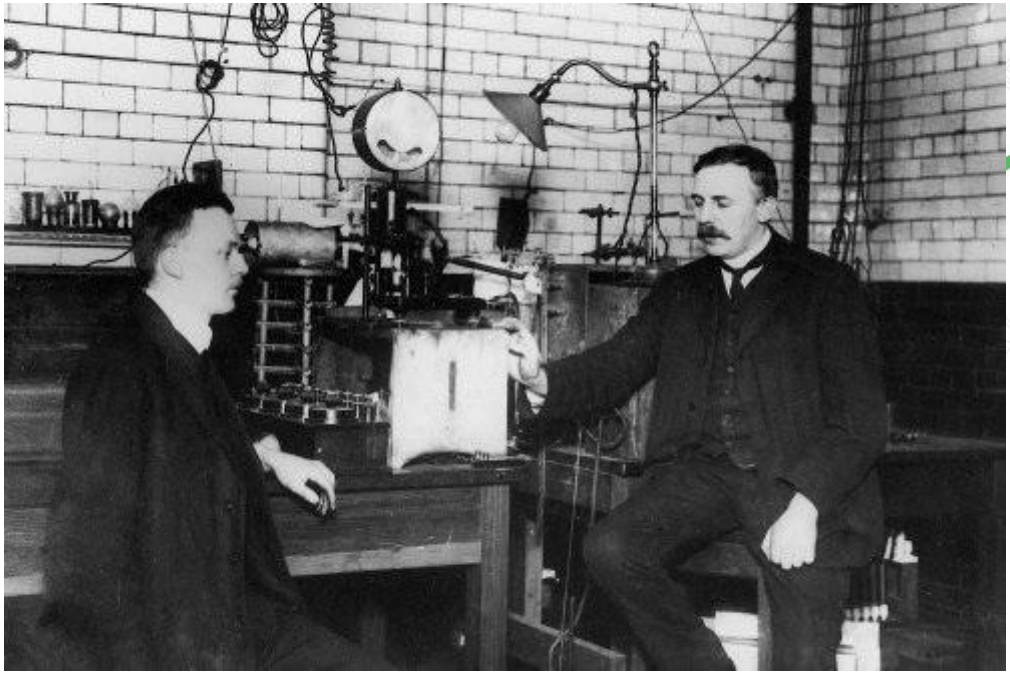
100 Years of Proton



Xiangdong JI, Shanghai Jiao Tong University

18th International Conference on Hadron Spectroscopy and Structure, Guilin, China, Aug. 19, 2019

Outline

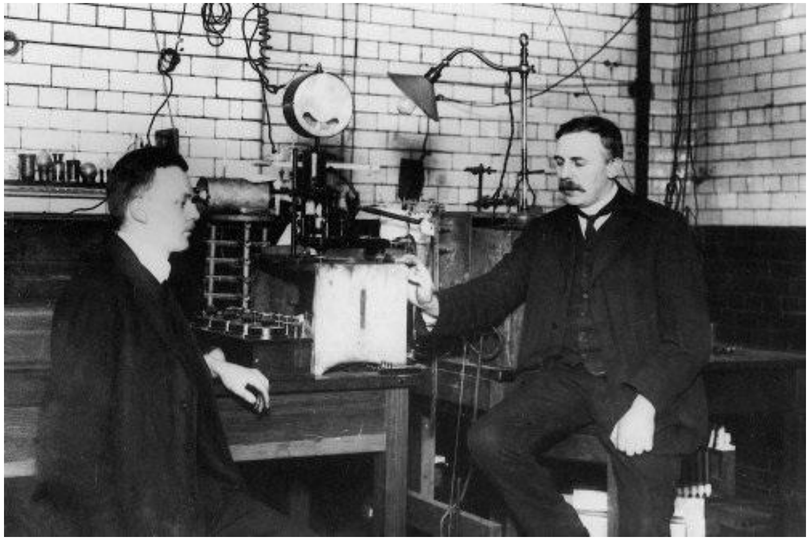
- Discovery of the proton
- What's inside a proton?
- Challenges to picture a proton
- Way forward: Exa-scale supercomputing and Electron-Ion Collider
- Conclusion

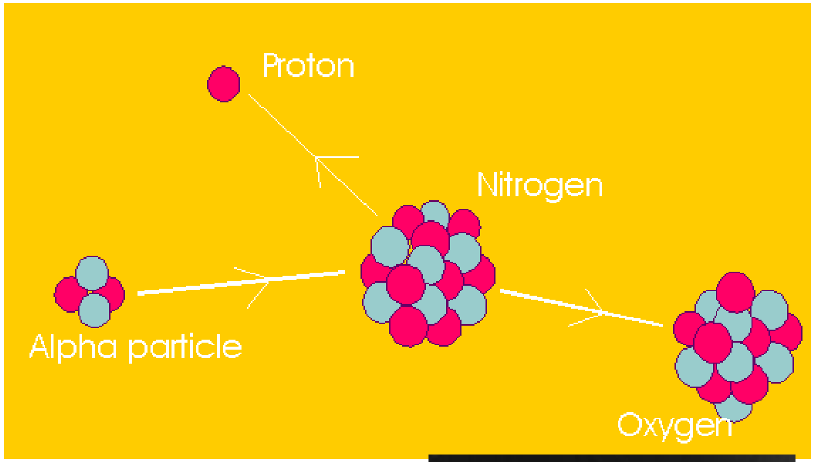
Discovery of the proton

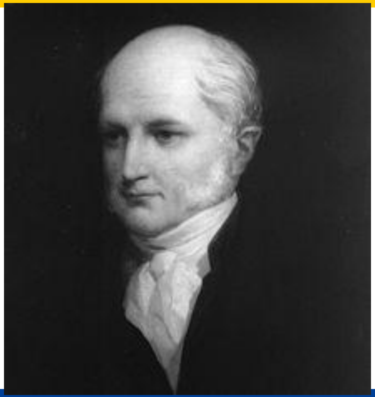
Discovery of proton through nuclear reaction

- Proton was discovered in nuclear reaction

$$^{14}N + \alpha \rightarrow {}^{17}O + p \quad (1917)$$







Confirmed the hypothesis by W. Prout that all elements contain hydrogen.

1919 publication by Rutherford

Journal

The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science ›

Series 6

Volume 37, 1919 - Issue 222

[581]

LIV. *Collision of α Particles with Light Atoms.* IV. *An Anomalous Effect in Nitrogen. By* Professor Sir E. Rutherford, *F.R.S.**

IT has been shown in paper I. that a metal source, coated with a deposit of radium C, always gives rise to a number of scintillations on a zinc sulphide screen far beyond the range of the α particles. The swift atoms causing these scintillations carry a positive charge and are deflected by a magnetic field

“Collision of α Particles with Light Atoms,” p. 586):

- *“From the results so far obtained, it is difficult to avoid the conclusion that the long-range atoms arising from collision of α particles with nitrogen are not nitrogen atoms but probably atoms of hydrogen⋯. If this be the case, we must conclude that the nitrogen atom is disintegrated under the intense forces developed in a close collision with a swift α particle, and that the hydrogen atom which is liberated formed a constituent part of the nitrogen nucleus.”*

The name

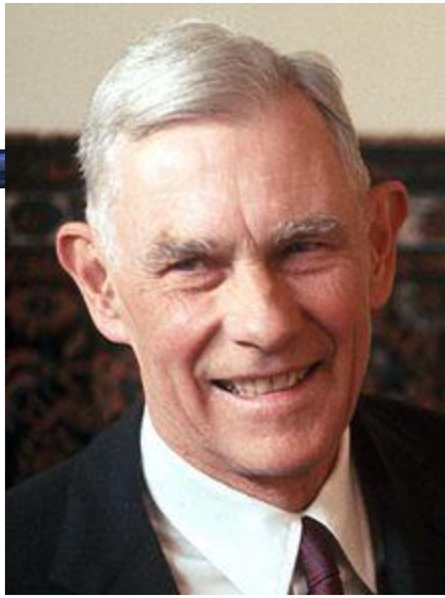
- Rutherford was asked by Oliver Lodge for a new name for the positive hydrogen nucleus.
- He initially suggested both proton (Greek “first”) and prouton (after Prout).
- The (RS) meeting had accepted that the hydrogen nucleus be named the "proton", following Prout's word "protyle". The first use of the word "proton" in the scientific literature appeared in

  Nature. 106 (2663): 357–358. 1920

What's inside a proton?

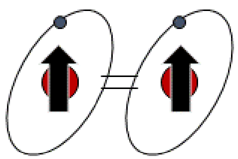
Proton's Spin

- It was first discovered through the quantum theory of the specific heat of atomic hydrogen in 1927 by David Dennison (1900-1976)



W. Heisenberg, Nobel Prize 1932,
"for the creation of quantum mechanics, the application of which has, inter alia, led to the discovery of the allotropic forms of hydrogen!"

Heat capacity of H_2

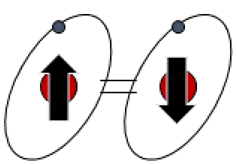


Orthohydrogen

$$\underset{(antisym)}{\psi_{tot}} = \underset{(sym)}{\psi_{vib}}\,\underset{(antisym)}{\psi_{rot}}\,\underset{(sym)}{\psi_{spin}}$$

$$\psi_{rot} = 1,3,5\ldots$$

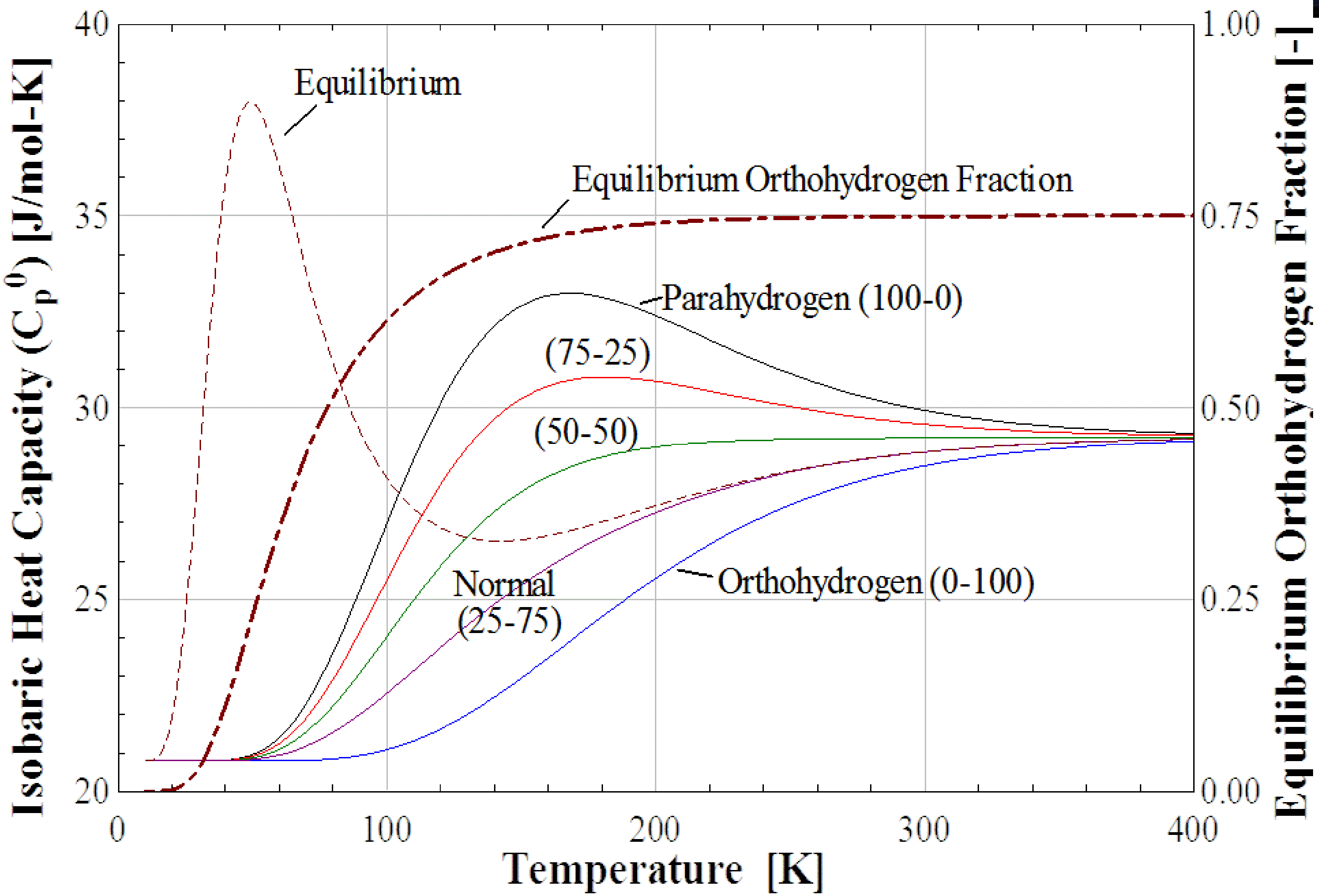
Normal Hydrogen
3-ortho:1-para



Parahydrogen

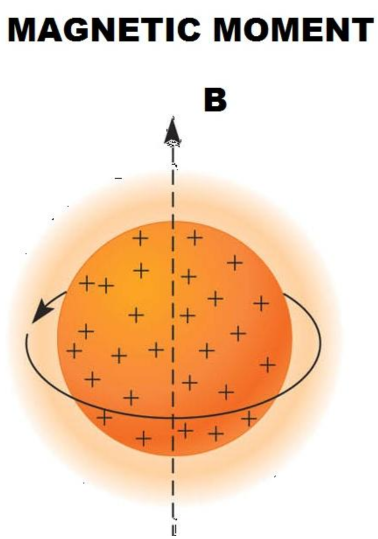
$$\underset{(antisym)}{\psi_{tot}} = \underset{(sym)}{\psi_{vib}}\,\underset{(sym)}{\psi_{rot}}\,\underset{(antisym)}{\psi_{spin}},$$

$$\psi_{rot} = 0,2,4\ldots$$



Proton's magnetic moment (1933)

- A spinning proton with a charge must have a magnetic moment.



- The first attempted by Otto Stern in 1933 (Stern-Gerlach exp)

Theorists' embarrassment

- Before Stern got his result, he asked great theorists of the time to make a prediction. And everyone wrote,

$$\mu_p = \frac{e\hbar}{2m_N c} \equiv \mu_N$$

- And Stern's result was,

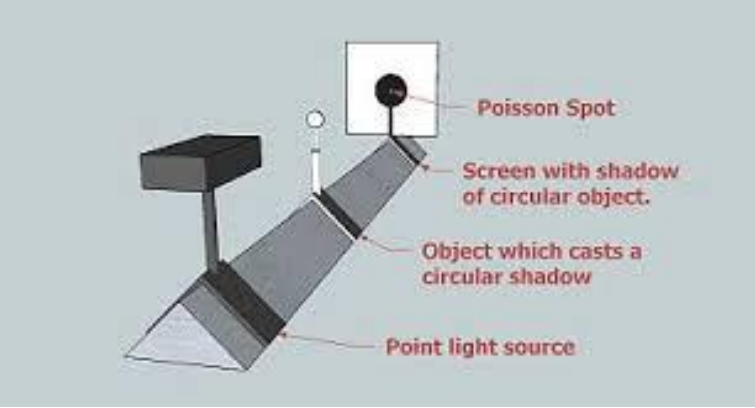
$$\mu_p = 2.5\mu_N$$

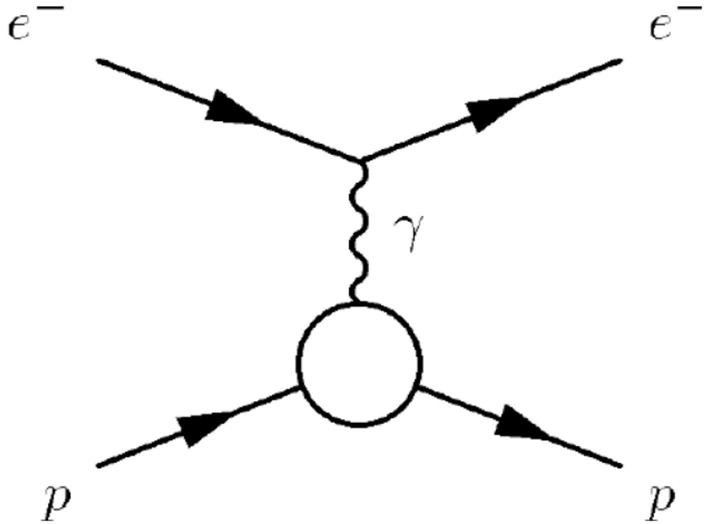
Nobel prize in 1943

"for his contribution to the development of the molecular ray method and his discovery of the magnetic moment of the proton".

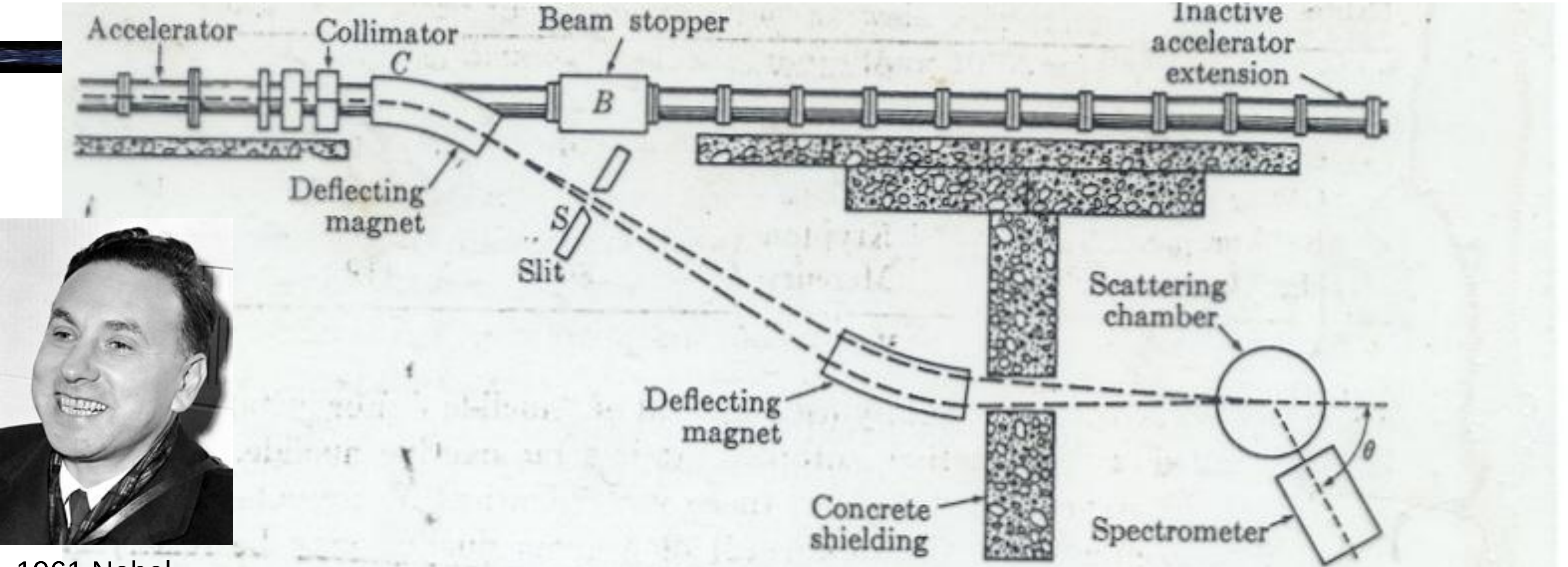
Proton must has a finite size!

- A method of measuring small size is diffraction
- Electron diffractive scattering can measure the charge radius of a proton.



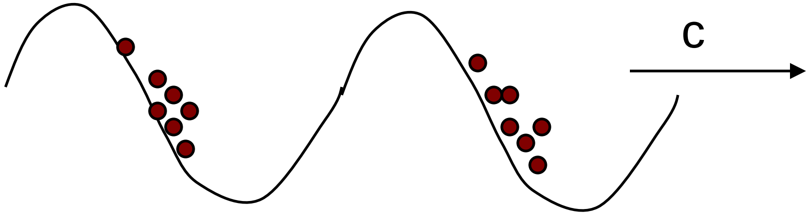


Electron scattering at Stanford (1954 – 57)



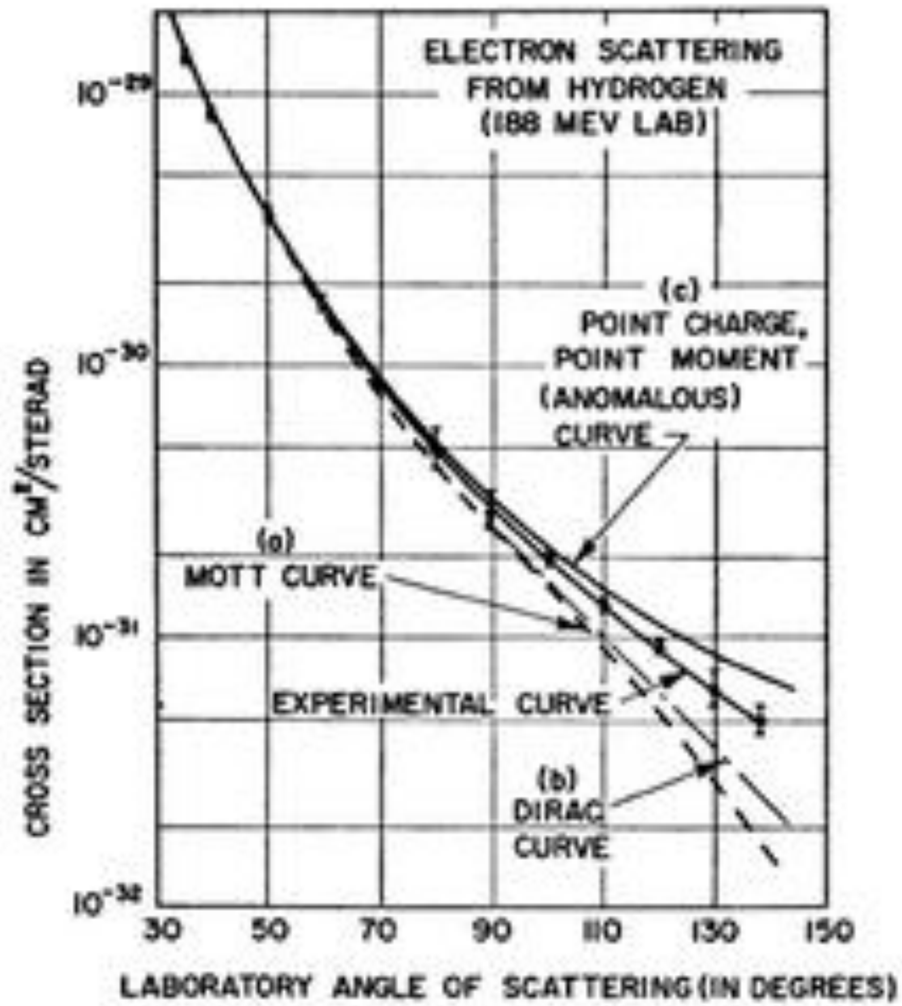
1961 Nobel Prize winner

Professor Hofstadter's group worked here at SLAC during the 1960s and were the first to find out about the charge distribution of protons in the nucleus – using high energy

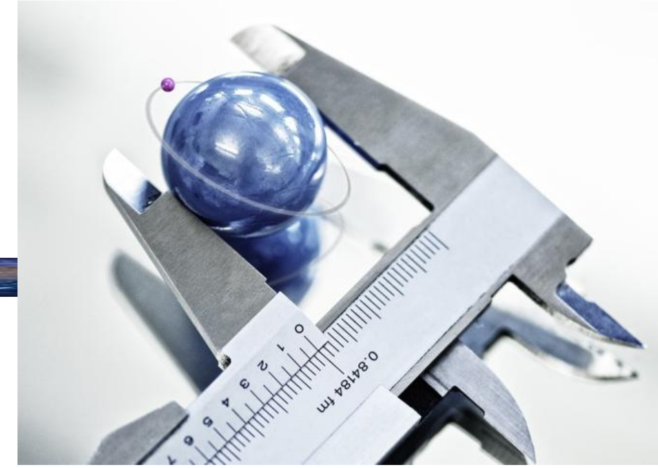


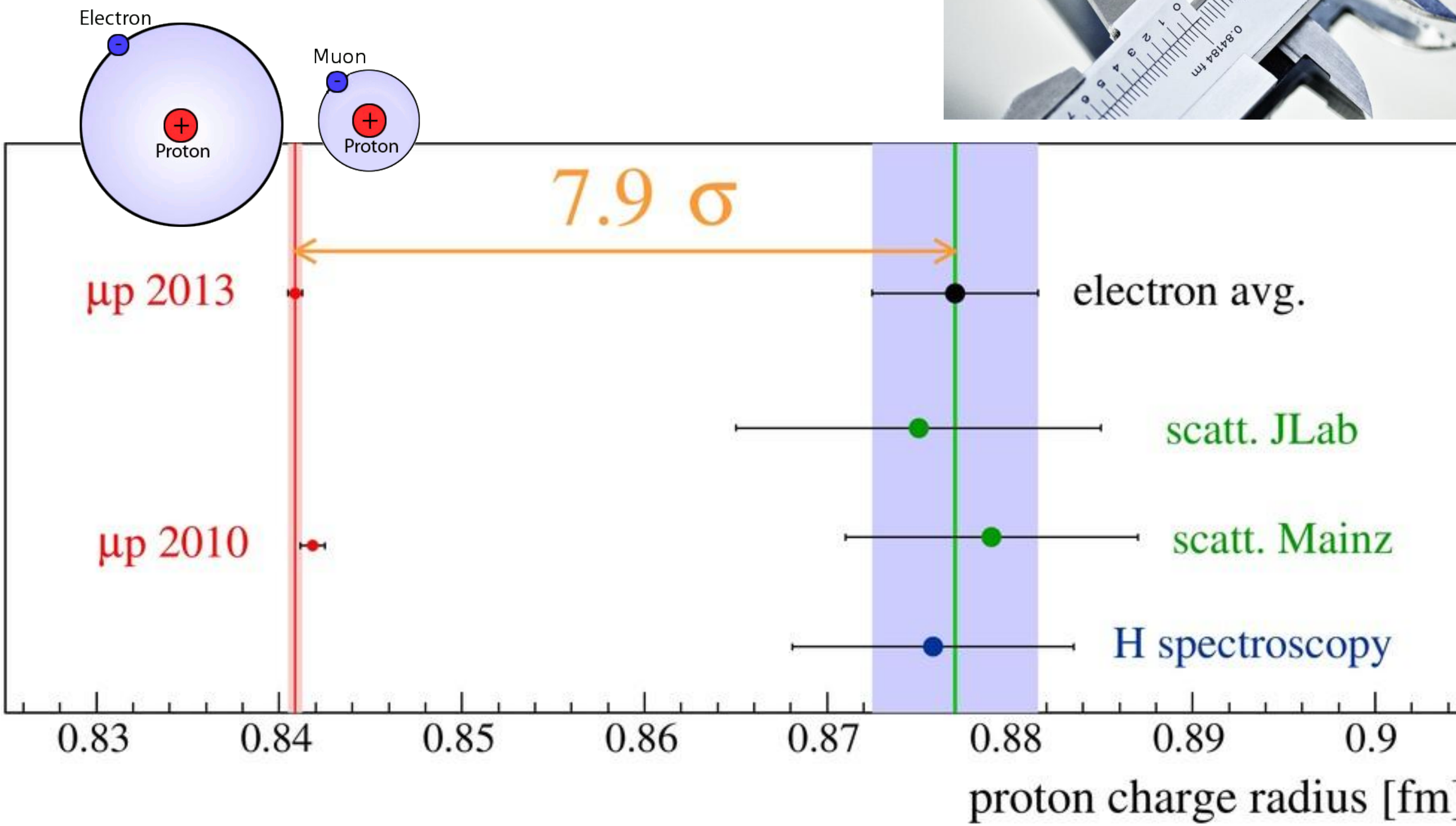
A linear accelerator LINAC was used to accelerate the electrons

Elastic Electron Scattering



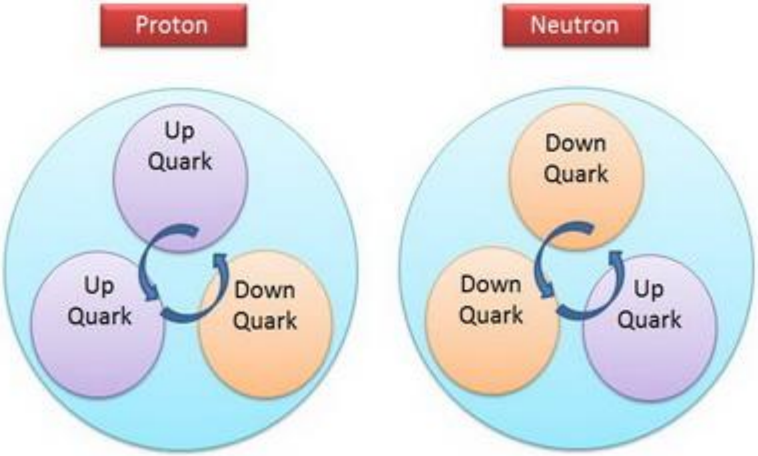
Charge radius puzzle?





Quark Model (1964)

- Gell-Mann and Zweig, speculate entirely from SU(3) symmetry principle
- Protons are made of three s=1/2 quarks.



- There was no direct experimental evidence.

Proton mass and spin

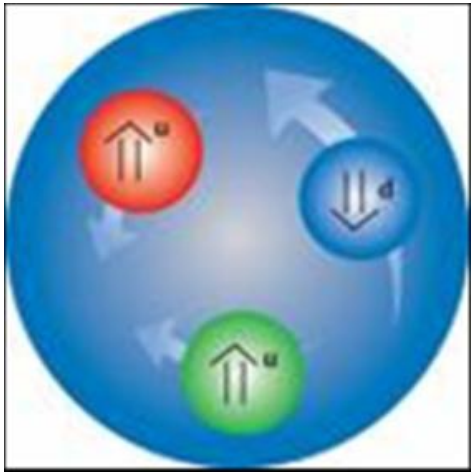
- Mass is about the sum of three constituent quark mass

$$M_p \sim 3\, M_q$$

M_q is about 300 MeV.

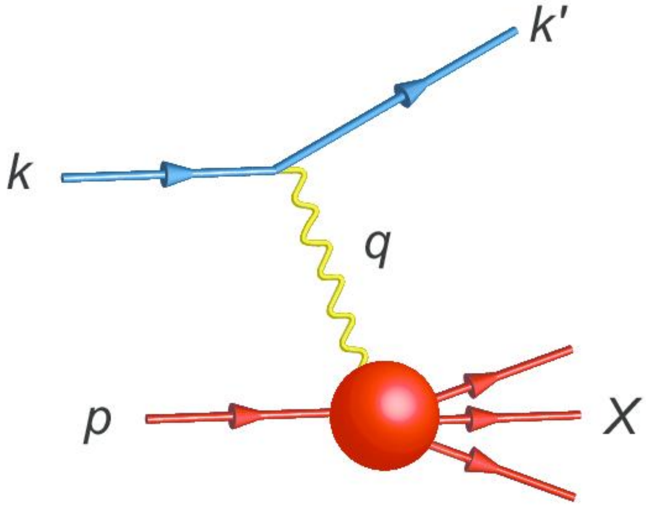
- Spin

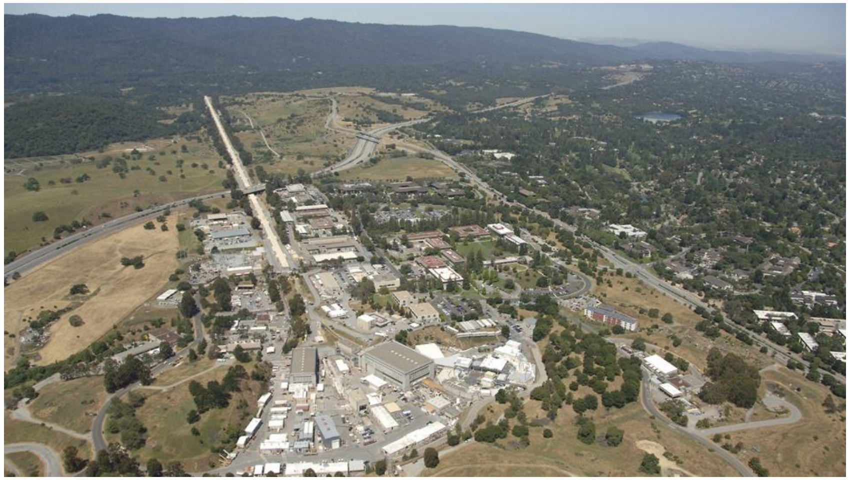
$$1/2 = 1/2 \oplus 1/2 \oplus 1/2$$

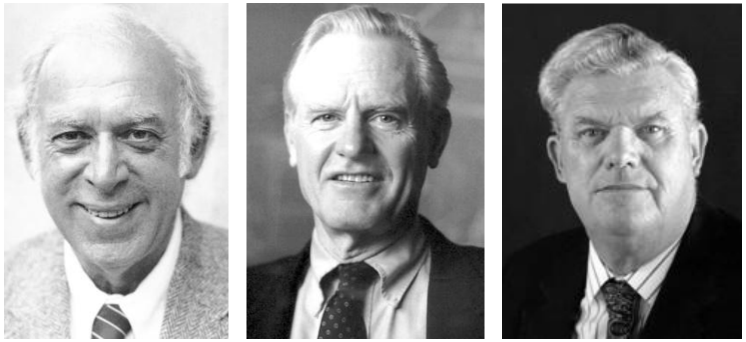


Deep-inelastic scattering

- **Protons were broken into pieces by high-energy electrons**

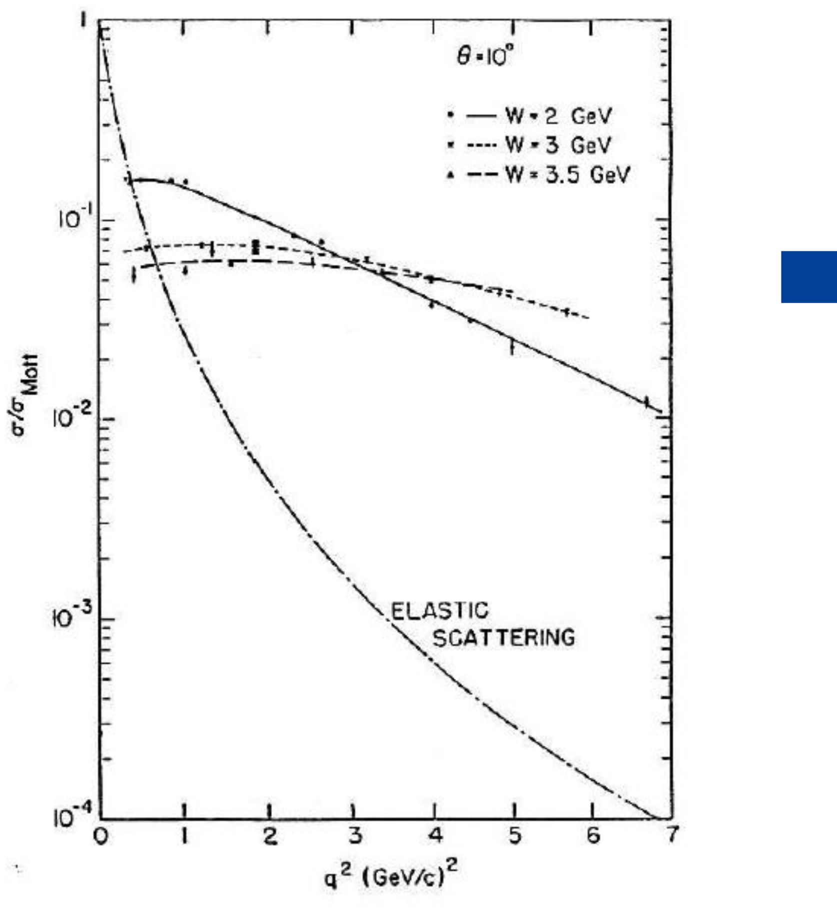




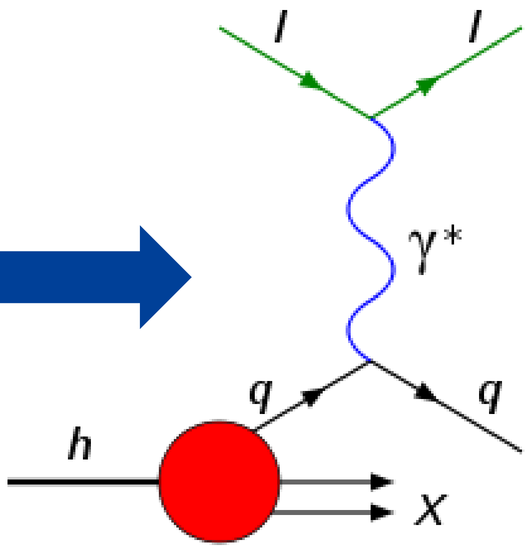


Nobel Prize 1990

Discovery of quarks



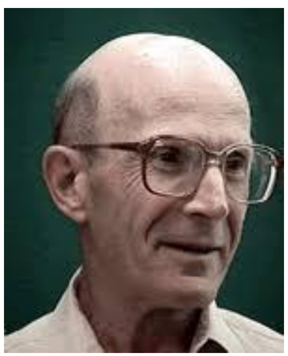
: Inelastic electron scattering data versus Q^2 at fixed W.



Birth of QCD (1964-1973)

- **The fundamental theory for proton**
  Quantum Chromodynamics (QCD)

Quantum field theory (quantum + relativity)





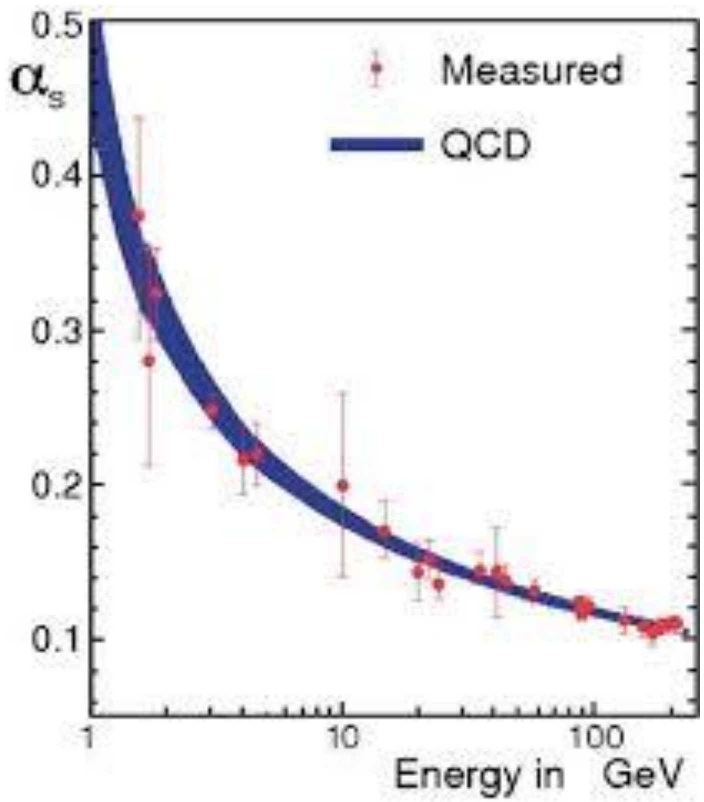




Difficulty with QCD

- An SU(3) gauge theory, with color charges.
- **Don't know how to calculate!**

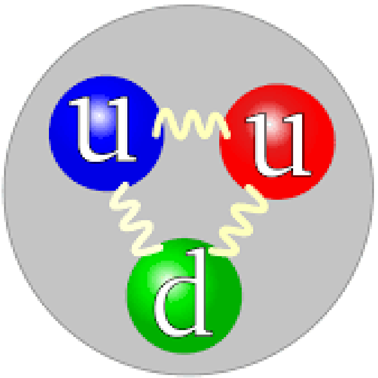
Strong interaction coupling constant

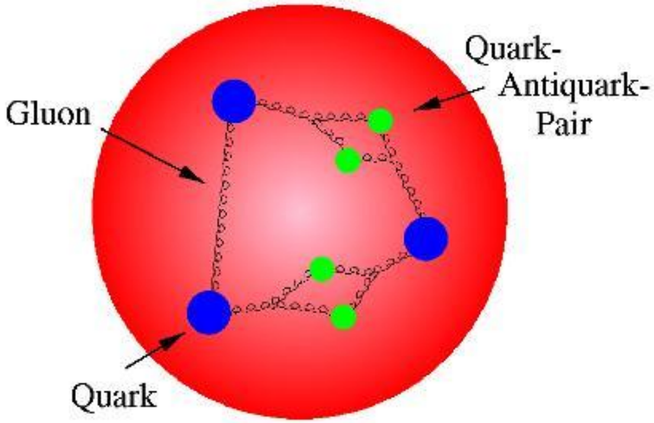


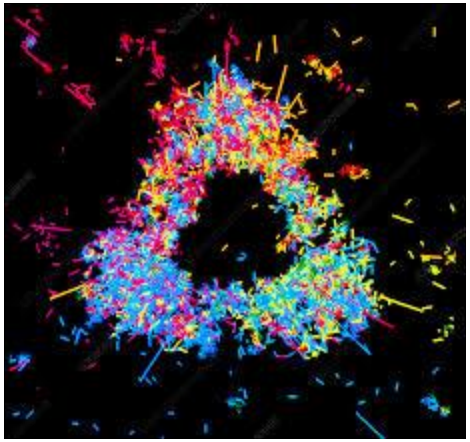
Quark model lead us to QCD, but once we have QCD, it is difficult to understand quark model

Challenges to picture a proton

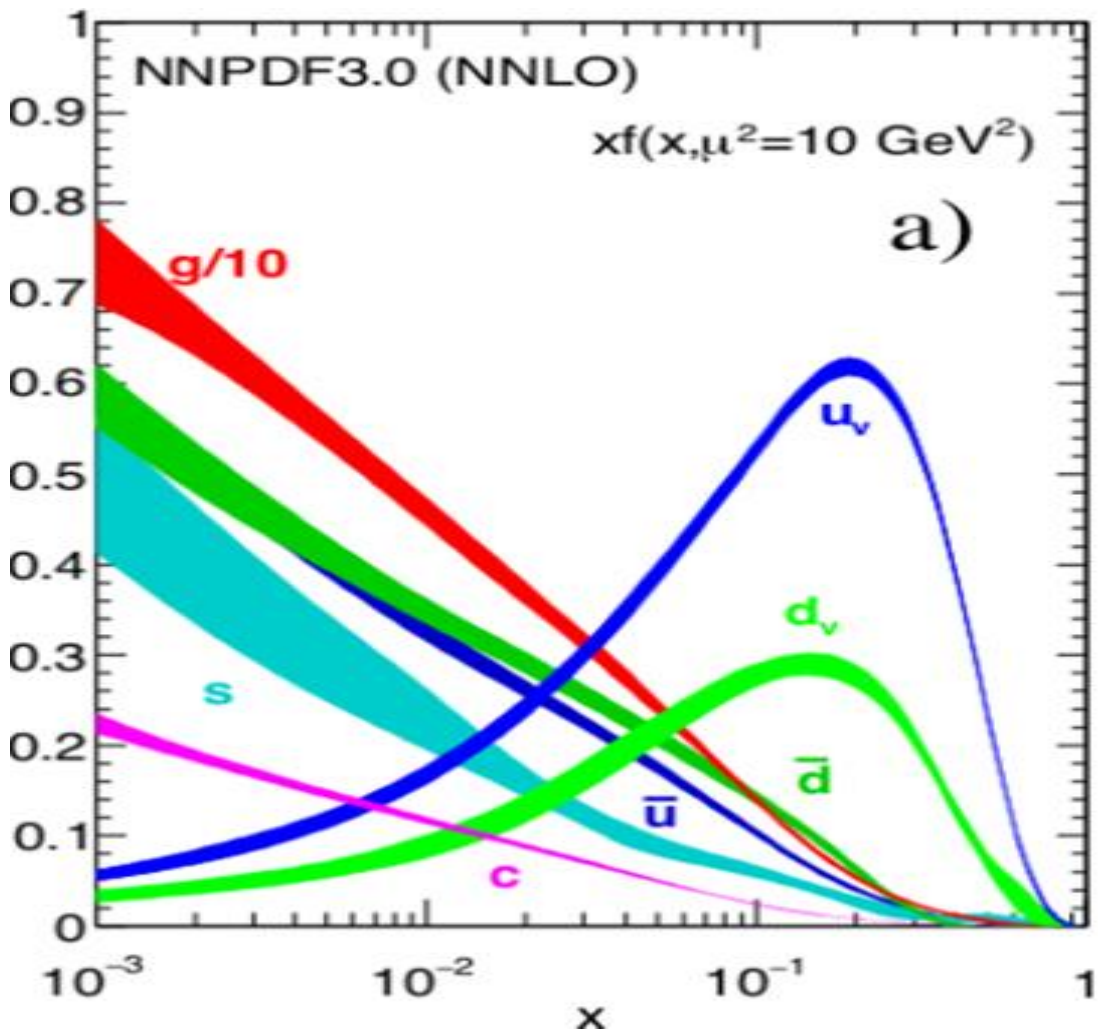
Many Pictures of Proton

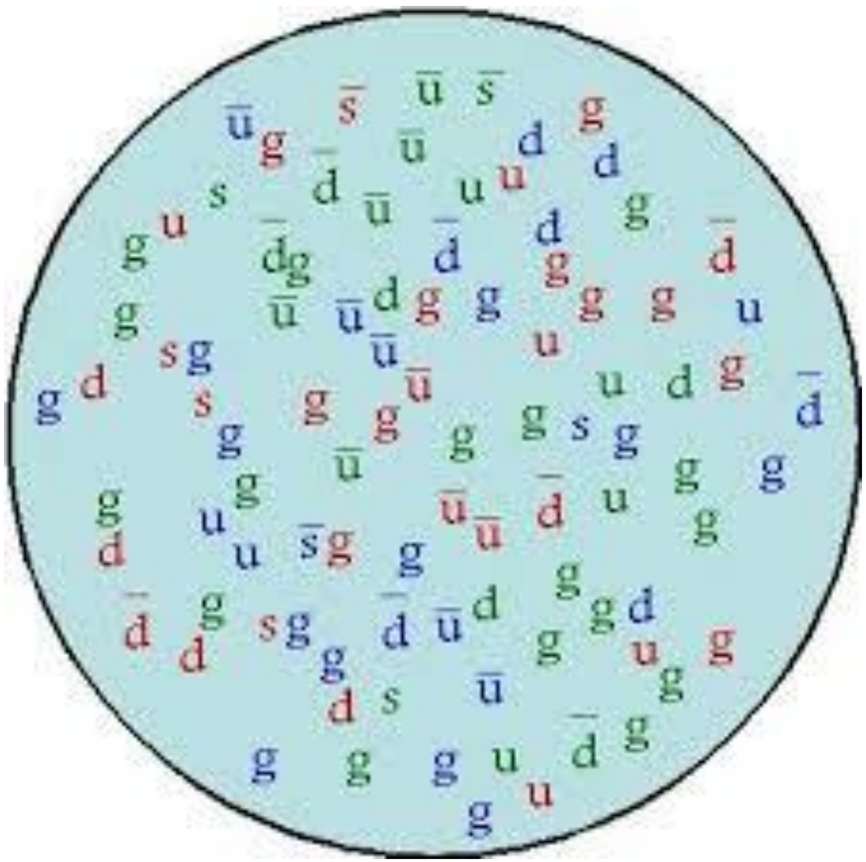


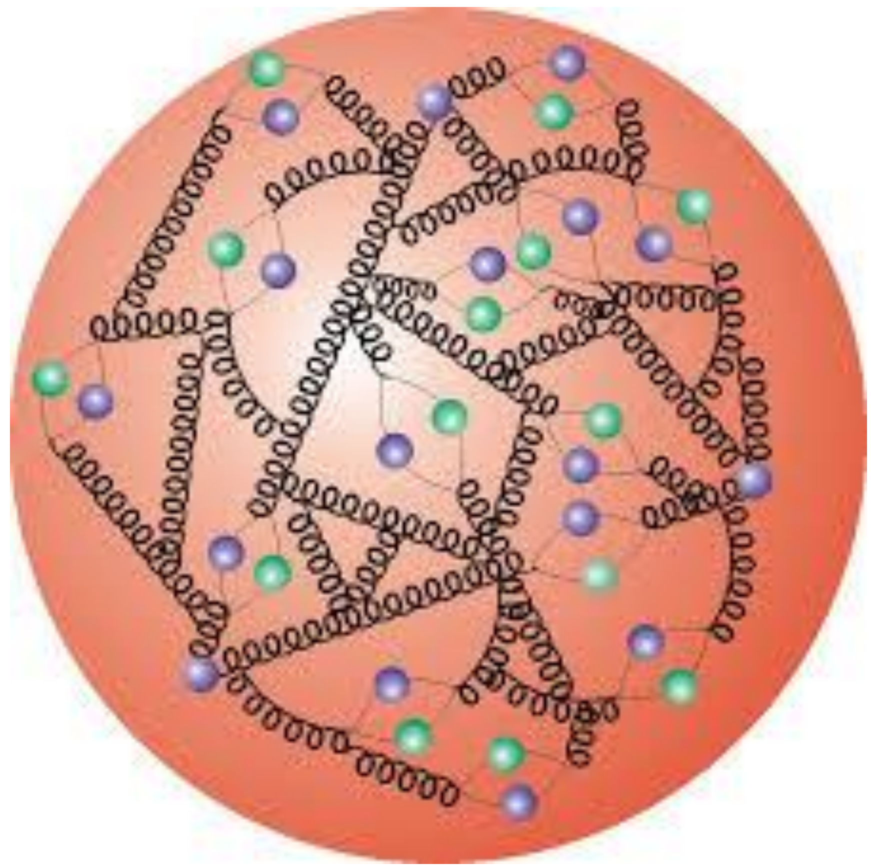




Parton (quark and gluon) distributions as measured in DIS







What is the proton like?

Going back to the basics:

Where do the proton's spin and mass come from?

Spin Structure of the proton

Vernon Hughes

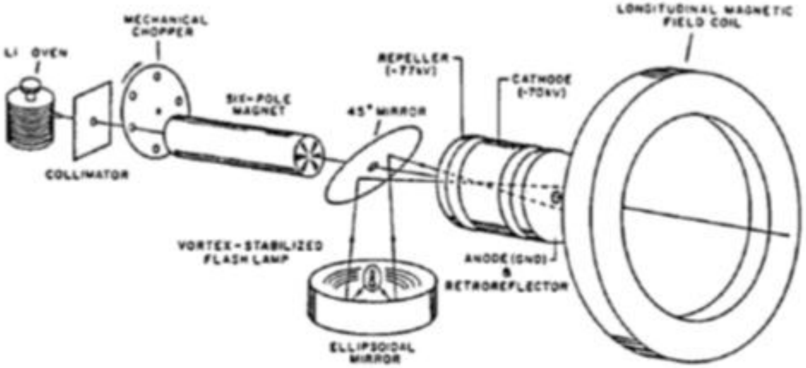


Figure 13 Schematic diagram of the Yale polarized electron source, PEGGY, showing the principal components of the lithium atomic beam, the ultraviolet optics, and the ionization region electron optics.

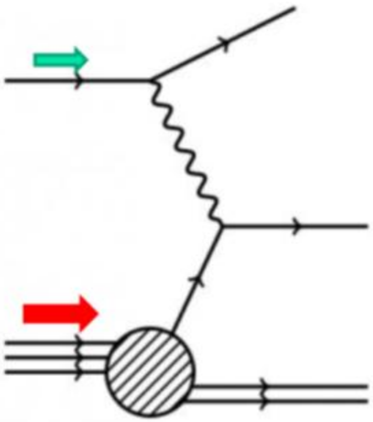
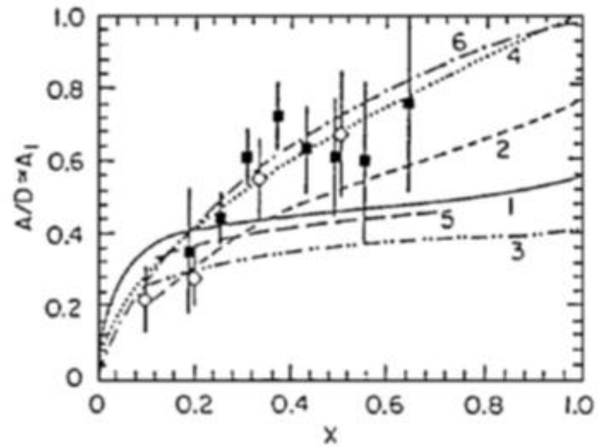


Figure 14 Experimental values A_1 compared with theories. (1) Symmetrical valence-quark model. (2) Current quarks. (3) Orbital angular momentum. (4) Unsymmetrical model (63). (5) MIT bag model. (6) Source theory. (See Reference 62 for references for theoretical curves.)



$$A = (\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow})/(\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow})$$

European Muon Collaboration (EMC)) exp.

- EMC polarized DIS, lead by Yale, Lancaster, and Liverpool groups.
- The asymmetry can determine the fraction of the proton spin carried in the spin of the quarks.

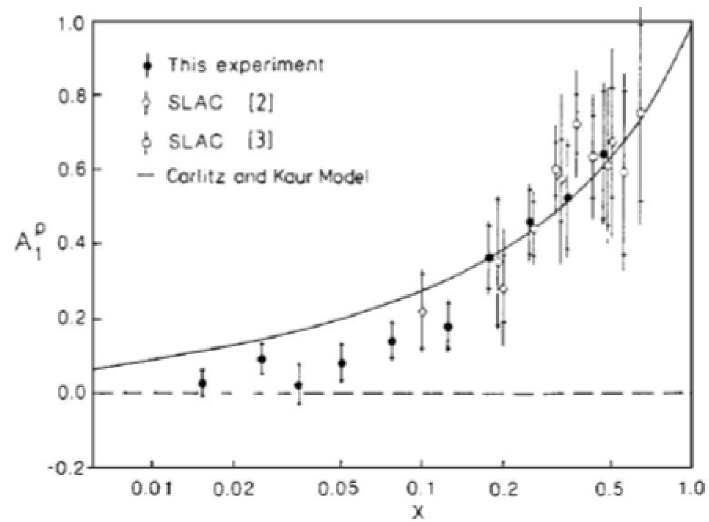


Figure 17 The asymmetry A_1^p for the proton as a function of x from the EMC ("this experiment") and SLAC experiments (62). The curve is from the model of Reference 63.

Using the measured value of Γ_1^p we compute the mean z component of spin for each quark flavor: $\langle s_z \rangle_u = 0.39(3)$; $\langle s_z \rangle_d = -0.24(3)$; $\langle s_z \rangle_s = -0.095(30)$; $\langle s_z \rangle_{\text{quarks}} = 0.06(8)$ with $s^p = \frac{1}{2}$.

This surprising result that the quark spins carry only a small fraction of the proton spin and, in addition, that the strange quarks have a negative polarization constitute the spin crisis or, perhaps better, the spin puzzle.

"Spin Crisis"

An Investigation of the Spin Structure of the Proton in Deep Inelastic Scattering of Polarized Muons on Polarized Protons
European Muon Collaboration (J. Ashman (Sheffield U.) *et al.*). Jun 1989. 35 pp.
Published in **Nucl.Phys. B328 (1989) 1**
CERN-EP-89-73
DOI: 10.1016/0550-3213(89)90089-8
Conference: C94-01-05.1, p.351-385 Proceedings

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server
Data: INSPIRE | HepData

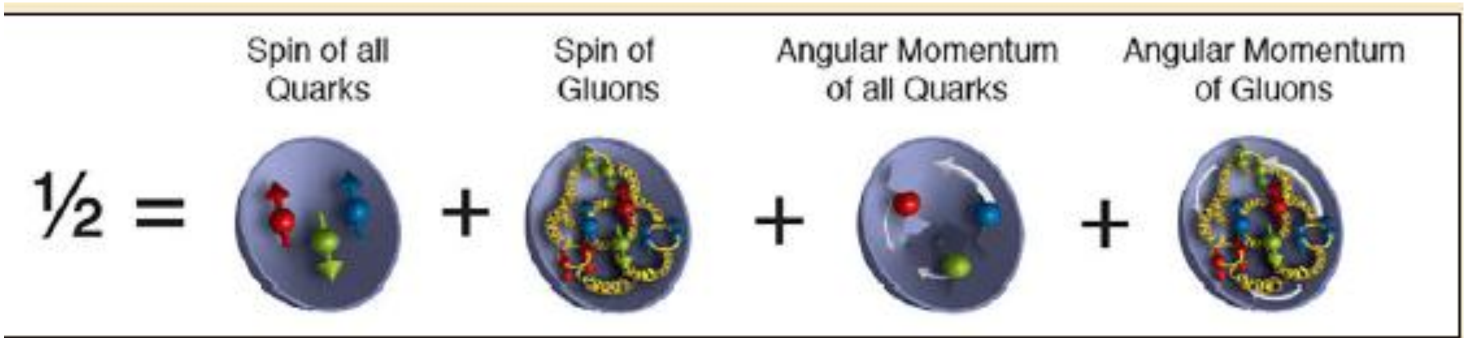
详细记录 - Cited by 1747 records 1000+

A Measurement of the Spin Asymmetry and Determination of the Structure Function g(1) in Deep Inelastic Muon-Proton Scattering
European Muon Collaboration (J. Ashman (Sheffield U.) *et al.*). Dec 1987. 7 pp.
Published in **Phys.Lett. B206 (1988) 364**
CERN-EP-87-230
DOI: 10.1016/0370-2693(88)91523-7
Conference: C94-01-05.1, p.340-346 Proceedings

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service
Data: INSPIRE | HepData

详细记录 - Cited by 2079 records 1000+

Spin structure of the proton



- Two pictures about the proton spin:
  - Jaffe & Manohar, 1990

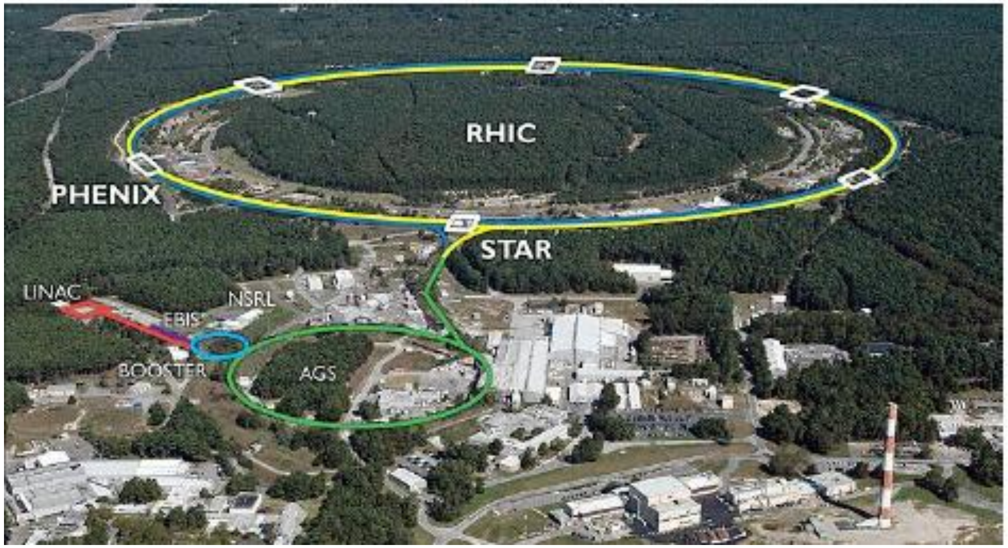
$$\frac{1}{2} = \frac{1}{2}\ \Delta\Sigma + \Delta G + \ell_q^z + \ell_g^z$$

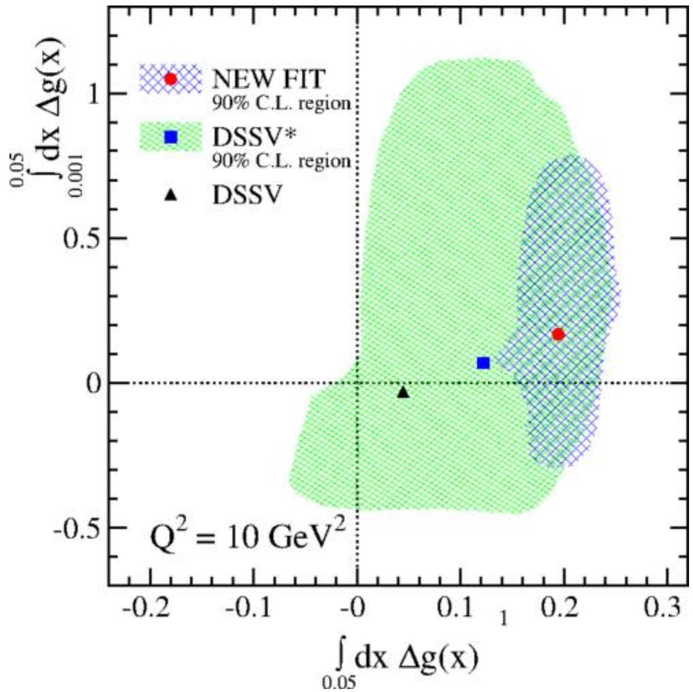
    - Parton picture for longitudinally polarized nucleon
  - X. Ji, 1996

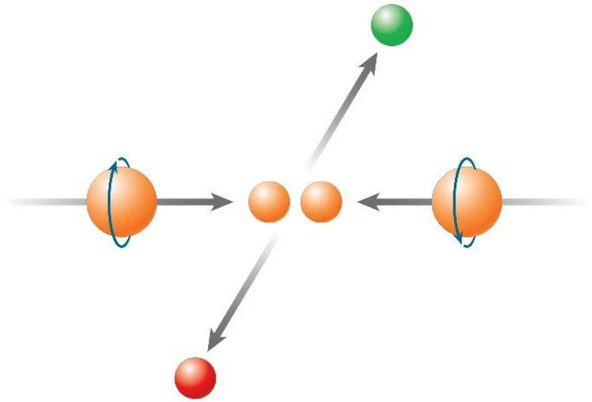
$$\frac{1}{2} = J_q + J_g = \frac{1}{2}\Delta\Sigma + L_q^z + \mathrm{J_g}$$

    - Naturally relate to the partons in a trans. polarized nucleon

How much gluon contributes?







Vogelsang et al

$\Delta G \sim 0.2\hbar$

Proton mass

- M_p = 938 MeV/c^2
- Proton's constituents

  $m_u \sim 2.3$ MeV/c^2 , $m_d \sim 4.8$ MeV/c^2

  $m_g \equiv 0$
- Where does the proton get mass?

  Einstein: $M_p = E_p/c^2$

Proton's internal energy

- Quark's kinetic energy

$$H_q = \int d^3\vec{x}\ \bar{\psi}(-i\mathbf{D}\cdot\alpha)\psi,$$

- Gluon energy

$$H_g = \int d^3\vec{x}\ \frac{1}{2}(\mathbf{E}^2 + \mathbf{B}^2),$$

- Quark mass and Quantum anomaly

How to measure them? what do they tell us about the strong interaction forces?

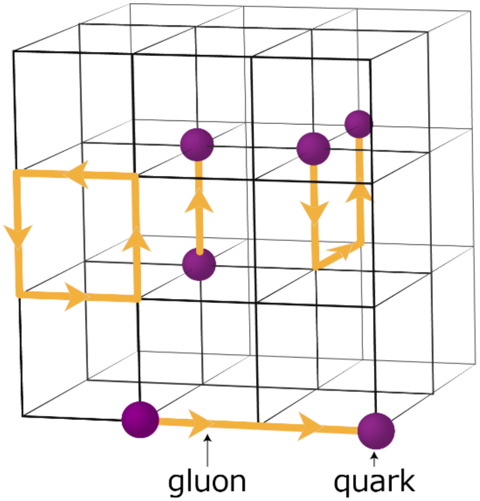
Way Forward:

Exa-Scale Supercomputing

Lattice Field Theory

- Simulating Quantum Field Theory on a classical computer! (1974)

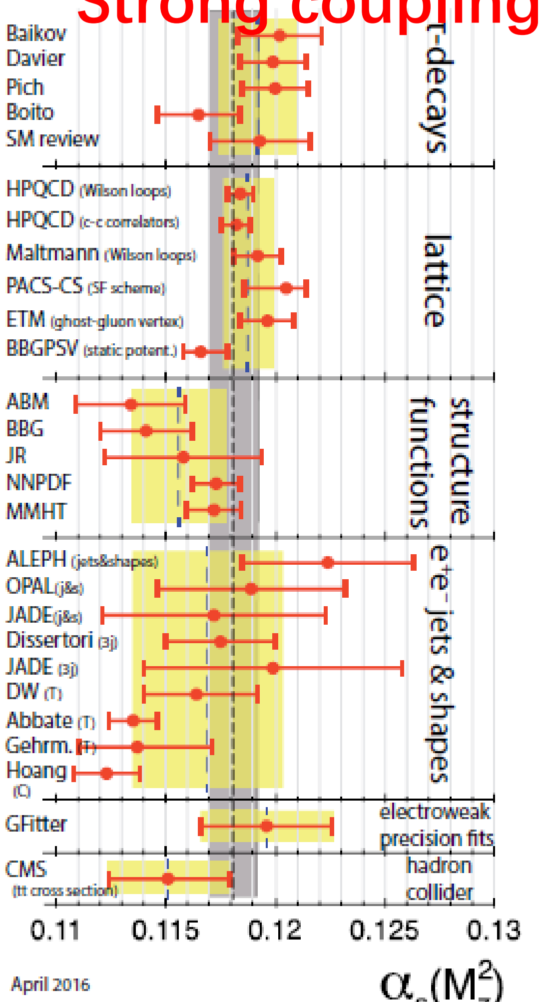
Ken Wilson
Nobel Prize, 1982



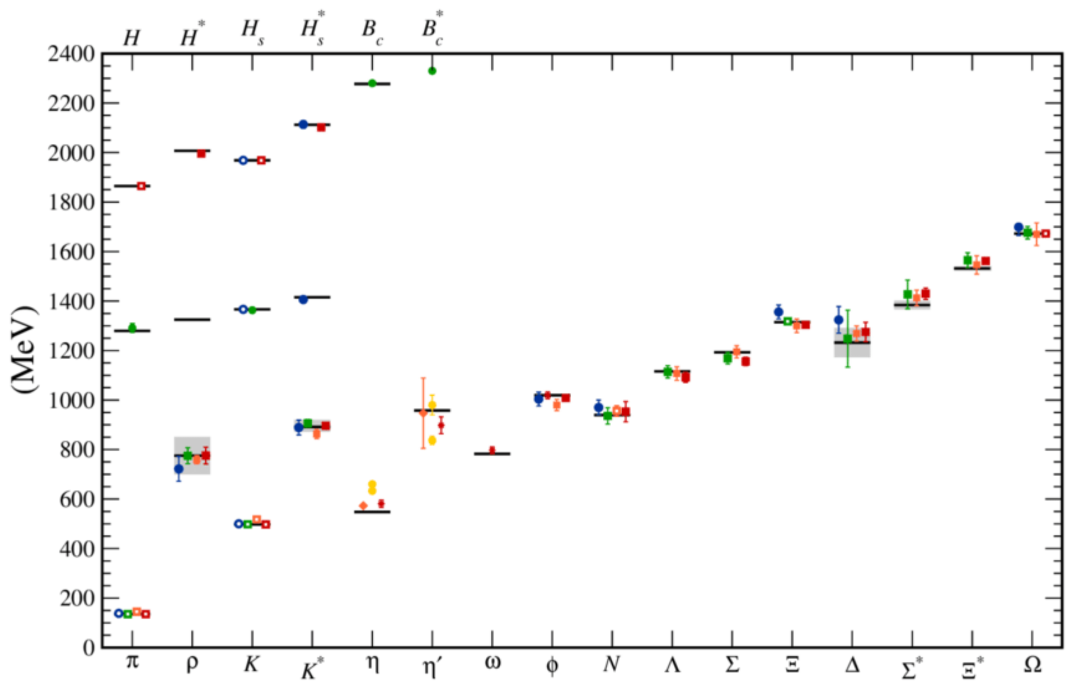
- A discrete space and "time"
- "Fields" instead of "particles"

Hugely successful

Strong coupling



Hadron spectrum



$$\hat{H}\psi_n = E_n\psi_n$$

NuclearScience
Computing CenteratCCNU

计算决定未来！

N: Nuclear S: Science C^3: Color 3 -> QCD

“道生一，一生二，二生三，三生万物。” —《道德经》老子 600 BC

"Tao gives birth to One, One gives birth to Two, Two gives birth to Three, Three gives birth to everything."- Lao Tzu

18 computing nodes
(144 V100 GPUs)
Peak performance:
1 Pflops(千万亿）/s
Storage:
1 PB

June, 2018

TOP500 The List.

The GREEN 500

Why Exa-Scale computing?

- Lattice QCD standards
  - Small lattice spacing
  - Large volume
  - Physical quark masses⋯
- Additional complexity for the proton
  - 3 or 4 point functions
  - Gluon dynamics
  - High-energy scattering probes partons

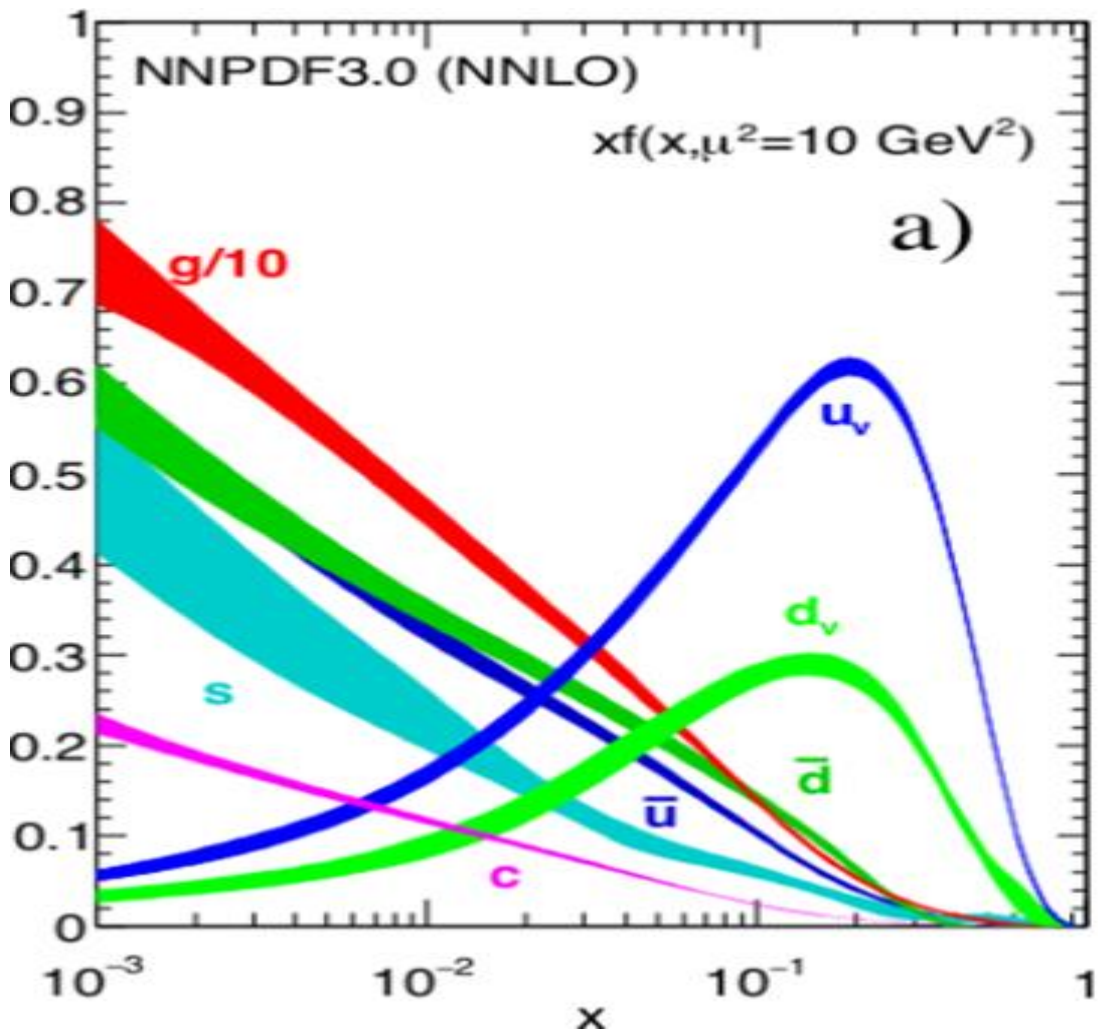
Recent theory advances

- It has been realized in 2013 that the Large momentum frame (Feynman) or Schrodinger picture interpretation of the parton physics provides a hope in lattice calculations

Large momentum effective field theory, or LaMET

- X. Ji, Phys. Rev. Lett. 110, 262002 (2013)
  arXiv:1305.1539 [hep-ph].
- X. Ji, Sci. China Phys. Mech. Astron. 57, 1407 (2014),
  arXiv:1404.6680 [hep-ph].

Parton (quark and gluon) distributions as measured in DIS



Large momentum effective field theory (LaMET, 2013)

- Large but not infinite momentum nucleons are created on QCD lattices.
- Static quark and gluon correlation functions of various types can be calculated in such a nucleon state using standard lattice QCD approach.
- These lattice correlations can be matched directly to parton observables through QCD perturbation theory.
- There are severable groups in the world pursuing this approach

LP3 Lattice Calculation

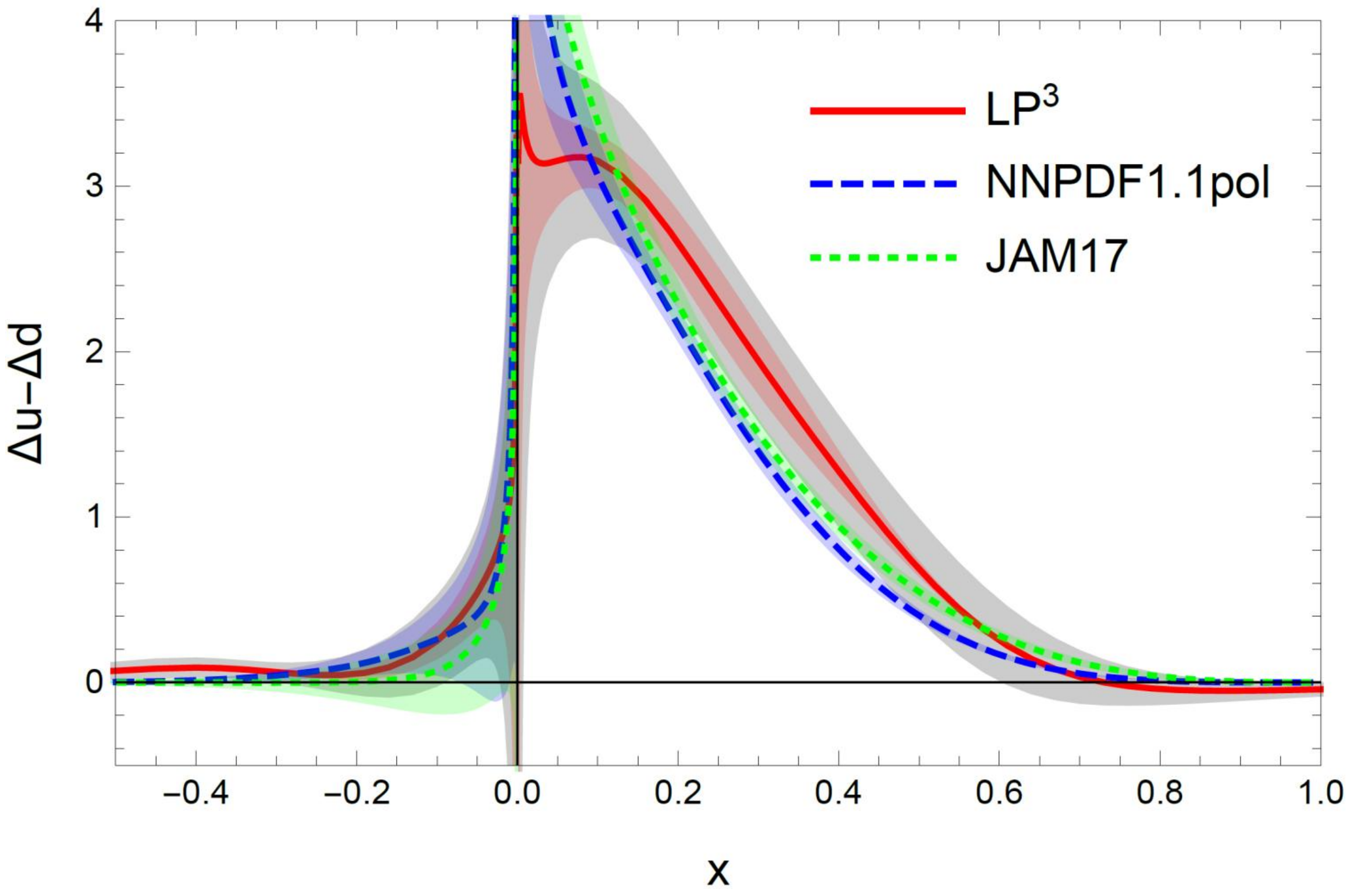
- Lattice space $\mathrm{a} = 0.09$ fm
- Box size $64^3 \times 96$ ($L = 5.8$ fm)
- $m_\pi = 135$ MeV ($m_\pi L \approx 4.0$)
- clover valence fermions
- gauge configurations with $N_f = 2 + 1 + 1$ HISQ [1] generated by MILC Collaboration [2]
- The gauge links are hypercubic (HYP)-smeared [3]
- The quark field is Gaussian momentum smeared [4]

[1] E. Follana, Q. Mason, C. Davies, K. Hornbostel, G. P. Lepage, J. Shigemitsu, H. Trottier, and K. Wong (HPQCD, UKQCD), Phys. Rev. D75, 054502 (2007), arXiv:hep-lat/0610092 [hep-lat].
[2] A. Bazavov et al. (MILC), Phys. Rev. D87, 054505 (2013), arXiv:1212.4768 [hep-lat].
[3] A. Hasenfratz and F. Knechtli, Phys. Rev. D64, 034504 (2001), arXiv:hep-lat/0103029 [hep-lat].
[4] G. S. Bali, B. Lang, B. U. Musch, and A. Schfer, Phys. Rev. D93, 094515 (2016), arXiv:1602.05525.

Lattice Calculation

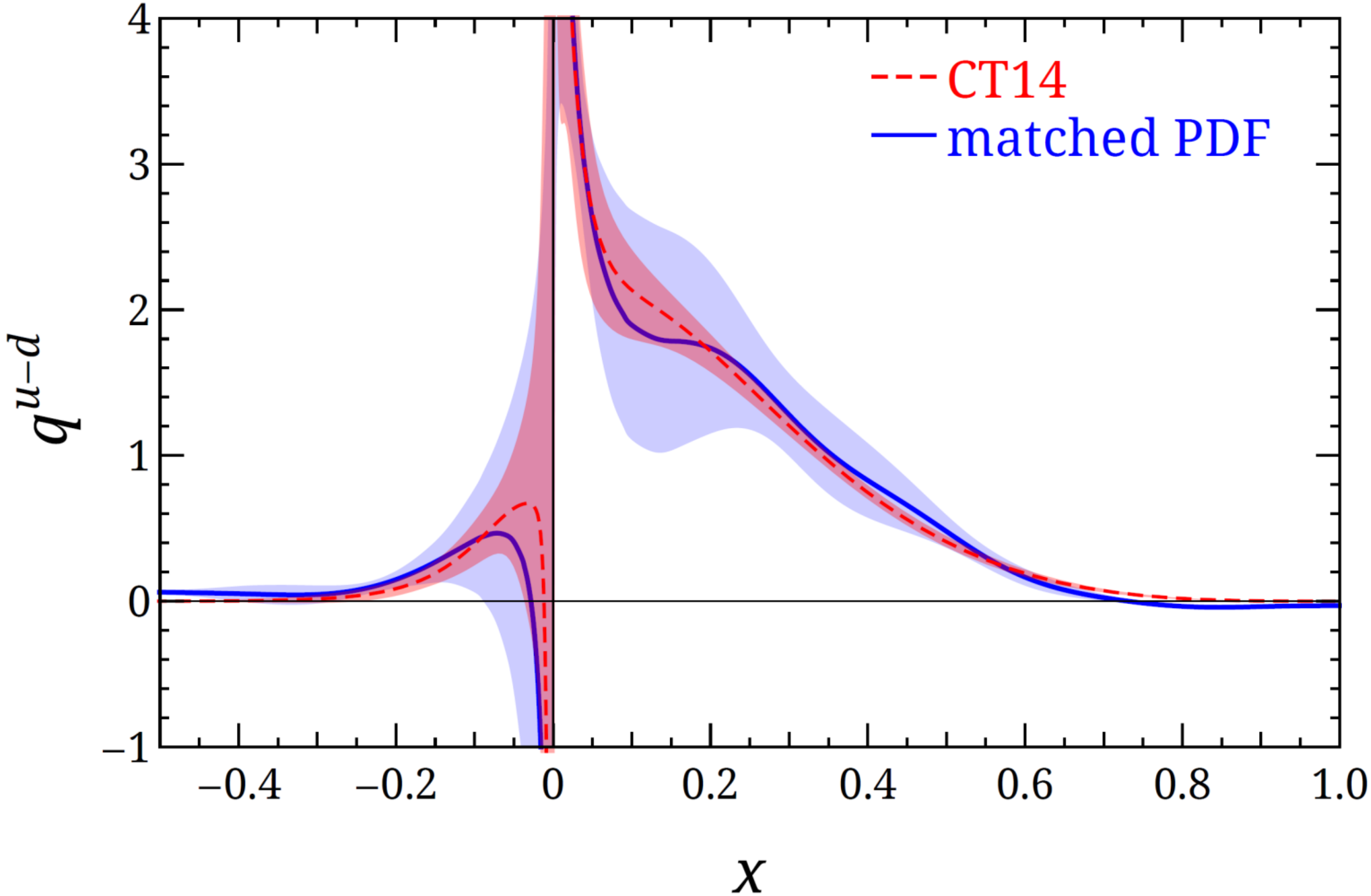
- The nucleon momentum $P^z = \{2.2, 2.6, 3.0\}$ GeV
- 884 gauge configurations
- measure the proton matrix elements with six source-sink separations {0.54, 0.72, 0.81, 0.90, 0.99, 1.08} fm with the number of {16, 32, 32, 64, 64, 128}k measurements, respectively

Isovector Helicity PDF [1]



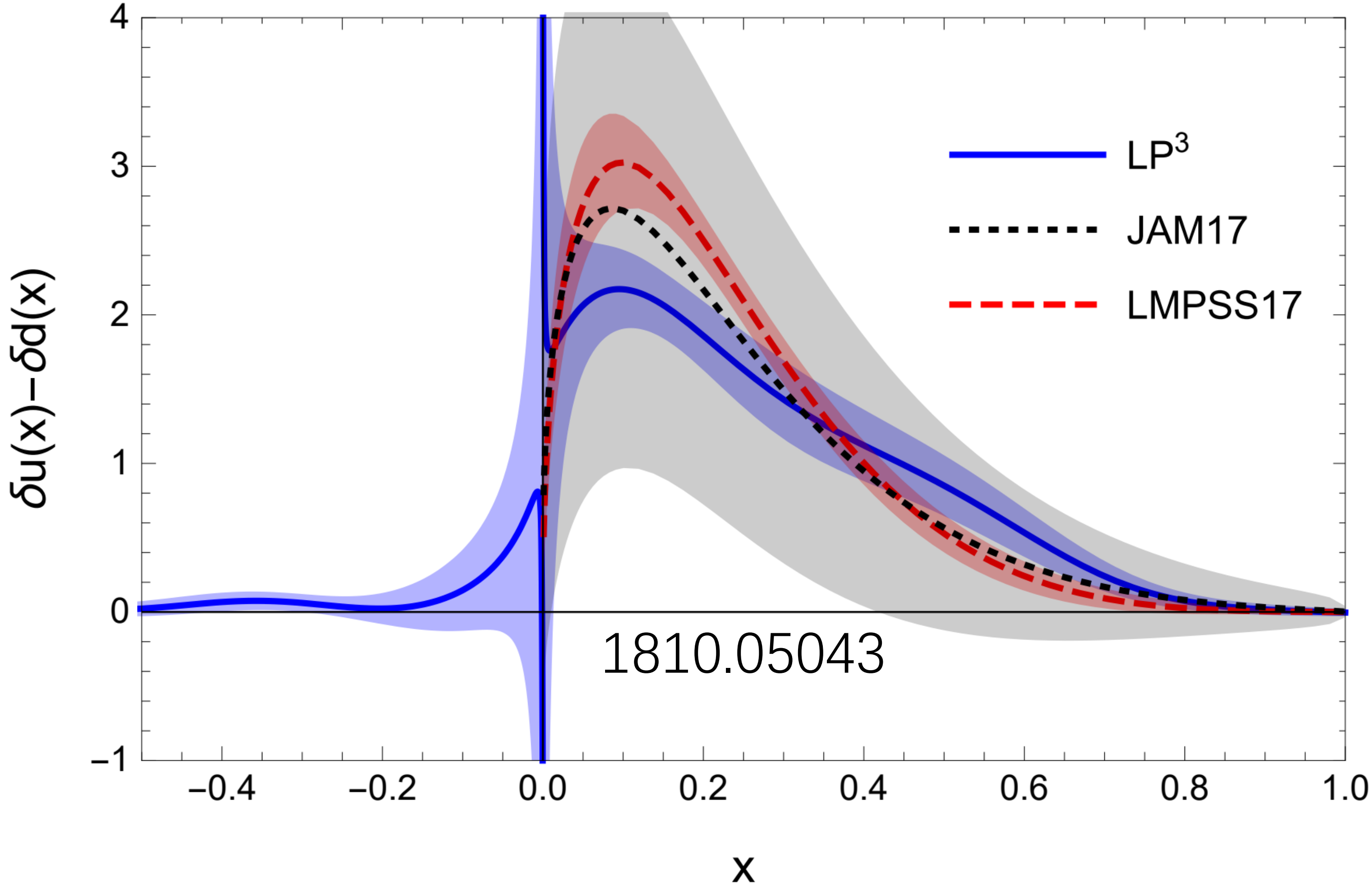
[1] H. W. Lin, J. W. Chen, X. Ji, L. Jin, R. Li, Y. S. Liu, Y. B. Yang, J. H. Zhang and Y. Zhao, Phys.Rev.Lett. 121 (2018) 242003, arXiv:1810.05043 [hep-lat]

Isovector Unpolarized PDF [1]



[1] J. W. Chen, L. Jin, H. W. Lin, Y. S. Liu, Y. B. Yang, J. H. Zhang and Y. Zhao, arXiv:1803.04393 [hep-lat].

Isovector Transversity PDF [1]



[1] Y. S. Liu, J. W. Chen, L. Jin, R. Li, H. W. Lin, Y. B. Yang, J. H. Zhang and Y. Zhao, arXiv:1810.05043 [hep-lat].

Gluon helicity contribution to spin

- In QCD factorization, one can show that the gluon polarization is a matrix element of non-local light-cone correlations.

$$\Delta G = \int dx \frac{i}{2xP^+} \int \frac{d\xi^-}{2\pi} e^{-ixP^+\xi^-} \langle PS|F_a^{+\alpha}(\xi^-) \\ \times \mathcal{L}^{ab}(\xi^-, 0)\tilde{F}^{+}_{\alpha,b}(0)|PS\rangle,$$

- No one knows how to calculate this for nearly 30 years!

LaMET calculations

- In LaMET theory, one can start with the local operator $\vec{E} \times \vec{A}$, in a physical gauge in the sense that the gauge condition shall allow transverse polarized gluons:
  - Coulomb gauge $\nabla \cdot E = 0$
  - Axial guage A_z=0
  - Temporal gauge A_0 =0
- Their matrix elements in the large momentum limit all go to ΔG.

Ji, Zhang, Zhao, Phys. Rev. Lett.,111,112002(2013)

First calculation (Yang et al, PRL (2017))

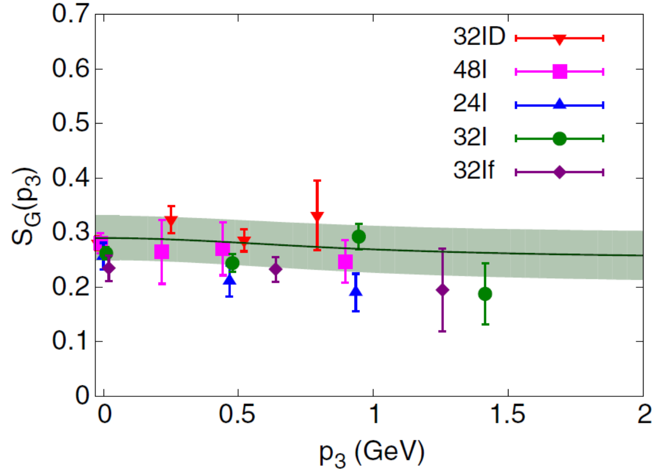
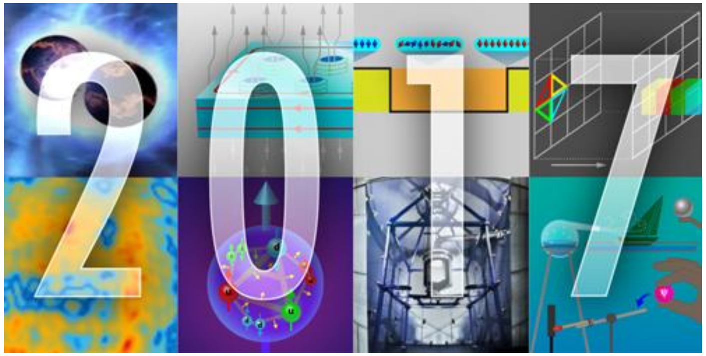


FIG. 4. The results extrapolated to the physical pion mass as a function of the absolute value of $\vec{p} = (0, 0, p_3)$, on all the five ensembles. All the results have been converted to $\overline{\mathrm{MS}}$ at $\mu^2 = 10\ \mathrm{GeV}^2$. The data on several ensembles are shifted horizontally to enhance the legibility. The green band shows the frame dependence of the global fit [with the empirical form in Eq. (11)] of the results.



Gluons Provide Half of the Proton's Spin

The gluons that bind quarks together in nucleons provide a considerable chunk of the proton's total spin. That was the conclusion reached by Yi-Bo Yang from the University of Kentucky, Lexington, and colleagues (see Viewpoint: Spinning Gluons in the Proton). By running state-of-the-art computer simulations of quark-gluon dynamics on a so-called spacetime

Way Forward:

Electron-ion collider

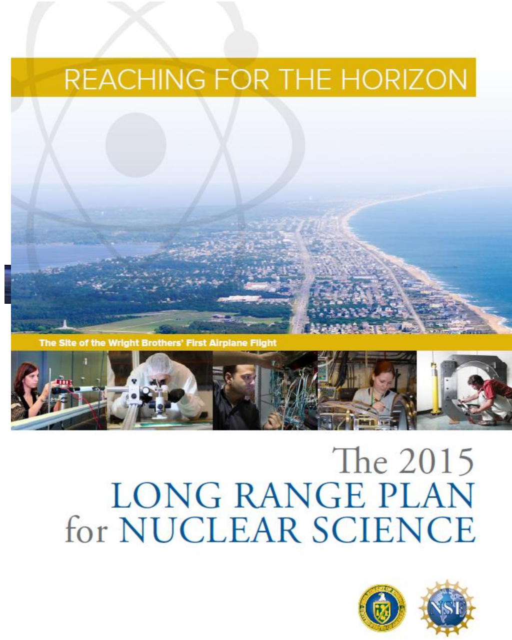
Electron-Ion Collider

- Electron scattering has provided the most important information about the proton structure.
  - SLAC
  - HERA
  - Jefferson LAB
  - EIC in USA
  - EIC in China

RECOMMENDATION III

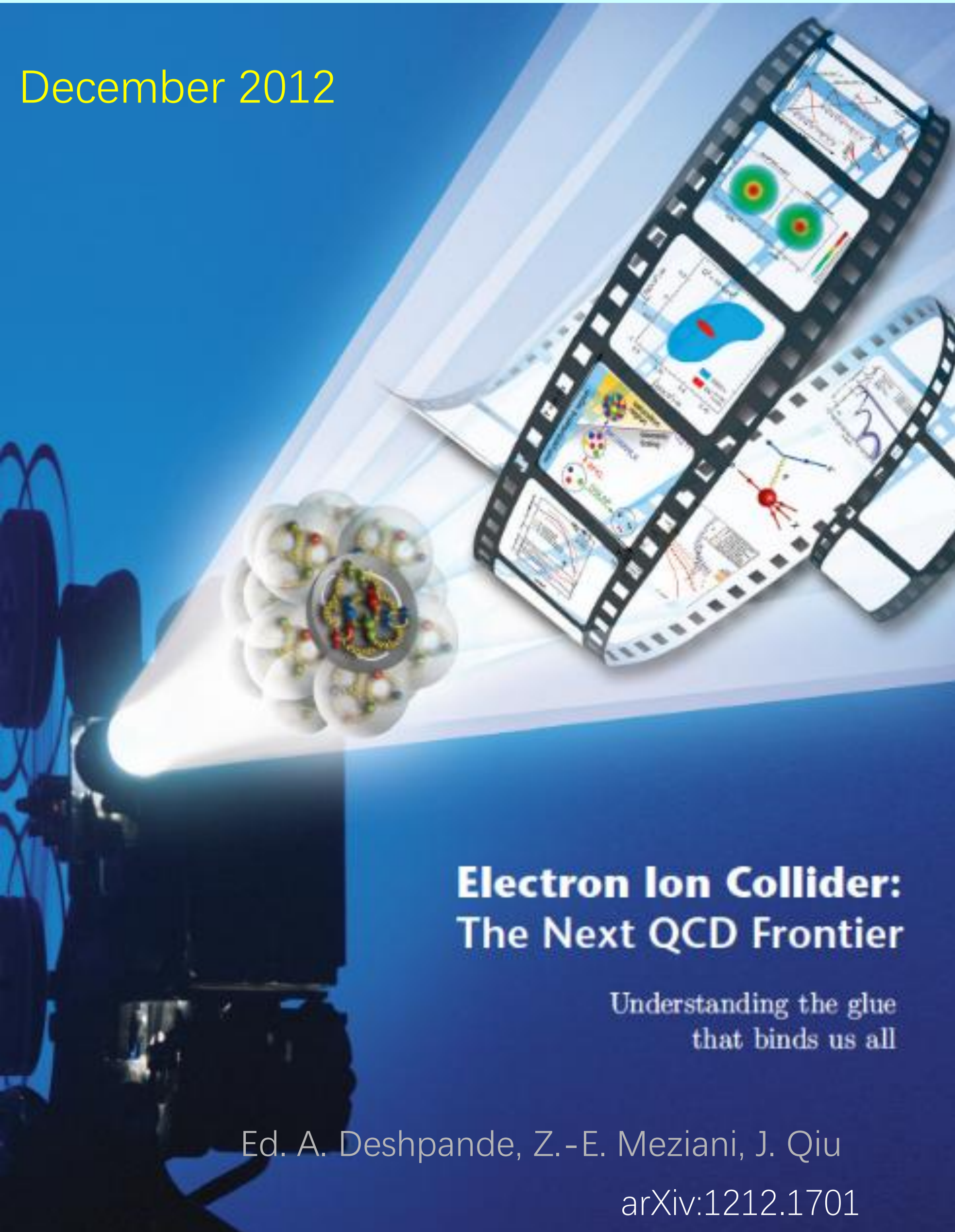
Gluons, the carriers of the strong force, bind the quarks together inside nucleons and nuclei and generate nearly all of the visible mass in the universe. Despite their importance, fundamental questions remain about the role of gluons in nucleons and nuclei. These questions can only be answered with a powerful new electron ion collider (EIC), providing unprecedented precision and versatility. The realization of this instrument is enabled by recent advances in accelerator technology.

We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.



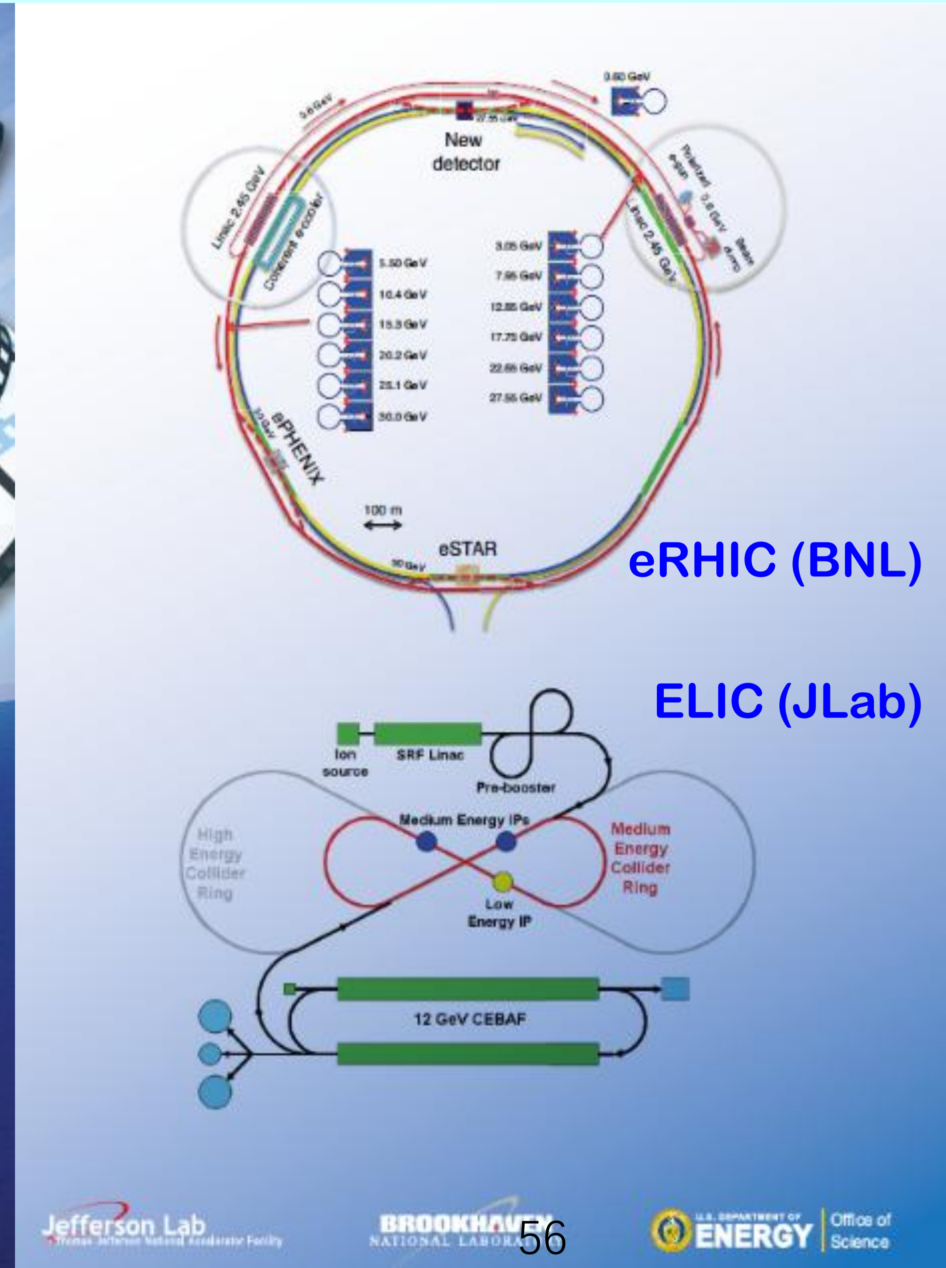
White Paper for the Electron-Ion Collider

December 2012



Ed. A. Deshpande, Z.-E. Meziani, J. Qiu

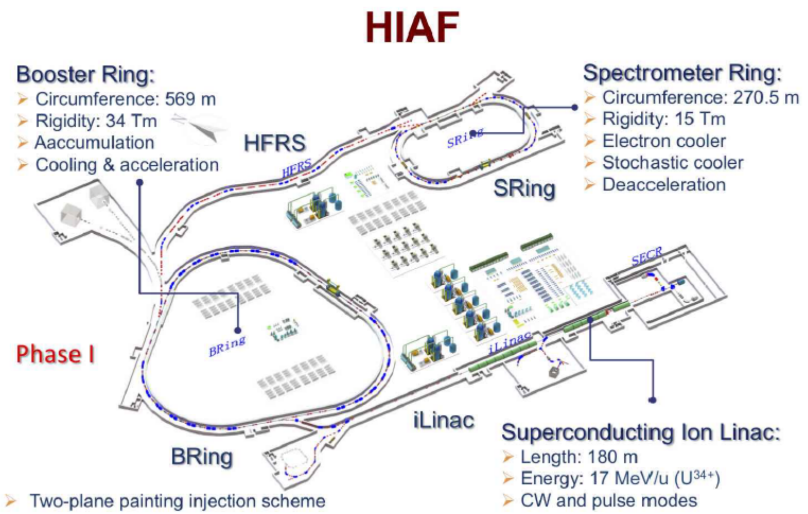
arXiv:1212.1701

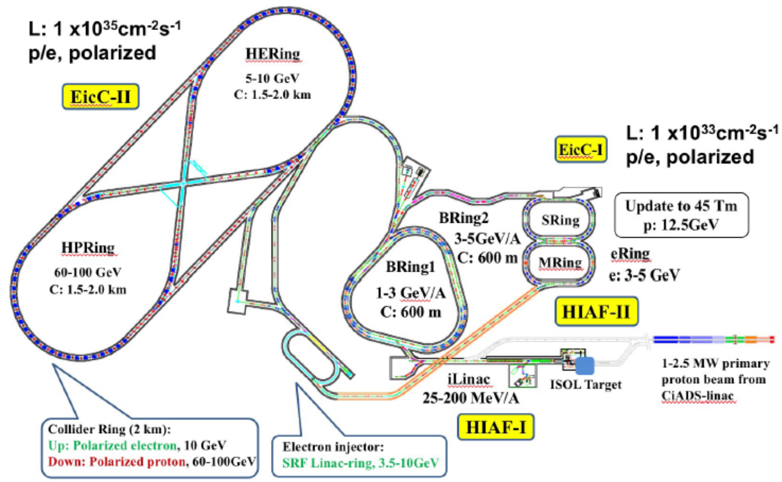


eRHIC (BNL)

ELIC (JLab)

Status and Impact of Electron Ion Collider in China





- Based on the High Intensity Ion Facility (HIAF) which is currently under construction in Huizhou, Guangdong province.
- Leading cutting edge nuclear physics research.
- Significant advances in accelerator and collider technology.
- Impacts on other fields of physics and attracting young talents.

Proton tomography

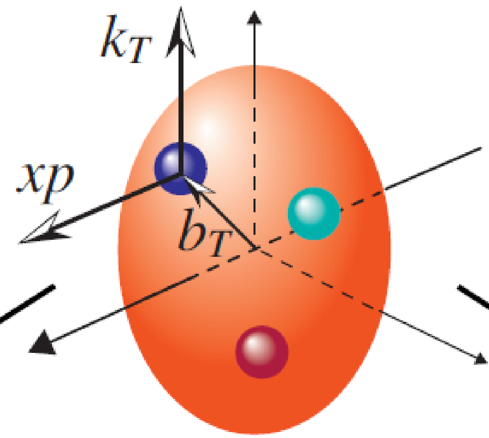
❑ **3D boosted partonic structure:**

Momentum Space

TMDs

Coordinate Space

GPDs



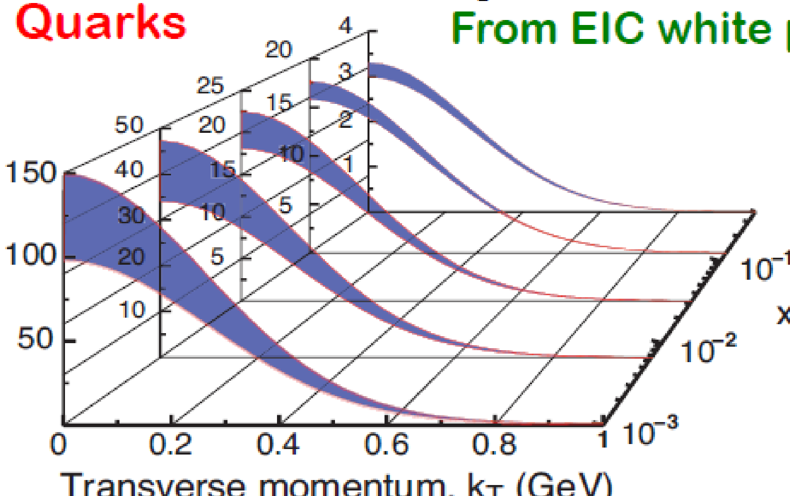
$\int d^2b_T$ $\qquad$ $\int d^2k_T$

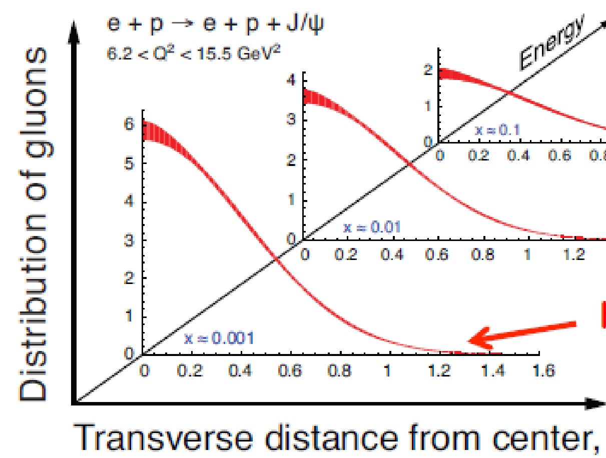
$f(x,k_T)$ $\qquad$ $f(x,b_T)$

Quarks

From EIC white paper: arXiv:1212.1701

Gluons





How far does it spread?

Conclusion

- Proton is one of the most important particles that make up our world.
- Despite significant progress made in the last century, we do not have a good description of its structure.
- Next generation of computers and exp. facility promise to make a great progress.