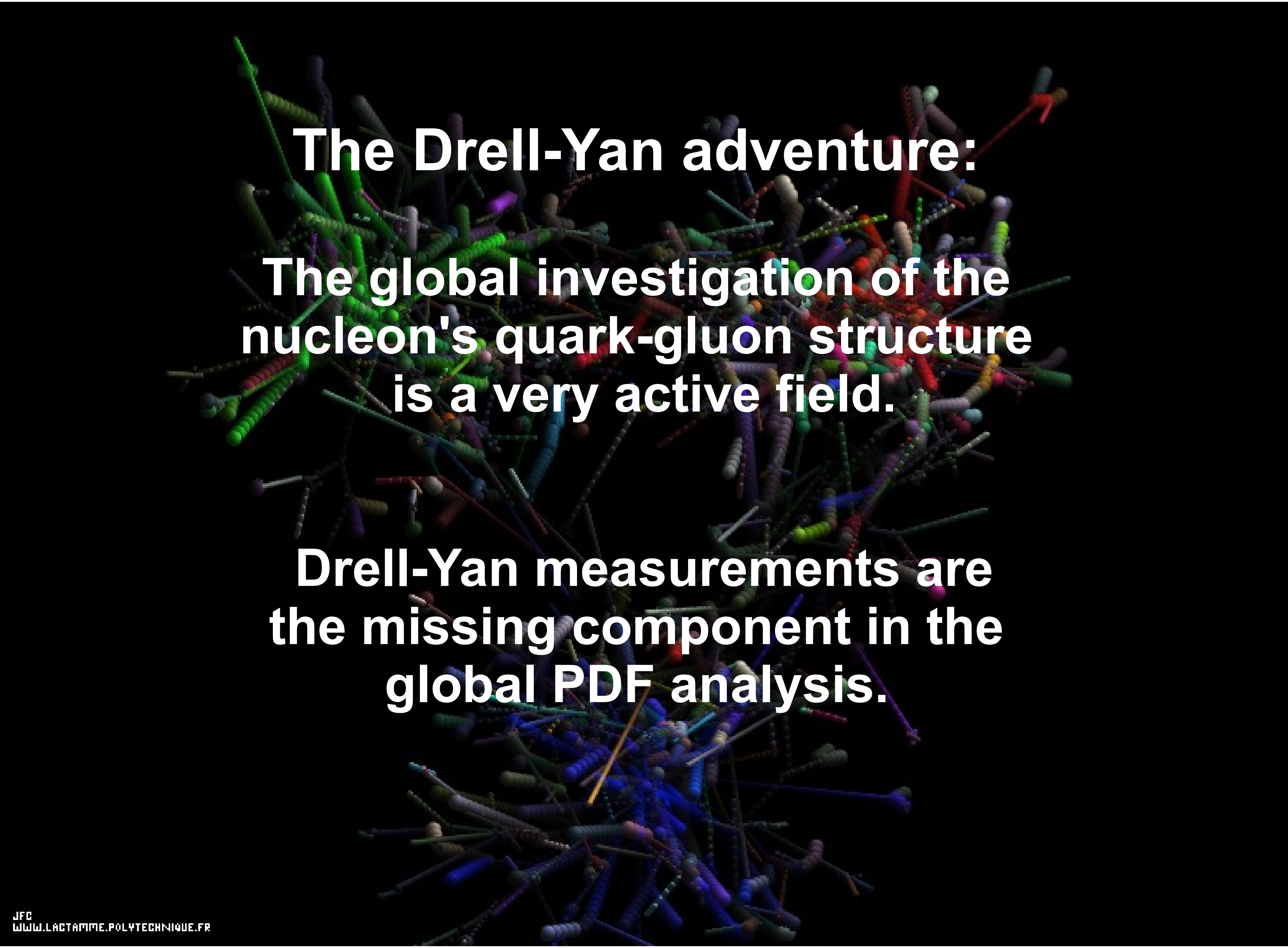






: unique sensitivity to sea quarks





The Drell-Yan adventure:

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

Drell-Yan measurements are the missing component in the global PDF analysis.

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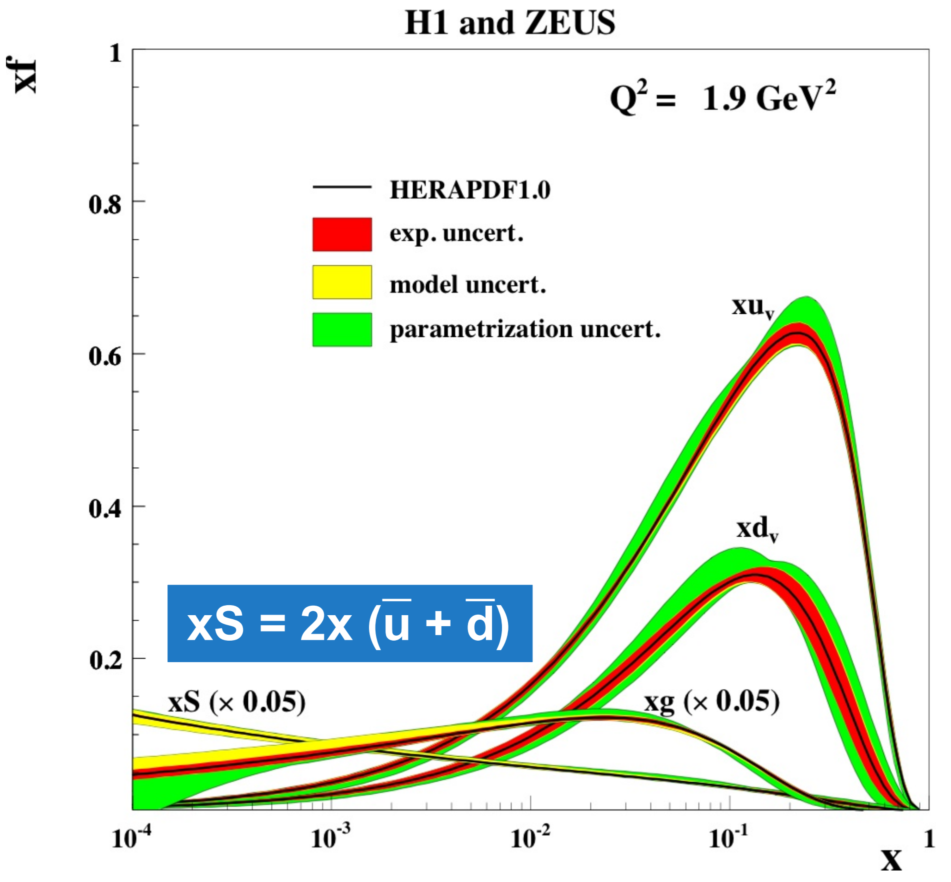
The nucleon sea



$xS = 2x(\bar{u} + \bar{d})$

valence quark distributions not flavor symmetric

- **atomic physics**: relatively minor role of particle-antiparticle pairs
- **hadronic physics**:
  - large strong coupling strength α_S
  - **quark-antiquark pairs** are readily produced in strong interactions
  - **integral part of nucleon's structure**
- **first evidence for nucleon sea**: structure functions continue to rise as $x \rightarrow 0$
- assumptions in earliest parton models:
  - proton sea assumed to be SU(3) flavor symmetric
  - comparable masses for u and d
  - nearly up-down flavor symmetric nucleon sea

Seminal result by NMC

- **Gottfried integral I_G in DIS**:

$$I_G = \int_0^1 \left[F_2^p(x) - F_2^n(x)\right]/x\, dx = \frac{1}{3} + \frac{2}{3}\int_0^1 \left[\bar{u}_p(x) - \bar{d}_p(x)\right] dx,$$

$$\bar{d}(x) = \bar{u}(x) \rightarrow I_G = ⅓$$

- derived assuming charge symmetry (CS) at the partonic level:

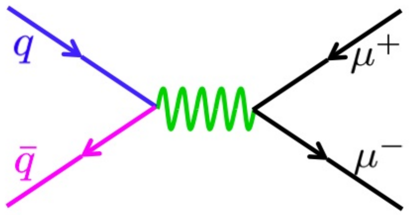
$$u_p(x) = d_n(x),\ \bar{u}_p(x) = \bar{d}_n(x),\ d_p(x) = u_n(x),\ \bar{d}_p(x) = \bar{u}_n(x)$$

- **New Muon Collaboration (NMC)** at CERN:

$$I_G = 0.235 \pm 0.026 < ⅓$$

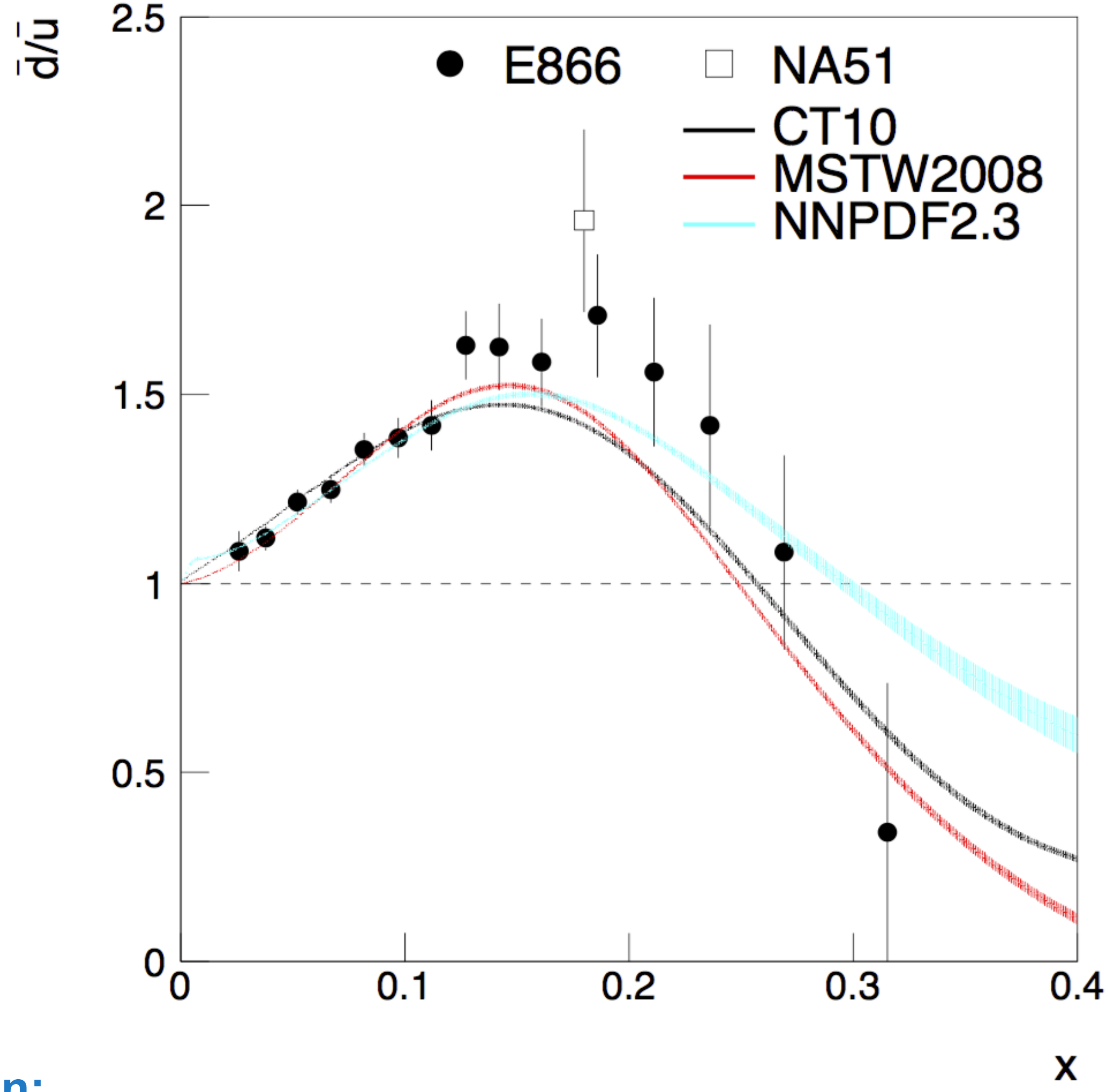
- Possible interpretation from the NMC result:
  - unusual behavior of the parton distributions at unmeasured small x region
  - violation of CS at partonic level
  - **$\bar{d}(x) \neq \bar{u}(x)$**

Experimental evidence for $\bar{d}(x) \neq \bar{u}(x)$



NA51 at CERN:
450 GeV proton beams

E866 at FNAL:
800 GeV proton beams



forward rapidity region:

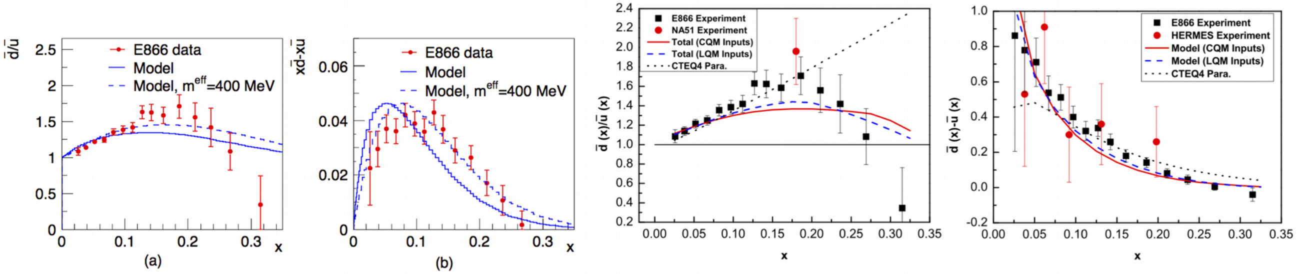
$$\left.\frac{\sigma^{pd\to\mu^+\mu^-}}{\sigma^{pp\to\mu^+\mu^-}}\right|_{x_b \gg x_t} \approx \frac{1}{2}\left[1+\frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right]$$

Implications of $\bar{d}(x)$ / $\bar{u}(x)$ asymmetry

- many theoretical models have been proposed to explain **$\bar{d}(x)$ / $\bar{u}(x)$ asymmetry**:

+ Pauli-blocking (however, too small)

+ instanton model

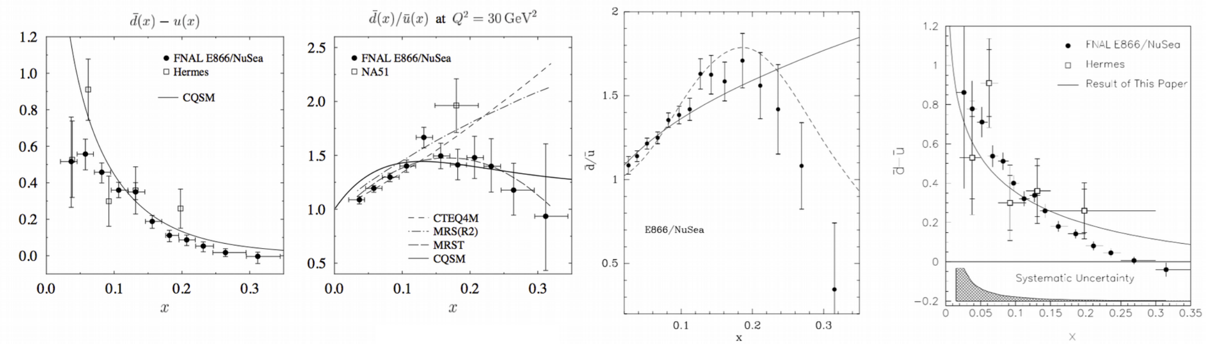


(a) Meson cloud model.

(b) Chiral quark model.

x < 0.25: successful explanation

x > 0.3: turn over (if confirmed) challenges model



(c) Chiral quark soliton model.

(d) Statistic model.

(e) Balance model.

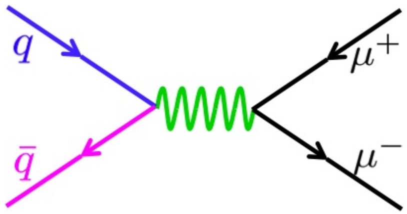
- most of these models emphasize the important contribution of **meson cloud** to nucleon's sea quark content:

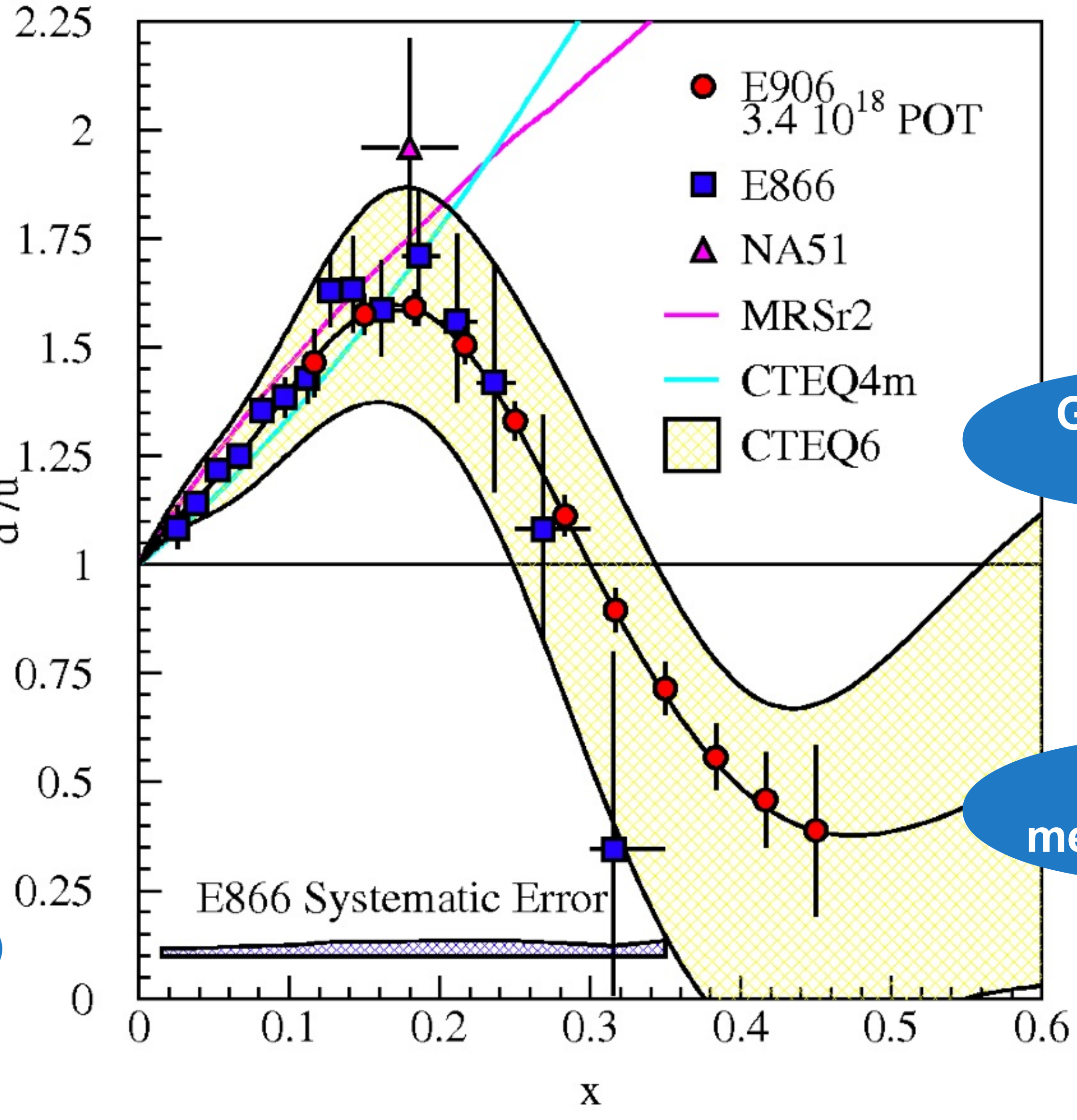
$$
\begin{aligned}
|p\rangle \;=\;& \sqrt{Z}\,|p_0\rangle + a_{N\pi/p}\,\Big[-\sqrt{\tfrac{1}{3}}|p_0\pi^0\rangle + \boxed{\sqrt{\tfrac{2}{3}}|n_0\pi^+\rangle}\Big] \\
&+ a_{\Delta\pi/p}\,\Big[\boxed{\sqrt{\tfrac{1}{2}}|\Delta_0^{++}\pi^-\rangle} - \sqrt{\tfrac{1}{3}}|\Delta_0^{+}\pi^0\rangle + \sqrt{\tfrac{1}{6}}|\Delta_0^{0}\pi^+\rangle\Big] \\
&+ a_{\Lambda K/p}\,|\Lambda_0 K^+\rangle + a_{\Sigma K/p}\,\Big[-\sqrt{\tfrac{1}{2}}|\Sigma_0^+ K^0\rangle + \sqrt{\tfrac{1}{2}}|\Sigma_0^0 K^+\rangle\Big] + \dots
\end{aligned}
$$

dominant configuration

less probable configuration

SeaQuest: $\bar{d}(x)/\bar{u}(x)$ at high x





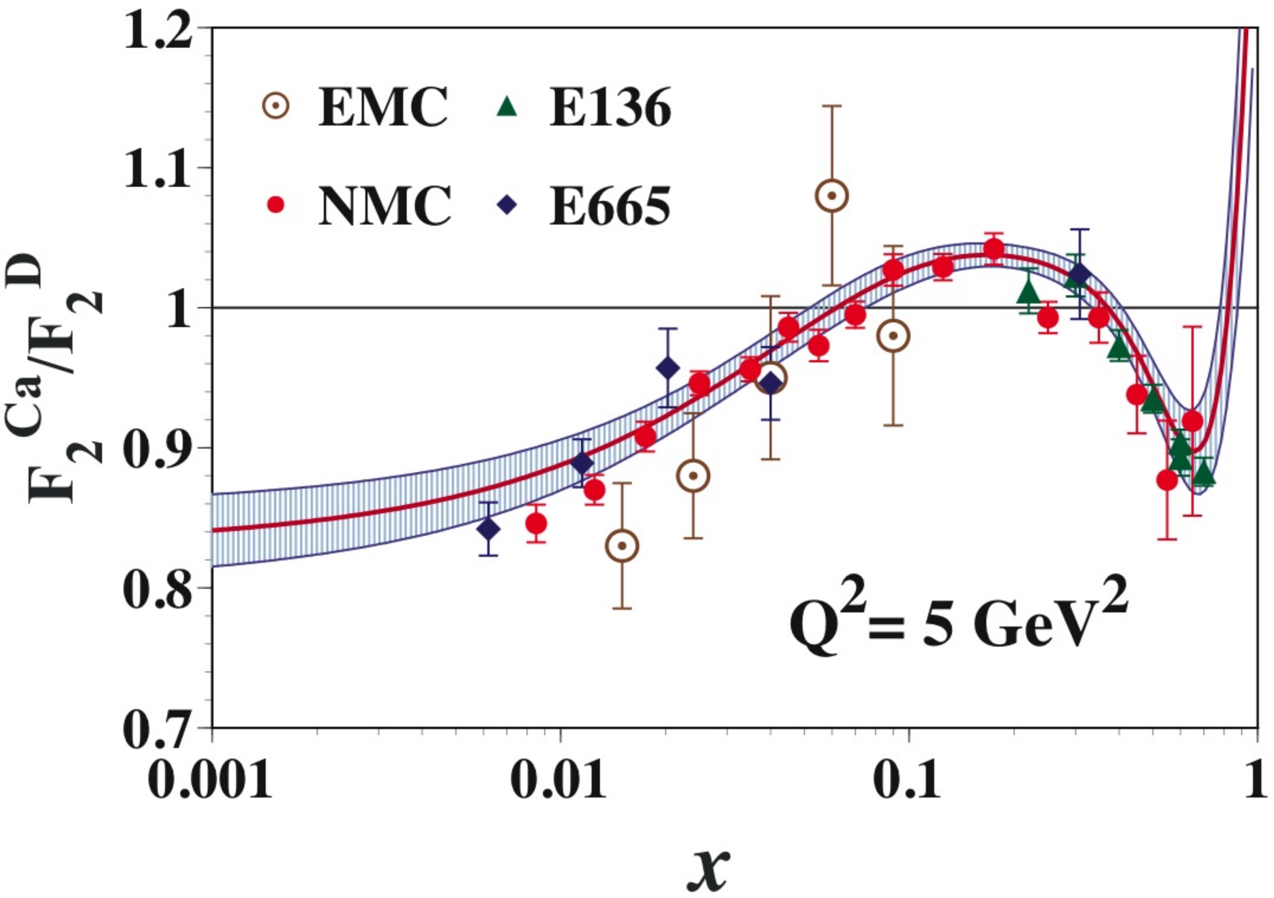
Global NLO PDF fit

extend measurement

SeaQuest: Syst. ~ 1%

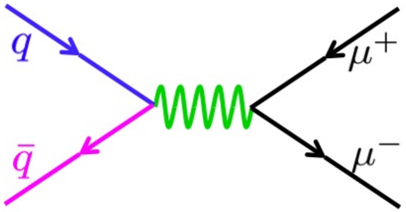
Nucleons embedded in nuclei

- Do nucleons change their internal properties when embedded in a nucleus? Is confinement influenced by the nuclear medium?

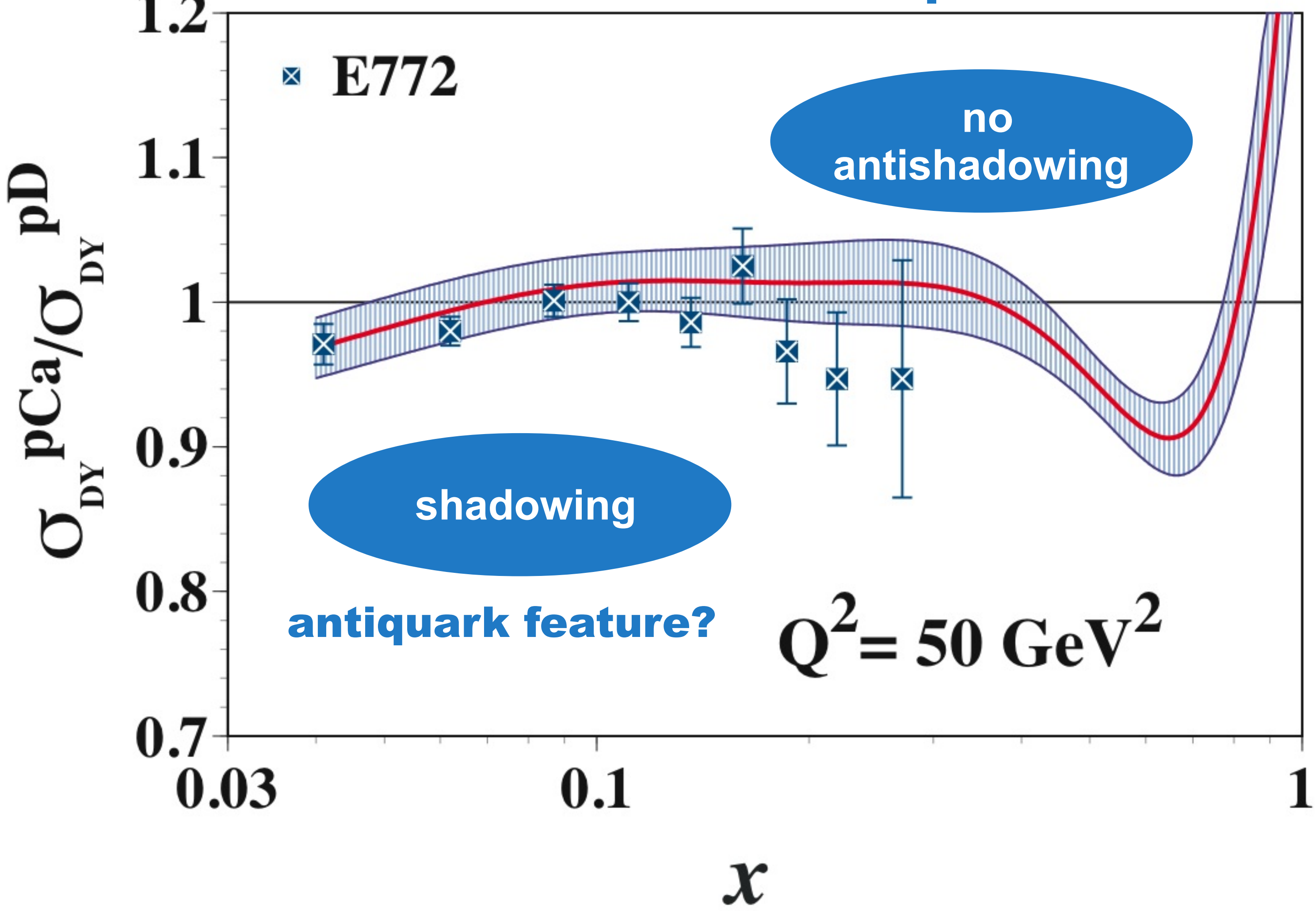


- Do quarks and gluons play any role in the understanding of nuclear forces?

Nuclear dependence in



valence quark effect?



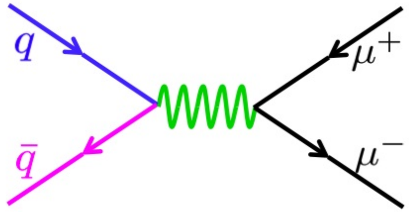
no antishadowing

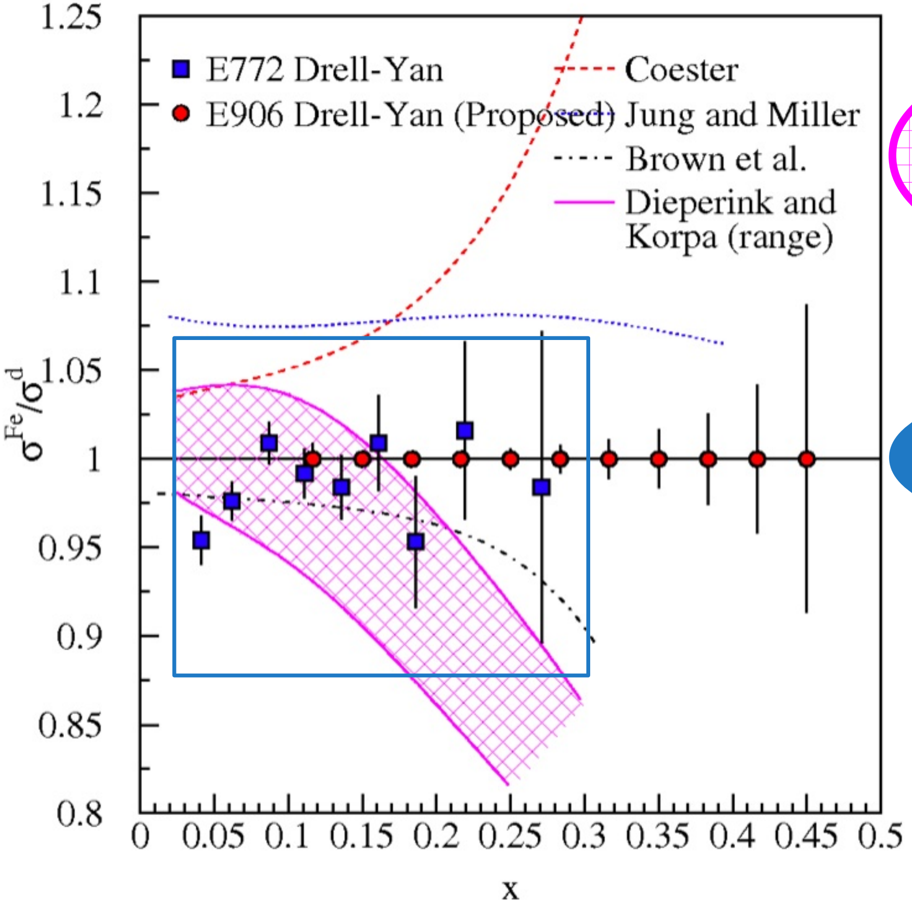
shadowing

antiquark feature?

The inner structure of a nucleus

- nuclear force mediated by meson exchange





large effects to antiquark PDF predicted as x increases

no antiquak enhancement

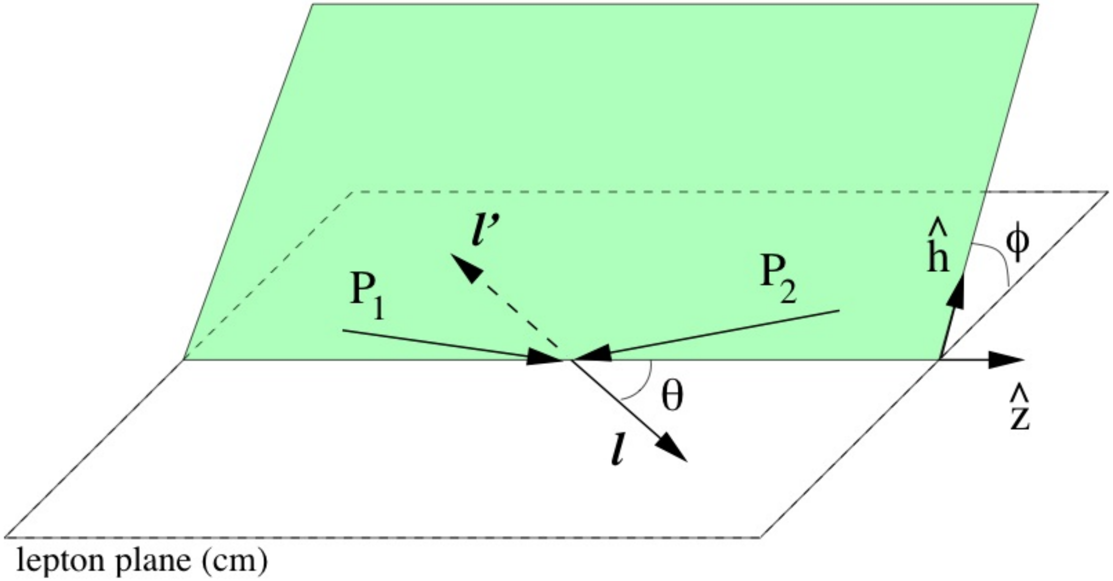
- **Where are the *nuclear* pions?**

The Lam-Tung relation

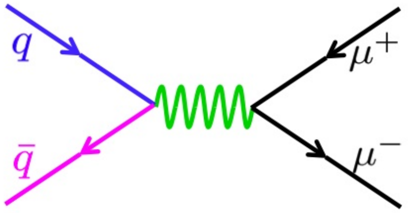
- **angular dependence** of the Drell-Yan cross-section:

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

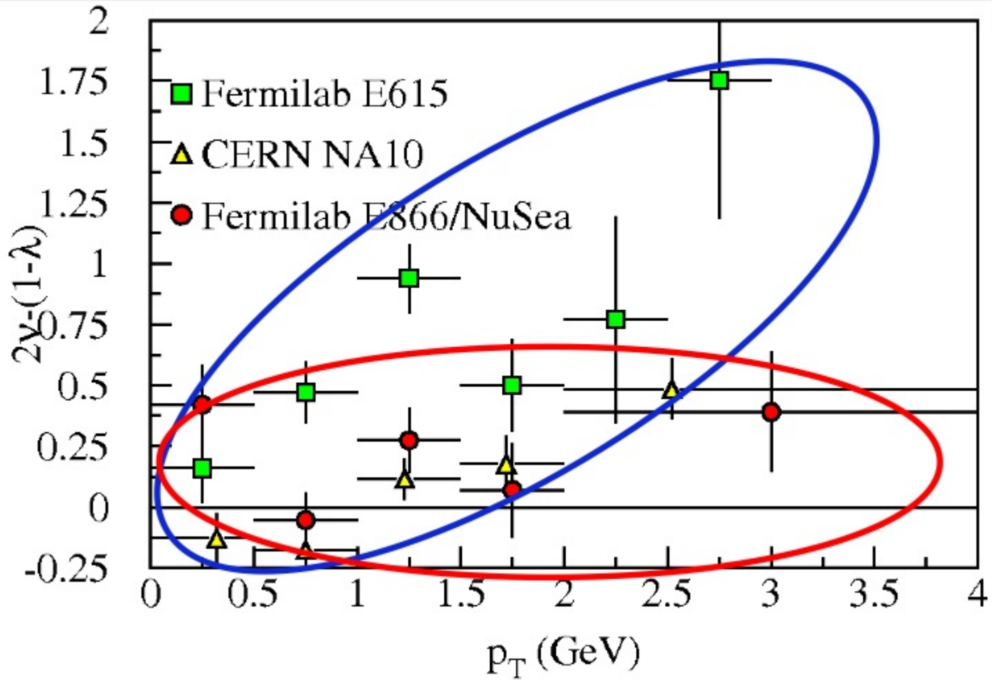
- **Lam-Tung relation**: $1 - \lambda = 2\nu$

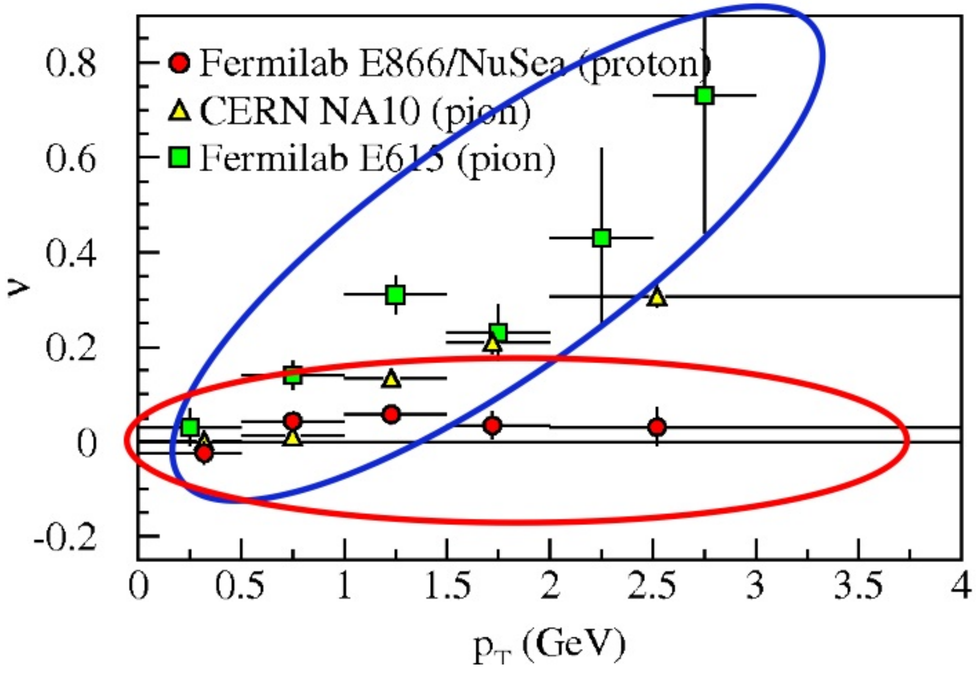


Angular dependence in



- **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**:

$h_1^{\perp,q}(x,\mathbf{p}_T^2)$

$-$

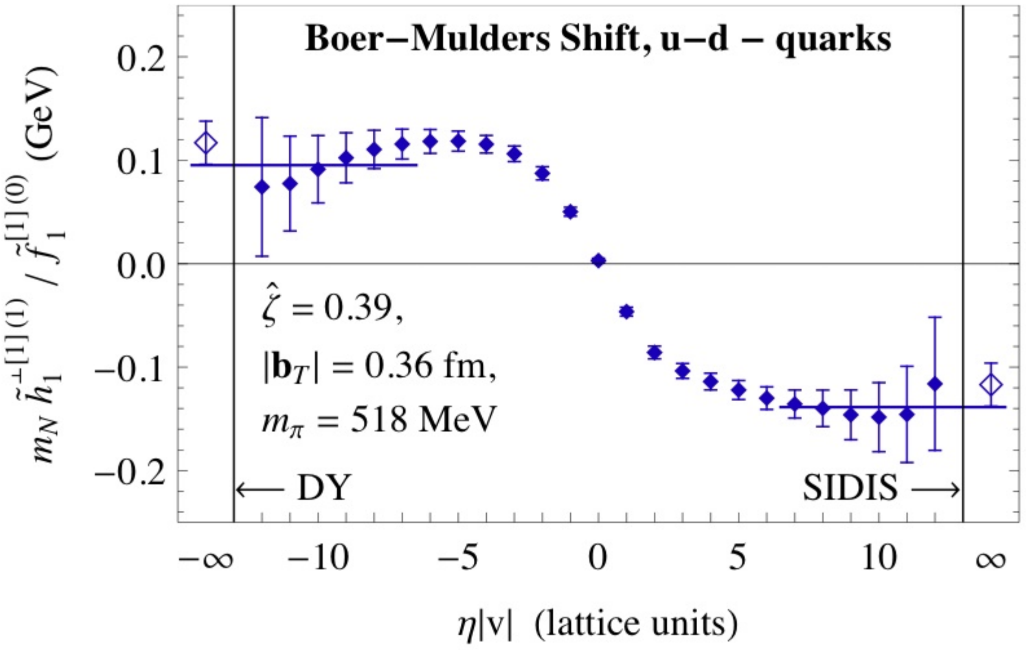
$s_T^i \varepsilon^{ij} p_T^j \frac{1}{M}$

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

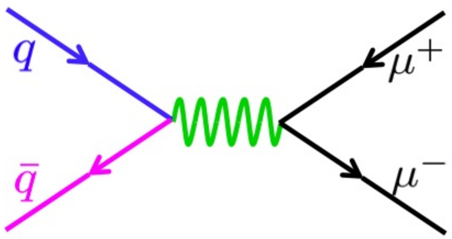
  ↔ initial (Drell-Yan) and final state (SIDIS) interactions

  → **single-spin asymmetries**

- challenging the concept of factorization and universality



The SeaQuest mission

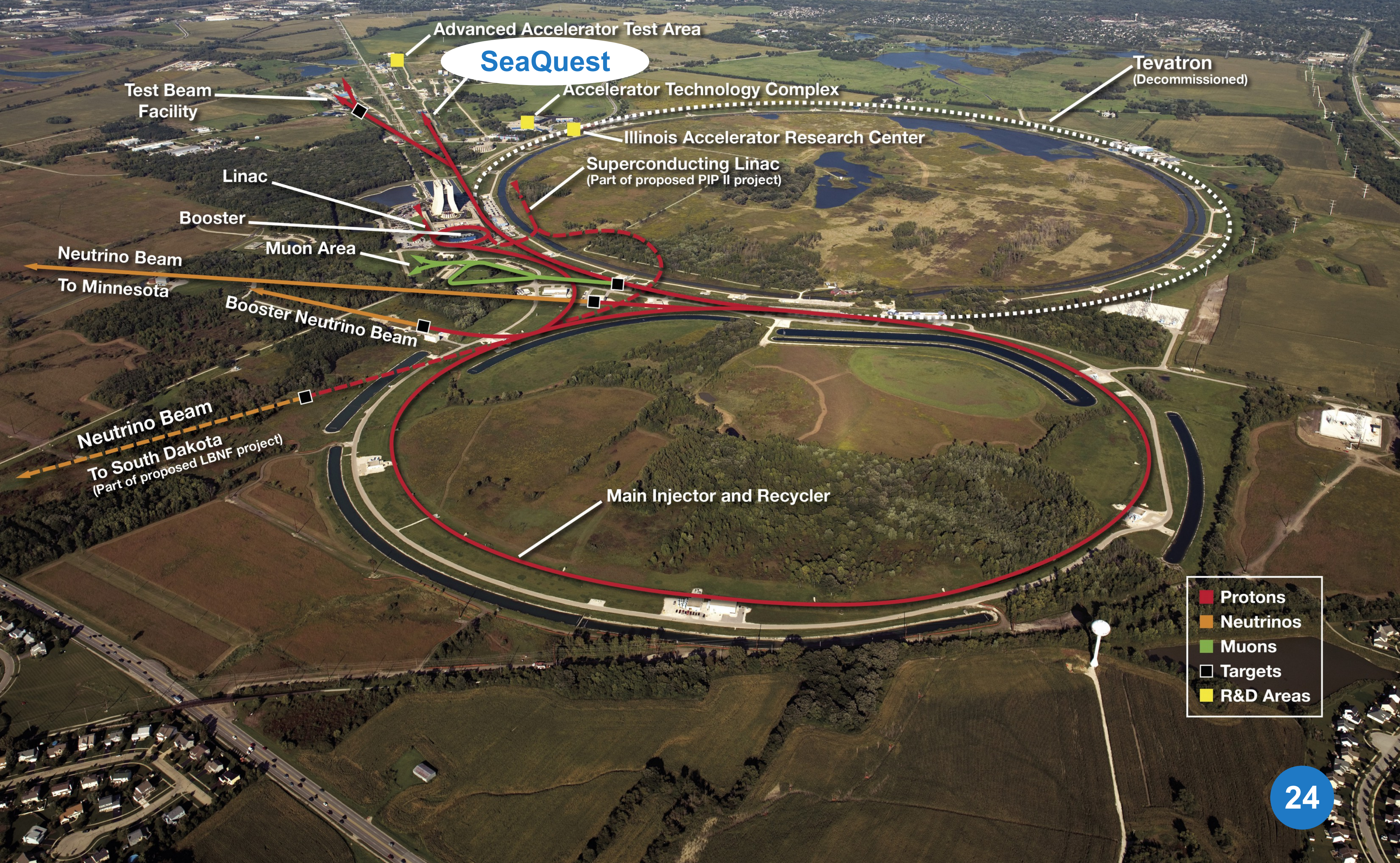


What is the structure of the nucleon?

  - 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 (E1067)?**
- **Answers from SeaQuest:**
  - significant increase in physics reach
  - unique access to **sea quarks at high-x**

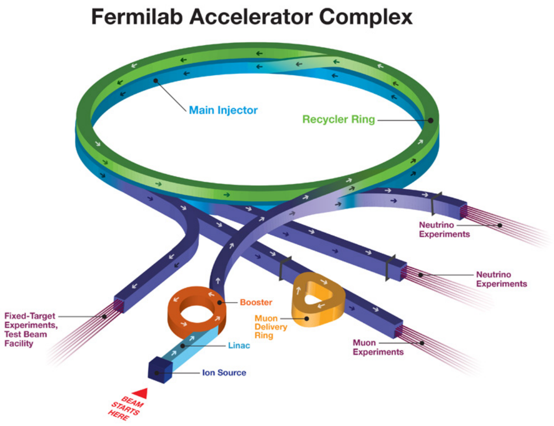
The SeaQuest experiment

Fermilab (FNAL)



The SeaQuest Experiment

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



Proton Beam

slow extraction from MI

6x10^{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)

2012 02 23

Target Table

liquid target flasks:

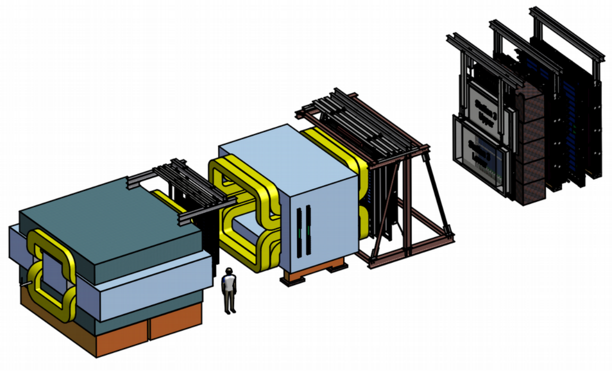
H_2, D_2

solid state targets:

C, Fe, W

empty flask, no target

moves between spills



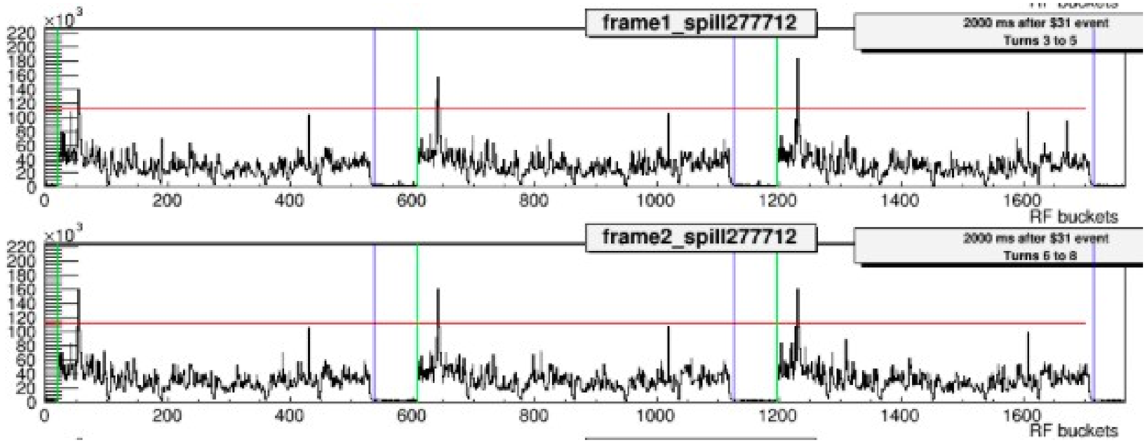
Spectrometer

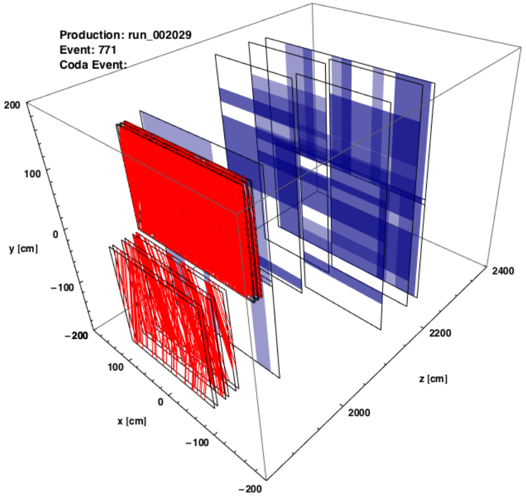
reused and recycled components

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

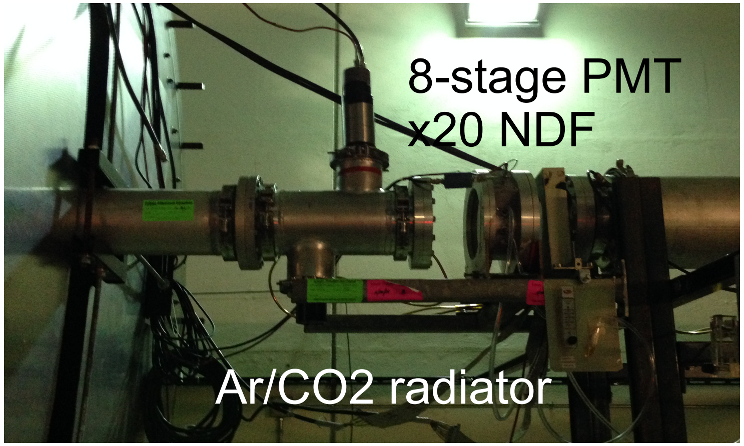
Spill Structure

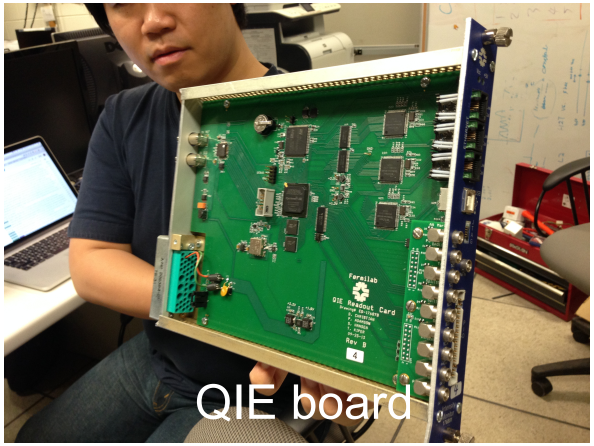
large **variations** in **instantaneous beam intensity** → high hit occupancy





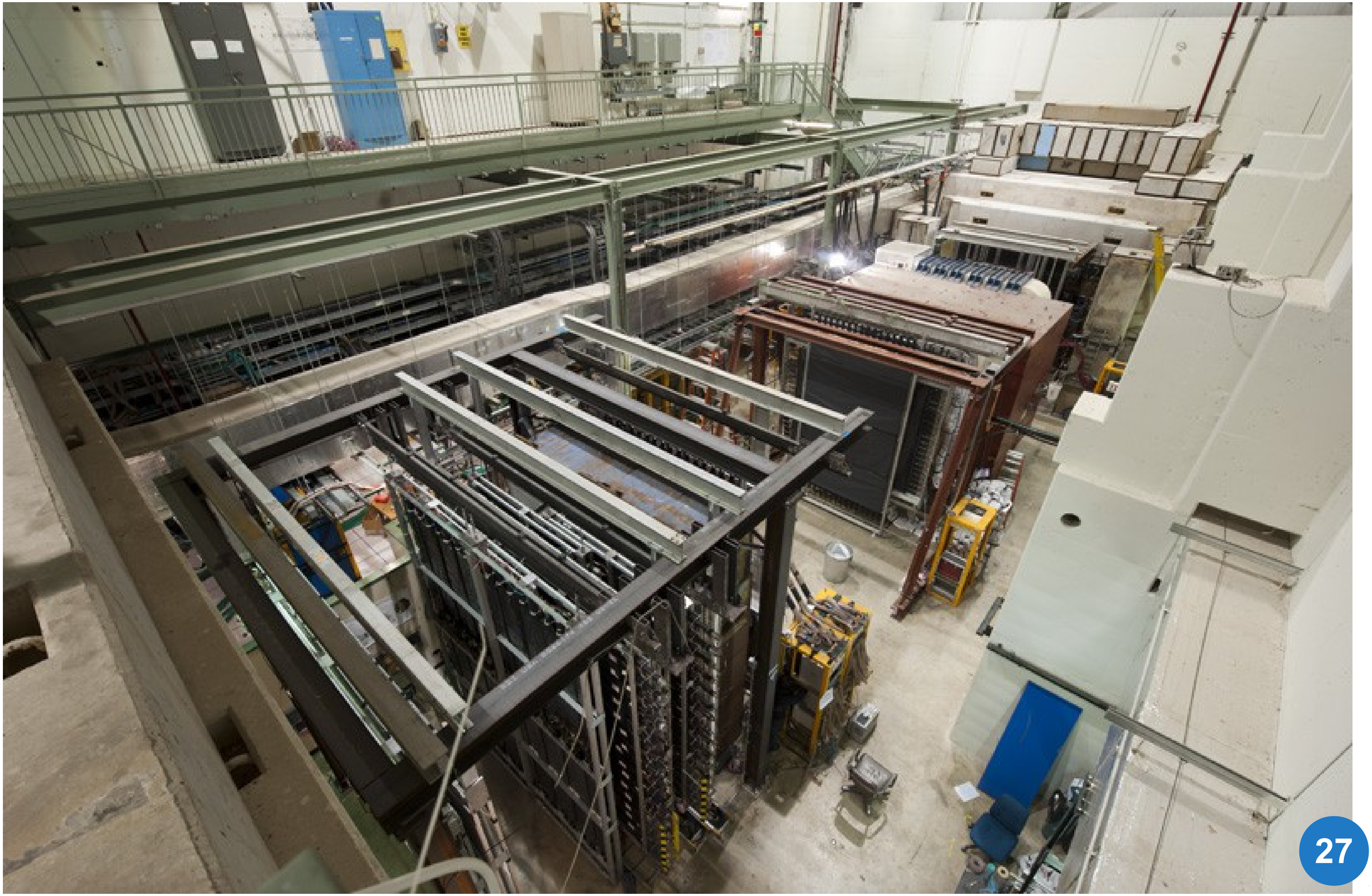
beam-line Cherenkov monitor for beam diagnostics:





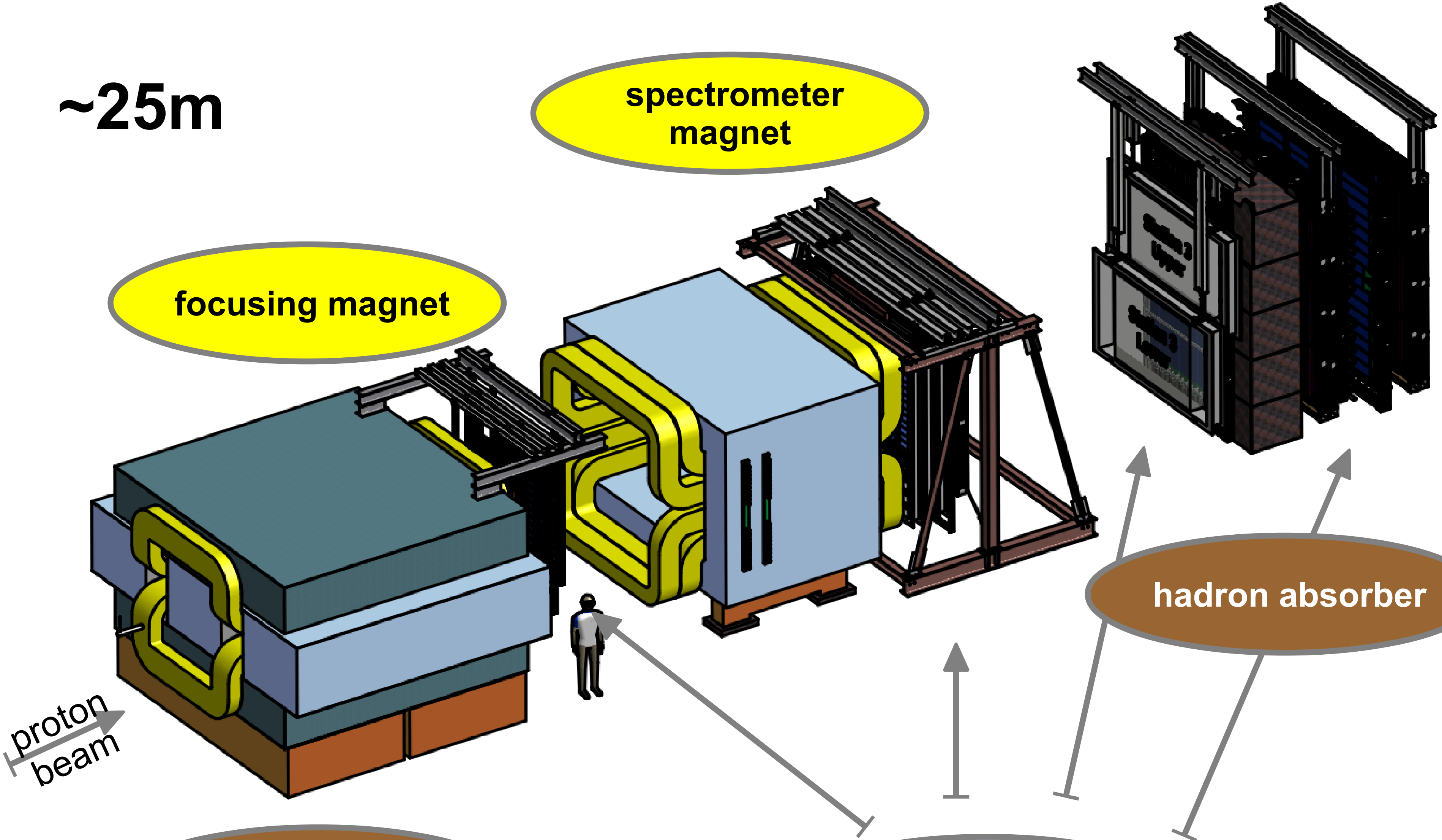
→ **beam diagnostics**: measurement of RF-bucket by RF-bucket intensity
→ **trigger inhibit**: veto on single RF buckets as a function of intensity,
½ beam inhibited due to 10x expected beam/RF-bucket

The SeaQuest spectrometer



The SeaQuest spectrometer

The SeaQuest Spectrometer (arXiv:1706.09990)



~25m

spectrometer magnet

focusing magnet

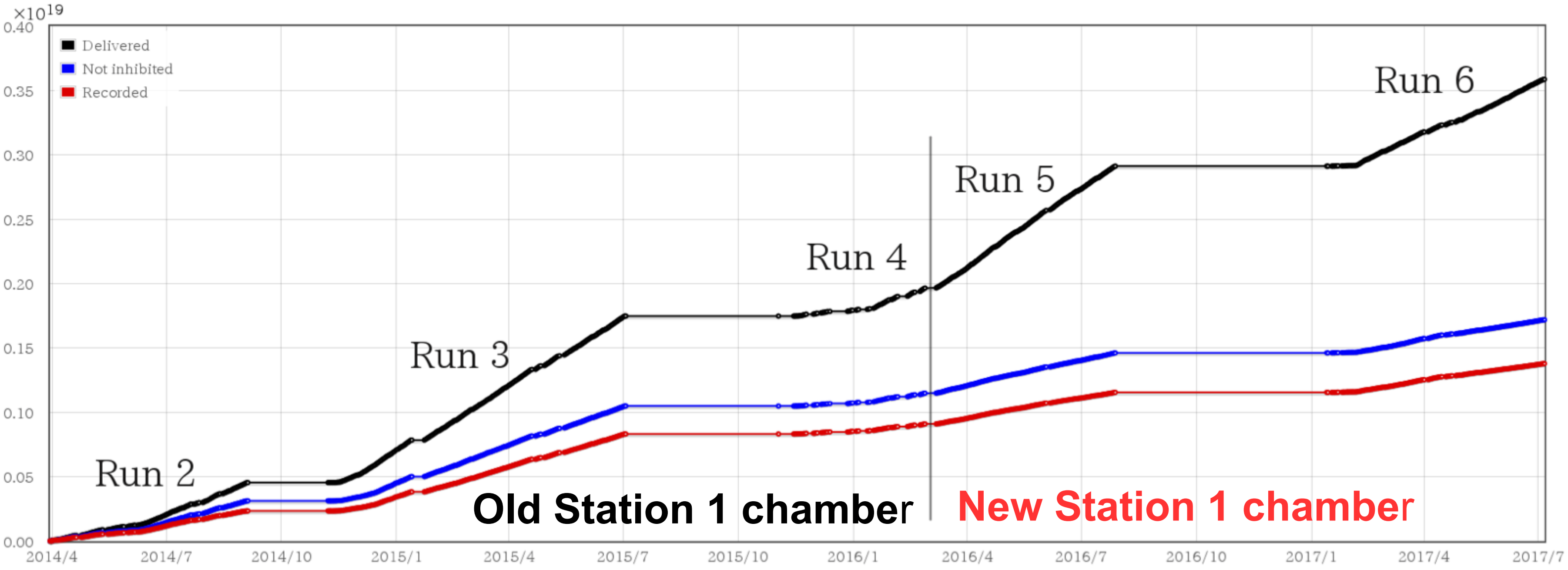
hadron absorber

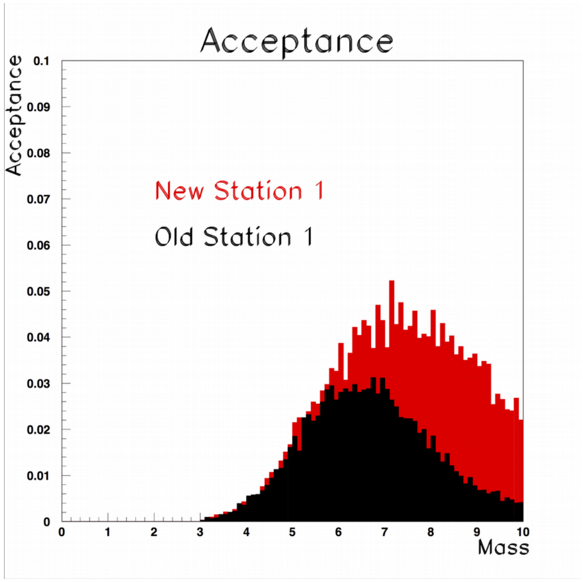
proton beam

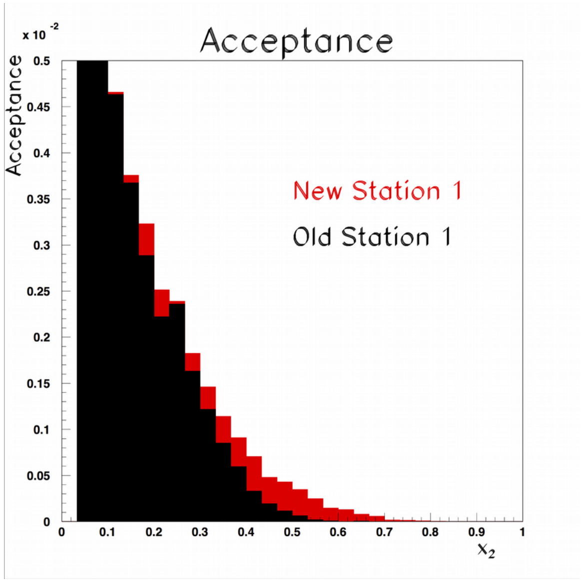
hadron absorber beam dump

hodoscope, tracking

Data taking (completed)



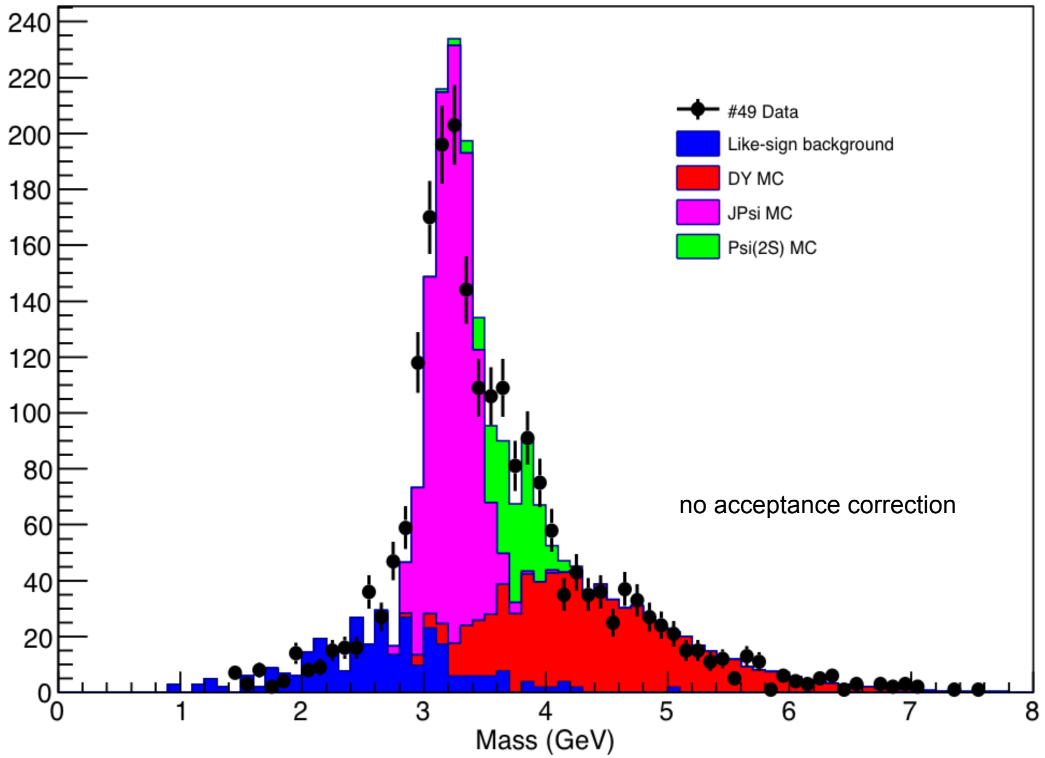




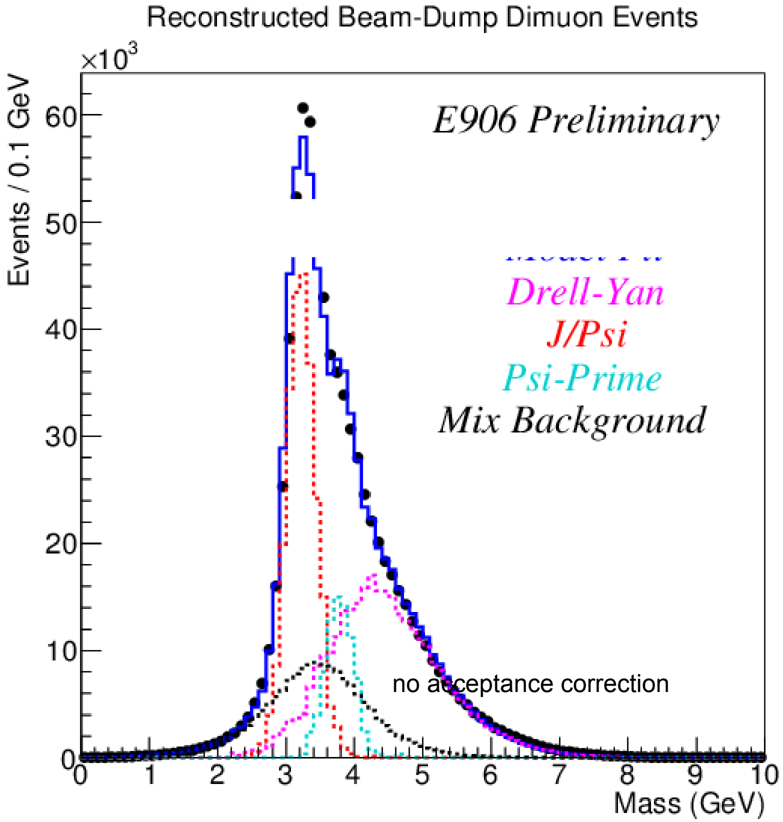
Status of the analysis

- first preliminary physics results at APS April meetings 2015 and 2016
- **track and dimuon reconstruction** (from early Run II data sample):

dimuon events from target

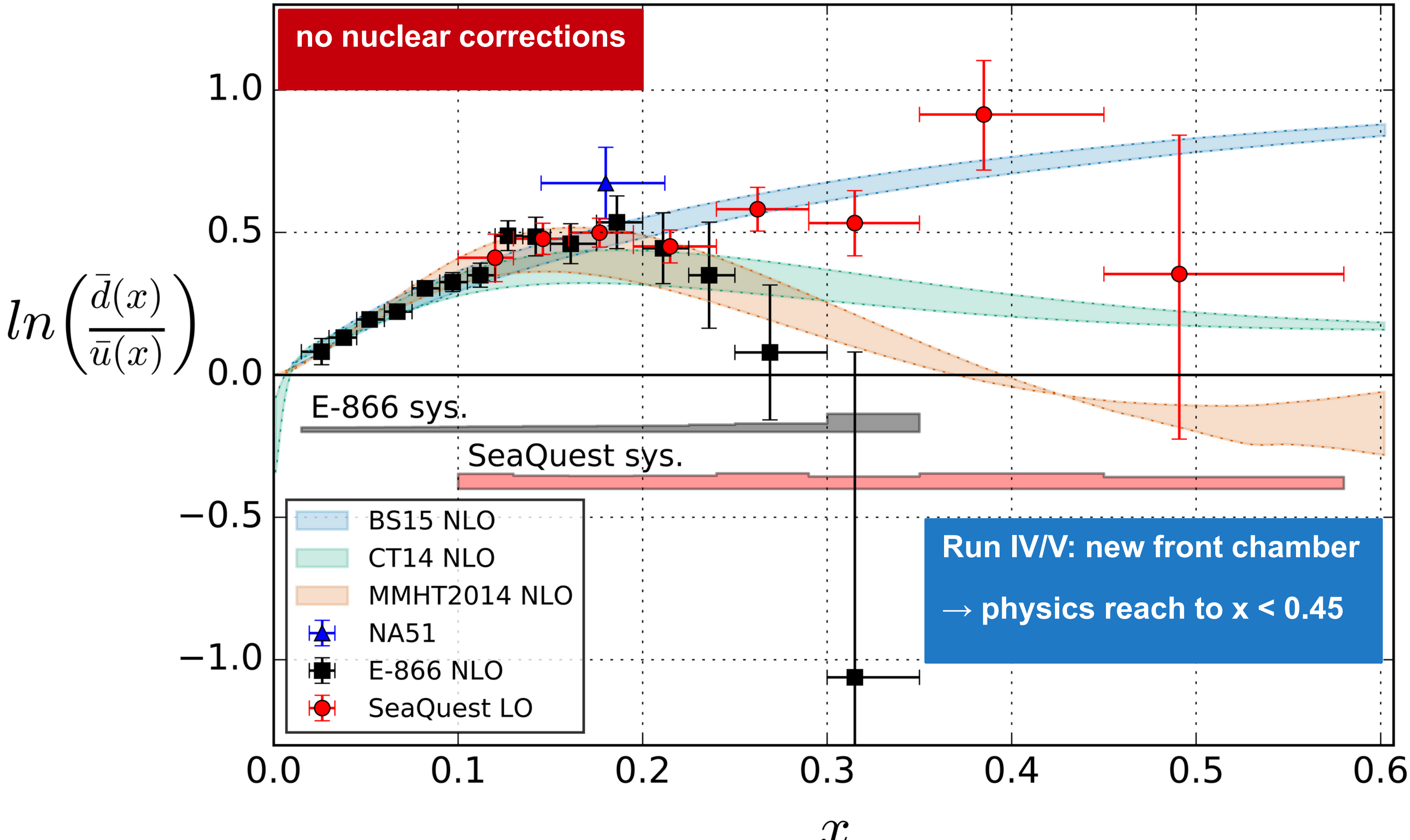


dimuon events from dump



reasonable MC description of the mass dependence of the acceptance

Preliminary result on $\bar{d}(x) / \bar{u}(x)$



no nuclear corrections

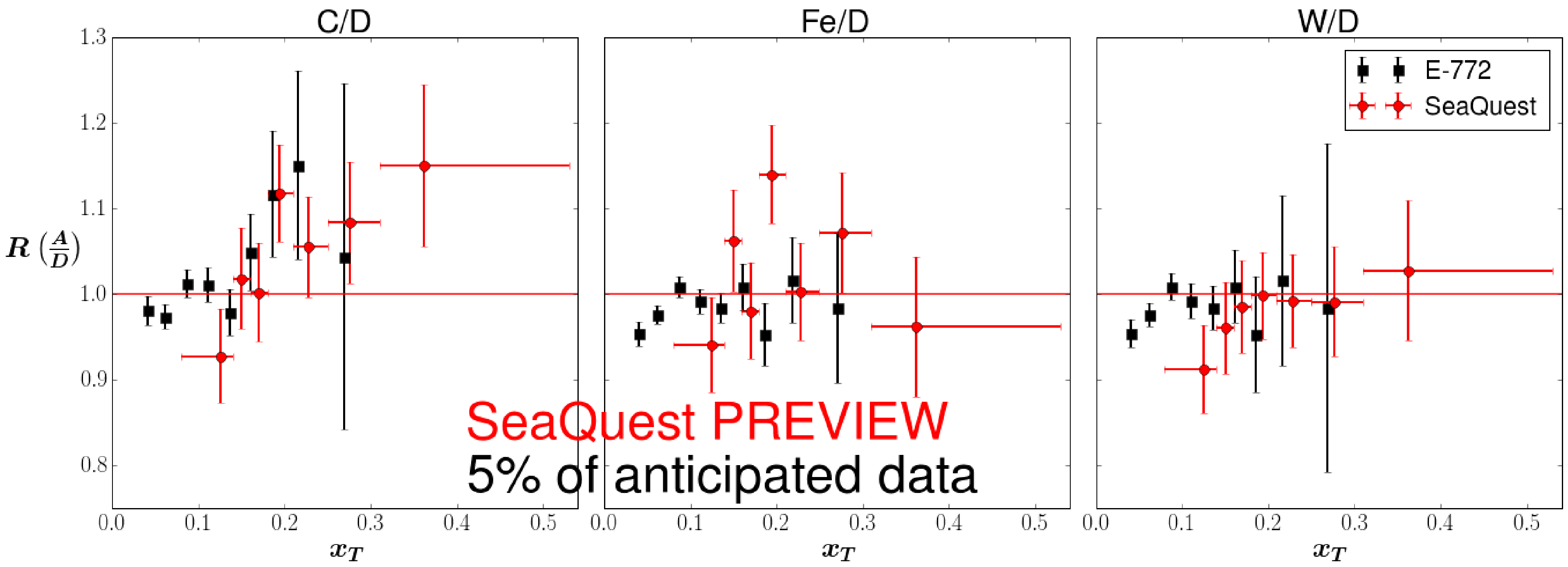
Run IV/V: new front chamber

→ physics reach to x < 0.45

corrected for rate-dependent effects

(tracking efficiency, empty target correction)

Preview on nuclear dependence



SeaQuest PREVIEW

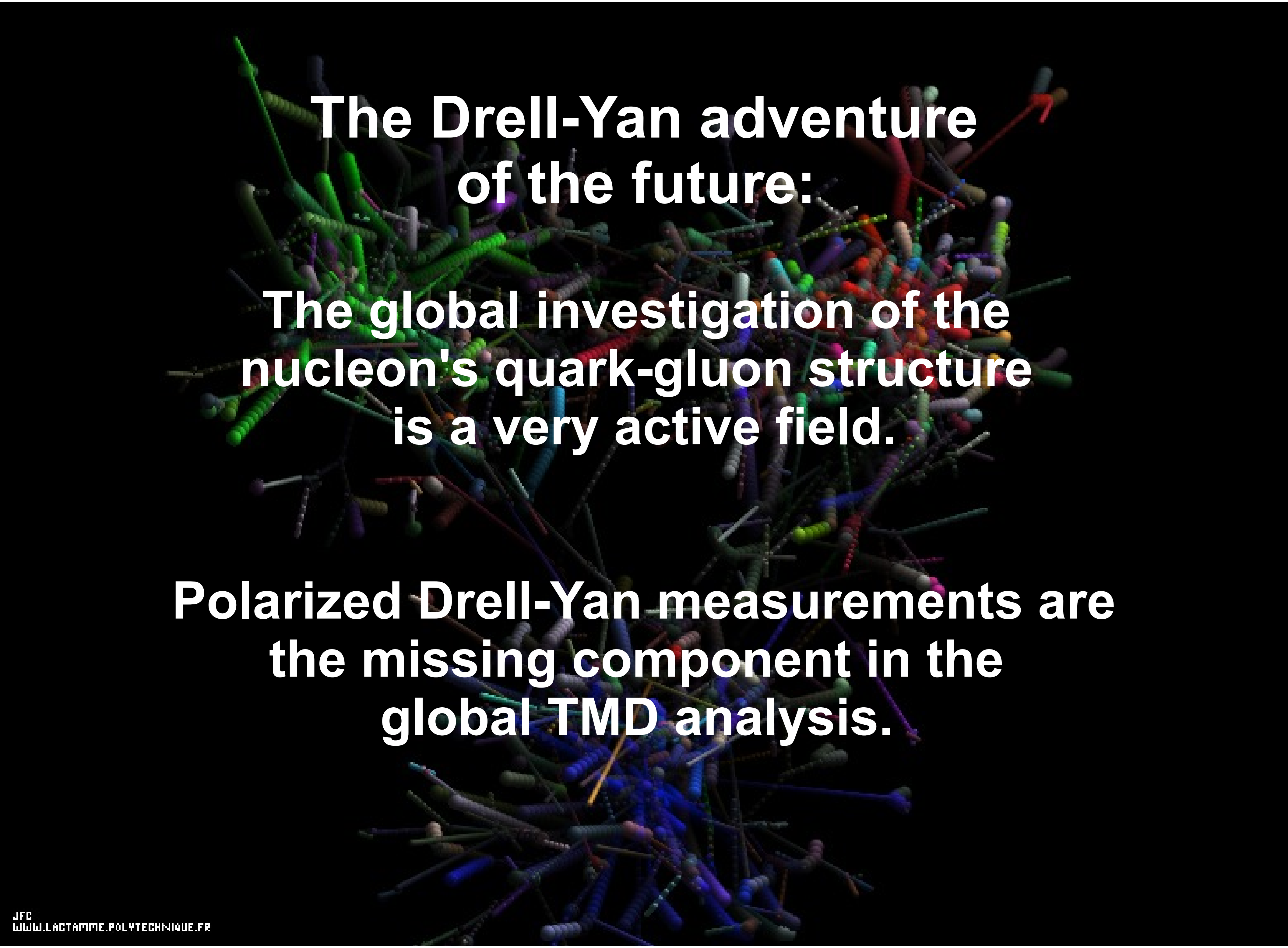
5% of anticipated data

not corrected for (kinematic-dependent) rate-dependent effects

The Drell-Yan adventure of the future:

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

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



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Polarized Drell-Yan measurements

- pioneering analysis of TMDs in (polarized) SIDIS:
  - 3D-densities in momentum space
  - spin-orbit correlations within the nucleon
  - possible link to orbital angular momentum contribution to proton spin?
- complementary information from **polarized Drell-Yan:**
  - **missing piece** in the global TMD analysis
  - **verify sign change of Sivers TMD**: “Test unique QCD predictions for relations between single-transverse spin phenomena in p-p scattering and those observed in deep-inelastic scattering.” (NSAC Milestone HP13 (2015))
  - TMDs for **sea quarks**
- **polarized Drell-Yan measurements at:**

COMPASS II, RHIC Spin, polarized SeaQuest

Planned Drell-Yan experiments

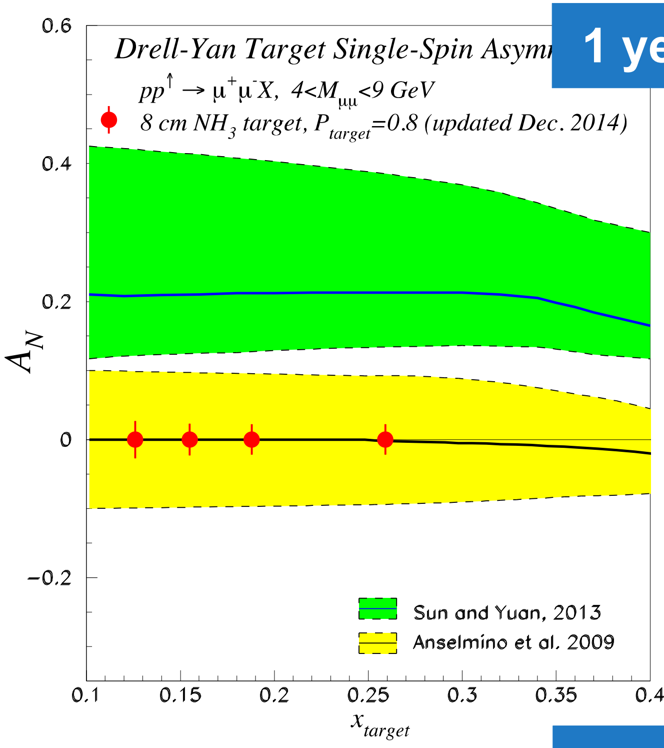
Experiment	Particles	Energy (GeV)	x_b or x_t	Luminosity ($cm^{-2} s^{-1}$)	$A_T^{\sin\phi_S}$	P_b or P_t (f)	rFOM#	Timeline
COMPASS (CERN)	$\pi^{\pm} + p^{\uparrow}$	160 GeV $\sqrt{s} = 17$	$x_t = 0.1 - 0.3$	2×10^{33}	0.14	$P_t = 90\%$ $f = 0.22$	1.1×10^{-3}	2015, 2018
PANDA (GSI)	$\bar{p} + p^{\uparrow}$	15 GeV $\sqrt{s} = 5.5$	$x_t = 0.2 - 0.4$	2×10^{32}	0.07	$P_t = 90\%$ $f = 0.22$	1.1×10^{-4}	>2018
PAX (GSI)	$p^{\uparrow} + \bar{p}$	collider $\sqrt{s} = 14$	$x_b = 0.1 - 0.9$	2×10^{30}	0.06	$P_b = 90\%$	2.3×10^{-5}	>2020?
NICA (JINR)	$p^{\uparrow} + p$	collider $\sqrt{s} = 26$	$x_b = 0.1 - 0.8$	1×10^{31}	0.04	$P_b = 70\%$	6.8×10^{-5}	>2018
PHENIX/STAR (RHIC)	$p^{\uparrow} + p^{\uparrow}$	collider $\sqrt{s} = 510$	$x_b = 0.05 - 0.1$	2×10^{32}	0.08	$P_b = 60\%$	1.0×10^{-3}	>2018
fsPHENIX (RHIC)	$p^{\uparrow} + p^{\uparrow}$	$\sqrt{s} = 200$ $\sqrt{s} = 510$	$x_b = 0.1 - 0.5$ $x_b = 0.05 - 0.6$	8×10^{31} 6×10^{32}	0.08	$P_b = 60\%$ $P_b = 50\%$	4.0×10^{-4} 2.1×10^{-3}	>2021
SeaQuest (FNAL: E-906)	$p + p$	120 GeV $\sqrt{s} = 15$	$x_b = 0.35 - 0.9$ $x_t = 0.1 - 0.45$	3.4×10^{35}	---	---	---	2012 - 2016
Pol tgt DY[‡] (FNAL: E-1039)	$p + p^{\uparrow}$	120 GeV $\sqrt{s} = 15$	$x_t = 0.1 - 0.45$	4.4×10^{35}	0 – 0.2*	$P_t = 85\%$ $f = 0.176$	0.15	2017-2018
Pol beam DY[§] (FNAL: E-1027)	$p^{\uparrow} + p$	120 GeV $\sqrt{s} = 15$	$x_b = 0.35 - 0.9$	2×10^{35}	0.04	$P_b = 60\%$	1	>2018

[‡] *8 cm NH_3 target* / [§] *L= 1×10^{36} $cm^{-2} s^{-1}$ (LH_2 tgt limited) / L= 2×10^{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, f=0.22 for π^- beam on NH_3)

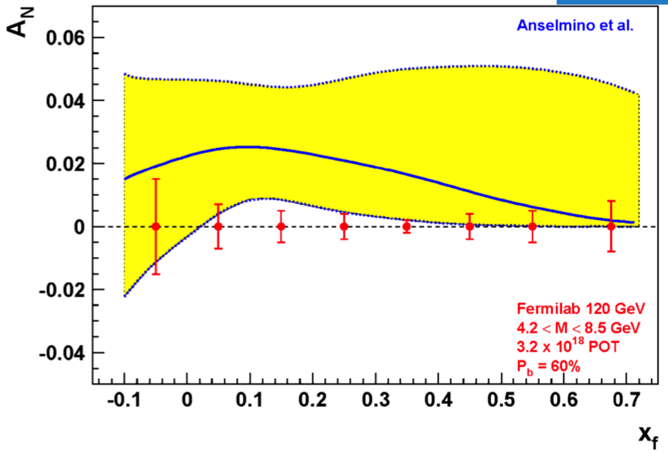
Reestablishing spin at Fermilab

- **E-1039: SeaQuest with polarized target**
  - sensitive to Sivers TMD for sea quarks
  - hint for substantial role of sea quark Sivers effect in HERMES data
  - LANL and UVa provide polarized proton (NH3) target
  - DOE NP provides 2M$ for installation and running of E-1039
  - production running as early as FY19
- **E-1027: SeaQuest with polarized beam**
  - Stage-1 approval
  - sensitive to beam valence quarks at high-x
  - large effects → sign, size, and maybe shape of Sivers TMD



1 year

2 years



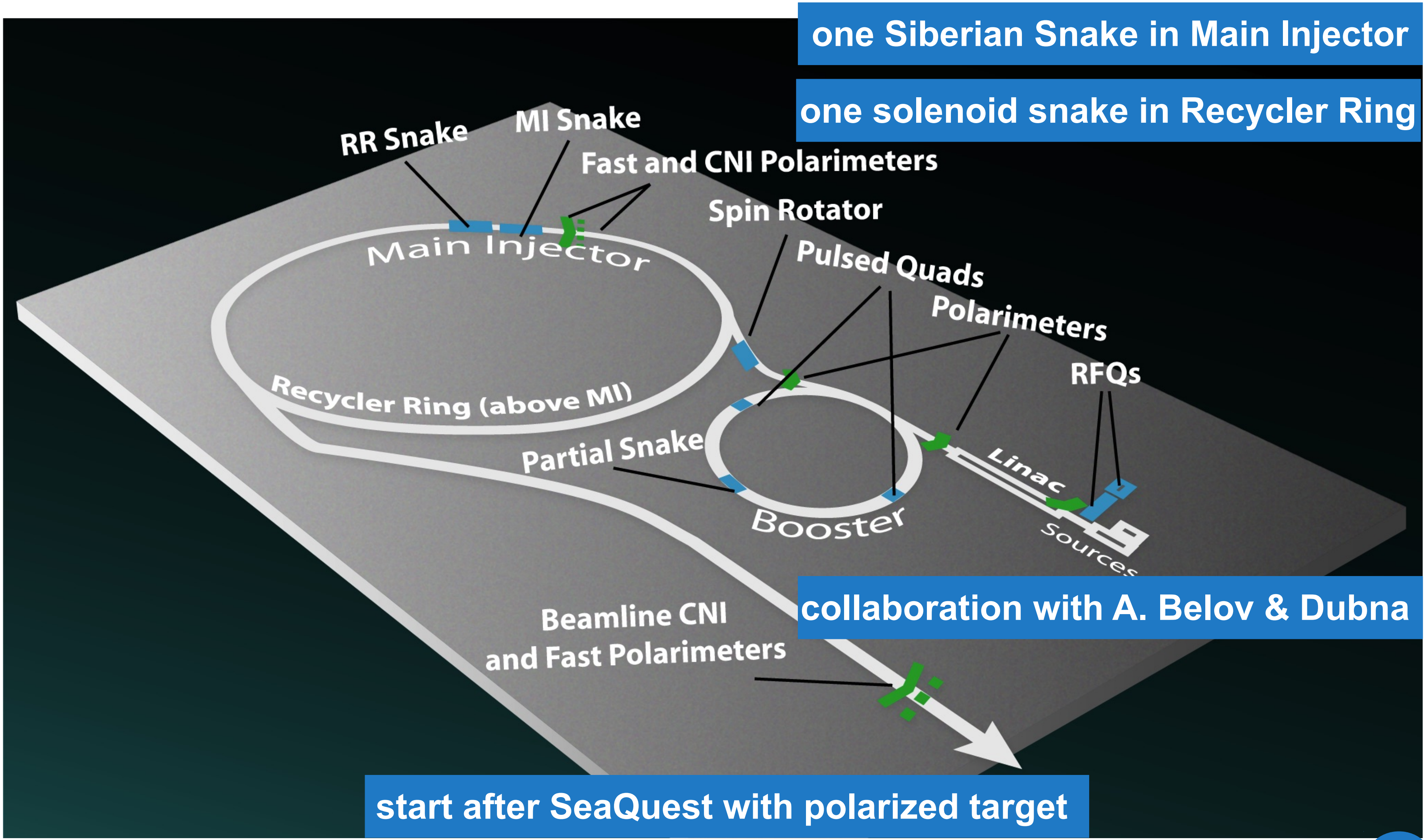
The polarized beam project

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

start after SeaQuest with polarized target

support by FNAL AD

Polarized Drell-Yan experiments

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

The SeaQuest mission

unique laboratory for sea quarks at high-x

→ structure of nucleons and nucleonic matter

physics running from FY14 - FY17

→ first preliminary results shown at APS2016

→ first publications in preparation

polarized Drell-Yan measurements

→ missing piece in the global spin program

→ SeaQuest with polarized target funded