

# State and Future of Spin Physics

- Personal Perspective
- Nuclear Gluonometry
- Report from the ISPC

*With slides from E. Aschenauer, V. Burkert, W. Detmold, J. Maxwell, P. Shanahan*

# Building Blocks of Matter 2016

## *The Standard Model of Physics*

1968: SLAC <b><math>u</math></b> up quark	1974: Brookhaven & SLAC <b><math>c</math></b> charm quark	1995: Fermilab <b><math>t</math></b> top quark	1979: DESY <b><math>g</math></b> gluon
1968: SLAC <b><math>d</math></b> down quark	1947: Manchester University <b><math>s</math></b> strange quark	1977: Fermilab <b><math>b</math></b> bottom quark	1923: Washington University* <b><math>\gamma</math></b> photon
1956: Savannah River Plant <b><math>\nu_e</math></b> electron neutrino	1962: Brookhaven <b><math>\nu_\mu</math></b> muon neutrino	2000: Fermilab <b><math>\nu_\tau</math></b> tau neutrino	1983: CERN <b><math>W</math></b> W boson
1897: Cavendish Laboratory <b><math>e</math></b> electron	1937 : Caltech and Harvard <b><math>\mu</math></b> muon	1976: SLAC <b><math>\tau</math></b> tau	1983: CERN <b><math>Z</math></b> Z boson



+

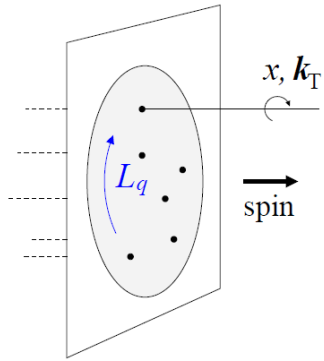


# Search for Physics Beyond Standard Model

- Search for non-zero EDMs of fundamental particles: neutron, storage ring experiments
- Parity-violating electron scattering
- Atomic parity-violation
- Muon anomalous magnetic moment
- Muonium hyperfine structure

# 21<sup>st</sup> Century View of the Nucleon

Theorists have developed a powerful formalism for studying the 3D partonic picture of the nucleon. It is encoded in **Generalized Parton Distributions** and **Transverse Momentum Dependent Distributions**



**T**ransverse  
**M**omentum  
**D**ependent  
distributions

Wigner distribution

$$W(\mathbf{p}, \mathbf{x})$$

$$d^3 r$$

$$d^3 p$$

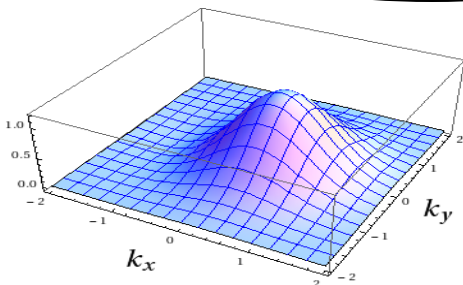
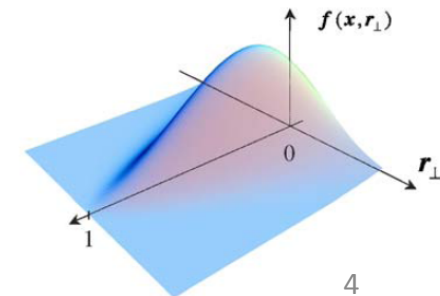
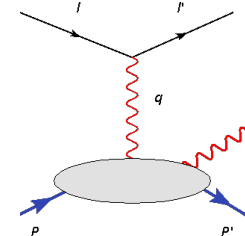
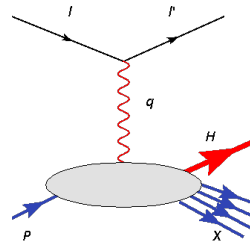
**G**eneralized  
**P**arton  
**D**istributions

$$f(x, \mathbf{k}_\perp)$$

$$H(x, \xi, t)$$

**SIDIS**

**DES**



Richard Milner



University of Illinois



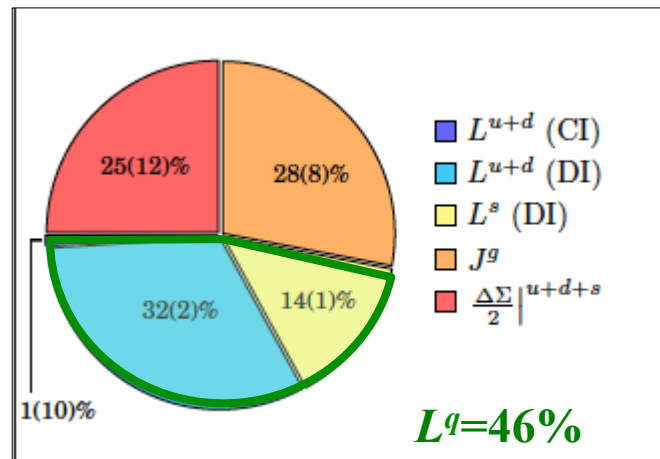
# Towards an Era of Precision QCD

- Spin physics has played a crucial role in developing this modern perspective
  - Collins, Sivers effects
  - Fermilab (E704), HERMES, COMPASS, JLab, RHIC
- Both transverse and longitudinal asymmetries are important
  - Transversity
- Going forward we have a powerful, unifying framework to map out the structure of the nucleon
  - COMPASS, JLab, RHIC-spin, Mainz, LHC (?),..... -----> EIC
- Understanding nuclear structure from the perspective of high energy QCD is also a high priority – connect to the quark gluon plasma
- Lattice QCD is an increasingly important element in making progress.

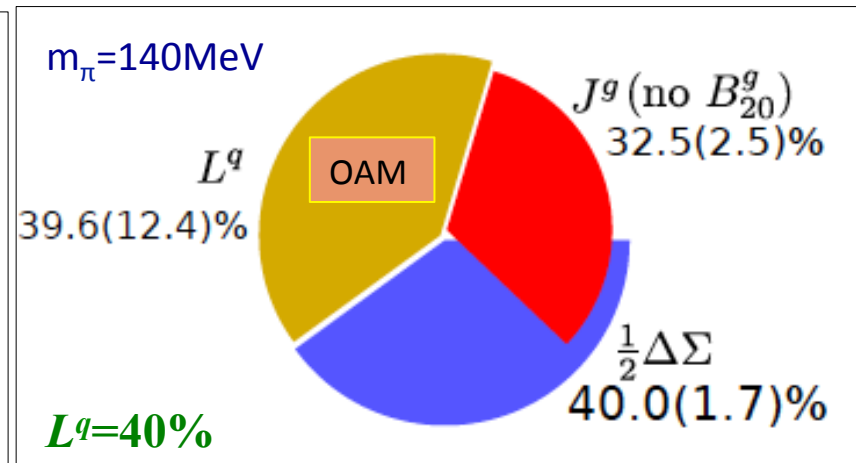
# Proton Spin Decomposition

In LQCD, gauge invariant decomposition (X. Ji):

$$\mathbf{J}_p = \frac{1}{2} = (\frac{1}{2} \Delta \Sigma^q + L^q) + J^g$$



K.F. Liu, C. Lorce, arXiv:1508.00911



C. Alexandrou et al., arXiv:1609.00253

- LQCD projections: OAM 40-50%, nearly all quark OAM is the result of disconnected interactions.
- Quark OAM is experimentally the least constrained contribution  
=> Strong motivation of spin physics at 12 GeV

# Nuclei on the Lattice

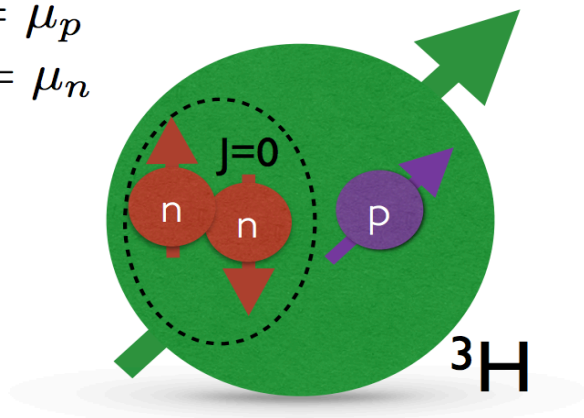
- Numerical values are surprisingly interesting

- Shell model expectations

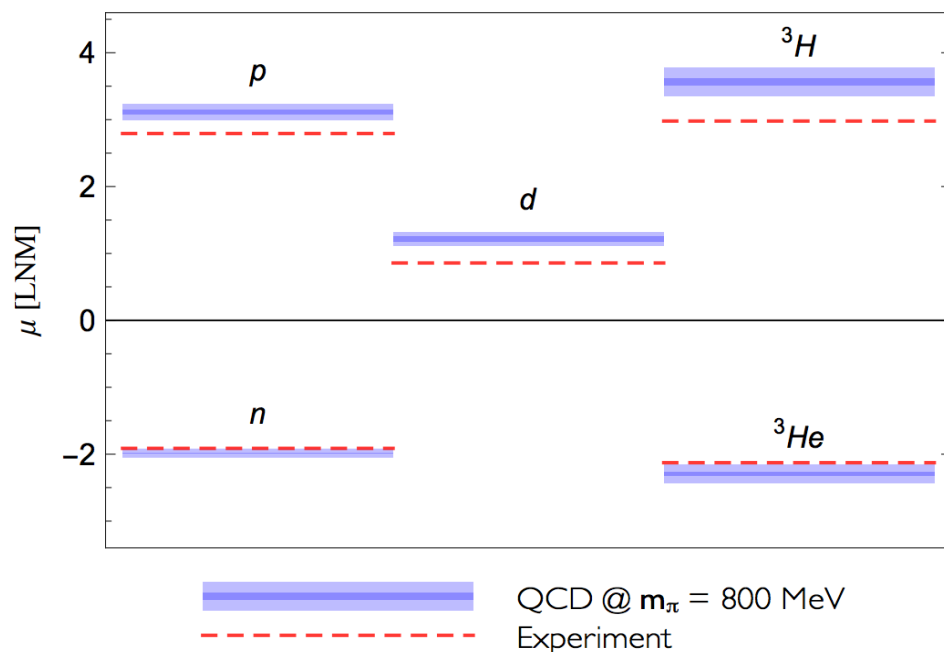
$$\mu_d = \mu_p + \mu_n$$

$$\mu_{^3\text{H}} = \mu_p$$

$$\mu_{^3\text{He}} = \mu_n$$



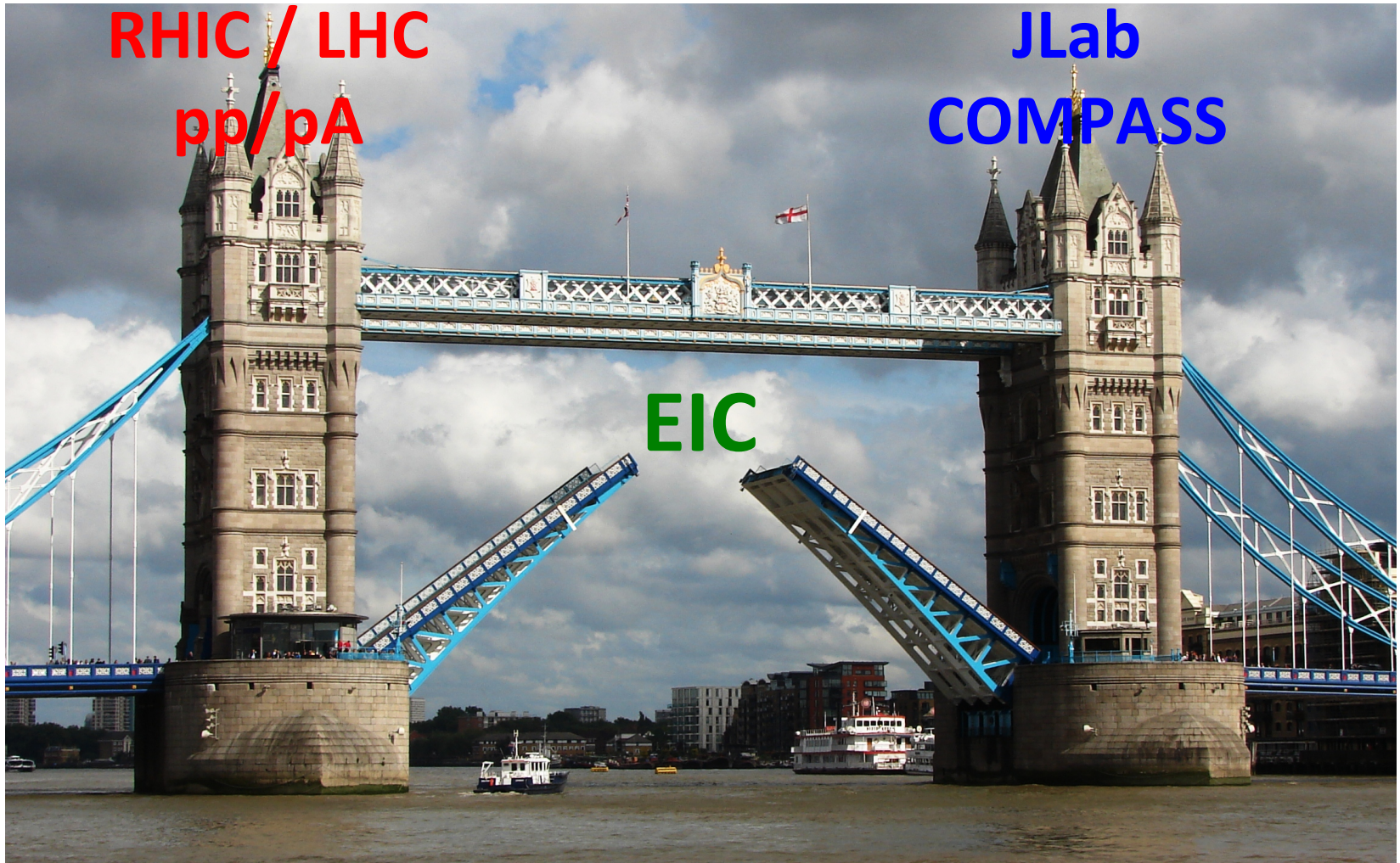
- Lattice results appear to suggest heavy quark nuclei are shell-model like!



	n	p	d	$^3\text{He}$	$^3\text{H}$
$\mu$	-1.98(1)(2)	3.21(3)(6)	1.22(4)(9)	-2.29(3)(12)	3.56(5)(18)

In units of appropriate nuclear magnetons (heavy  $M_N$ )  
 [NPLQCD PRL **113**, 252001 (2014)]

# EIC unifies

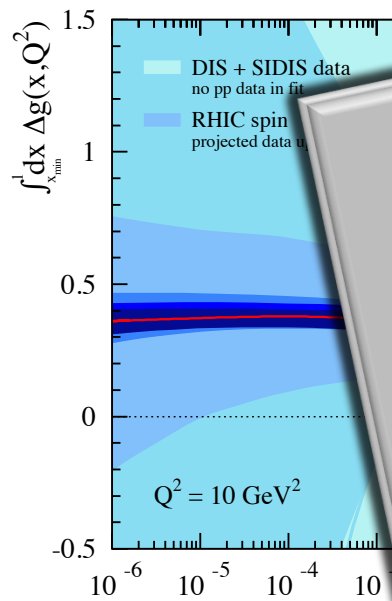




# Where does the Spin of the proton hide?

“Helicity sum rule:”

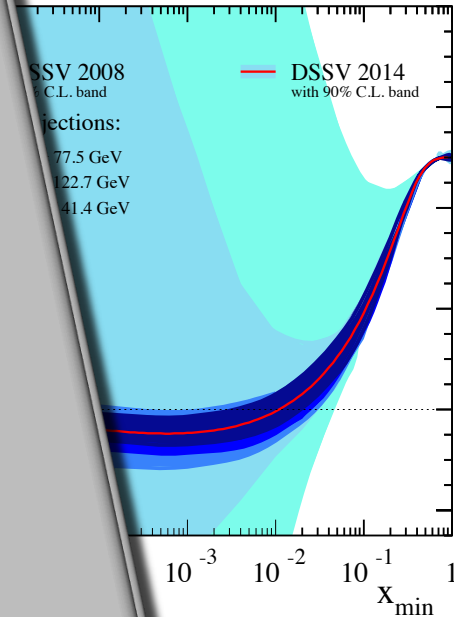
$$\frac{1}{2}\hbar = \left\langle P, \frac{1}{2} \left| J_{QCD}^z \right| P, \frac{1}{2} \right\rangle = \sum_q \overbrace{\frac{1}{2} S_q^z}^{\text{total quark spin}} + \overbrace{S_g^z}^{\text{gluon spin}} + \overbrace{\Delta \Sigma}^{\text{angular momentum}}$$



1/2 -

Glu

After EIC:  
spin puzzle will be solved



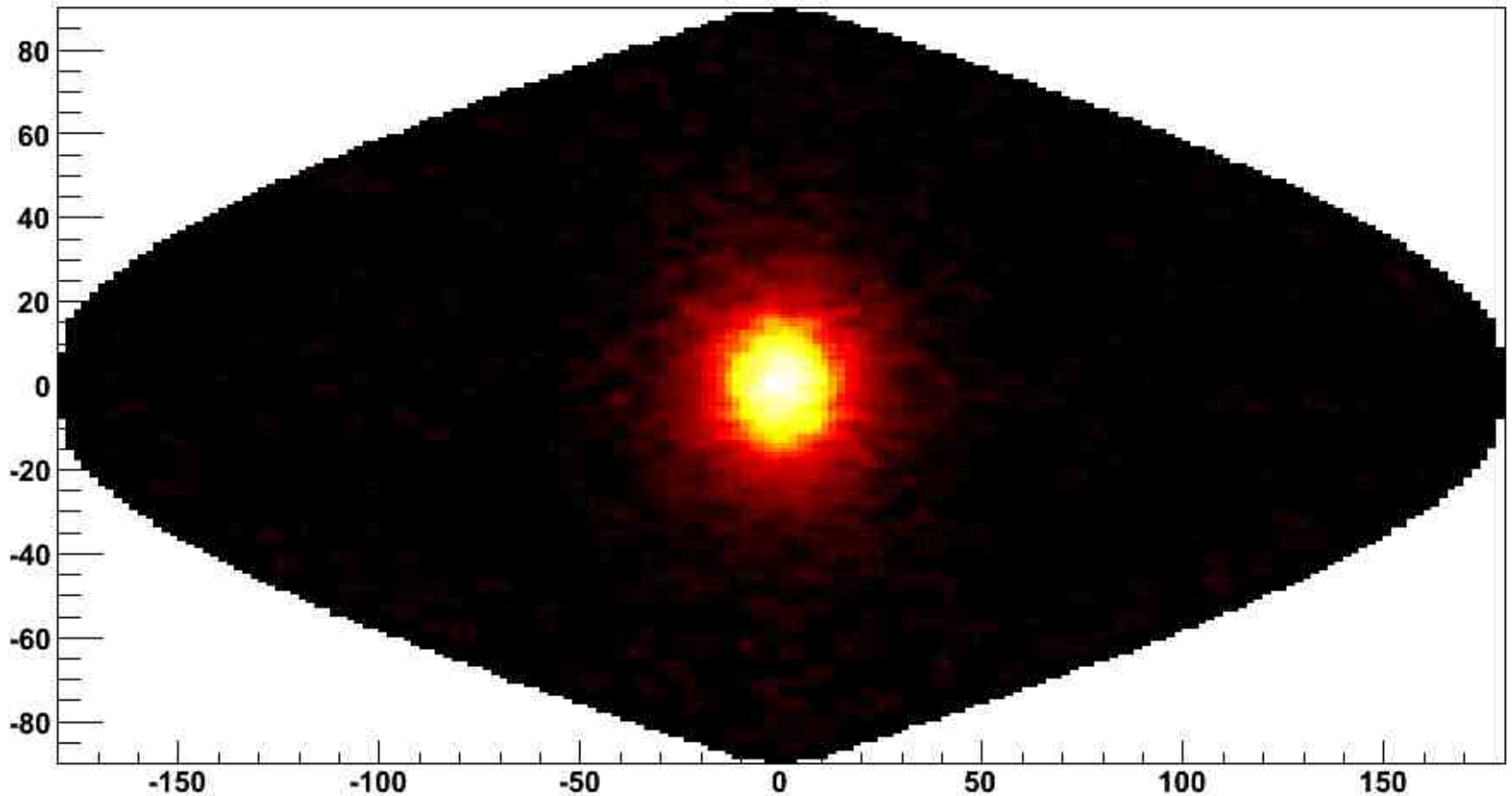
total angular  
momentum

## Challenge:

*Can we put all this detailed information together to provide to the interested non-scientist a compelling visualization of the proton?*

*Can we visualize the microcosm?*

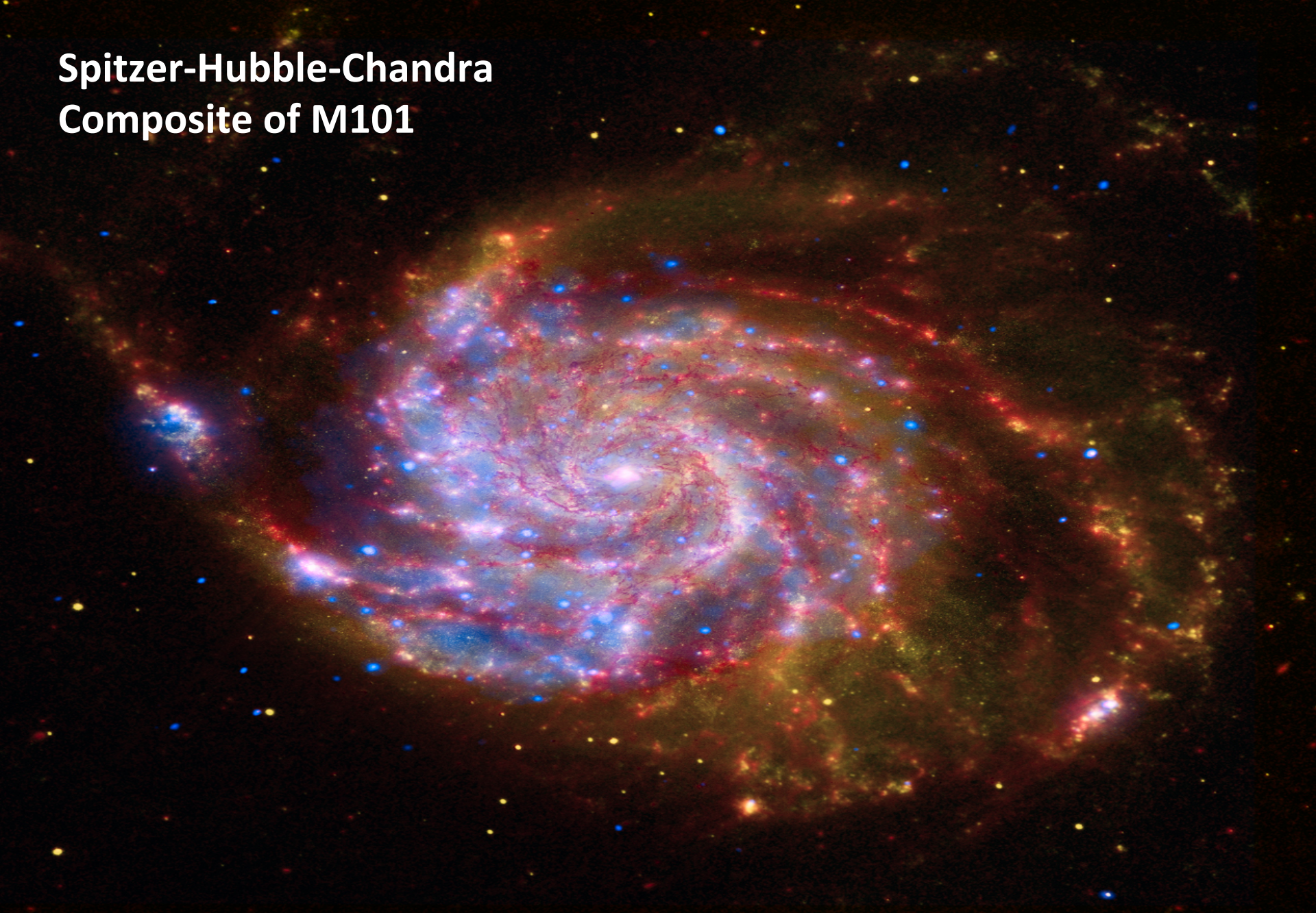
# The Sun as viewed by neutrino detection deep underground



Super-Kamiokande experiment in 4504 days of data taking



# Spitzer-Hubble-Chandra Composite of M101

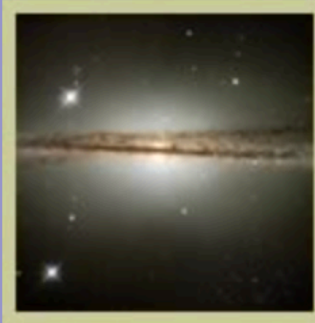




# Crab Nebula

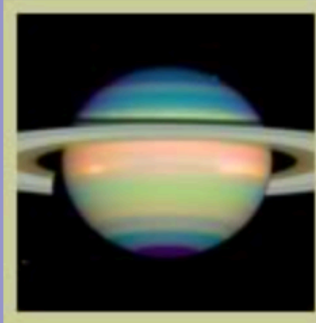


# Color as a Tool



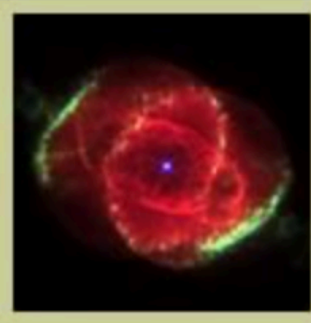
## Natural Color

The colors in this image of a galaxy were chosen to simulate the colors that our eyes might see if we were able to visit it in a spacecraft.



## Representative Color

Representative color helps scientists visualize what would otherwise be invisible, such as the appearance of an object in infrared light.



## Enhanced Color

Enhancing the visible colors in an image often brings out an object's subtle structural detail.

Color in Hubble images is used to highlight interesting features of the celestial object being studied. It is added to the separate black-and-white exposures that are combined to make the final image.

Creating color images out of the original black-and-white exposures is equal parts art and science.

We use color:

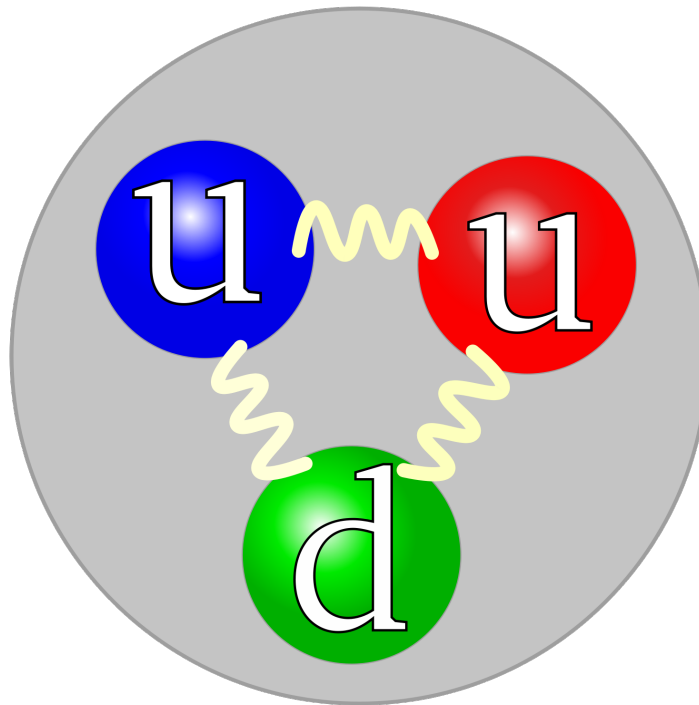
- To depict how an object might look to us if our eyes were as powerful as Hubble
- To visualize features of an object that would ordinarily be invisible to the human eye
- To bring out an object's subtle details.



# Google “proton” -> Images



# Scroll down several pages



## NUCLEAR GLUONOMETRY ☆

R.L. JAFFE and Aneesh MANOHAR

*Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

Received 24 March 1989

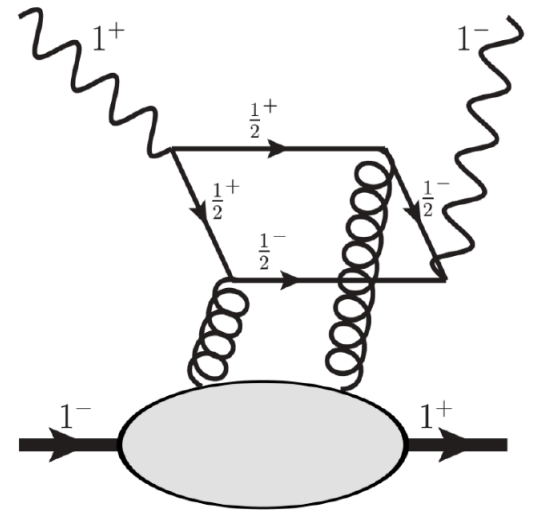
We identify a new leading twist structure function in QCD which can be measured in deep elastic scattering from polarized targets (such as nuclei) with spin  $\geq 1$ . The structure function measures a gluon distribution in the target and vanishes for a bound state of protons and neutrons, thereby providing a clear signature for exotic gluonic components in the target.

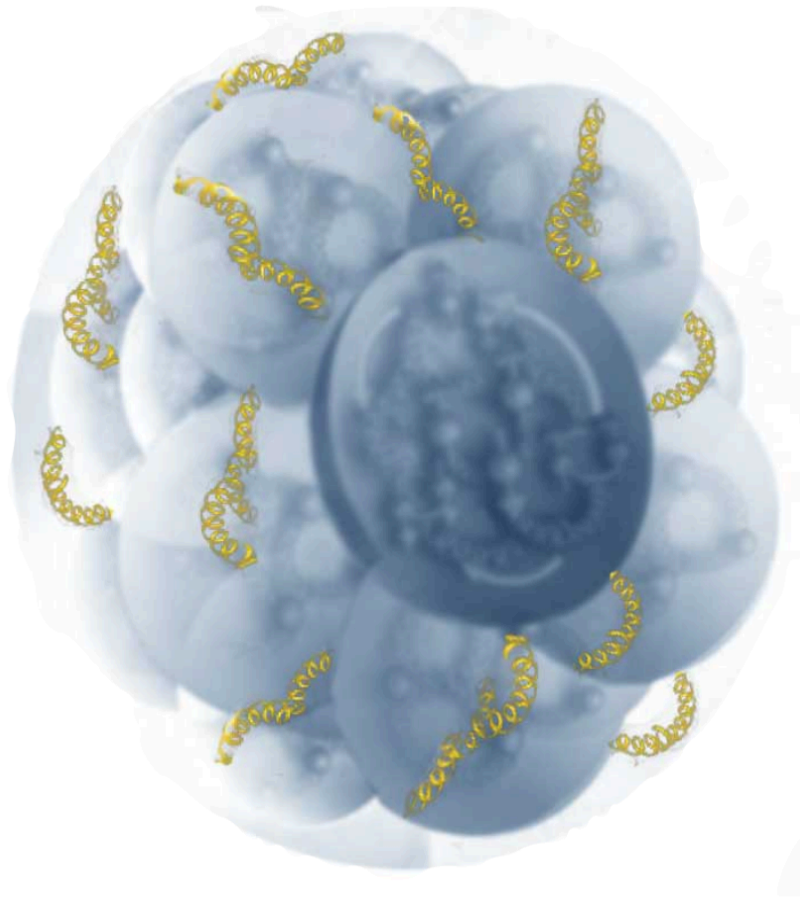
# Double Helicity Flip Gluon Structure Function $\Delta(x, Q^2)$

- Jaffe and Manohar in 1989 identified a leading-twist, double-helicity flip structure function  $\Delta(x, Q^2)$
- Would be a clear signature for exotic glue in nuclei, i.e. gluons not associated with individual nucleons
- Accessed via inclusive DIS from transversely polarized nucleus with  $J \geq 1$
- Experiment using polarized target under development at Jefferson Lab (J. Maxwell)
- Under consideration for future EIC

# Can it be measured?

- $\Delta(x, Q^2)$  corresponds to a helicity amplitude  $A_{+-,-+}$
- Photon helicity flip of two
- Unavailable to bound nucleons or pions in nucleus
- Virtual  $\rho$  or  $\Delta$ ? Gluons not associated with a nucleon?
- New lattice QCD result for first moment of  $\Delta(x, Q^2)$  in a  $\varphi$  meson is preliminary but promising





## Exotic glue in nuclei



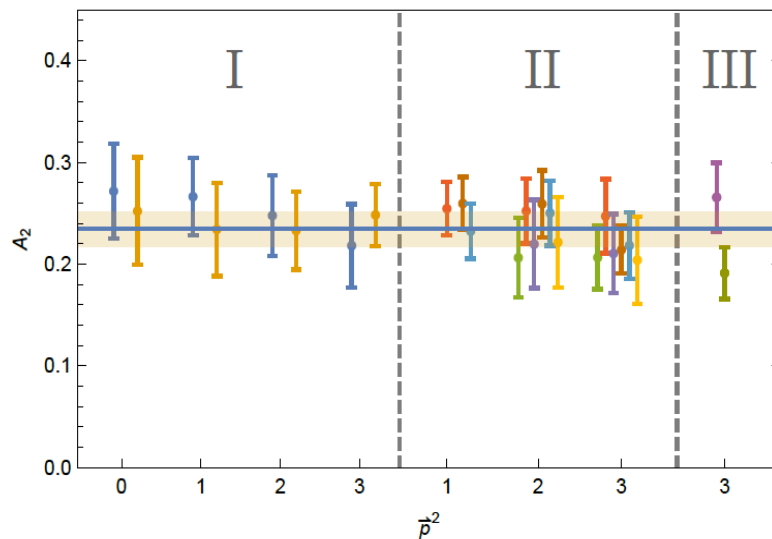
# Gluonic Transversity from Lattice QCD

W. Detmold and P. E. Shanahan

*Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, U.S.A.*

We present an exploratory study of the gluonic structure of the  $\phi$  meson using lattice QCD (LQCD). This includes the first investigation of gluonic transversity via the leading moment of the twist-two double-helicity-flip gluonic structure function  $\Delta(x, Q^2)$ . This structure function only exists for targets of spin  $J \geq 1$  and does not mix with quark distributions at leading twist, thereby providing a particularly clean probe of gluonic degrees of freedom. We also explore the gluonic analogue of the Soffer bound which relates the helicity flip and non-flip gluonic distributions, finding it to be saturated at the level of 80%. This work sets the stage for more complex LQCD studies of gluonic structure in the nucleon and in light nuclei where  $\Delta(x, Q^2)$  is an ‘exotic glue’ observable probing gluons in a nucleus not associated with individual nucleons.

**1606.04505, Aug 2016**



- Statistically clean and theoretically consistent signal
- $A_2$  – second moment of  $\Delta(x, Q^2)$
- Find  $A_2 \sim 0.23(2)(5)$

# JLab: Fixed Polarized Target Approach

For a spin-1 target polarized at angle  $\theta_m$  from the  $z$ -axis and electron incident from  $-z$ , target spin  $\lambda_m = (1, 0, -1)$ :

$$(3 \cos^2 \theta_m - 1) \left( b_1 + \frac{1-y}{xy^2} b_2 \right) - \frac{1-y}{y^2} \sin^2 \theta_m \Delta(x, Q^2) \cos(2\phi)$$

- Leverage  $\cos 2\phi$  to isolate  $\Delta$ : need azimuthal detector acceptance
- Form tensor asymmetry
  - $\theta_m = 54.7^\circ$  cancels  $b_1$  and  $b_2$  dependence
  - change polarization sub-states
- Form difference of vector asymmetry and unpolarized cross section
  - $\theta_m = 54.7^\circ$  cancels  $b_1$  and  $b_2$  dependence
  - Lose cancellation of acceptances and efficiencies

# Kinematic Reach with 12 GeV CEBAF in Hall C

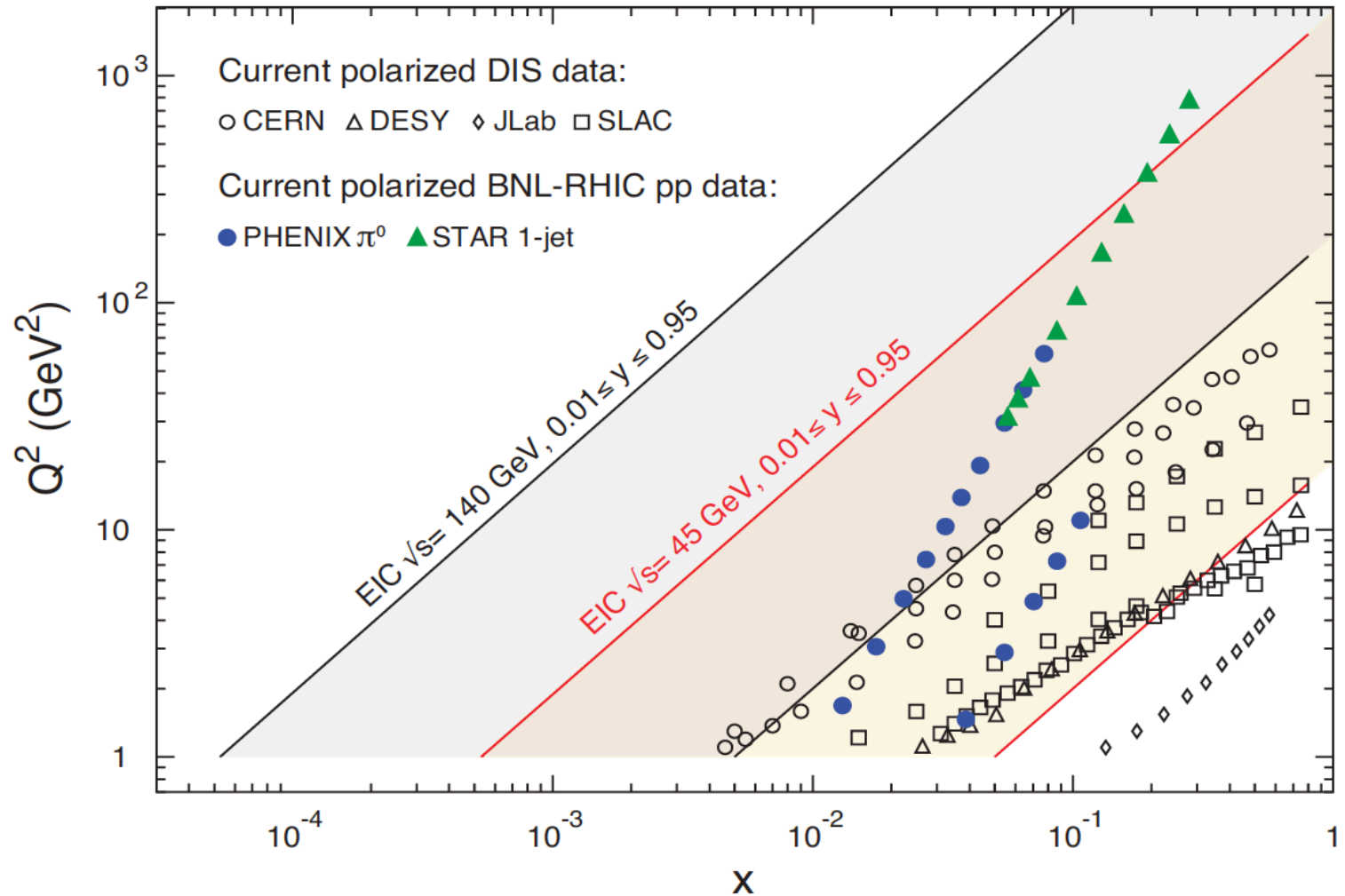
- 11 GeV, unpolarized  $e^-$  on fixed, polarized  $^{14}\text{NH}_3$
- Preliminary SHMS Monte Carlo (Gaskell, Arrington)
  - Transverse (not  $54.7^\circ$ !) UVa magnet (M. Jones)

$\theta$	E (GeV)	E' (GeV)	$Q^2$ (GeV $^2/c^2$ )	$x$	Rate (Hz)
10.5	11	5	1.842	0.164	170
10.5	11	4	1.474	0.112	152
10.5	11	3	1.105	0.074	138
10.5	11	2	0.737	0.044	100
15	11	5	3.748	0.333	28
15	11	4	2.999	0.228	30
15	11	3	2.249	0.15	32
15	11	2	1.499	0.089	34

# Transverse (Not Longitudinal) Polarized Target?

- Need a  $\text{spin} \geq 1$  nucleus, but this is a **nuclear** effect
  - Higher atomic number, higher spin more likely to reveal exotic gluonic components
- Deuteron? Expect two nucleons to good approximation
- Something heavier: Li?  $\alpha + d$
- Practical limitations from available polarized targets
  - Long history of polarized  $p$  and  $d$  in solid targets
  - Lithium Hydride and Deuteride:  ${}^6\text{LiH}$ ,  ${}^6\text{LiD}$ , also  ${}^7\text{LiH}$
  - Ammonia:  ${}^{14}\text{NH}_3$ ,  ${}^{14}\text{ND}_3$ , also  ${}^{15}\text{NH}_3$
- Leverage spin-1 Nitrogen in  ${}^{14}\text{NH}_3$ 
  - Reliable performance in beam
  - Augment polarization via transfer from H to N

# Kinematic Reach at Electron-Ion Collider



# Nuclei of Interest for Nuclear Gluonometry

Nucleus	Spin	Pol. technique	Lab.	Max. pol.	Flux	Ref.
$^2\text{H}$	1	OP, ABS	Erlangen, Madison	100%	$1\mu\text{A}$	[1]
$^6\text{Li}$	1	ABS	Madison	88%	$0.28\mu\text{A}$	[2]
$^7\text{Li}$	$\frac{3}{2}$	ABS	Madison	$\sim 1\%$		[4]
$^8\text{Li}$	2	TFM	Osaka			
$^{10}\text{B}$	3	Not known				
$^{14}\text{N}$	1	DNP	SMC	40%		[5]
$^{23}\text{Na}$	$\frac{3}{2}$	ABS+OP	Heidelberg	40%	$\text{Na}^+ 65\mu\text{A}$ $\text{Na}^{9+} 30\text{ nA}$	[3] [3]

ABS: atomic beam source

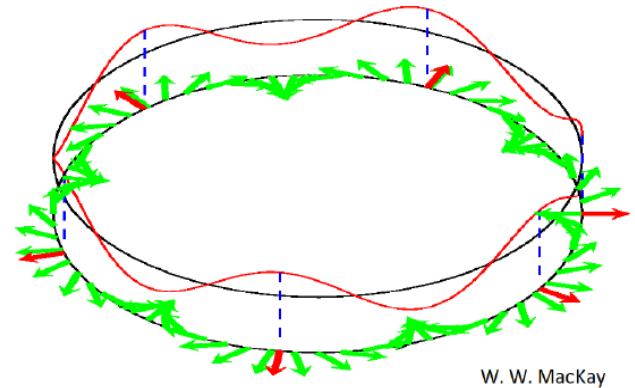
DNP: dynamic nuclear polarization

OP: optical pumping

TFM: tilted foil method

# Spin Manipulation in Ring

- Depolarizing resonances when spin precession frequency = frequency of perturbing B field<sup>7</sup>
- Imperfection:  $\nu_s = G\gamma = n$
- Intrinsic:  $\nu_s = G\gamma = Pn + \nu_y$
- Anomalous  $g$ -factor  $G$ 
  - ${}^7\text{Li}$ :  $G$  of 1.53 (like proton's 1.79)  $\Rightarrow$  easy
  - ${}^6\text{Li}$ :  $G$  of -0.18 (like deuteron's -0.14)  $\Rightarrow$  hard
  - ${}^{23}\text{Na}$ :  $G$  of 0.55 could work at RHIC with more snakes
  - Figure-8 makes for easier manipulation at lower  $G$



<sup>7</sup>Bai, Courant *et al.*, BNL-96726-2012-CP, 2012.

# Towards Design of an Optimized EIC Experiment

- Exploration of  $\Delta$  in  $x$ ,  $Q^2$ ,  $S$ , &  $A$ 
  - How does effect change for different nuclear spin  $\geq 1$ ?
  - Spin-1/2 species important cross-check
  - How does effect change for different atomic masses?
  - Spin-1  ${}^6\text{Li}$  vs. Spin-3/2  ${}^7\text{Li}$
- Simulate measurement for Inclusive DIS on Nuclei
- Estimate running time for given statistical uncertainties
  - Species choice informed by simulation
  - Loss of luminosity compared to JLab made up for by lack of dilution, kinematic coverage

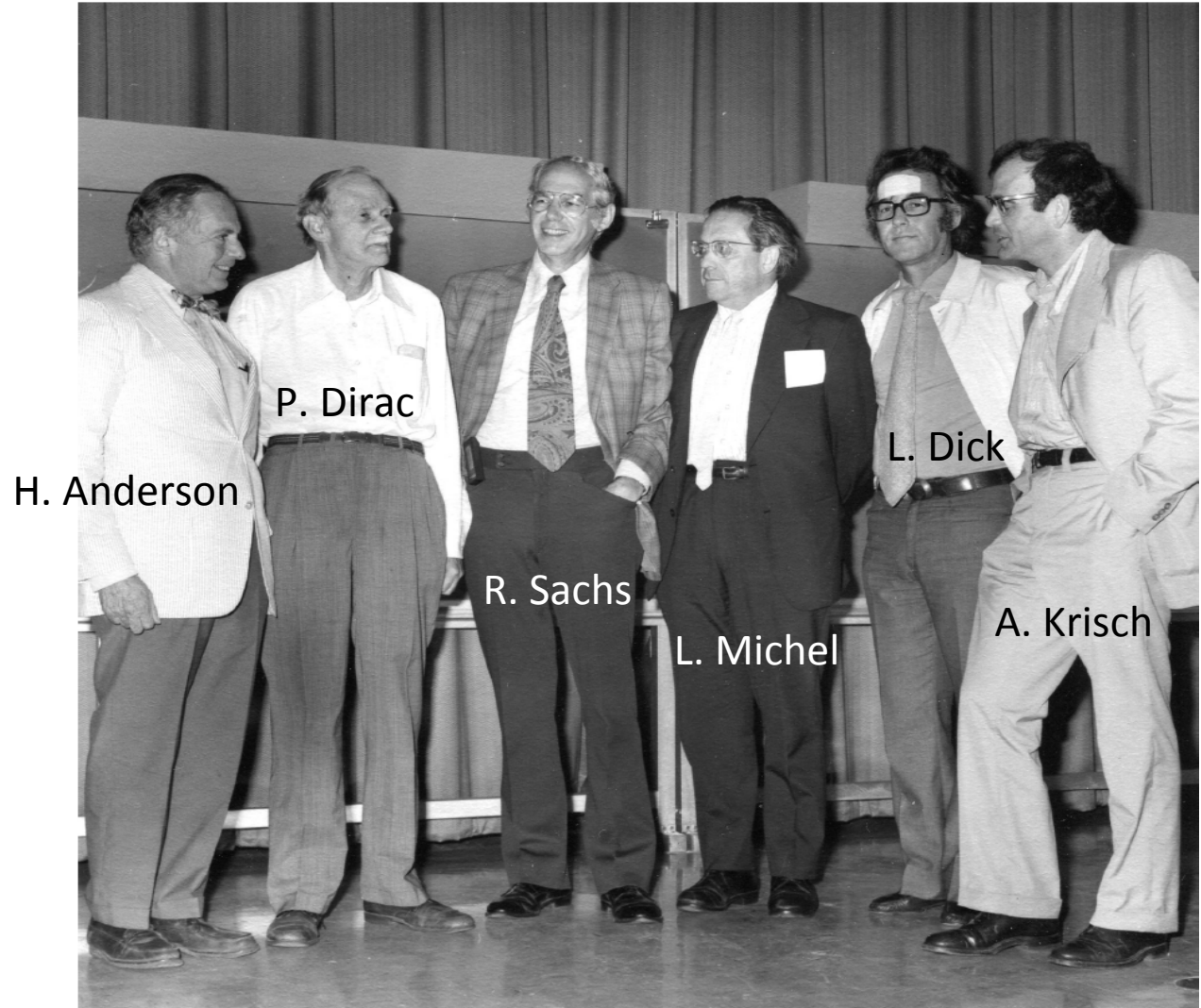


# **Report from International Spin Physics Committee**

# Symposia on High Energy Spin Physics

- Started at Argonne in 1974 at ANL: First polarized HE proton beam in the 12 GeV **Z**ero-**G**radient-**S**ynchrotron)
- Following, every two years:
  - Argonne (1976, 1978)
  - Lausanne (1980)
  - BNL (1982)
  - Marseille (1984)
  - Protvino (1986)
  - Minneapolis (1988)
  - Bonn (1990)
  - Nagoya (1992)
  - Bloomington (1994)

# 1<sup>st</sup> International High Energy Spin Physics Symposium at Argonne, 1974



# Joint International Symposia on Spin Physics

- Started at Amsterdam in 1996
- Following every 2 years:
  - Protvino (1998)
  - Osaka (2000)
  - BNL (2002)
  - Trieste (2004)
  - Kyoto (2006)
  - Charlottesville (2008)
  - Juelich (2010)
  - Dubna (2012)
  - Beijing (2014)
  - Urbana-Champaign (2016)

# International Spin Physics Committee

## Membership of the International Committee for Spin Physics Symposia (ISPC)

1 January 2015 to 31 December 2016

### ***Voting Members:***

R. Milner – MIT (Chair)  
E. Aschenauer - BNL  
Hideto En'yo (RIKEN)  
N. Makins – Illinois  
M. Poelker – Jlab  
H. Stroeher – Juelich

E. Steffens - Erlangen (Past-Chair)  
A. Belov – INR Moscow  
P. Lenisa – Ferrara  
A. Martin – Trieste  
R. Prepost – Wisconsin  
O. Teryaev - Dubna

M. Anselmino – Torino  
H. Gao – Duke (Chair-Elect)  
B.-Q. Ma – Peking  
A. Milstein – Novosibirsk  
N. Saito – KEK

### ***Honorary Members:***

F. Bradamante – Trieste  
A.V. Efremov – JINR  
A.D. Krisch – Michigan  
T. Roser – BNL

E.D. Courant – BNL  
G. Fidecaro – CERN  
A. Masaike – Kyoto  
V. Soergel – Heidelberg

D.G. Crabb – Virginia  
W. Haeberli – Wisconsin  
C.Y. Prescott – SLAC  
W.T.H. van Oers – Manitoba

**Haiyan Gao succeeds Richard Milner as Chair January 1, 2017 for a four-year term**

# Workshop on Polarized Sources, Targets and Polarimetry PSTP 2017

- It was decided by the ISPC that PSTP 2017 will be held at the Center for Axion and Precision Physics at the Institute for Basic Science, Daejeon, South Korea in September or October, 2017
- The co-organizers are Yannis Semertzidis and Seongtae Park



# 23<sup>rd</sup> International Spin Physics Symposium 2018

- It was decided by the ISPC that the next International Spin Physics Symposium will be held at the University of Ferrara, Italy in September, 2018.
- The organizer is Paolo Lenisa from the University of Ferrara and INFN.



# Summary

- It is an exciting time for spin physics.
- It is shaping our view of the microcosm.
- Upgrades of existing facilities ensure vitality for about a decade.
- Polarization technical developments reported at SPIN 2016 are truly impressive.
- In the long term we absolutely must have the electron-ion collider.
- We must find effective ways to convey what we are learning about the fundamental structure of matter to the non-specialist.
- I wish to congratulate Matthias and Anselm and their colleagues for a fantastic SPIN 2016.
- See you in Ferrara in September 2018!