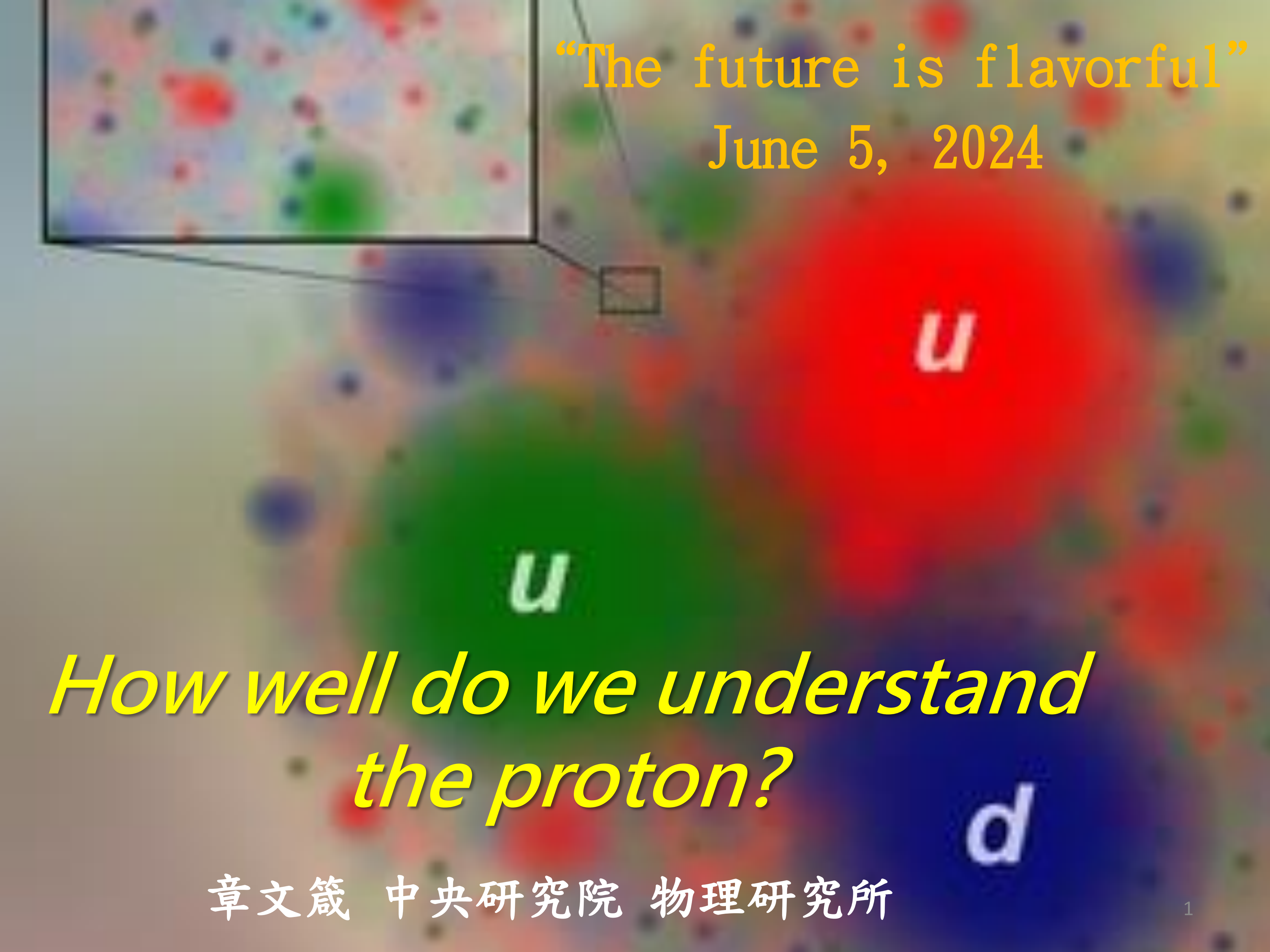
“The future is flavorful”

June 5, 2024



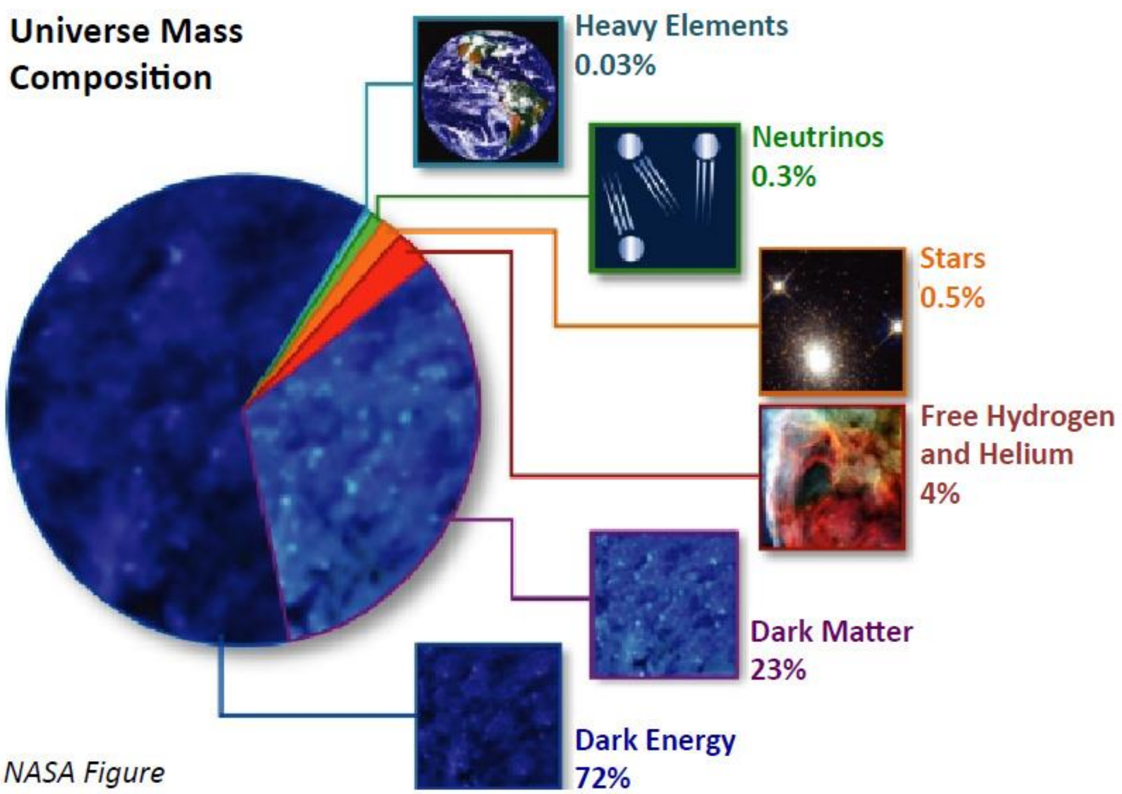

# *How well do we understand the proton?*

章文箴 中央研究院 物理研究所

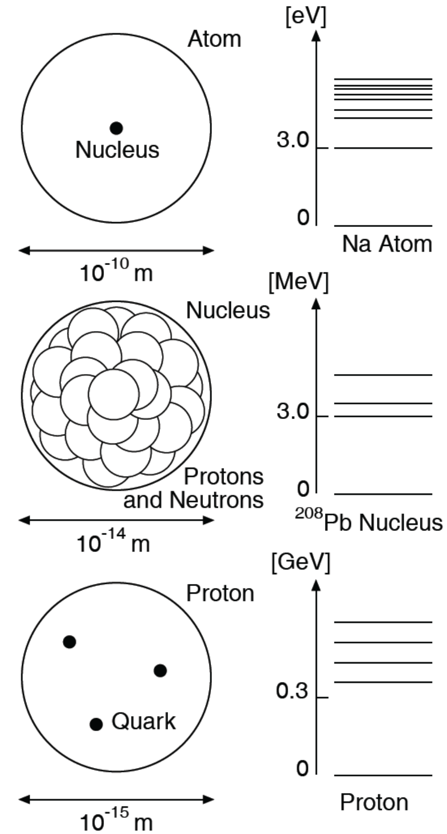
# Outline

- Proton as an composite fundamental particle: constituent quark model, parton model and QCD
- Flavor dependence of partonic structures:
  - Unpolarized and polarized PDFs of sea quarks
  - TMD Sivers function of valence quarks
- U.S. EIC program
- Summary

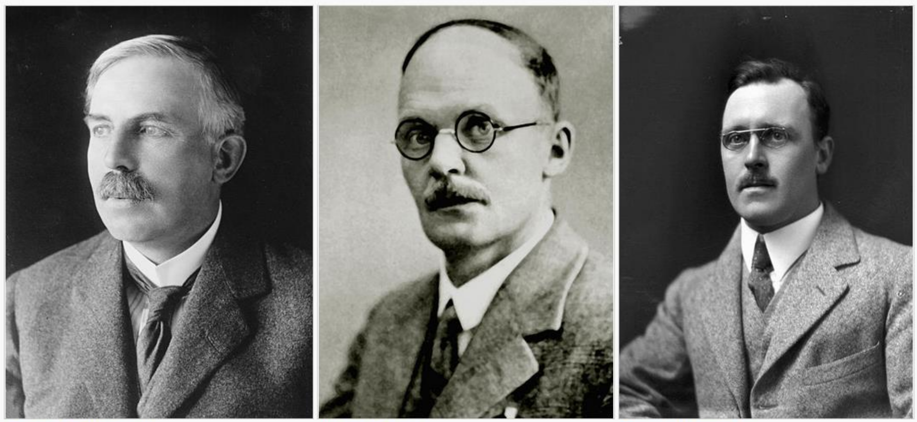
# Composition of the Universe



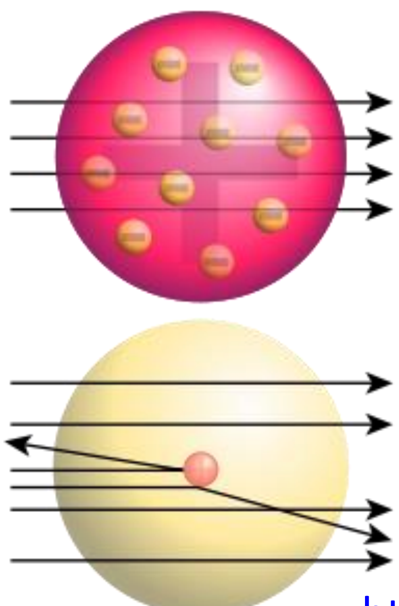

Bound states of QCD

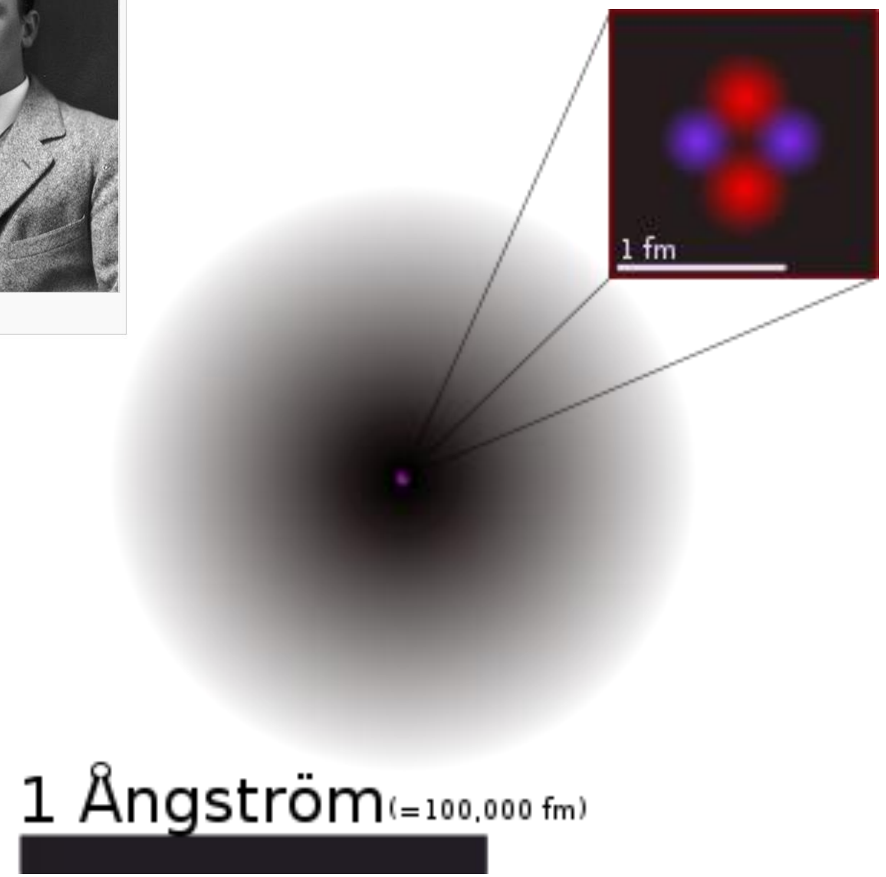


# Rutherford experiment (1913)
# : Nucleus and Sub-atomic Structure



Ernest Rutherford　Hans Geiger　Ernest Marsden






http://psroc.phys.ntu.edu.tw/bimonth/v29/732.pdf

# Quark: the Eightfold Way

## The Nobel Prize in Physics 1969

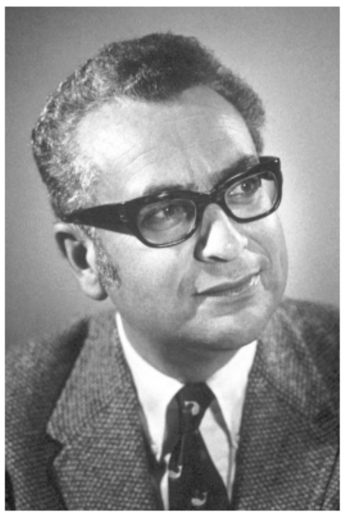
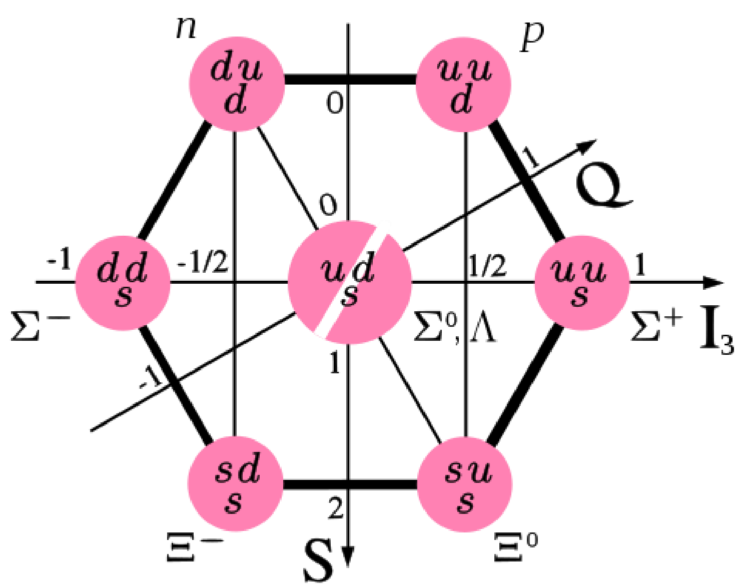
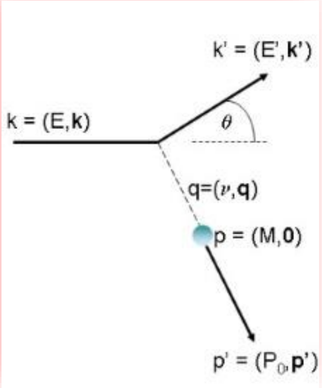


Photo from the Nobel Foundation archive.

Murray Gell-Mann



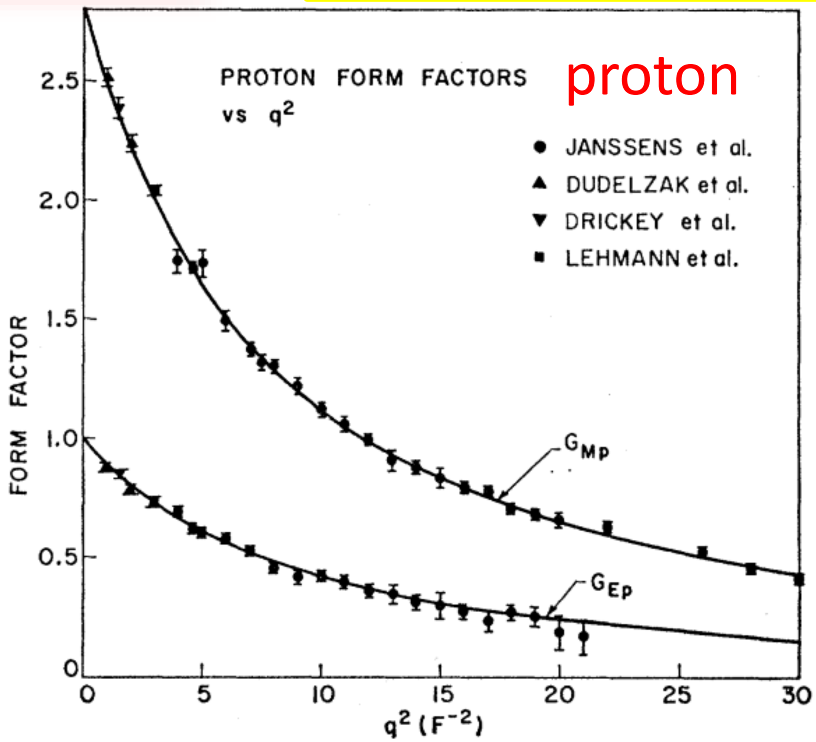

*"for his contributions and discoveries concerning the classification of elementary particles and their interactions"*

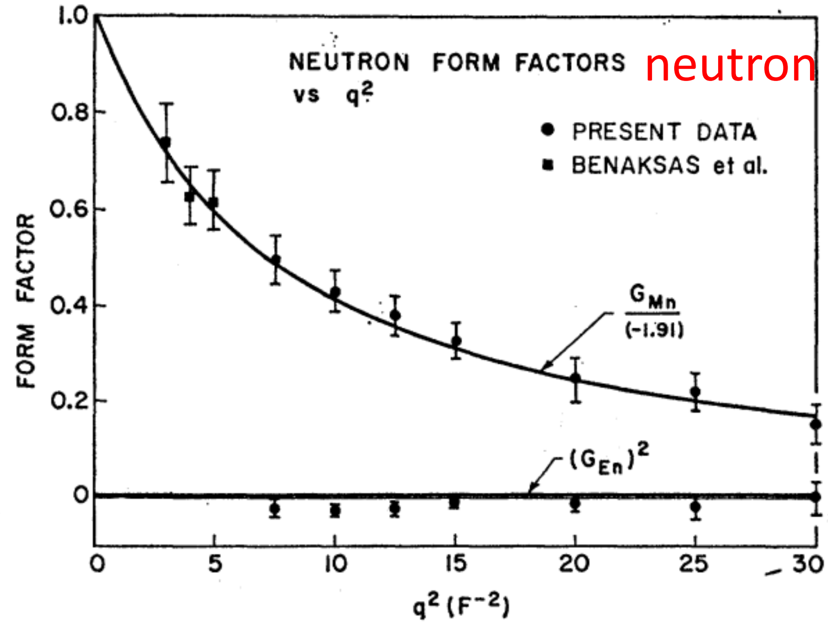



# e-N Elastic Scattering

## Electric ($G_E$) and Magnetic ($G_M$) Form Factors

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}} \cdot \left[\frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} + 2\tau G_M^2(Q^2)\tan^2\frac{\theta}{2}\right]$$




E.B. Hughes et al., Phys. Rev. **B139**, 458 (1965)

Anomalous magnetic moment

Otto Stern, Nobel Prize 1943

$$G_E^p(Q^2=0) = 1 \qquad G_E^n(Q^2=0) = 0$$

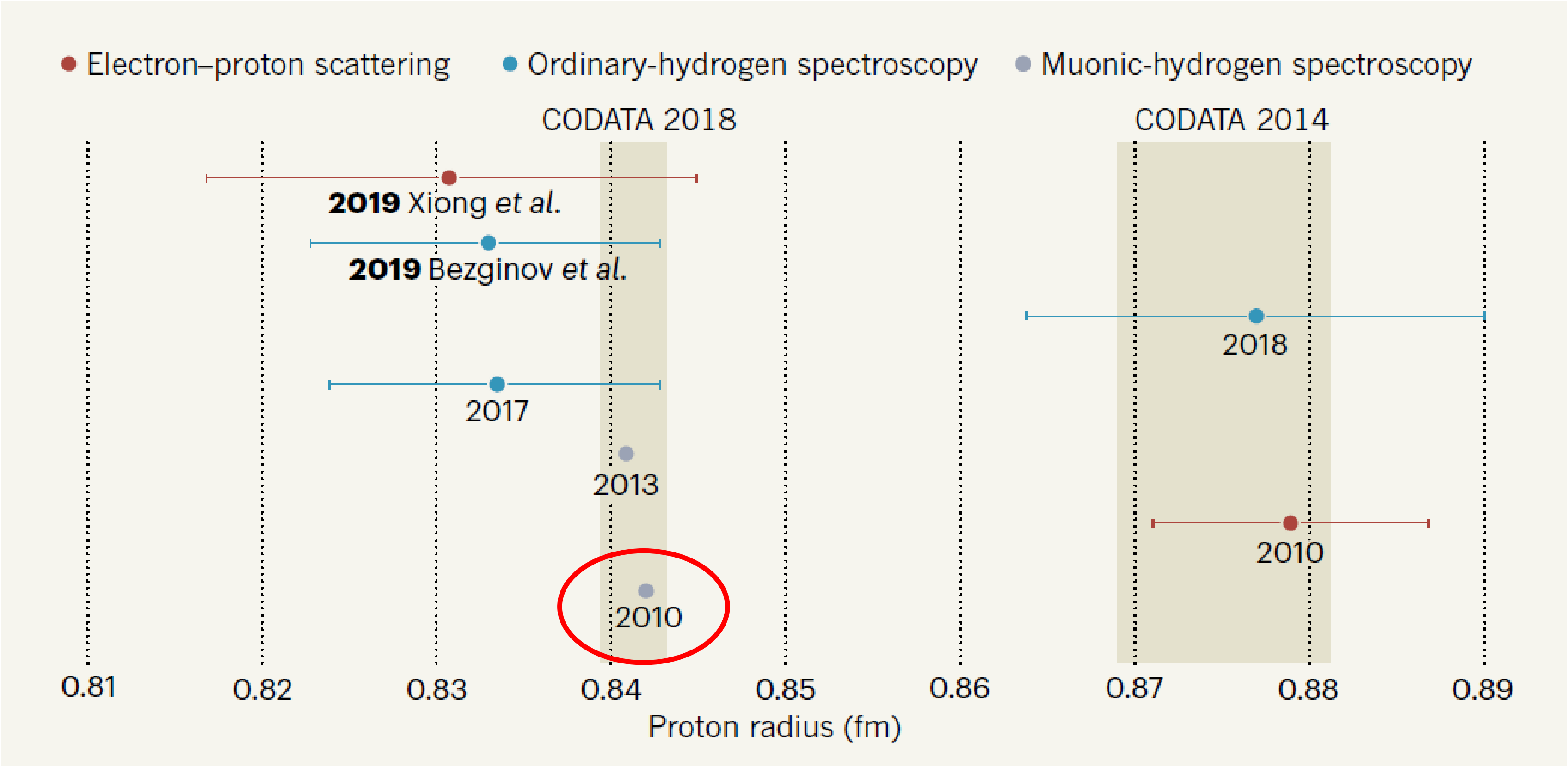
$$G_M^p(Q^2=0) = 2.793 \qquad G_M^n(Q^2=0) = -1.913$$

$$\mu_p = \frac{g_p}{2}\mu_N = +2.793 \cdot \mu_N \qquad \mu_N = \frac{e\hbar}{2M_p}$$

$$\mu_n = \frac{g_n}{2}\mu_N = -1.913 \cdot \mu_N$$

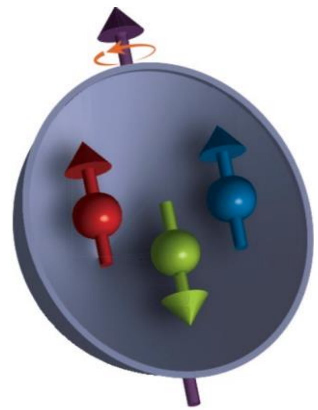
# Puzzle of Proton Charge Radius

$$\sqrt{\langle r^2 \rangle} = -6\hbar \frac{dG_E(Q^2)}{dQ^2}\Big|_{Q^2=0} \approx 0.879 \text{ fm}$$




https://www.nature.com/articles/d41586-019-03364-z

# Constituent Quark Model



Anomalous magnetic moment
Otto Stern, Nobel Prize 1943

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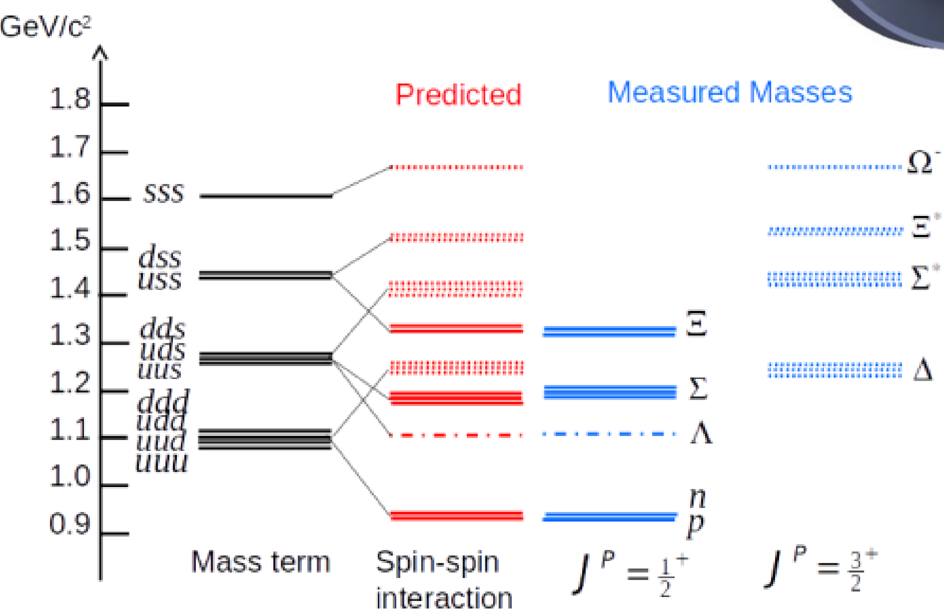



| Baryon | $\mu_B$ in Quark Model | Predicted $[\mu_N]$ | Observed $[\mu_N]$ |
|---|---|---|---|
| $p$ (uud) | $\frac{4}{3}\mu_u - \frac{1}{3}\mu_d$ | $+2.79$ | $+2.793$ |
| $n$ (ddu) | $\frac{4}{3}\mu_d - \frac{1}{3}\mu_u$ | $-1.86$ | $-1.913$ |
| $\Lambda$ (uds) | $\mu_s$ | $-0.61$ | $-0.614 \pm 0.005$ |
| $\Sigma^+$ (uus) | $\frac{4}{3}\mu_u - \frac{1}{3}\mu_s$ | $+2.68$ | $+2.46 \pm 0.01$ |
| $\Xi^0$ (ssu) | $\frac{4}{3}\mu_s - \frac{1}{3}\mu_u$ | $-1.44$ | $-1.25 \pm 0.014$ |
| $\Xi^-$ (ssd) | $\frac{4}{3}\mu_s - \frac{1}{3}\mu_d$ | $-0.51$ | $-0.65 \pm 0.01$ |
| $\Omega^-$ (sss) | $3\mu_s$ | $-1.84$ | $-2.02 \pm 0.05$ |

$$\mu_u = \frac{2}{3}\frac{e\hbar}{2m_u}, \quad \mu_d = -\frac{1}{3}\frac{e\hbar}{2m_d}, \quad \mu_s = -\frac{1}{3}\frac{e\hbar}{2m_s}$$

$$m_u = 0.362 \text{ GeV}, \; m_d = 0.366 \text{ GeV}, \; m_s = 0.537 \text{ GeV} \qquad m_u = m_d = 0.336 \text{ GeV}, \; m_s \sim 0.509 \text{ GeV}$$

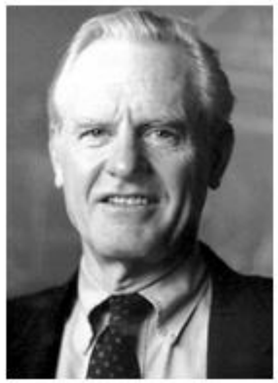
https://www.hep.phy.cam.ac.uk/~chpotter/particleandnuclearphysics/Lecture_08_QuarkModel.pdf

# Deep Inelastic Scattering (~1970)

## The Nobel Prize in Physics 1990

Jerome I. Friedman

Prize share: 1/3



Henry W. Kendall

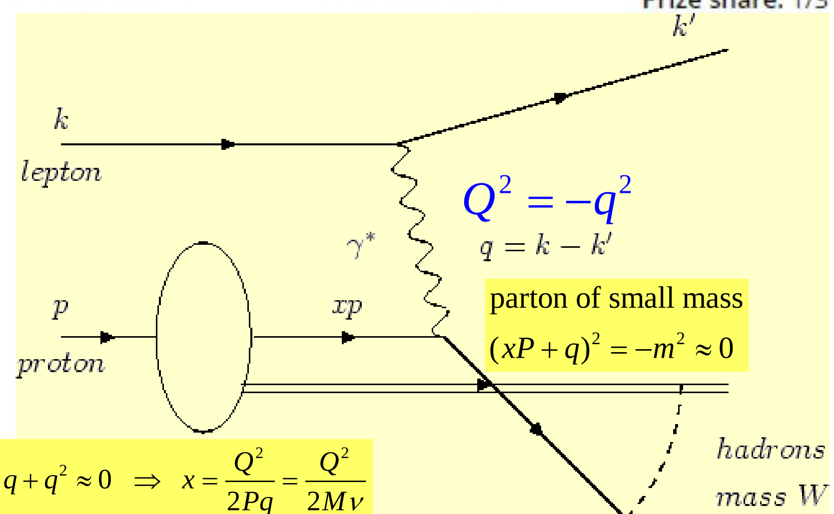
Prize share: 1/3

Photo: T. Nakashima

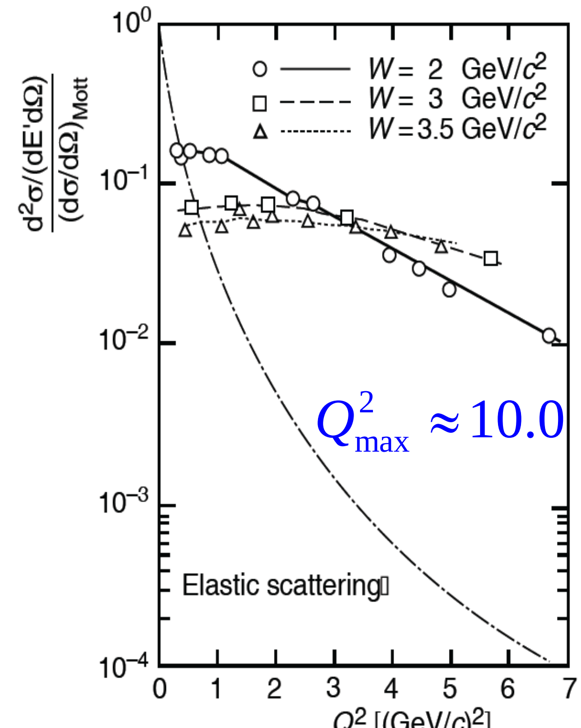
Richard E. Taylor

Prize share: 1/3

*“"for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics"*




$2xP \cdot q + q^2 \approx 0 \Rightarrow x = \frac{Q^2}{2Pq} = \frac{Q^2}{2M\nu}$



# Quantum Chromo-Dynamics (QCD)

$$L = \sum_f \bar{\psi}_f^\alpha \left[ i\gamma^\mu \partial_\mu \delta_{\alpha\beta} - g\gamma^\mu T_{a\alpha\beta} A_\mu^a - m_f \delta_{\alpha\beta} \right] \psi_f^\beta - \frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu}$$

$$G_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\mu A_\nu^a - g f^{abc} A_\mu^b A_\nu^c$$

Color index: $\alpha, \beta$=1, 2, 3, $N_c$=3; a, b, c = 1,2,…,8 for SU(3)

Lorentz index: $\mu, \nu$=0, 1, 2, 3

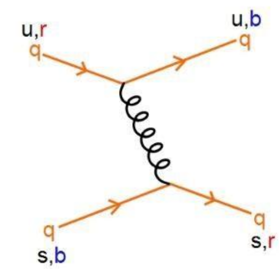
Spinor index: I, j = 1, 2, 3, 4

Flavor index: f=1,6

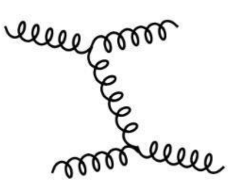
$T_{a\alpha\beta}$: generator of SU(3) color group

$f^{abc}$: structure constant of SU(3) color group

Gluon is flavor-blind!




gluon exchange by 2 quarks



gluon-gluon scattering

# Proton in PDG

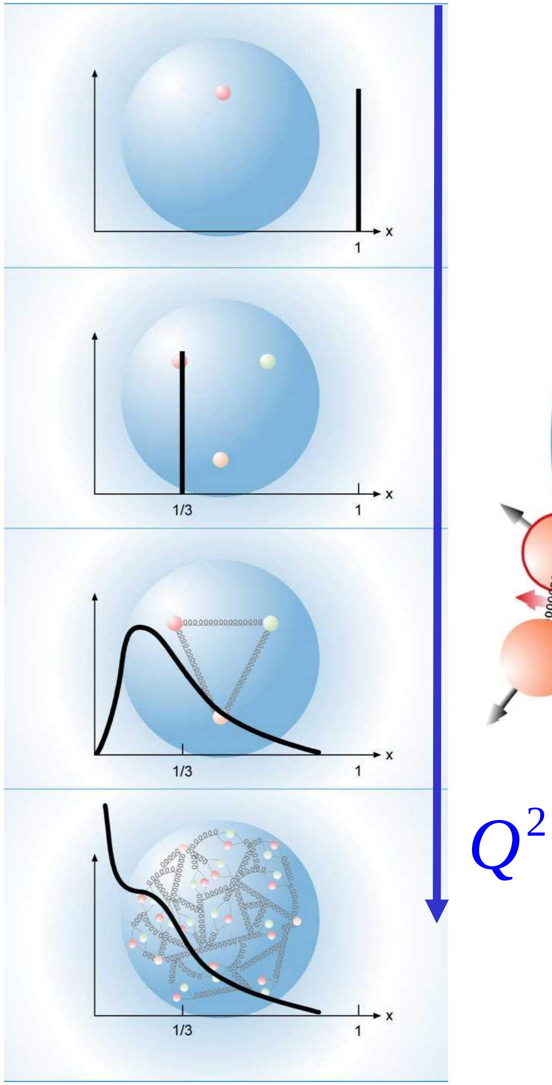
***N* BARYONS**
**($S = 0$, $I = 1/2$)**
$p$, $N^+ = u\,u\,d$; $n$, $N^0 = u\,d\,d$

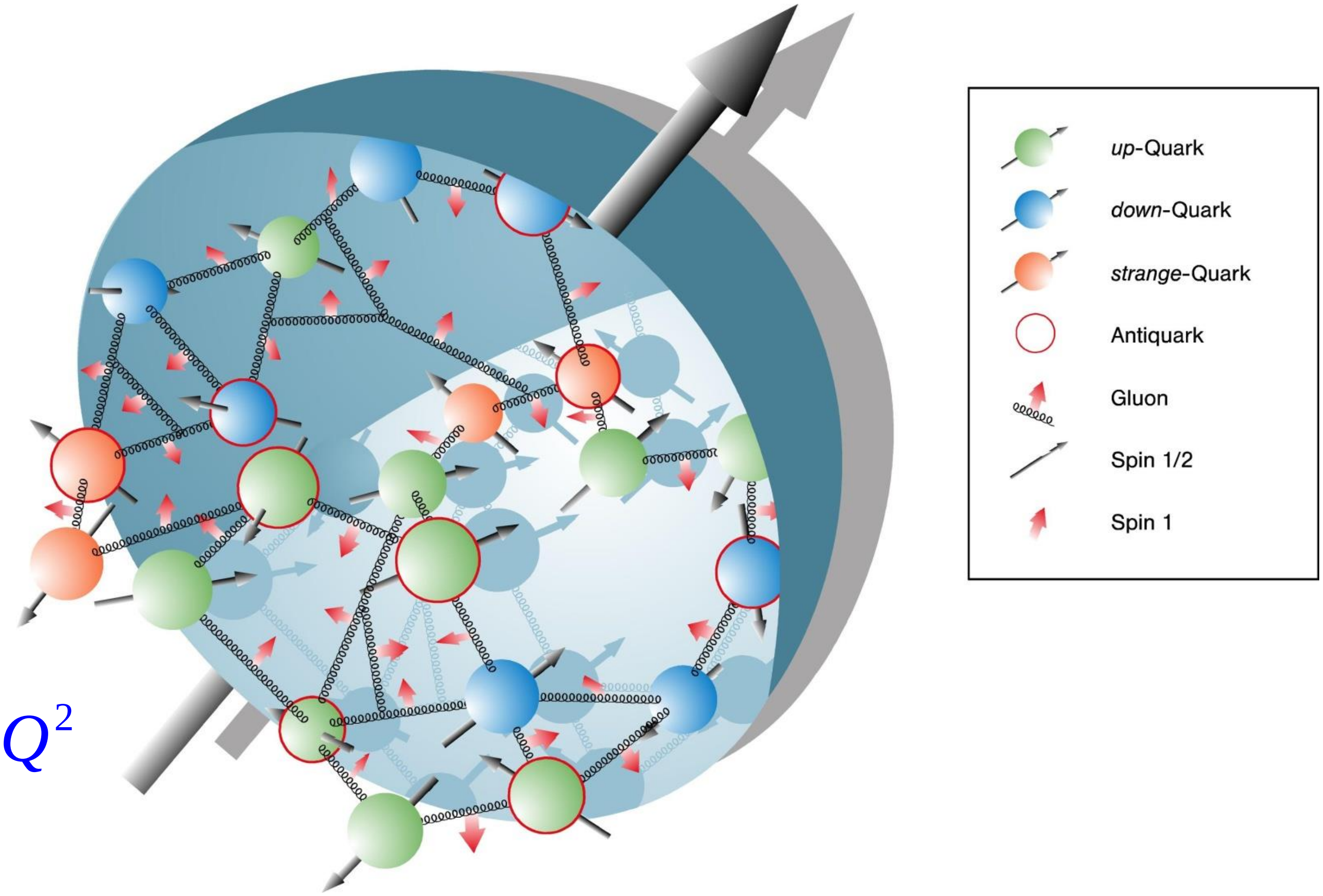
PDGID:S016 JSON INSPIRE

$p$ $\quad I(J^P) = 1/2(1/2^+)$ https://pdglive.lbl.gov/Particle.action?init=0&node=S016&home=BXXX005

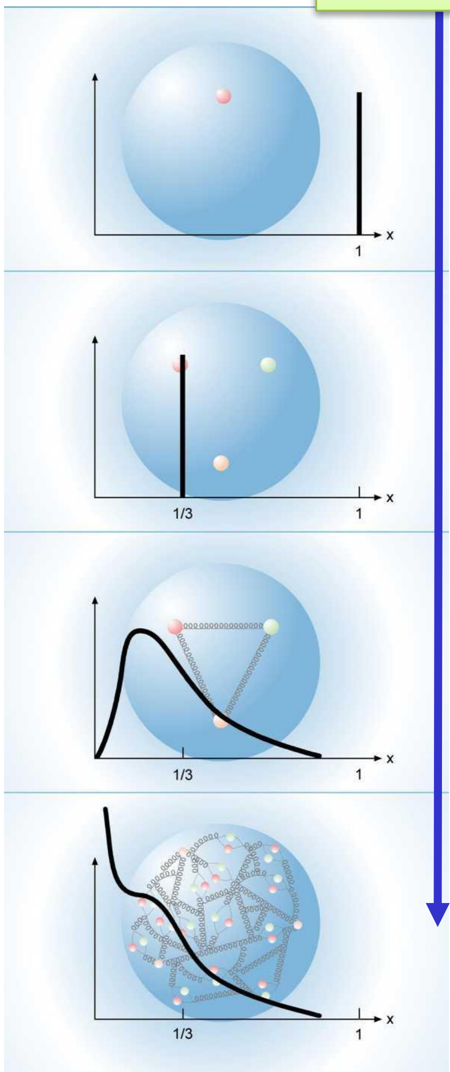
| | |
|---|---|
| $p$ MASS (atomic mass units u) | $1.007276466621 \pm 0.000000000053$ u |
| $p$ MASS (MeV) | $938.27208816 \pm 0.00000029$ MeV |
| $\lvert m_p - m_{\overline{p}} \rvert / m_p$ | $< 7 \times 10^{-10}$ CL=90.0% |
| $\overline{p}/p$ CHARGE-TO-MASS RATIO, $\lvert \frac{q_{\overline{p}}}{m_{\overline{p}}} \rvert / (\frac{q_p}{m_p})$ | $1.000000000003 \pm 0.000000000016$ |
| $(\lvert \frac{q_{\overline{p}}}{m_{\overline{p}}} \rvert - \frac{q_p}{m_p}) / \frac{q_p}{m_p}$ | $(0.3 \pm 1.6) \times 10^{-11}$ |
| $\lvert q_p + q_{\overline{p}} \rvert / e$ | $< 7 \times 10^{-10}$ CL=90.0% |
| $\lvert q_p + q_e \rvert / e$ | $< 1 \times 10^{-21}$ |
| $p$ MAGNETIC MOMENT | $2.7928473446 \pm 0.0000000008\ \mu_N$ |
| $\overline{p}$ MAGNETIC MOMENT | $-2.792847344 \pm 0.000000004\ \mu_N$ |
| $(\mu_p + \mu_{\overline{p}}) / \mu_p$ | $(2 \pm 4) \times 10^{-9}$ |
| $p$ ELECTRIC DIPOLE MOMENT | $< 2.1 \times 10^{-25}\ e$ cm |
| $p$ ELECTRIC POLARIZABILITY $\alpha_p$ | $0.00112 \pm 0.00004$ fm$^3$ |
| $p$ MAGNETIC POLARIZABILITY $\beta_p$ | $(2.5 \pm 0.4) \times 10^{-4}$ fm$^3$ (S = 1.2) |
| $p$ CHARGE RADIUS | $0.8409 \pm 0.0004$ fm |
| $p$ MAGNETIC RADIUS | $0.851 \pm 0.026$ fm |
| $p$ MEAN LIFE | $> 9 \times 10^{29}$ years CL=90.0% |
| $\overline{p}$ MEAN LIFE | |

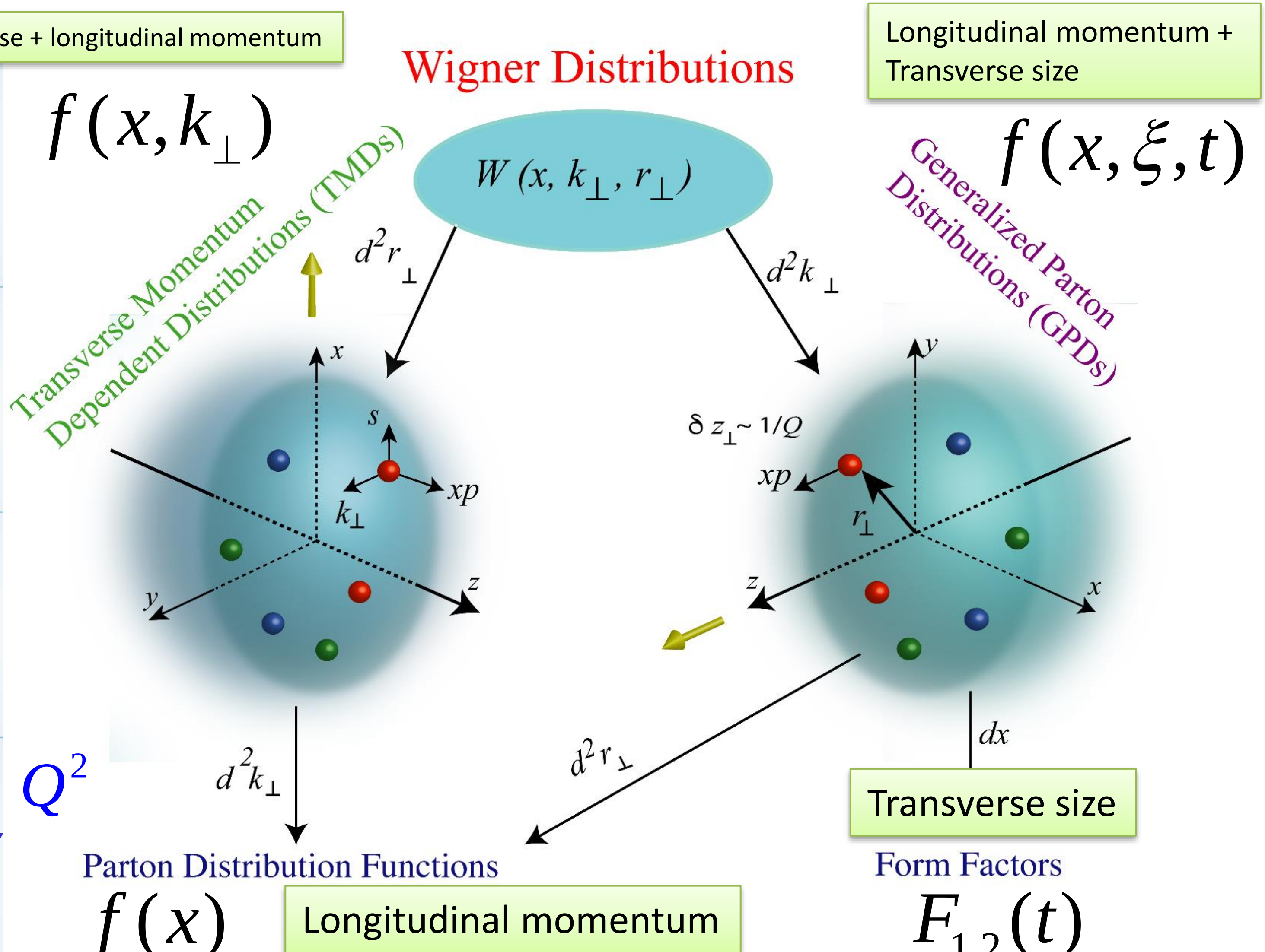
# Decomposition of Proton



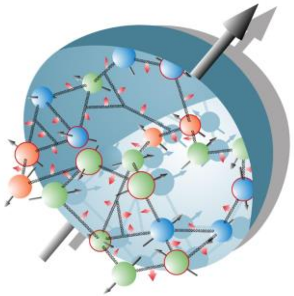
# Multi-dimensional Partonic Structures



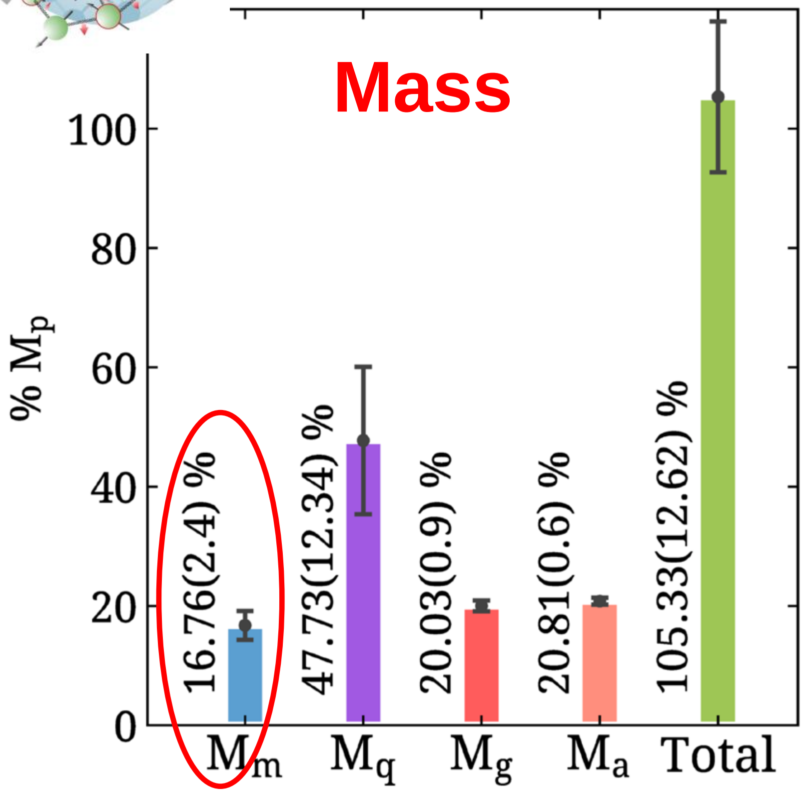




http://www.int.washington.edu/PROGRAMS/17-3/

# Mass/Spin Decomposition of Proton (Lattice QCD)

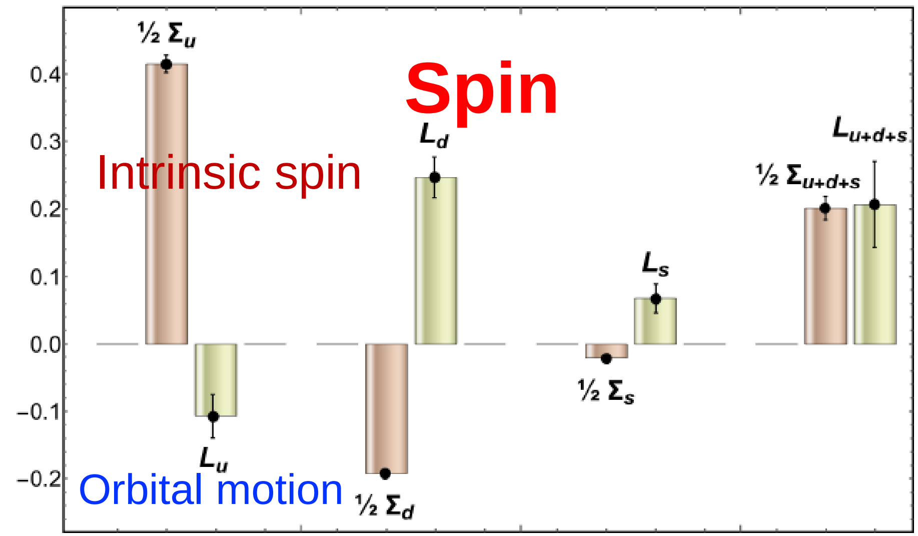


**PRL 116, 252001 (2016)**
**PRL 119, 142002 (2017)**




Quark mass
Quark energy
Gluon energy
**Trace Anomaly**

**PRL 119, 142002 (2017)**




**Quark orbital angular momentum extracted indirectly ($L_q = J_q - \Sigma_q$)**

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_{Q+G}$$

Can the nucleon mass and spin be understood by its partonic structure?

# Pressure distribution of Proton

Nature 557, 396 (2018)

$$\int x\,[H(x,\xi,t)+E(x,\xi,t)]\,\mathrm{d}x = 2J(t)$$

$$\int xH(x,\xi,t)\mathrm{d}x = M_2(t) + \boxed{\frac{4}{5}\xi^2 d_1(t)}$$

$$d_1(t) \propto \int \frac{j_0(r\sqrt{-t})}{2t} p(r)\mathrm{d}^3 r$$

$d_1(t)$: gravitational form factor

$p(r)$ : radial pressure distribution

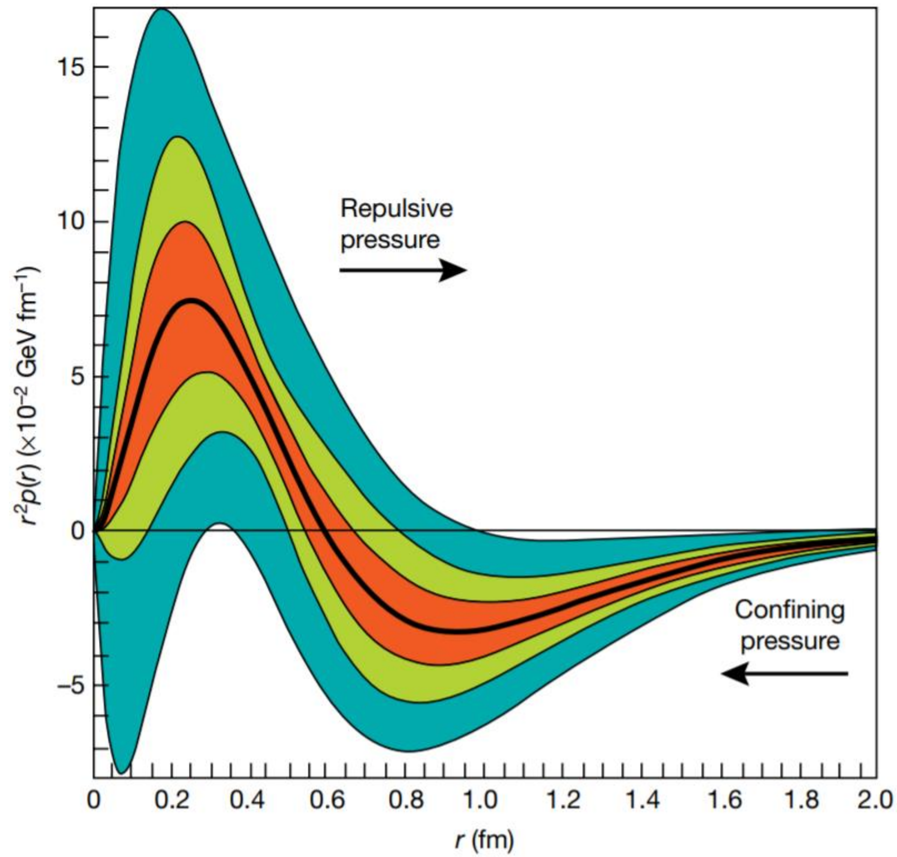
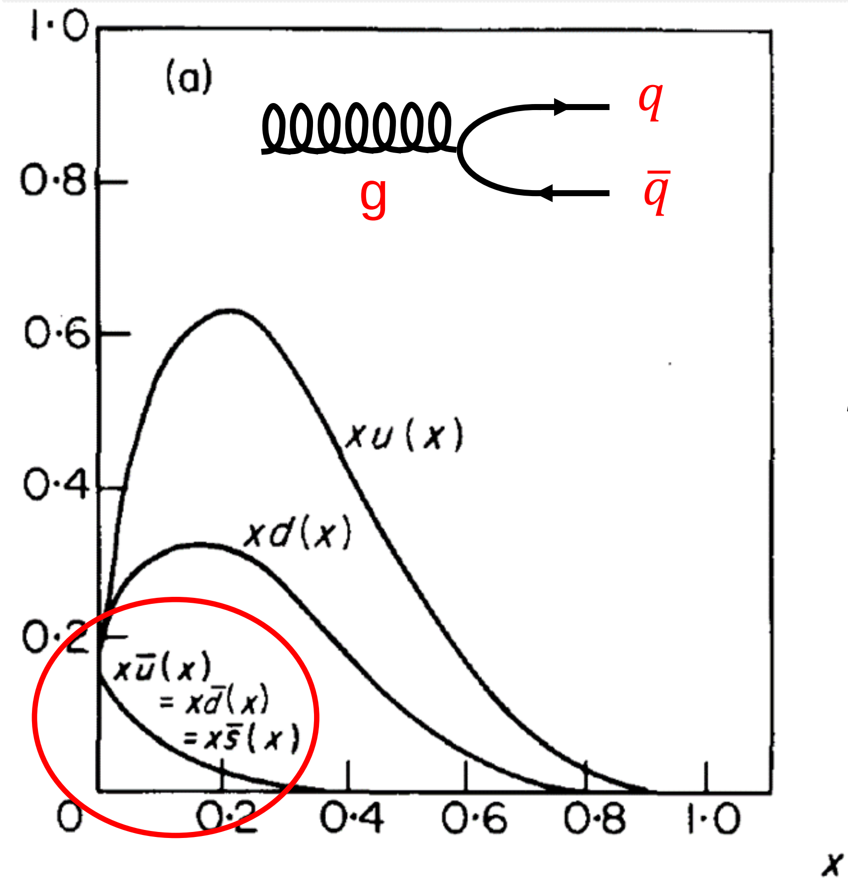



**Fig. 1 | Radial pressure distribution in the proton.** The graph shows the pressure distribution $r^2p(r)$ that results from the interactions of the

# Naïve Expectation of Sea
## SU(3) Symmetric




F.E. Close, “An Introduction to Quarks and Partons”


**Gottfried Sum Rule**

$$S_G = \int_0^1 [(F_2^p(x) - F_2^n(x))/x]\,dx$$

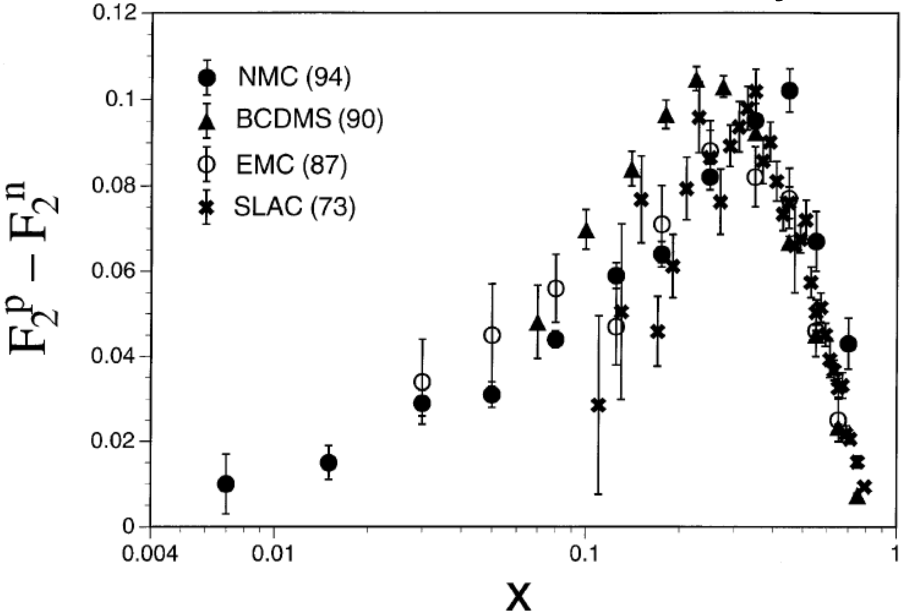
$$= \frac{1}{3}\int_0^1 (u_v(x) - d_v(x))\,dx + \frac{2}{3}\int_0^1 (\bar{u}(x) - \bar{d}(x))\,dx$$

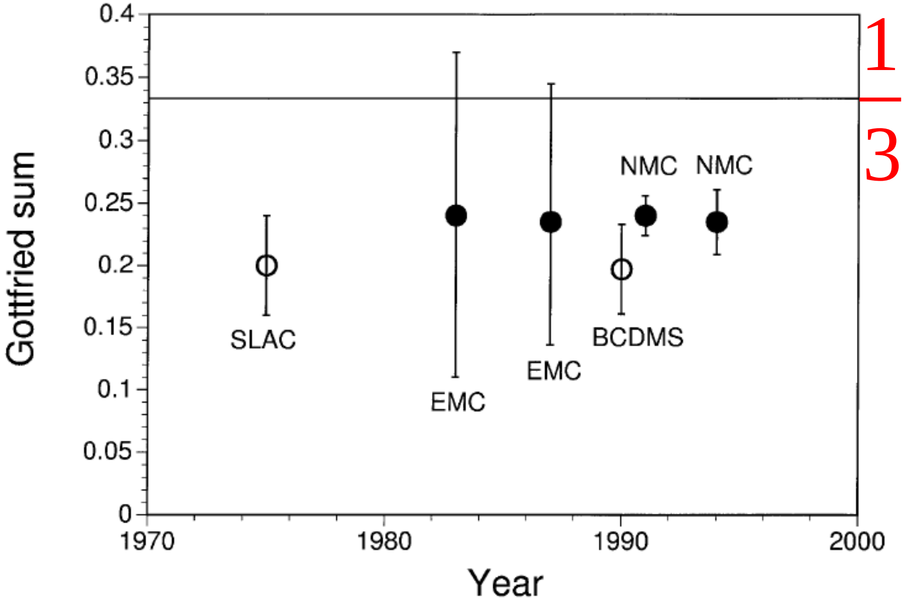
$$= \frac{1}{3} \quad (\text{if } \bar{u}(x) = \bar{d}(x))$$

$F_2^p, F_2^n$ : Structure functions of proton and neutron from DIS

# Gottfried Sum

*S. Kumano, Physics Reports, 303 (1998) 183*




New Muon Collaboration (NMC), Phys. Rev. D50 (1994) R1

$S_G = 0.235 \pm 0.026$

**( Significantly lower than 1/3 ! )**

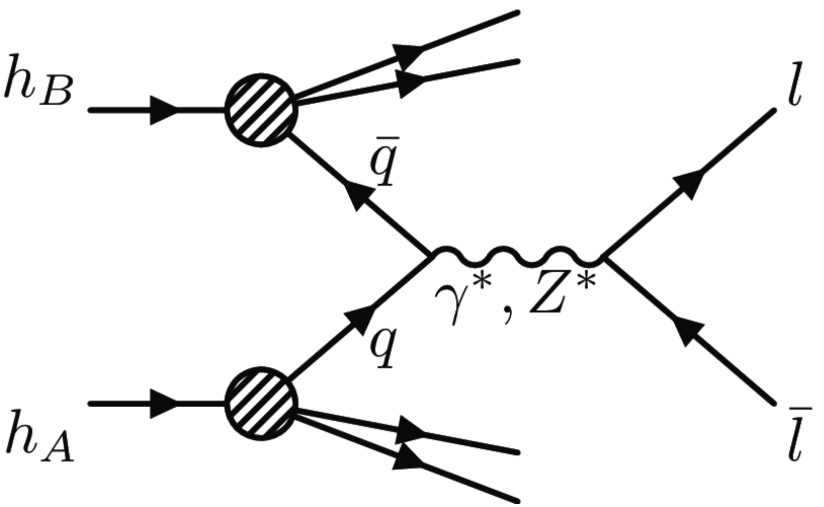
# Drell-Yan Process

S.D. Drell and T.M. Yan, PRL 25 (1970) 316

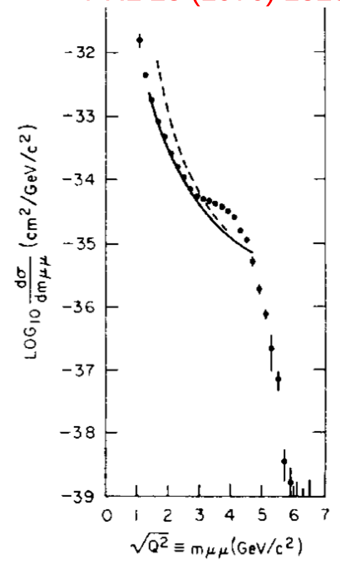
MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES*

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 $\nu W_2$ near threshold.



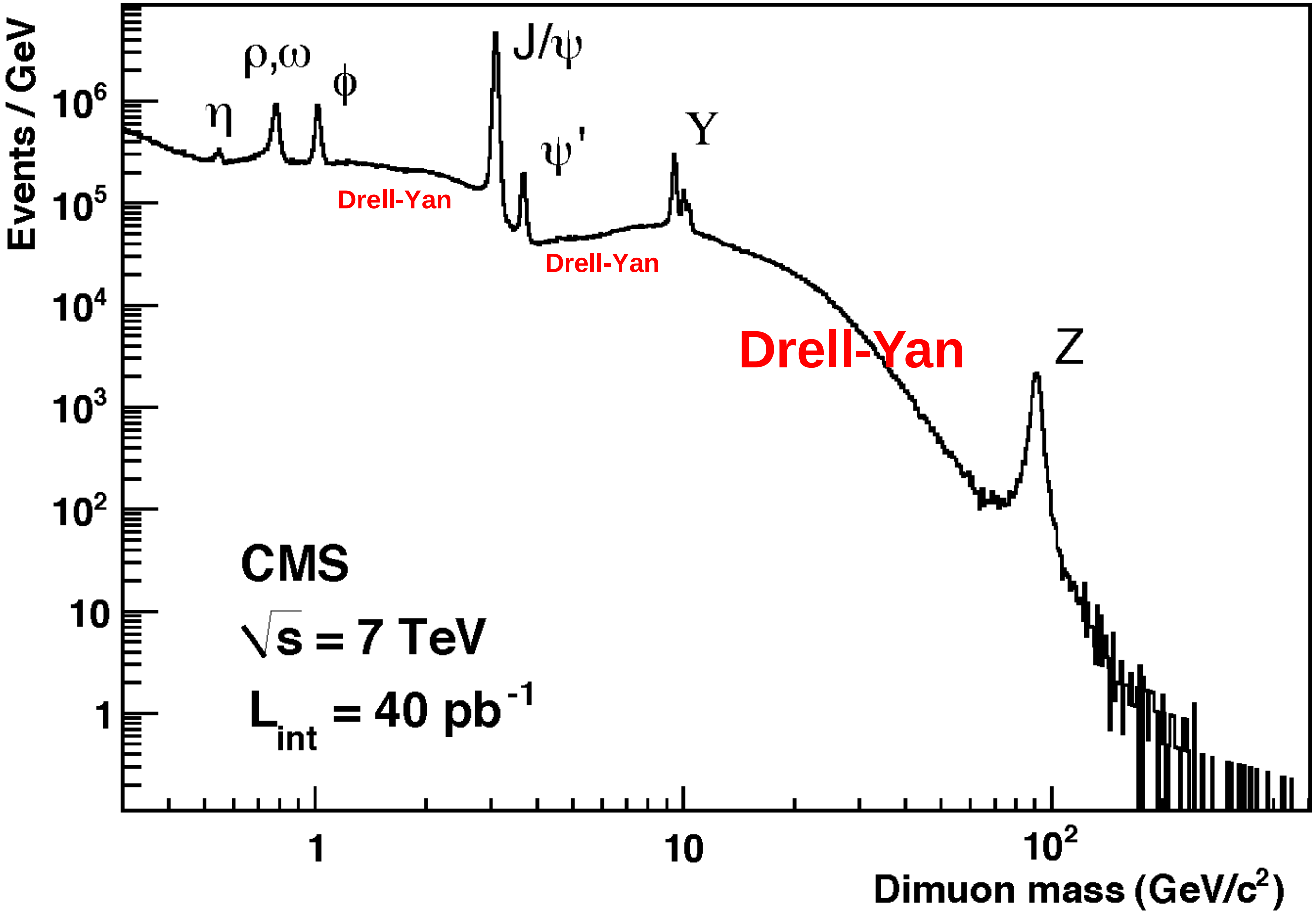

PRL 25 (1970) 1523




$$\tau = \frac{Q^2}{s} = x_1 x_2$$

$$\frac{d\sigma}{dQ^2} = \left(\frac{4\pi\alpha^2}{3Q^2}\right)\left(\frac{1}{Q^2}\right)\mathfrak{F}(\tau) = \left(\frac{4\pi\alpha^2}{3Q^2}\right)\left(\frac{1}{Q^2}\right)\int_0^1 dx_1 \int_0^1 dx_2\, \delta(x_1x_2-\tau)\sum_a \lambda_a^{-2} F_{2a}(x_1) F_{2\bar{a}}'(x_2),$$

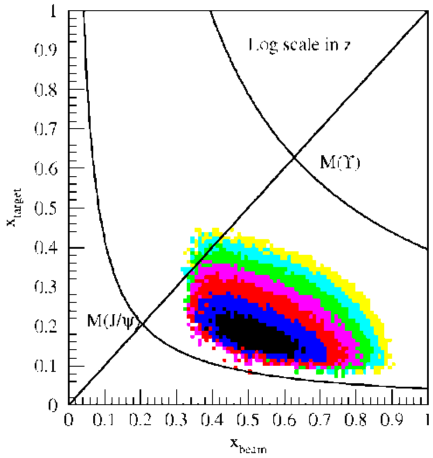
# Dimuon Invariant Mass Spectrum

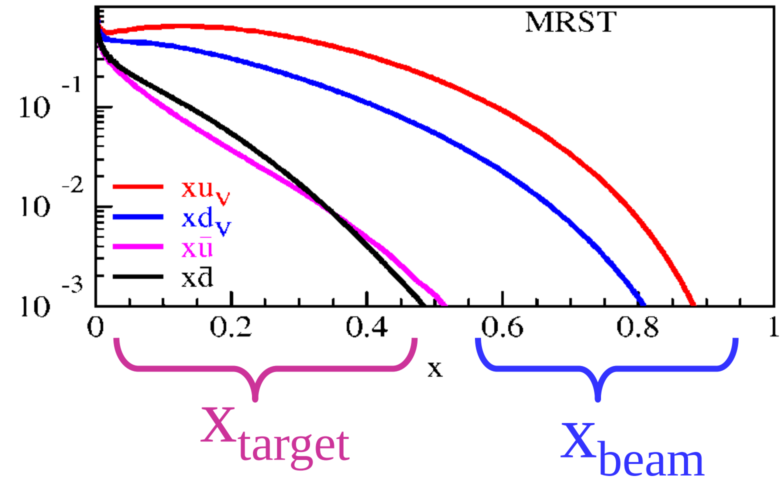


# x-dependence of Sea Quarks

Acceptance for fixed-target experiment:

$x_{beam} >> x_{target}$




$$\frac{d^2\sigma}{dx_{beam}dx_{target}} = \frac{4\pi\alpha^2}{9x_{beam}x_{target}}\frac{1}{s}\sum_i e_i^2[q_i(x_{beam})\bar{q}_i(x_{target}) + \bar{q}_i(x_{beam})q_i(x_{target})]$$

$$\frac{\sigma^{pd}}{2\sigma^{pp}}\Big|_{x_{beam} >> x_{target}} \approx \frac{1}{2}\left[1+\frac{\bar{d}(x_{target})}{\bar{u}(x_{target})}\right]$$

# Light Antiquark Flavor Asymmetry: Drell-Yan Experiments

- Naïve Assumption: $\bar{d}(x) = \bar{u}(x)$
- NMC (Gottfried Sum Rule):

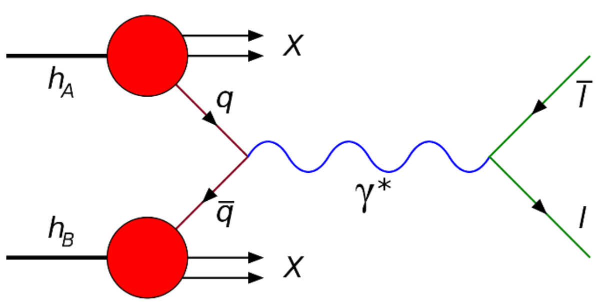
$$\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] dx \neq 0$$

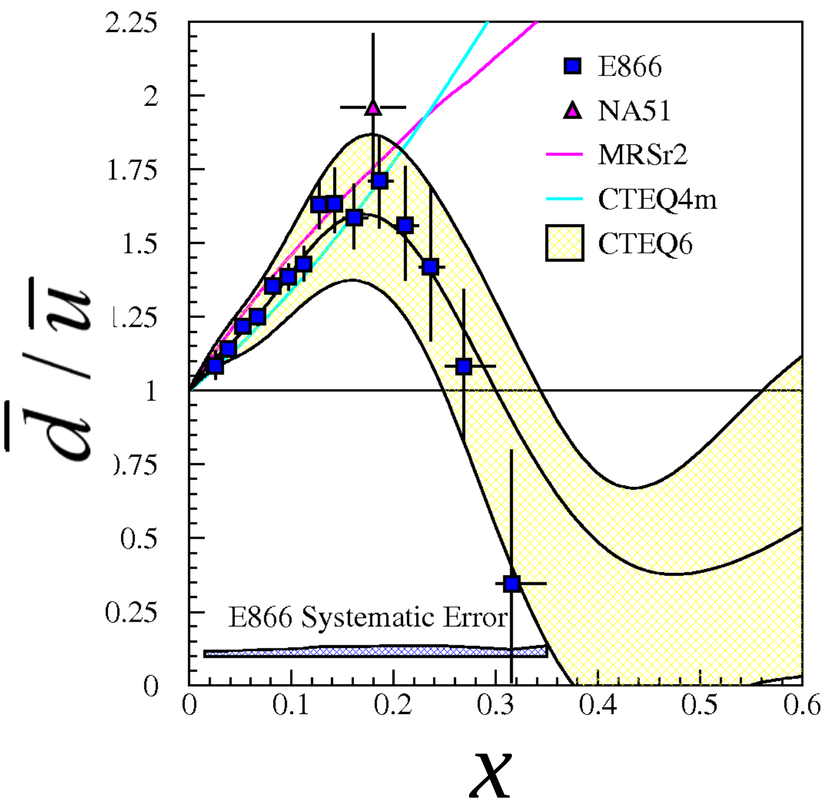
- NA51 (Drell-Yan, 1994):

$$\bar{d} > \bar{u} \text{ at } x = 0.18$$

- E866/NuSea (Drell-Yan, 1998):

$$\bar{d}(x)/\bar{u}(x) \text{ for } 0.015 \leq x \leq 0.35$$



# Pauli Exclusive Principle

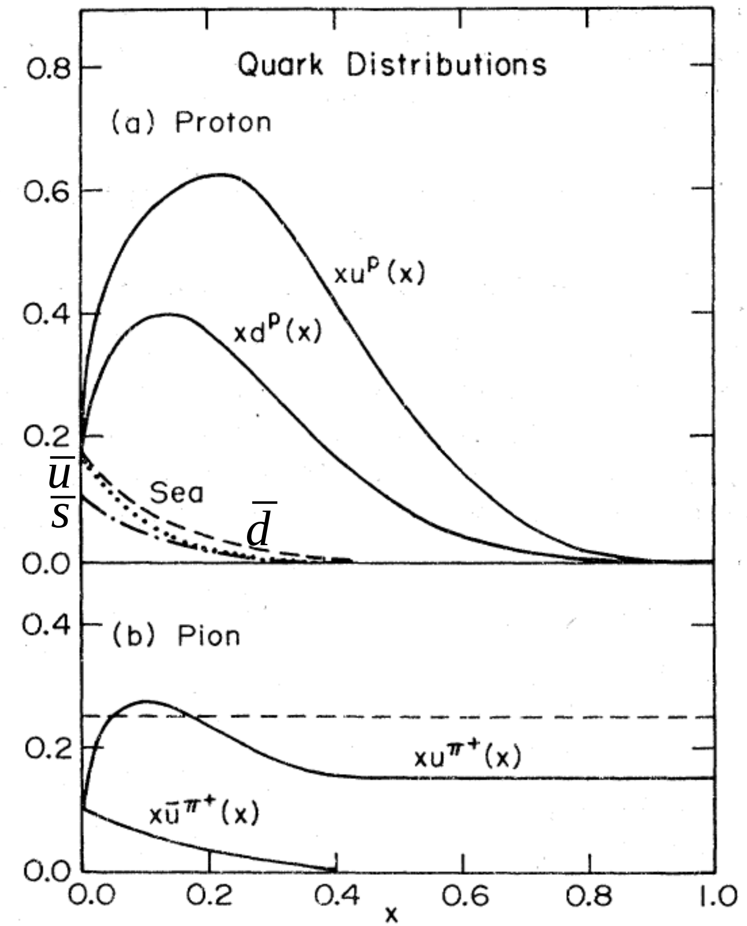
Field and Feynman, PRD 15, 2590 (1977)

There is no reliable neutrino information separating $\bar{u}$ from $\bar{d}$, but the $ep$ data tell us that the integral

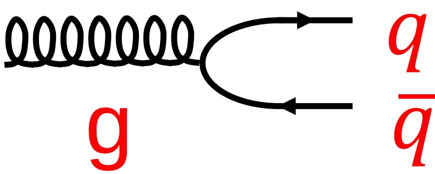
$$\int_0^1 [\nu W_2^{ep}(x) - \nu W_2^{en}(x)]\frac{dx}{x} = \int_0^1 \tfrac{1}{3}(u+\bar{u}-d-\bar{d})dx$$

$$= \tfrac{1}{3} + \tfrac{2}{3}\int_0^1 (\bar{u}-\bar{d})\,dx \qquad (2.6)$$

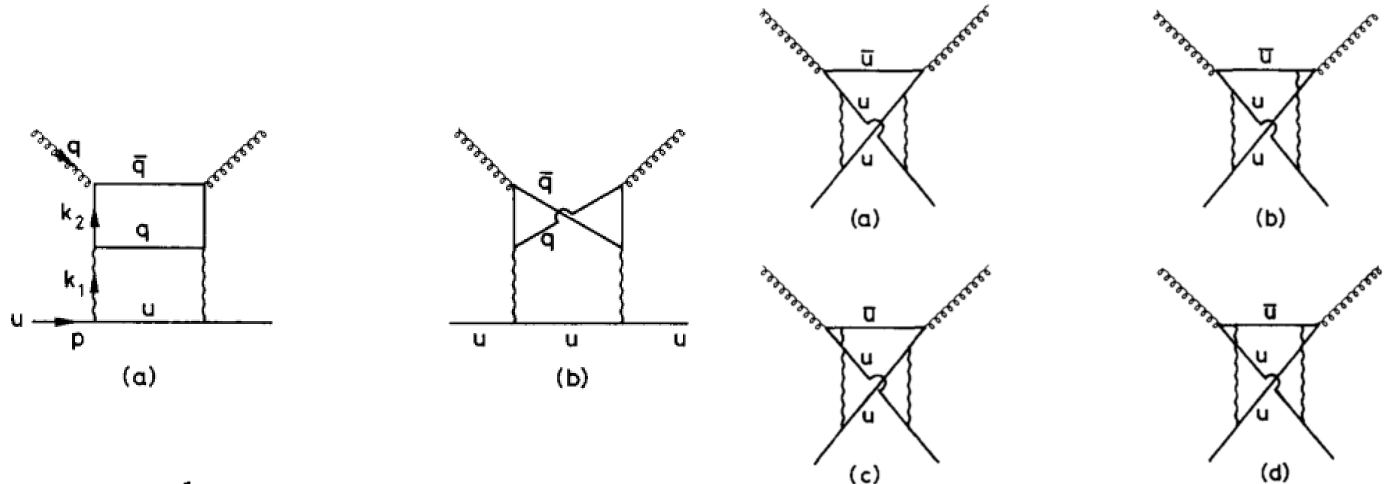
using the sum rules (2.2). Experimentally this integral is hard to determine for it depends on small differences near $x=0$. It seems, however, to be distinctly less than $\frac{1}{3}$[8] (from the data of Figs. 2 and 3(b) one gets about 0.27), indicating $\bar{u}<\bar{d}$ (although, of course, they must be equal as $x\to 0$). A likely physical reason for this is the presence of more of what are called "valence" $u$ quarks than $d$ quarks, so the pairs $u\bar{u}$ expected to occur in the small $x$ region (the "sea") are suppressed more than $d\bar{d}$ pairs by the exclusion principle. We have



# Origin of $\bar{u}(x) \neq \bar{d}(x)$: pQCD effect?




- Pauli blocking
  - $g \to u\bar{u}$ is more suppressed than $g \to d\bar{d}$ in the proton since |p>=|uud>
(*Field and Feynman 1977*)
  - pQCD calculation (*Ross & Sachrajda, NPB149 (1979) 497*)

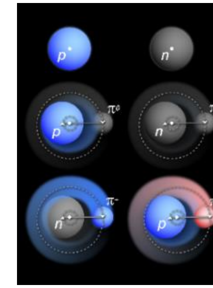



$$\int \frac{dx}{x} \{[\nu W_2^{ep}(x, q^2) - \nu W_2^{en}(x, q^2)] - [\nu W_2^{ep}(x, q_0^2) - \nu W_2^{en}(x, q_0^2)]\}$$

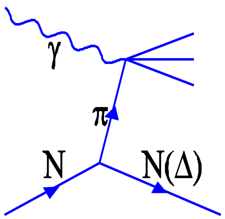
$$\simeq 0.01(\alpha_s(q^2) - \alpha_s(q_0^2)),$$

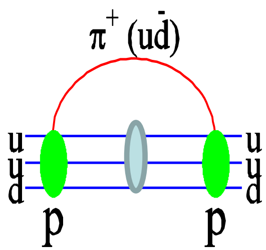
The perturbative effect is too small to explain the antiquark asymmetry!

# Origin of $\bar{u}(x) \neq \bar{d}(x)$: Non-perturbative QCD effect




- Meson cloud in the nucleons (Thomas 1983, Kumano 1991): Sullivan process in DIS.

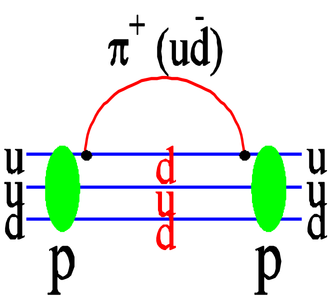



$$|p\rangle = \sqrt{Z}\,|p_0\rangle + a_{N\pi/p}\left[-\sqrt{\frac{1}{3}}|p_0\pi^0\rangle + \sqrt{\frac{2}{3}}|n_0\pi^+\rangle\right] + a_{\Delta\pi/p}\left[\sqrt{\frac{1}{2}}|\Delta_0^{++}\pi^-\rangle - \sqrt{\frac{1}{3}}|\Delta_0^{+}\pi^0\rangle + \sqrt{\frac{1}{6}}|\Delta_0^{0}\pi^+\rangle\right]$$
$$+ a_{\Lambda K/p}\,|\Lambda_0 K^+\rangle + a_{\Sigma K/p}\left[-\sqrt{\frac{1}{2}}|\Sigma_0^{+}K^0\rangle + \sqrt{\frac{1}{2}}|\Sigma_0^{0}K^+\rangle\right] + \cdots$$

n

- Chiral quark model (Eichten et al. 1992; Wakamatsu 1992): Goldstone bosons couple to valence quarks.

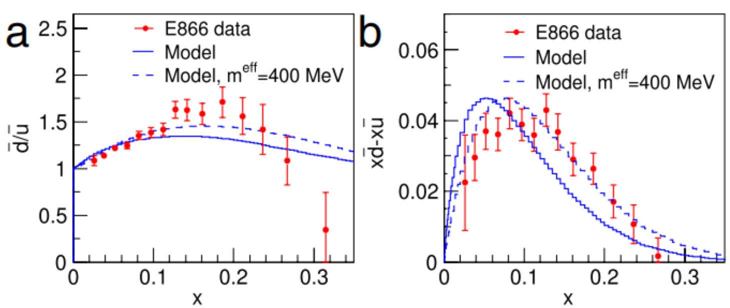



$$|U\rangle = \sqrt{Z}|u\rangle + \sqrt{\frac{1}{3}}a_{\pi/U}|u\pi^0\rangle + \sqrt{\frac{2}{3}}a_{\pi/U}|d\pi^+\rangle + a_{K/U}|sK^+\rangle + \cdots$$

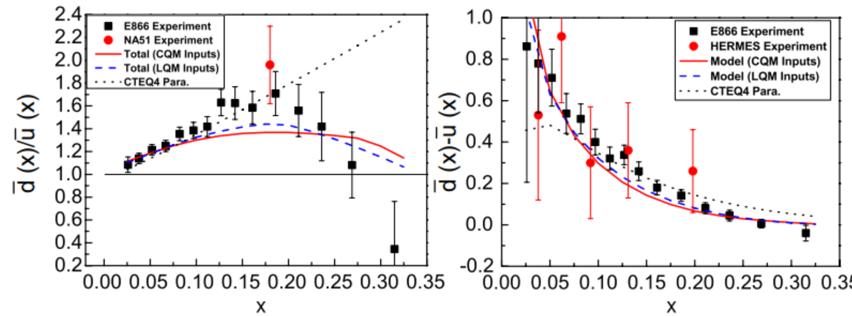
$$|D\rangle = \sqrt{Z}|d\rangle + \sqrt{\frac{1}{3}}a_{\pi/D}|d\pi^0\rangle + \sqrt{\frac{2}{3}}a_{\pi/D}|u\pi^-\rangle + a_{K/D}|sK^0\rangle + \cdots,$$

**Pion cloud is a source of antiquarks in the protons and it lead to $\bar{d} > \bar{u}$.**

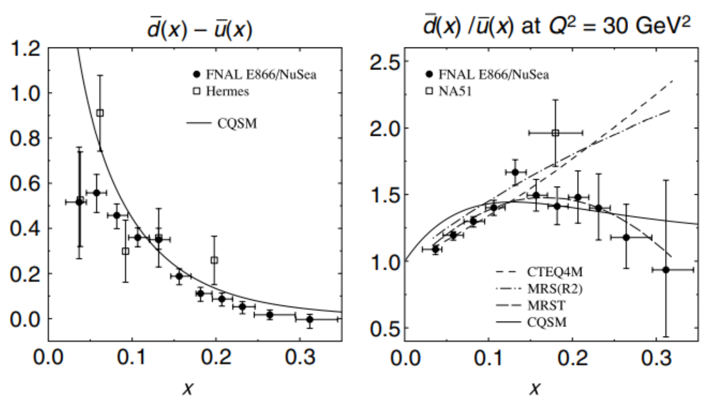
# Flavor structure of nucleon sea



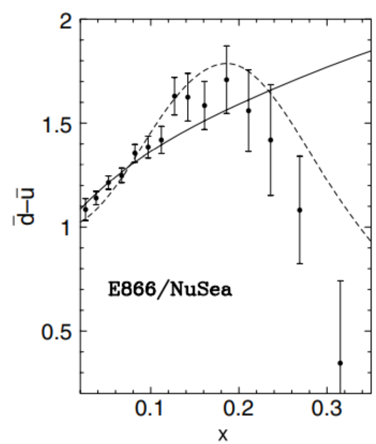

(a) Meson cloud model. Figure from [34].



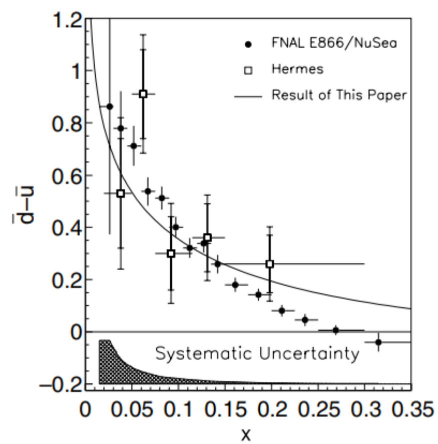

(b) Chiral quark model. Figure from [37].




(c) Chiral quark model. Figure from [37].




(d) Chiral quark model. Figure from [37].

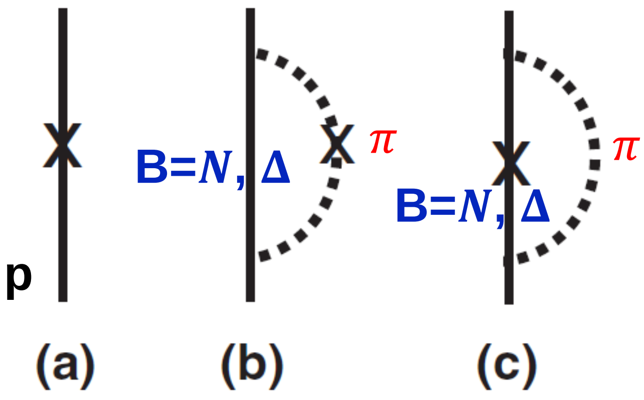



(e) Balance model. Figure from [47].

"*Flavor structure of the nucleon sea*", Wen-Chen Chang and Jen-Chieh Peng
Progress in Particle and Nuclear Physics 79 (2014) 95; arXiv:1406.1260

# Chiral Pion Cloud Model:

Alberg and Miller, PRC 100, 035205 (2019)

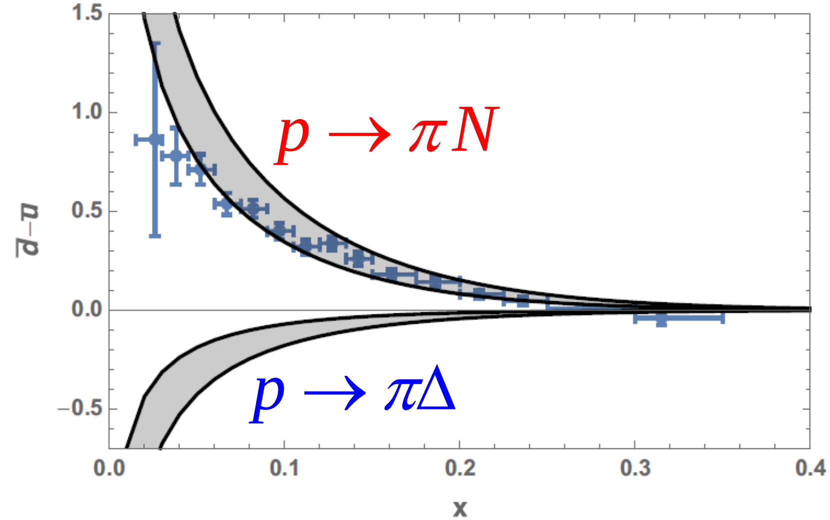


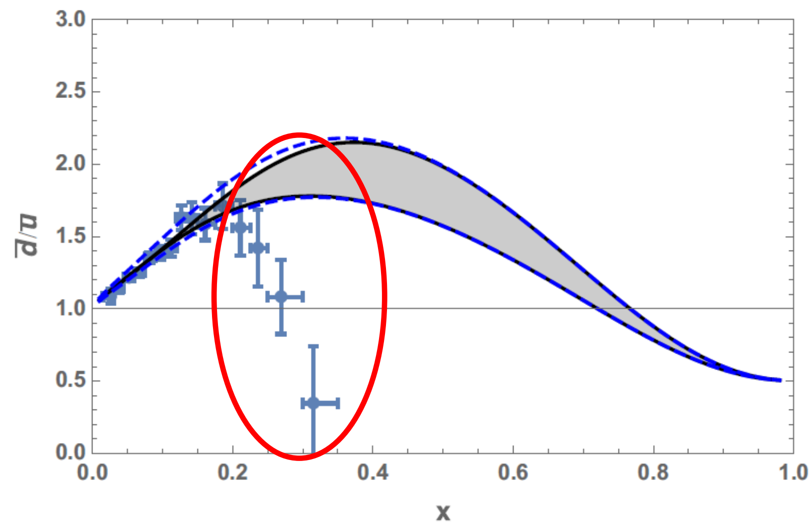

$$q_N^f(x) = Zq_{N0}^f(x) + \sum_{B=N,\Delta} f_{\pi B} \otimes q_\pi^f + \sum_B f_{B\pi} \otimes q_B^f$$

$$\bar{d}(x) = \left(\frac{5}{6} f_{\pi N} + \frac{1}{3} f_{\pi\Delta}\right) \otimes q_\pi^v + \bar{q}_{\rm sym}(x),$$

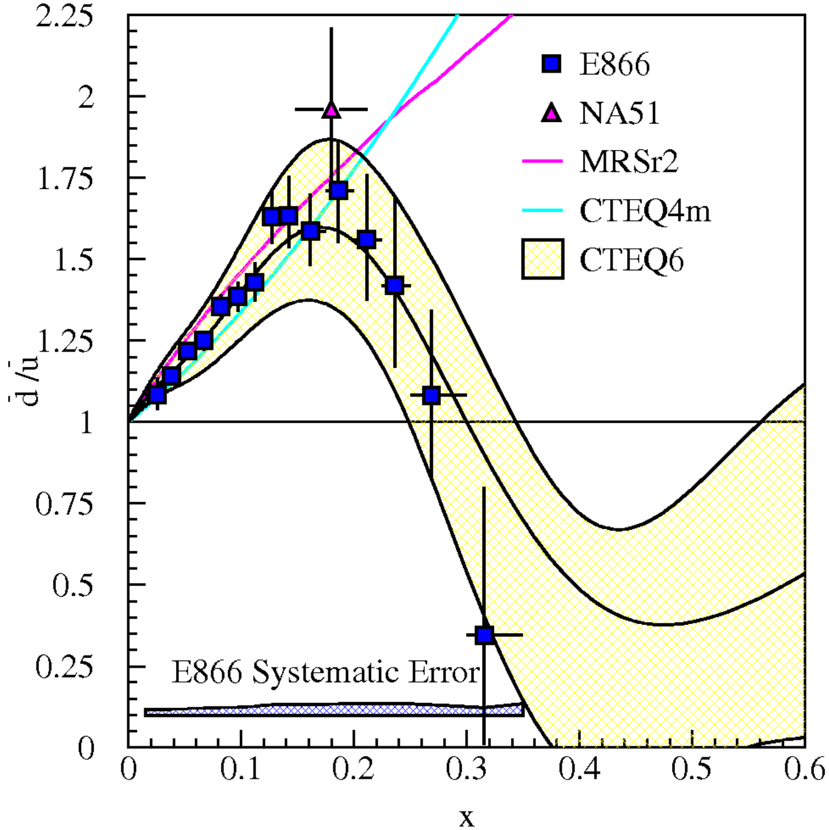
$$\bar{u}(x) = \left(\frac{1}{6} f_{\pi N} + \frac{2}{3} f_{\pi\Delta}\right) \otimes q_\pi^v + \bar{q}_{\rm sym}(x),$$

$$f_{\pi B} \otimes q_\pi^f \equiv \int_x^1 \frac{dy}{y} f_{\pi B}(y) q_\pi^f\left(\frac{x}{y}\right)$$

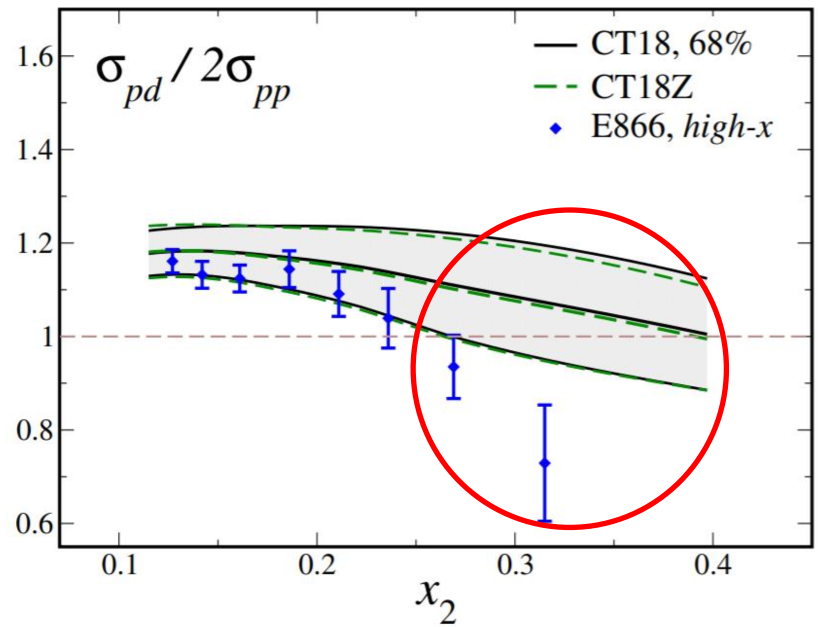


# $\bar{d}(x)/\bar{u}(x)$ vs. PDFs

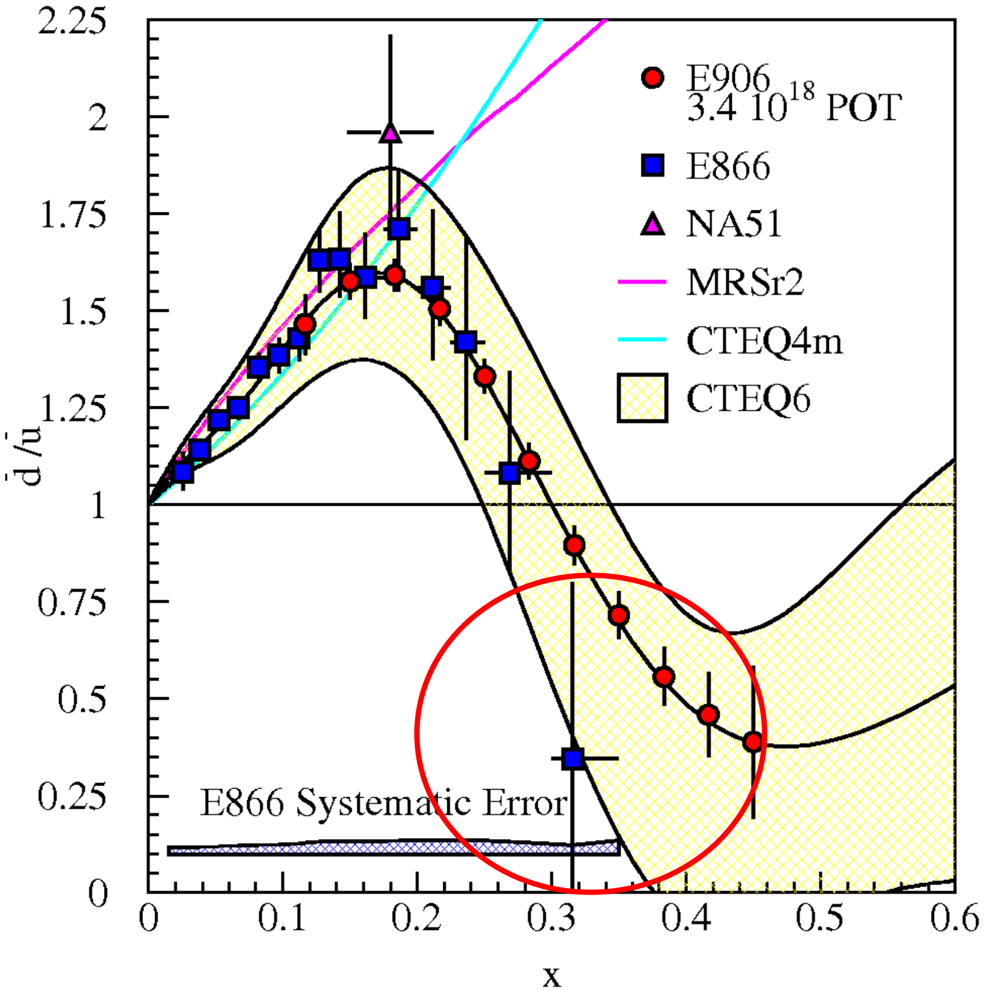



CT18NLO: PRD 103 (2021) 014013




Tension shows up with the collider data!

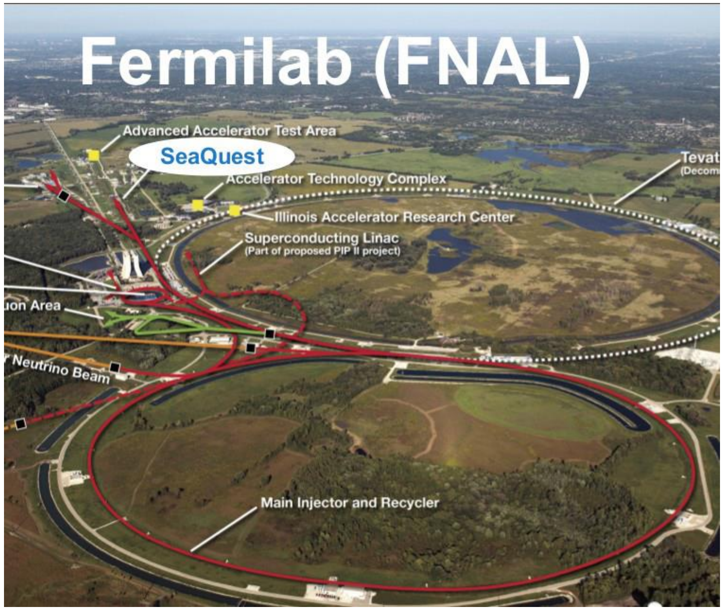
# $\bar{d}(x)/\bar{u}(x)$ Measured by FNAL E906/SeaQuest Experiment




$(\bar{d}(x)/\bar{u}(x))$ up to $x_T \sim 0.45$

Fermilab E906

- $x_B x_T = \frac{M}{s}$ ; smaller s, larger $x_T$
- Unpolarized Drell-Yan using 120 GeV proton beam from Main Injector
- $^1H$, $^2H$, and nuclear targets



# E906/SeaQuest Timeline

- Schedules:
  - **2002: E906 Approved by Fermilab PAC**
  - 2006: E906 funded by DOE Nuclear Physics
  - 2008: With participation of Japan and Taiwan groups, Stage-II approval by Fermilab Director. MOU between Fermilab and E906 Collaboration finalized.
  - 2009-2010: Construction and installation of spectrometer and readout electronics.
  - The commission of experiment was originally scheduled to start in September 2010. Unfortunately a leakage of the upstream beam pipe was found, and FNAL spent a lot of efforts in fixing it up.
  - Run 1 (Mar. 2012 – Apr., 2012): commissioning run
  - Run 2 (Nov. 2013 – Sep., 2014): 1st physics run
  - Run 3 (Nov. 2014 – Jul., 2015): 2nd physics run
  - Run 4 (Oct. 2015 – Aug., 2016): 3rd physics run
  - Run 5 (Nov. 2016 – Jul., 2017): 4th physics run

# Nature 590, 561–565 (2021)

Article

# The asymmetry of antimatter in the proton

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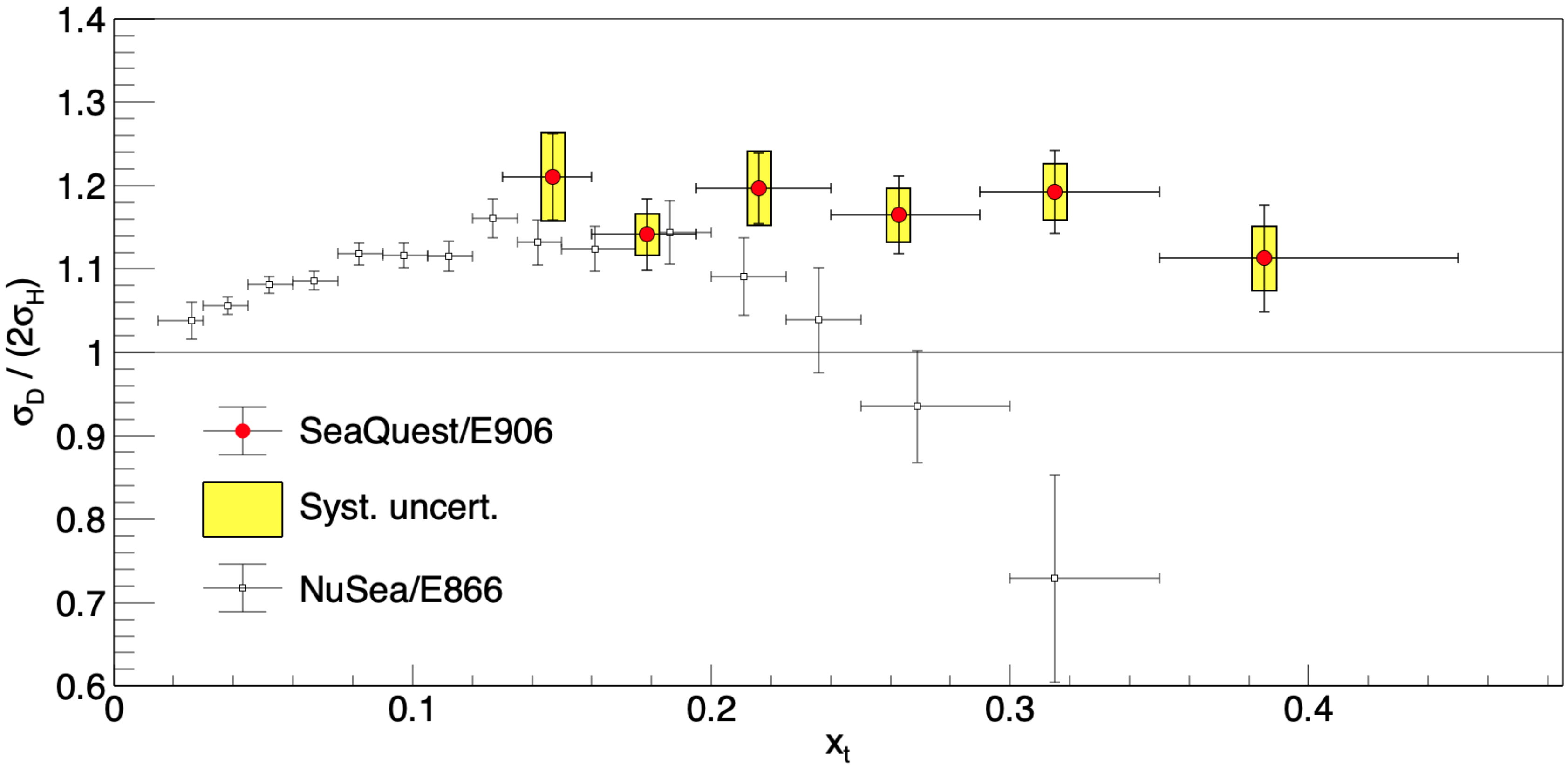
Check for updates

J. Dove[1], B. Kerns[1], R. E. McClellan[1,18], S. Miyasaka[2], D. H. Morton[3], K. Nagai[2,4], S. Prasad[1], F. Sanftl[2], M. B. C. Scott[3], A. S. Tadepalli[5,18], C. A. Aidala[3,6], J. Arrington[7,19], C. Ayuso[3,20], C. L. Barker[8], C. N. Brown[9], W. C. Chang[4], A. Chen[1,3,4], D. C. Christian[10], B. P. Dannowitz[1], M. Daugherity[8], M. Diefenthaler[1,18], L. El Fassi[5,11], D. F. Geesaman[7,21], R. Gilman[5], Y. Goto[12], L. Guo[6,22], R. Guo[13], T. J. Hague[8], R. J. Holt[7,23], D. Isenhower[8], E. R. Kinney[14], N. Kitts[8], A. Klein[6], D. W. Kleinjan[6], Y. Kudo[15], C. Leung[1], P.-J. Lin[14], K. Liu[6], M. X. Liu[6], W. Lorenzon[3], N. C. R. Makins[1], M. Mesquita de Medeiros[7], P. L. McGaughey[6], Y. Miyachi[15], I. Mooney[3,24], K. Nakahara[16,25], K. Nakano[2,12], S. Nara[15], J.-C. Peng[1], A. J. Puckett[6,26], B. J. Ramson[3,27], P. E. Reimer[7] ✉, J. G. Rubin[3,7], S. Sawada[17], T. Sawada[3,28], T.-A. Shibata[2,29], D. Su[4], M. Teo[1,30], B. G. Tice[7], R. S. Towell[8], S. Uemura[6,31], S. Watson[8], S. G. Wang[4,13,32], A. B. Wickes[6], J. Wu[10], Z. Xi[8] & Z. Ye[7]

The fundamental building blocks of the proton—quarks and gluons—have been known for decades. However, we still have an incomplete theoretical and

# Cross Section Ratios

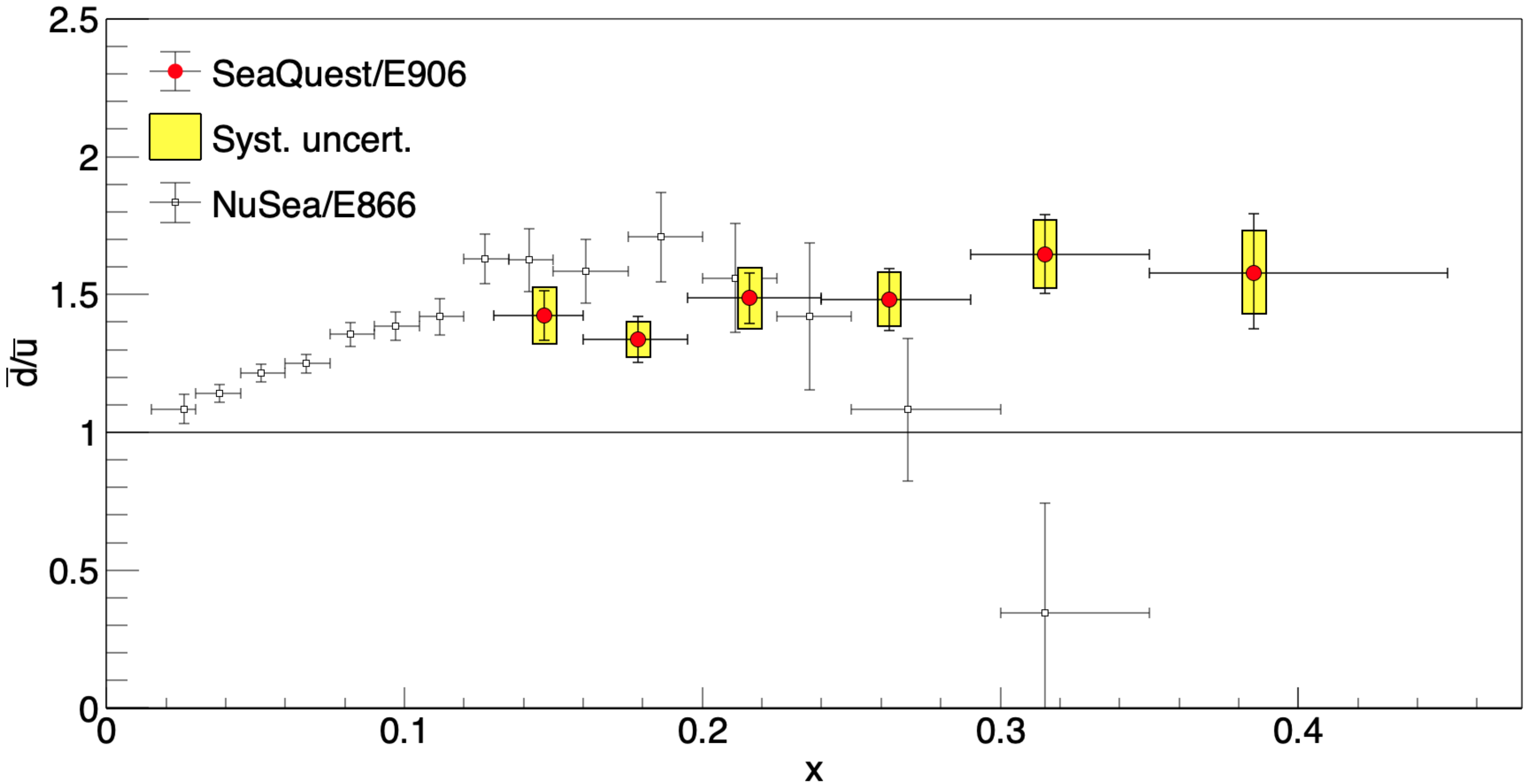
$$\left\langle M^2_{NuSea} \right\rangle = 54\ \mathrm{GeV}^2, \left\langle M^2_{SeaQuest} \right\rangle = 22 - 40\ \mathrm{GeV}^2$$




$$\frac{\sigma^{pd}}{2\sigma^{pp}} \Big|_{x_{\mathrm{beam}} >> x_{\mathrm{target}}} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_{\mathrm{target}})}{\bar{u}(x_{\mathrm{target}})}\right]$$

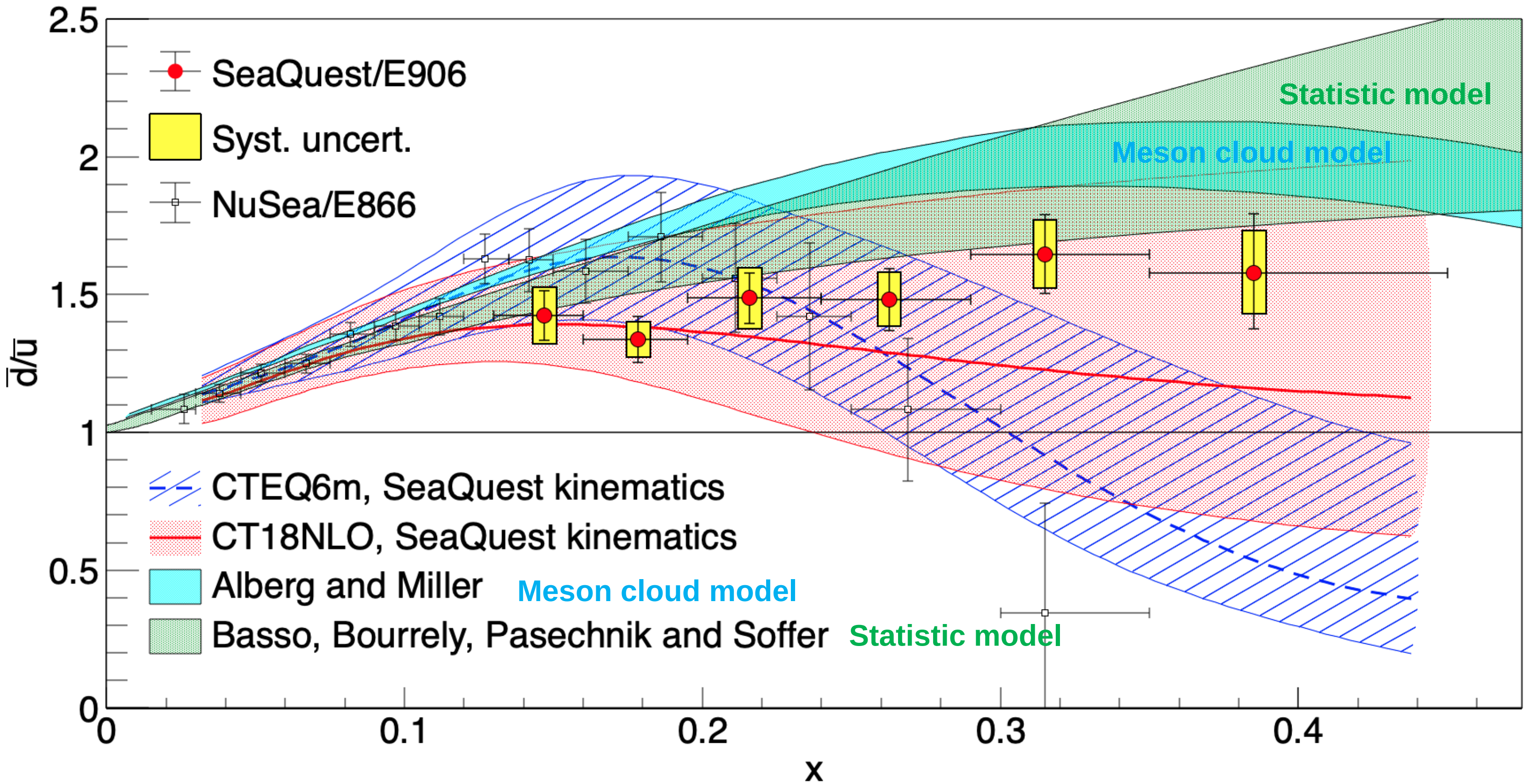
# $\bar{d}/\bar{u}(x)$

Extracting $\bar{d}/\bar{u}(x)$ by NLO calculations of $\sigma_D(x)/2\sigma_H(x)$




The trends between SeaQuest and NuSea at large x are quite different.
No explanation is found for these differences.

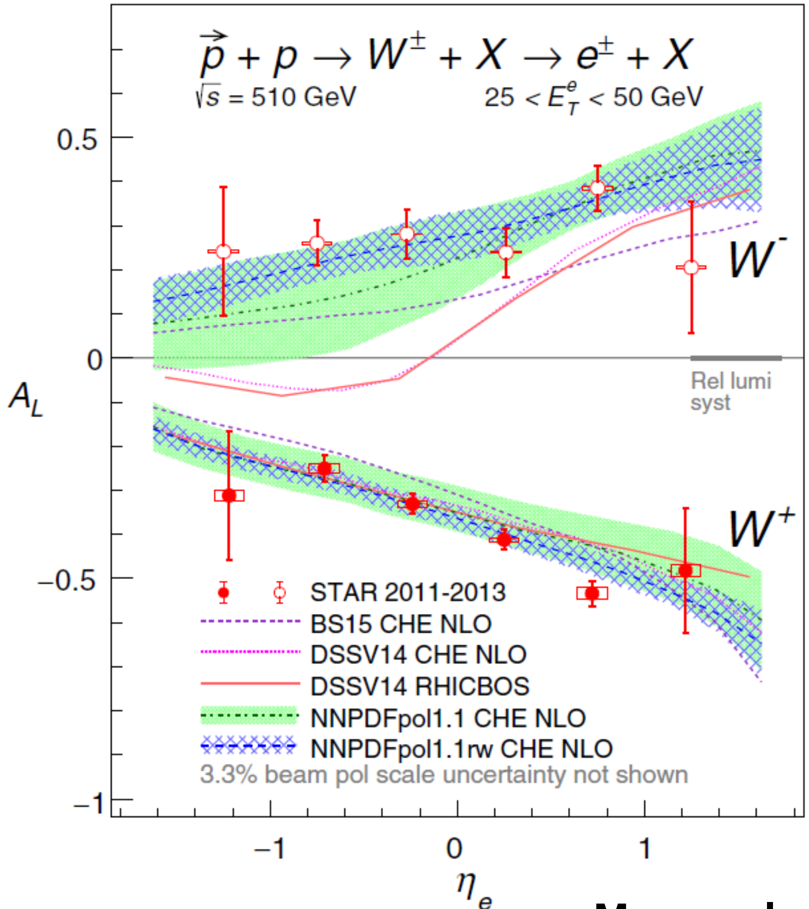
# $\bar{d}/\bar{u}(x)$



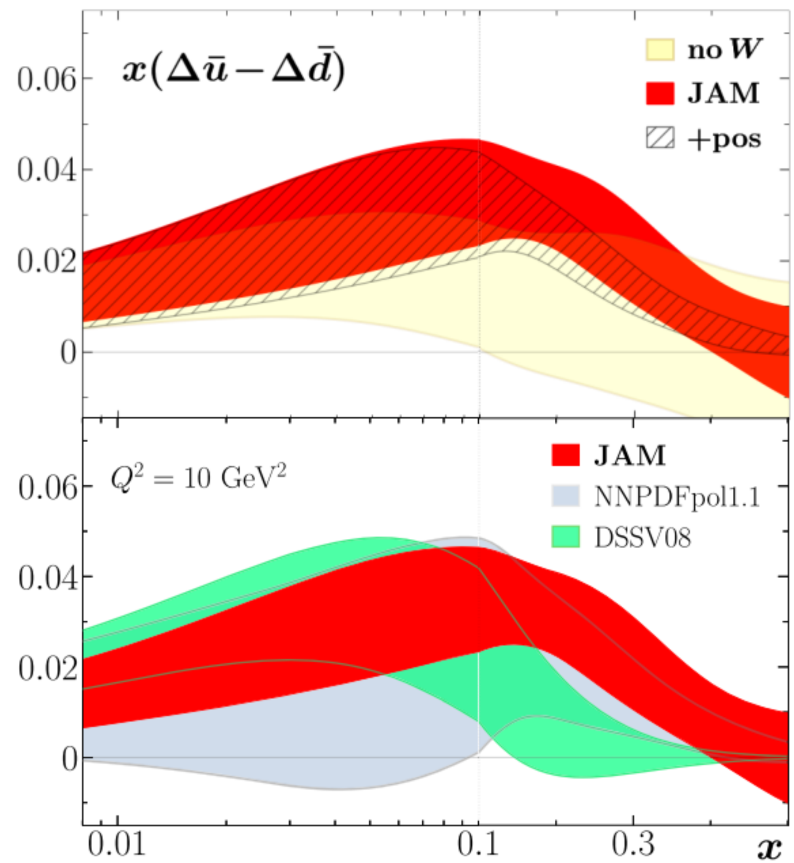

The extracted $\bar{d}/\bar{u}(x)$ are consistent with CT18NLO and predictions of pion-cloud model.

# Asymmetry of $\Delta\bar{\mathrm{d}}(x)$ and $\Delta\bar{\mathrm{u}}(x)$

**STAR, PRD 99, 051102(R) (2019)**




$\Delta\bar{d}(x) < \Delta\bar{u}(x)$ **JAM, PRD 106, L031502 (2022)**




Correlation between spin and isospin?

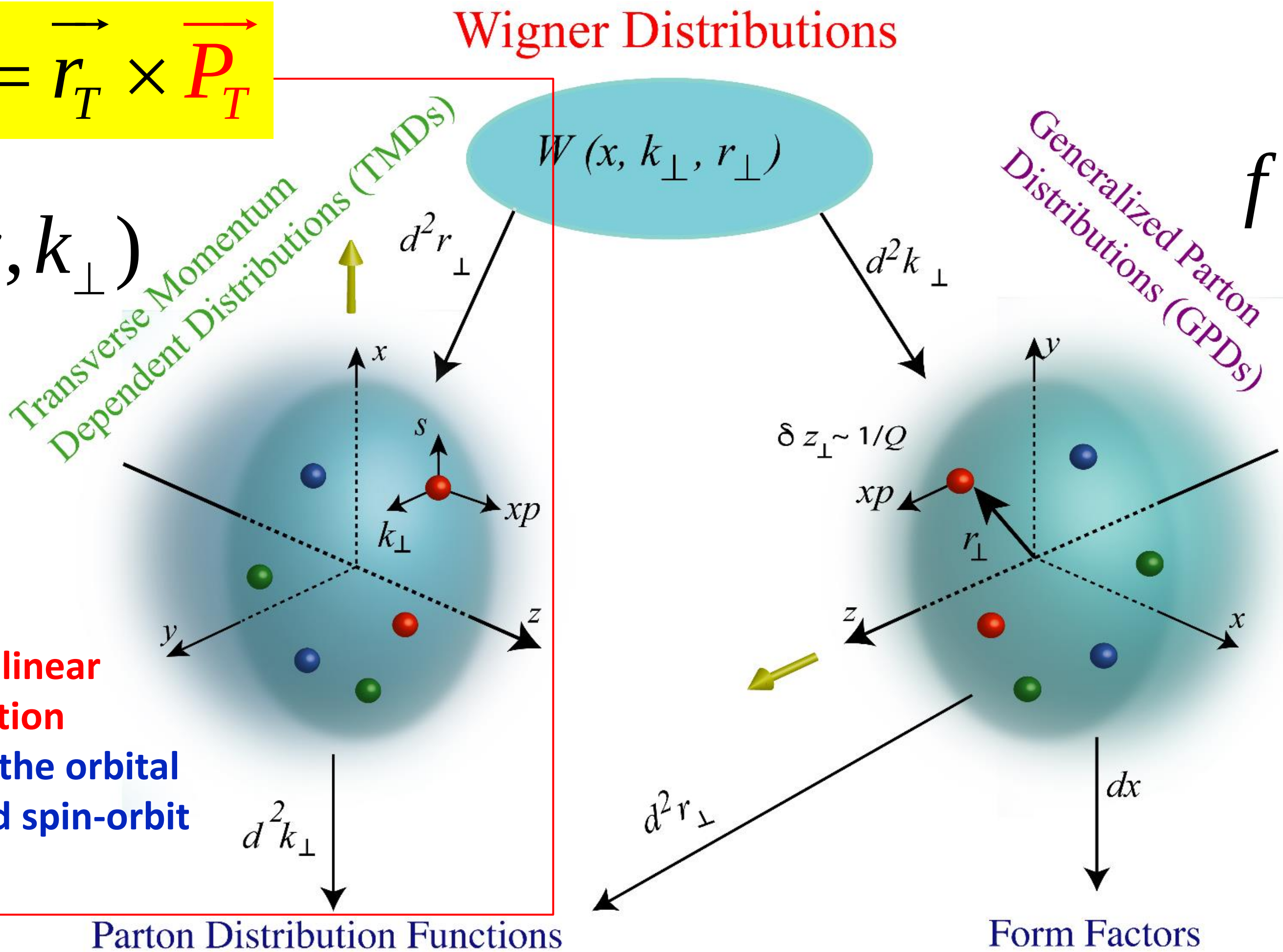
- **Meson cloud model**: little spin carried by sea quark.
- **Statistic model**: $\Delta\bar{\mathrm{d}}(x) - \Delta\bar{\mathrm{u}}(x) = -(\bar{\mathrm{d}}(x) - \bar{\mathrm{u}}(x))$
- **Chiral soliton model**: $\Delta\bar{\mathrm{d}}(x) - \Delta\bar{\mathrm{u}}(x) = -\frac{5}{3}(\bar{\mathrm{d}}(x) - \bar{\mathrm{u}}(x))$

# Multi-dimensional Partonic Structures

$$\overrightarrow{L_Z} = \overrightarrow{r_T} \times \overrightarrow{P_T}$$

$$f(x, k_\perp)$$

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




- **Beyond collinear approximation**
- **Related to the orbital motion and spin-orbit effects.**

$$f(x) \qquad\qquad F_{1,2}(t)$$

http://www.int.washington.edu/PROGRAMS/17-3/

# Leading-Twist Transverse-momentum Dependent **Parton Density Function** (TMDs)

**spin of the nucleon**

**spin of the parton**

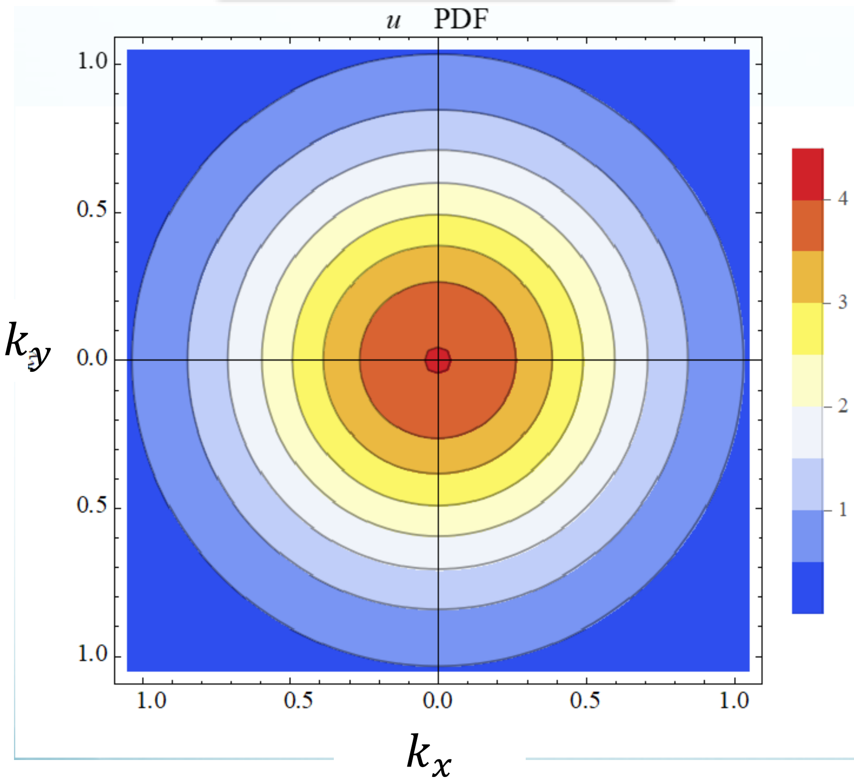
**$k_T$ of the parton**

| Nucleon \ Quark | U | L | T |
|---|---|---|---|
| **U** | **number density** $f_1^{q,g}(x, k_T^2)$ | | **Boer-Mulders** $h_1^{\perp q,g}(x, k_T^2)$ |
| **L** | | **Helicity** $g_{1L}^{q,g}(x, k_T^2)$ | **worm-gear L** $h_{1L}^{\perp q,g}(x, k_T^2)$ |
| **T** | **Sivers** $f_{1T}^{\perp q,g}(x, k_T^2)$ | **Kotzinian-Mulders worm-gear T** $g_{1T}^{\perp q,g}(x, k_T^2)$ | **Transversity** $h_1^{q,g}(x, k_T^2)$ **Pretzelosity** $h_{1T}^{\perp q,g}(x, k_T^2)$ |

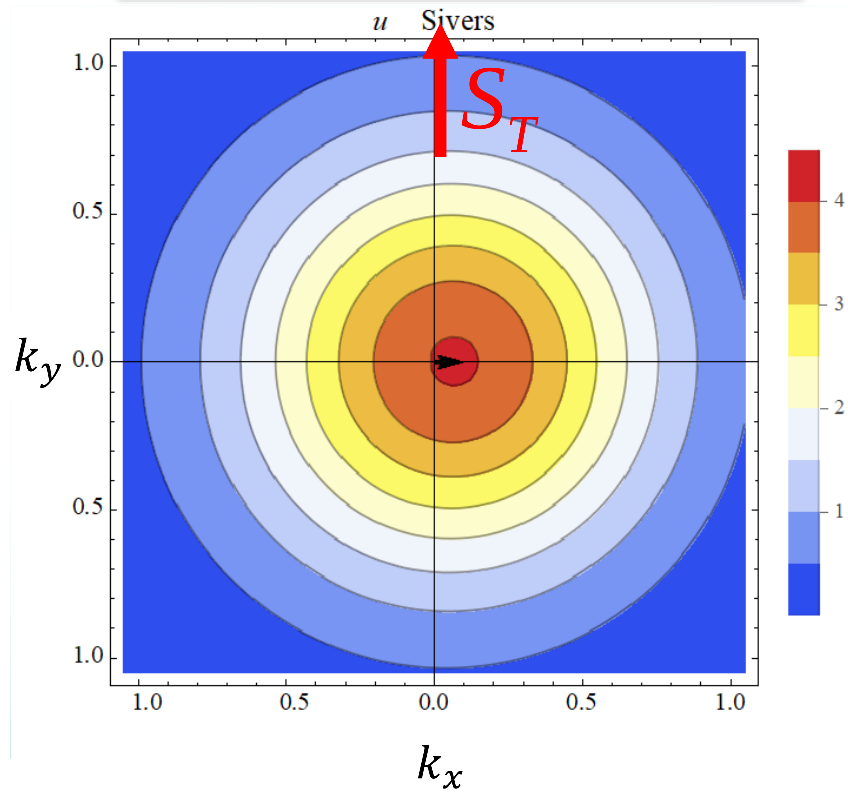
# TMD Sivers Function

$$f_{q/p\uparrow}(x,k_T,\overrightarrow{S_T}) = f_{q/p}(x,k_T) - \frac{1}{M} f_{1T}^{\perp q}(x,k_T)\overrightarrow{S_T}\cdot(\hat{p}_N \times k_T)$$

Unpolarized proton

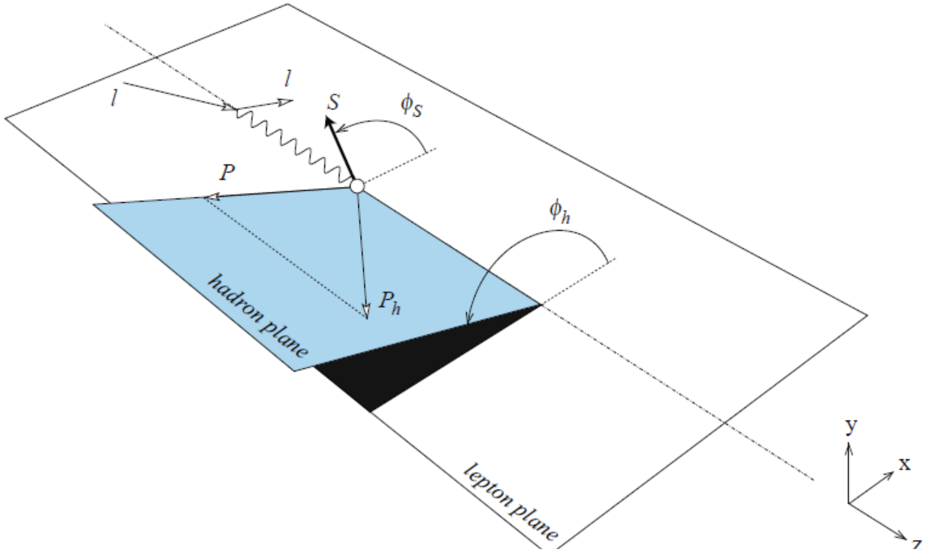



Transversely-polarized proton




- **A nonzero Sivers function is considered to be strong evidence for the presence of quark orbital angular momentum.**

# SIDIS cross-sections




$F_{UU}^{\cos(2\phi)}$, $F_{UT}^{\sin(\phi-\phi_S)}$, $F_{UT}^{\sin(\phi+\phi_S)}$ :
Structure Functions

$$\sigma(\phi,\phi_S) \equiv \frac{d^6\sigma}{dx\,dy\,dz\,d\phi\,d\phi_S\,dP_{hT}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\epsilon F_{UU,L}+\sqrt{2\epsilon(1+\epsilon)}\cos\phi\,F_{UU}^{\cos\phi}+\epsilon\cos(2\phi)\,F_{UU}^{\cos(2\phi)}+\lambda_e\left[\sqrt{2\epsilon(1-\epsilon)}\sin\phi\,F_{LU}^{\sin\phi}\right]$$

$$+S_L\left[\sqrt{2\epsilon(1+\epsilon)}\sin\phi\,F_{UL}^{\sin\phi}+\epsilon\sin(2\phi)\,F_{UL}^{\sin(2\phi)}\right]+S_L\lambda_e\left[\sqrt{1-\epsilon^2}\,F_{LL}+\sqrt{2\epsilon(1-\epsilon)}\cos\phi\,F_{LL}^{\cos\phi}\right]$$

$$+|S_T|\Big[\sin(\phi-\phi_S)\left(F_{UT,T}^{\sin(\phi-\phi_S)}+\epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\right)+\epsilon\sin(\phi+\phi_S)\,F_{UT}^{\sin(\phi+\phi_S)}+\epsilon\sin(3\phi-\phi_S)\,F_{UT}^{\sin(3\phi-\phi_S)}$$

$$+\sqrt{2\epsilon(1+\epsilon)}\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S)\,F_{UT}^{\sin(2\phi-\phi_S)}\Big]$$

$$+|S_T|\lambda_e\left[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)\,F_{LT}^{\cos(\phi-\phi_S)}+\sqrt{2\epsilon(1-\epsilon)}\cos\phi_S\,F_{LT}^{\cos\phi_S}+\sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)\,F_{LT}^{\cos(2\phi-\phi_S)}\right]\Big\},$$



Avakian et al., Eur. Phys.J. A52 (2016) 150

# Polarization-dependent Terms: Transverse Spin Asymmetry $A_{UT}$

$$A_{UT} = \frac{F_{UT}}{F_{UU}} = \frac{1}{fS_T} \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

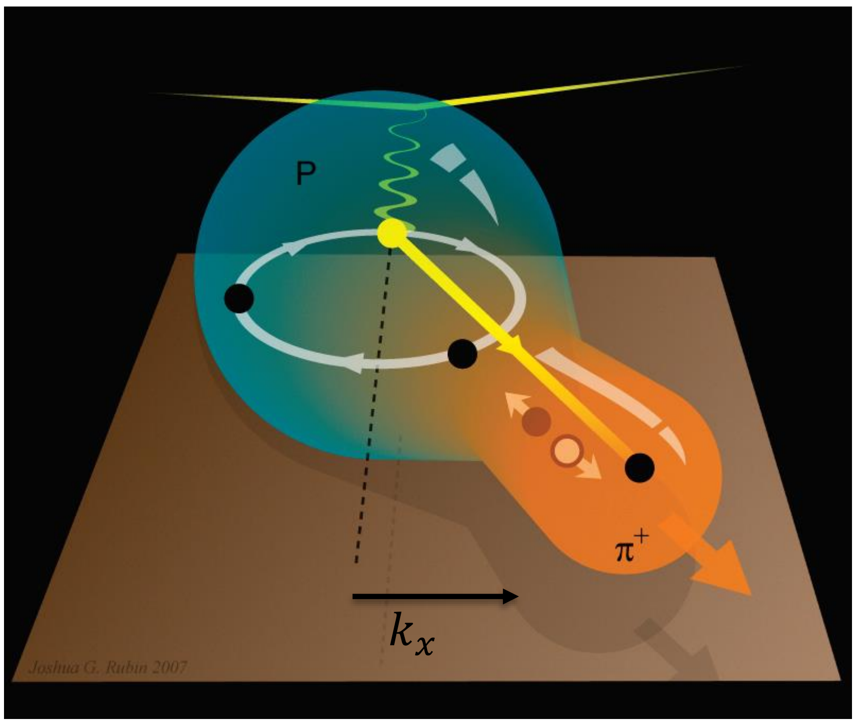
$f$: dilution factor due to non-polarizable component of the target

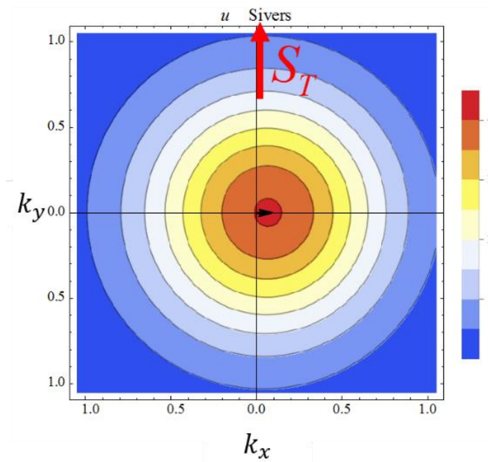
$S_T$: polarization degree of transverse spin

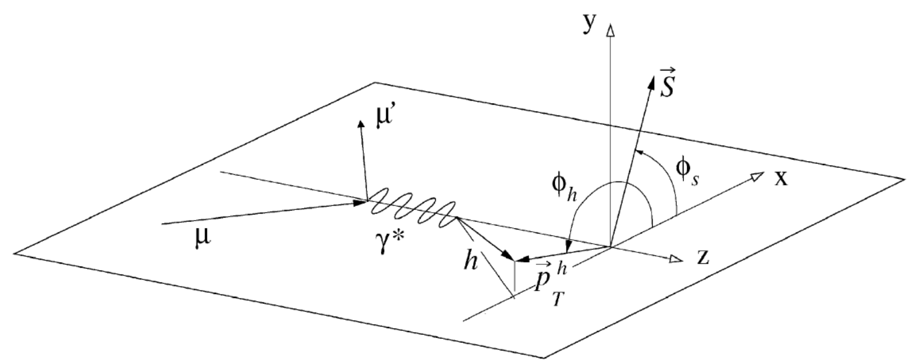
- **Advantage**: most of the systematics due to instrumental artifacts cancel.
- **Disadvantage**: the unpolarized structure function $F_{UU}$ has to be well known.

# Sivers Asymmetry $A_{Siv}$ in SIDIS (Left-Right Asymmetry w.r.t. $S_T$ )

The orbital motion of an u quark inside a proton causes positively charged pions ($u\bar{d}$) to fly off predominantly to beam-left.

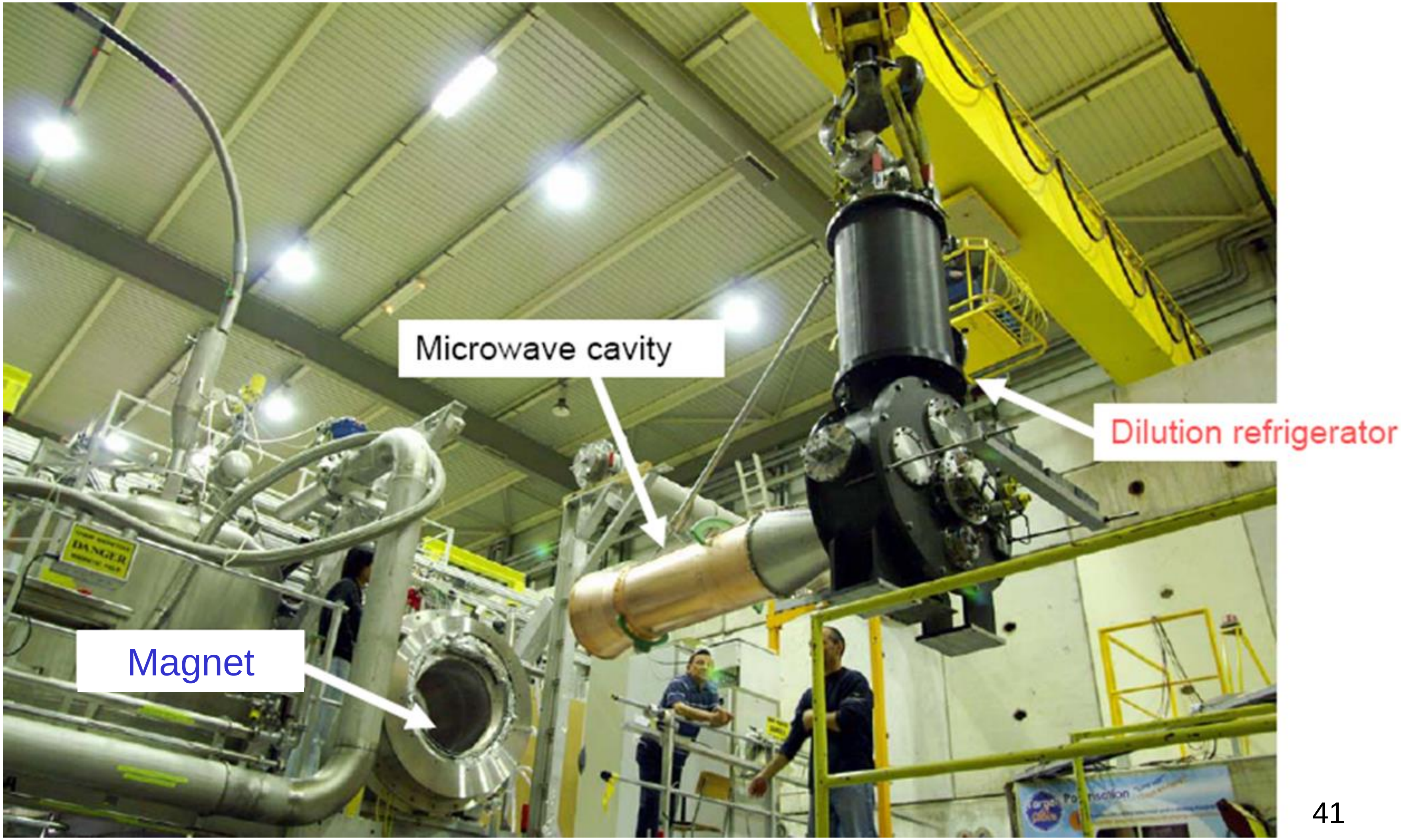


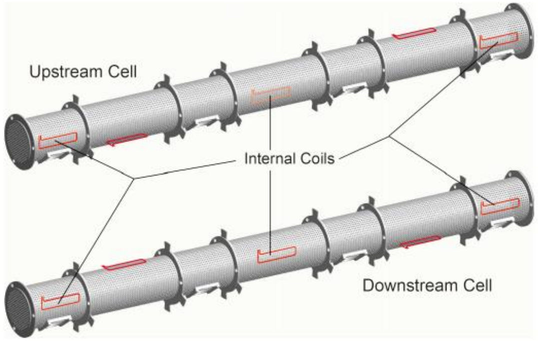



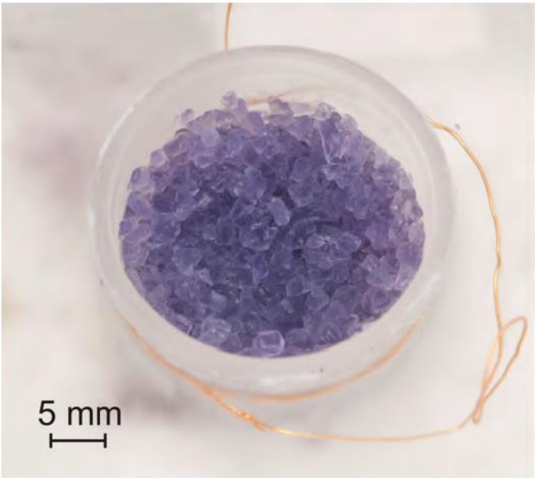

$$A_T^h \equiv \frac{d\sigma(\vec{S}_T) - d\sigma(-\vec{S}_T)}{d\sigma(\vec{S}_T) + d\sigma(-\vec{S}_T)} = \left|\vec{S}_T\right| \cdot [D_{NN} \cdot A_{Coll} \cdot \sin(\phi_h + \phi_S - \pi) + A_{Siv} \cdot \sin(\phi_h - \phi_S)]$$

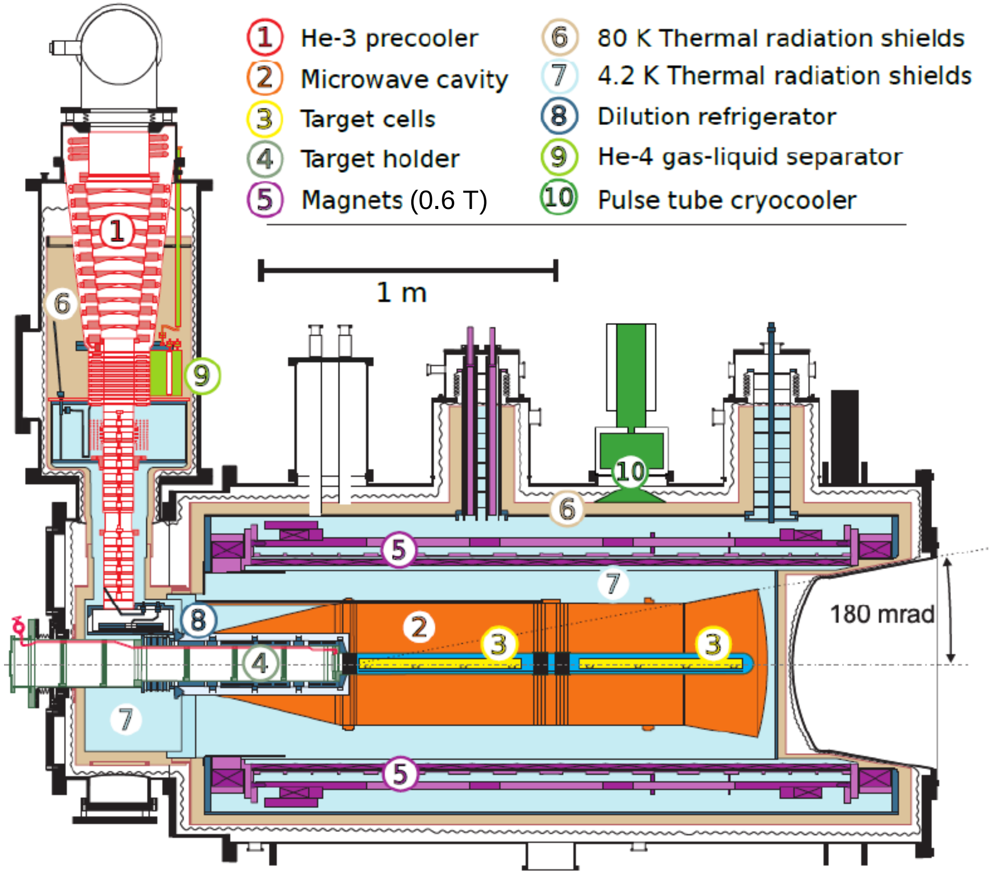
# Polarized $NH_3$ Target



# Polarized $NH_3$ Target

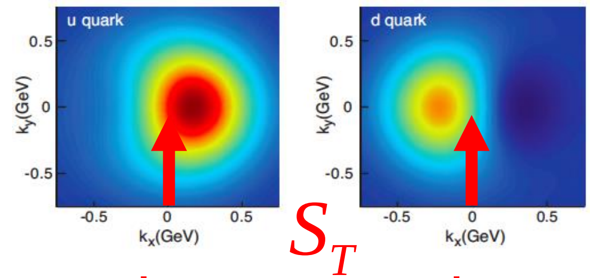


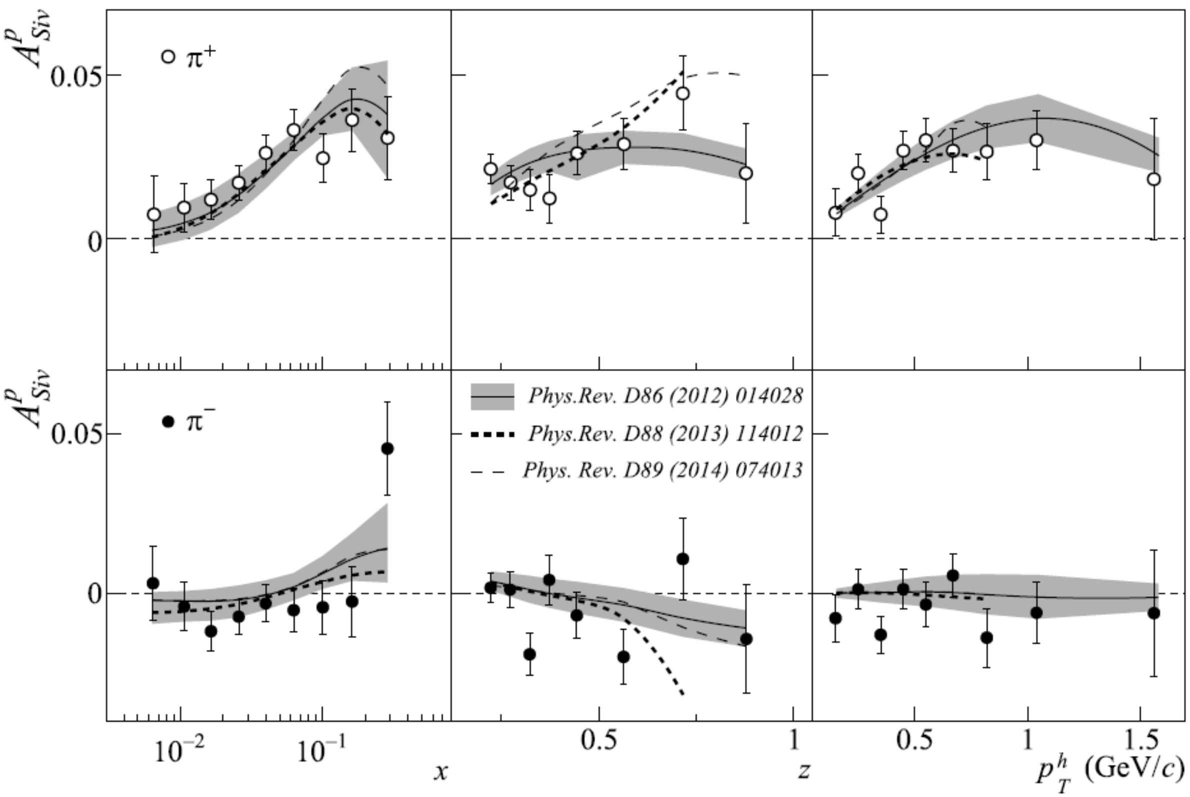




Polarization: 70%
Relaxation time: 1000 hrs

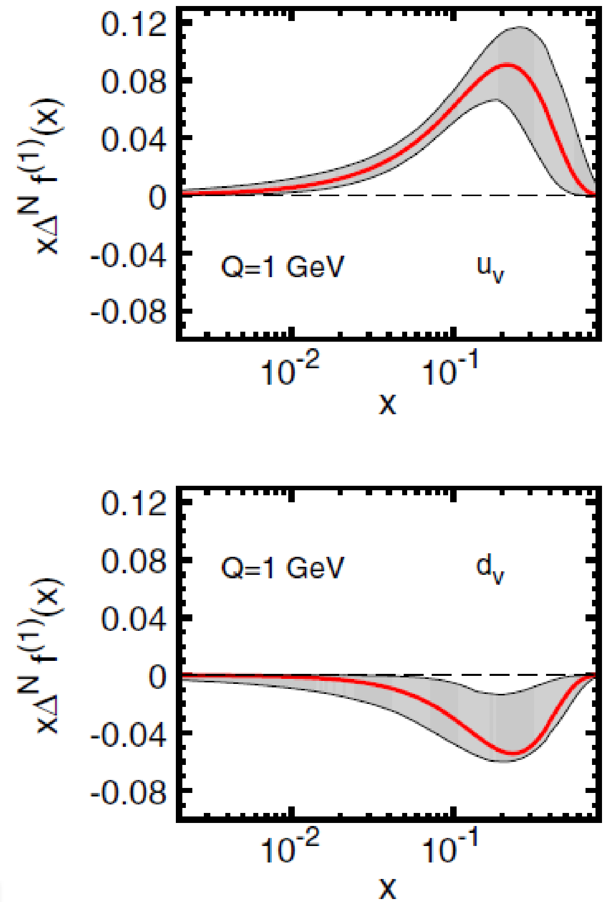
# Nonzero Sivers Asymmetries from SIDIS




COMPASS, PLB 744 (2015) 250




Sivers Functions



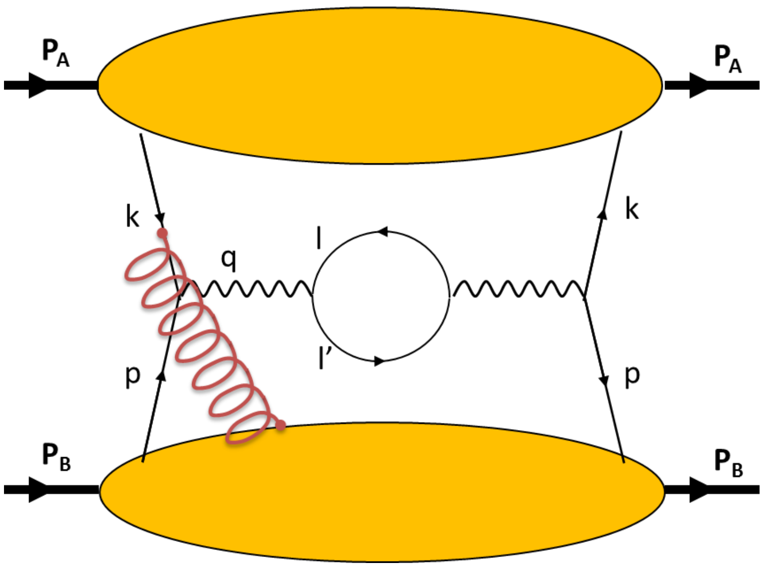

Signals of flavor-dependent Sivers functions in SIDIS

PRD 86, 014028 (2012)
[arXiv:1204.1239]

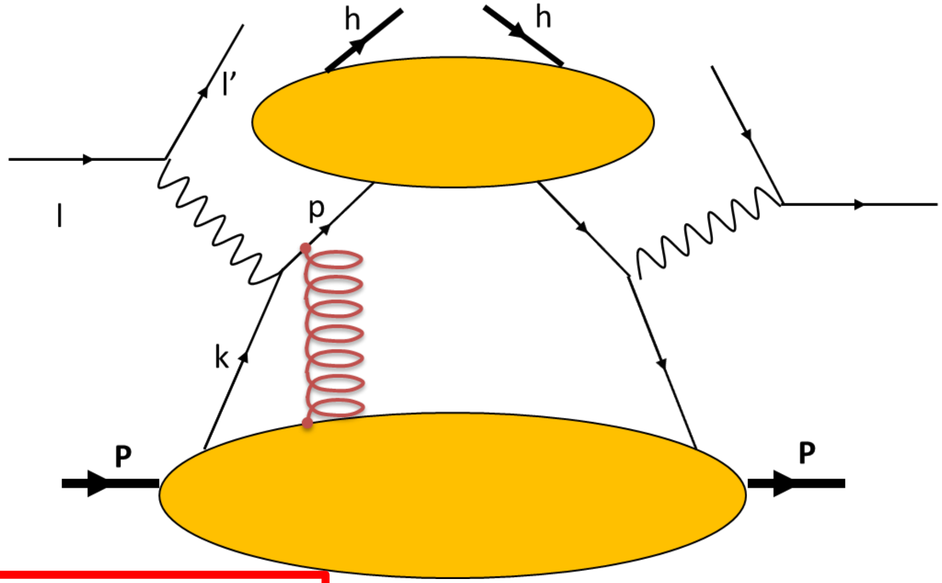
# Sign Change of Sivers Functions

*J.C. Collins, Phys. Lett. B 536 (2002) 43*
*A.V. Belitsky, X. Ji, F. Yuan, Nucl. Phys. B 656 (2003) 165*
*D. Boer, P.J. Mulders, F. Pijlman, Nucl. Phys. B 667 (2003) 201*
*Z.B. Kang, J.W. Qiu, Phys. Rev. Lett. 103 (2009) 172001*

**Drell-Yan**




**SIDIS**



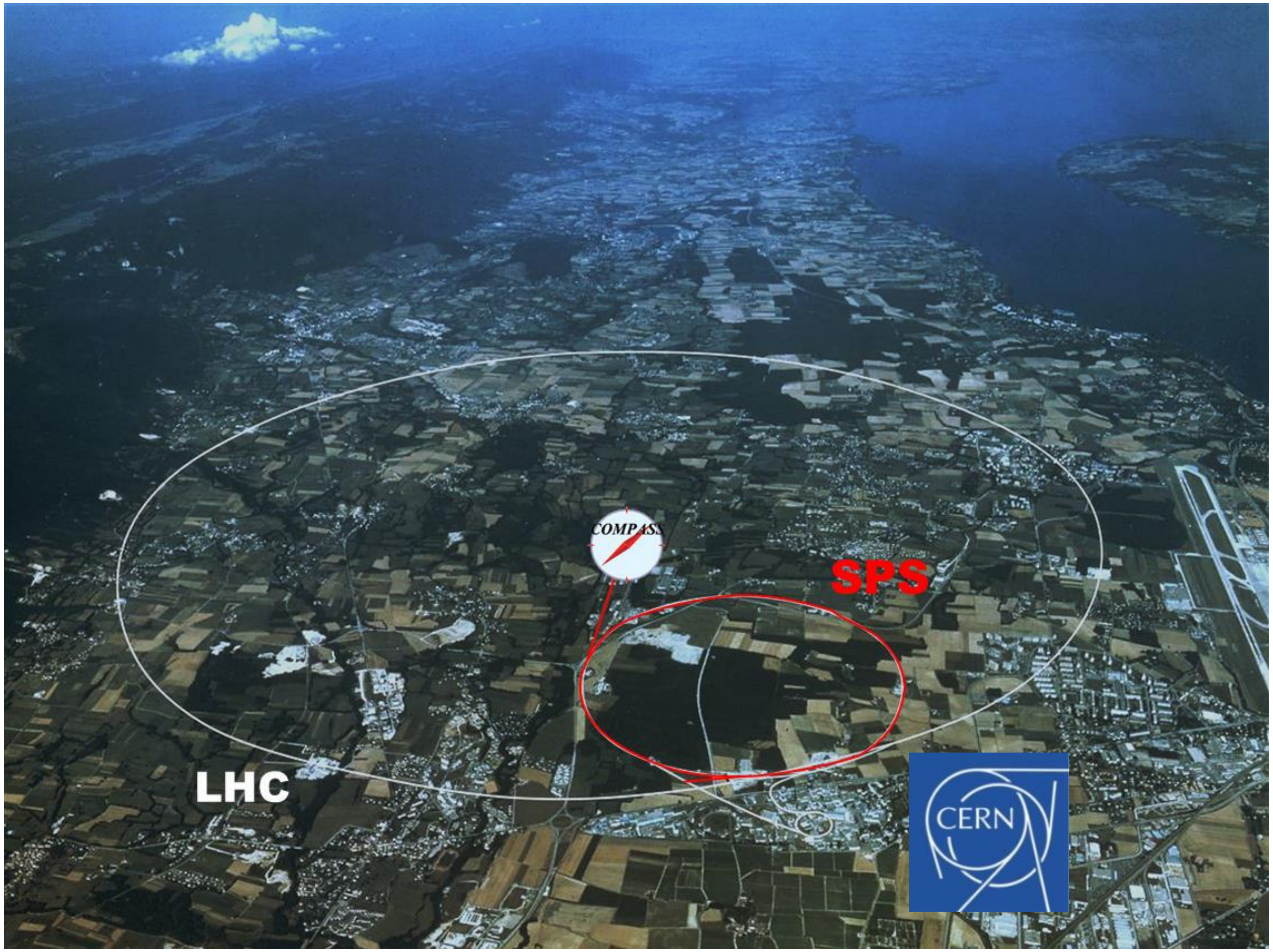

$$\text{Sivers}\,|_{DY} = -1 * \text{Sivers}\,|_{SIDIS}$$

- QCD gluon gauge link (Wilson line) in the initial state (DY) vs. final state interactions (SIDIS).
- ***Fundamental predictions from perturbative QCD and TMD physics will be tested.***

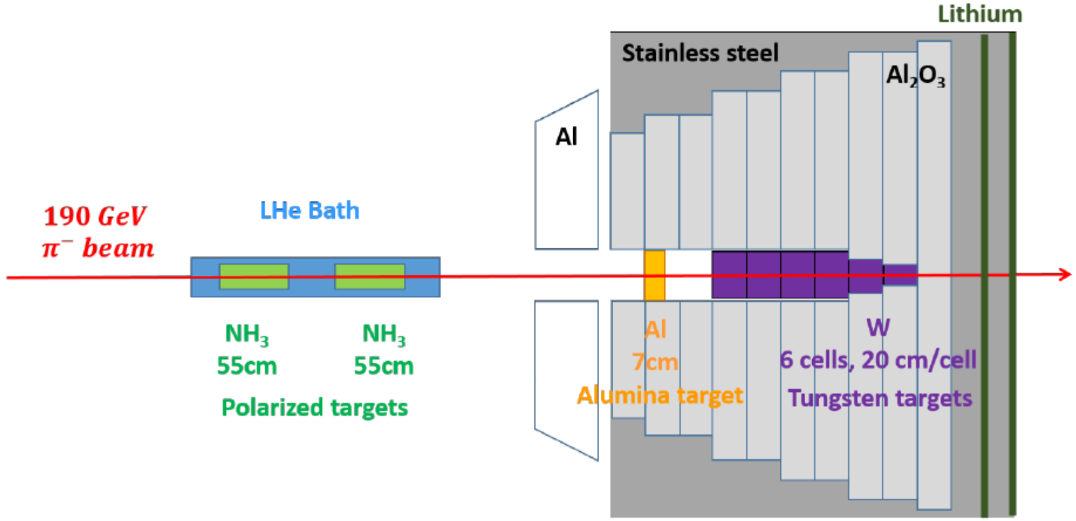
# COMPASS Collaboration

*(Common Muon and Proton Apparatus for Structure and Spectroscopy)*

- 24 institutions from 13 countries – nearly 250 physicists
- Fixed-target experiment at SPS north area
- Physics programs:
  - Nucleon spin and partonic structures
  - Hadron spectroscopy




# 2015 and 2018 Drell-Yan Runs

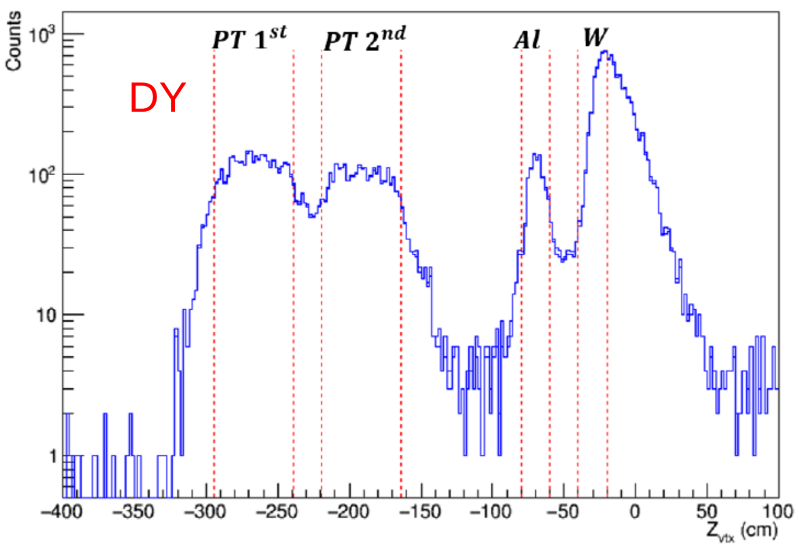


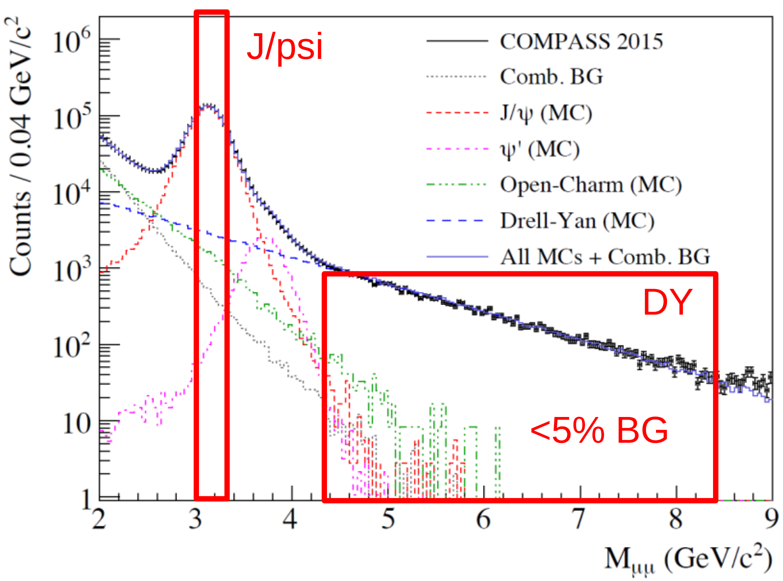

$$\pi^- + p \rightarrow \mu + \mu^- + X$$

$\pi^-$ beam, $NH_3$, Al, W targets, *Dimuon events*, *Hadron absorber*

- **Beam** : 190 GeV $\pi^-$
- **Target :**

Polarized ammonia targets(PT), Al, W

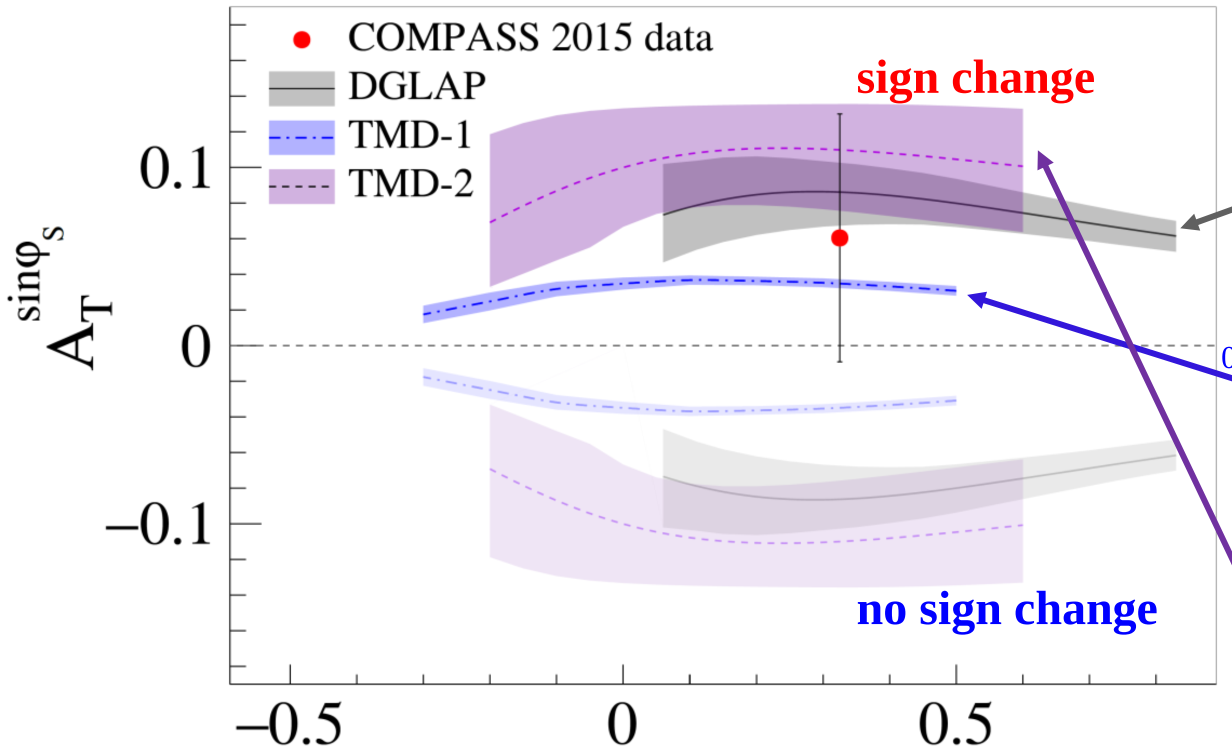


# Sivers Asymmetry in Drell-Yan:
## Hint of Sign Change!

2015 runs

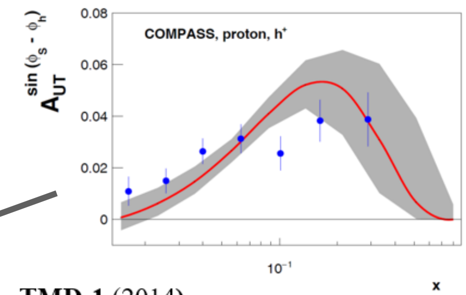
COMPASS, PRL 119 (2017) 112002



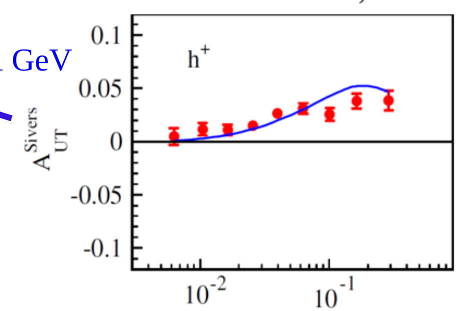

$$A_T^{\sin\varphi_s} = 0.060 \pm 0.057(stat.) \pm 0.040(sys.)$$

DY $\pi p_\uparrow \to \gamma^*(q^2 > 0)X$

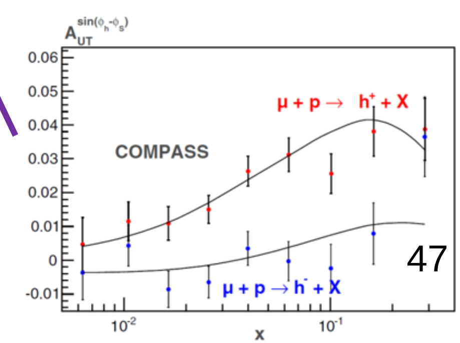
**DGLAP** (2016)
M. Anselmino et al., **arXiv:1612.06413**




**TMD-1** (2014)
M. G. Echevarria et al. **PRD89,074013**



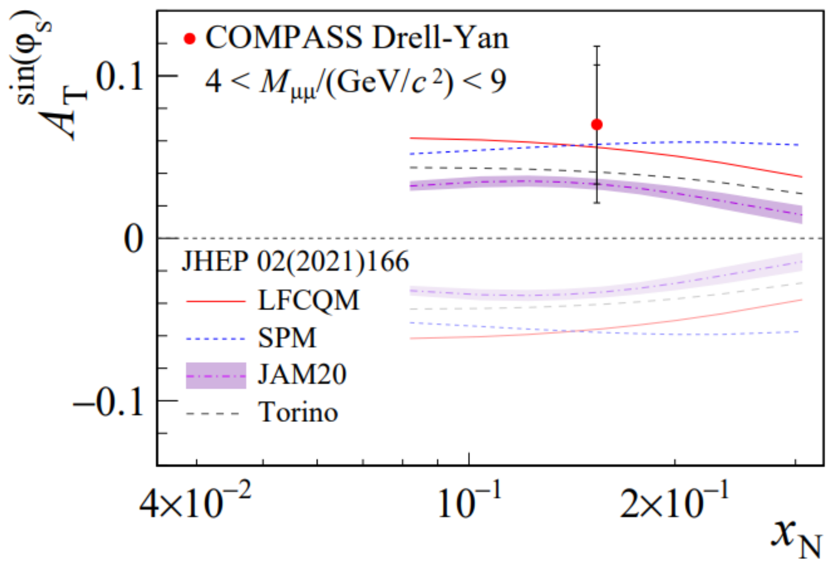

**TMD-2** (2013)
P. Sun, F. Yuan, **PRD88, 114012**

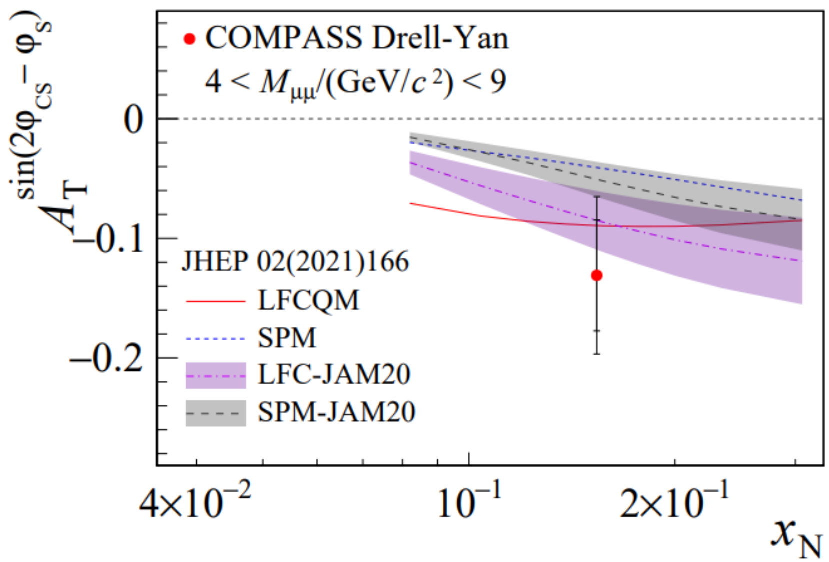


# Sivers Asymmetry in Drell-Yan:
## Hint of Sign Change!

Statistics:
2015: 35K
2018: 37K

COMPASS, 2312.17379, PRL accepted



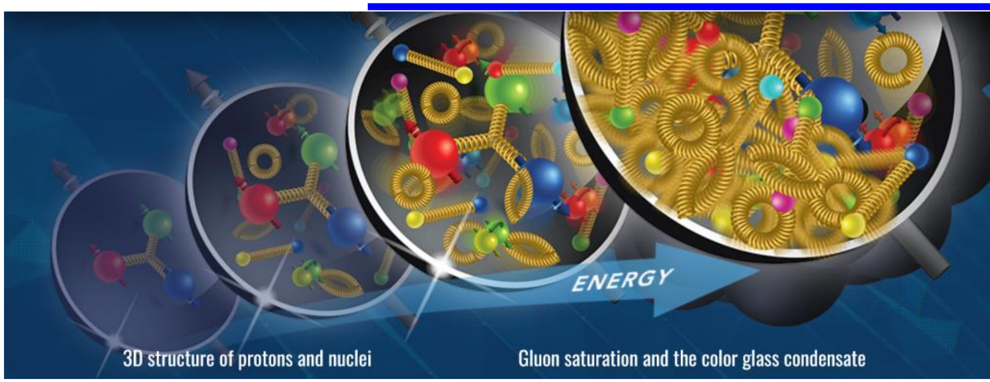



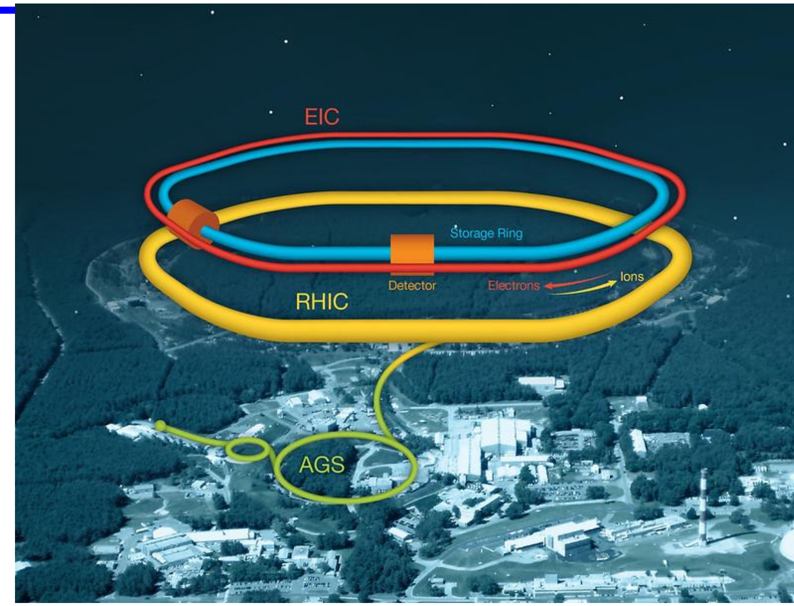

Agreeing with the sign-change hypothesis

Negative transversity TSA

Our results supports the general validity of the TMD approach!

# U.S. Electron-Ion Collider and ePIC Collaboration **Year >2035**




NTU

AS

NCU

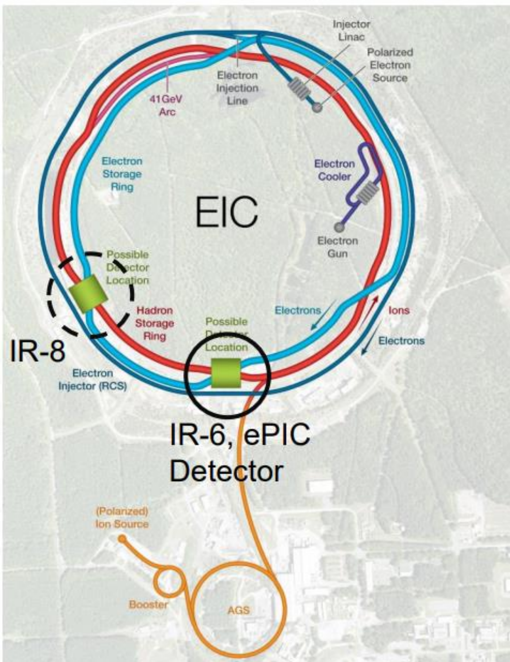
NTHU

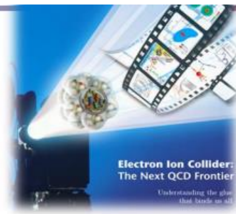
NCKU

**Physics Goals**

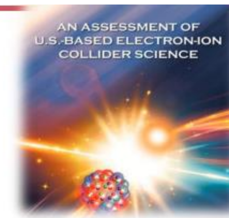
- Precision 3D imaging of protons and nuclei
- Solving the proton spin puzzle
- Search for gluon saturation
- Quark and gluon confinement
- Quarks and gluons in nuclei

# U.S. Electron-Ion Collider (EIC)








Project Design Goals

- High Luminosity: L= $10^{33} – 10^{34} cm^{-2} sec^{-1}$, 10 – 100 $fb^{-1}$/year
- Highly Polarized Beams: 70%
- Large Center of Mass Energy Range: $E_{cm}$ = 29 – 140 GeV
- Large Ion Species Range: protons – Uranium
- Large Detector Acceptance and Good Background Conditions
- Accommodate a Second Interaction Region (IR)

IR-8

**p: 41 GeV, 100 to 275 GeV** p/A beam → ← e beam **e: 5 GeV to 18 GeV**

https://indico.phys.sinica.edu.tw/event/88/contributions/416/attachments/501/1250/EIC_Status_NCKU_012924.pdf

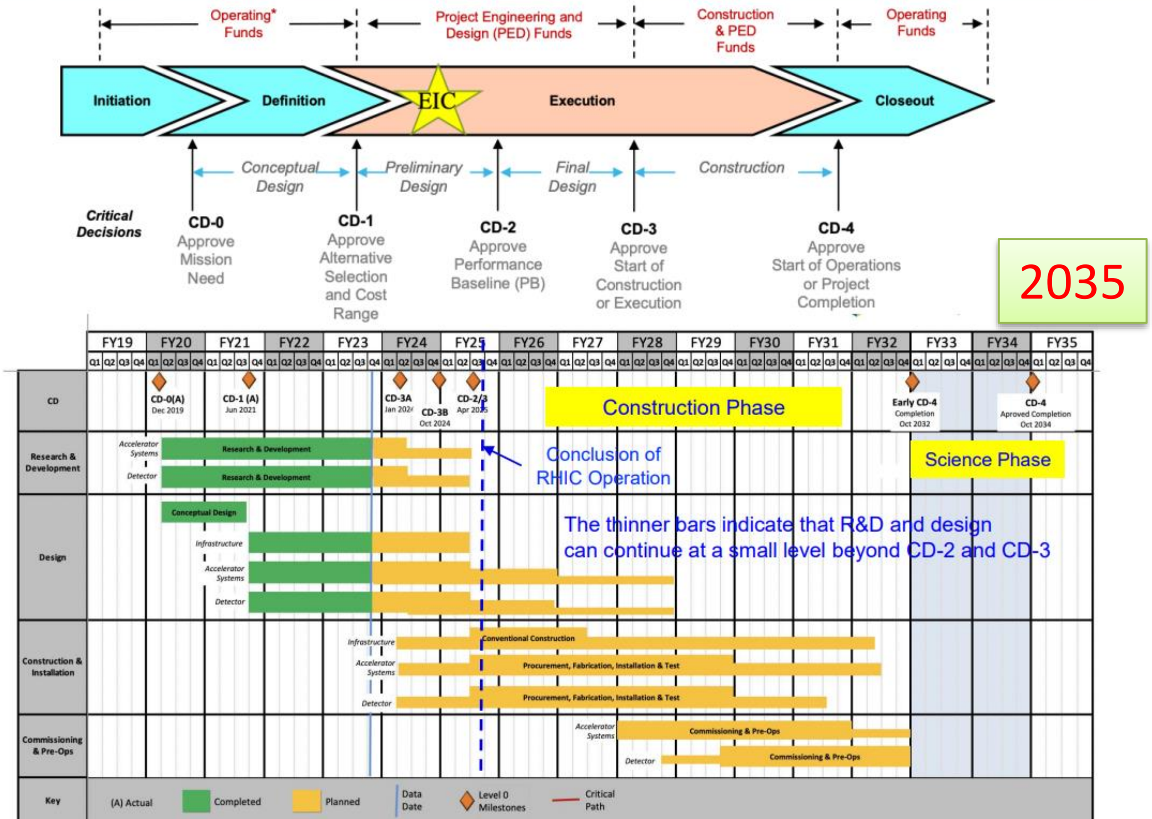
# EIC Schedule

**EIC Critical Decision Plan**

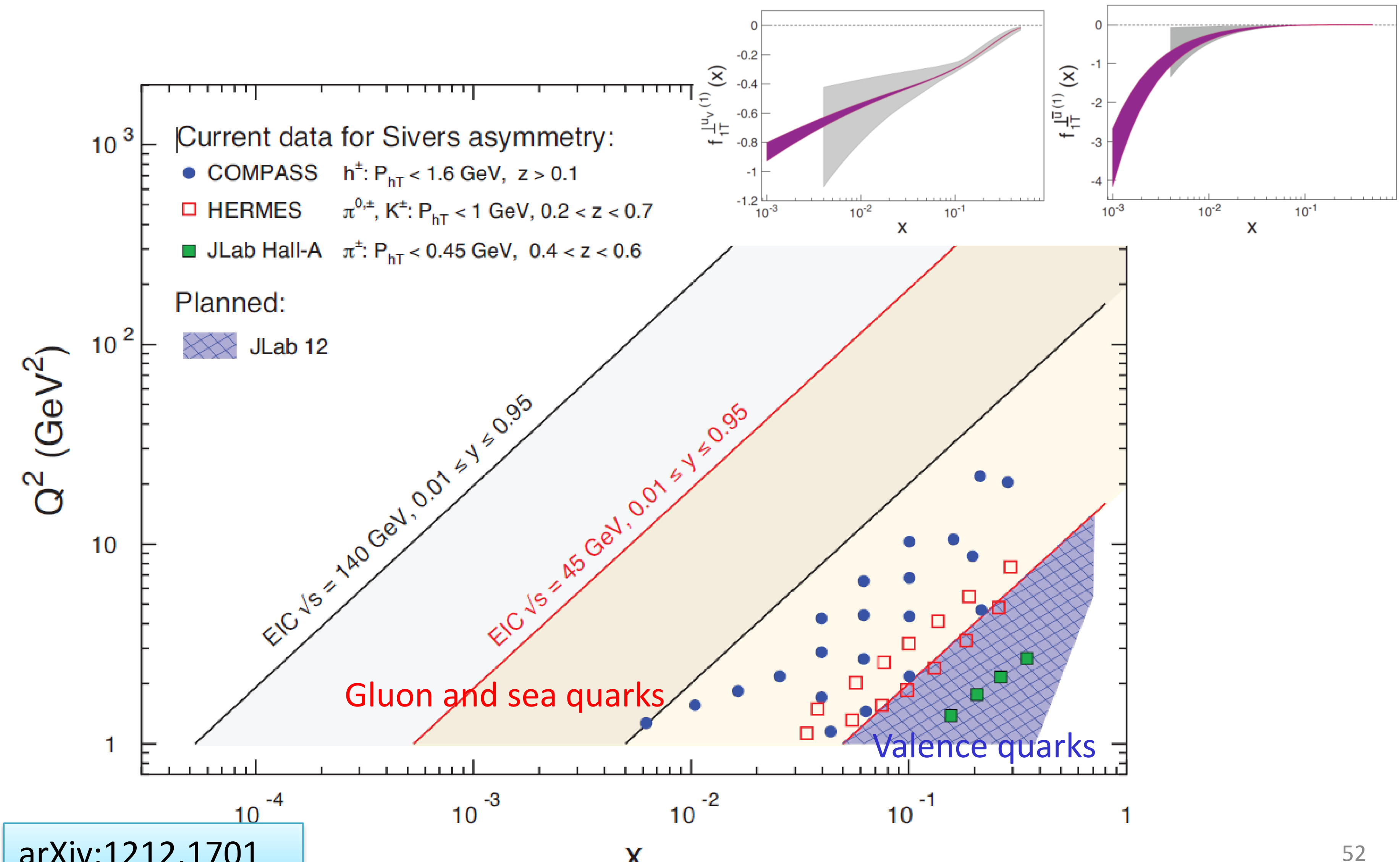
| | |
|---|---|
| CD-0/Site Selection | December 2019 ✓ |
| CD-1 | June 2021 ✓ |
| CD-3A | January 2024 |
| **CD-3B** | **October 2024** |
| **CD-2/3** | **April 2025** |
| early CD-4 | October 2032 |
| **CD-4** | **October 2034** |

**CD-2:**
Approve preliminary design for all subdetectors
Design Maturity: >60%
Need "pre-"TDR (or draft TDR)
Baseline project in scope, cost, schedule

**CD-3:**
Approve final design for all subdetectors
Design Maturity: ~90%
Need full TDR



# Explored Regions




arXiv:1212.1701

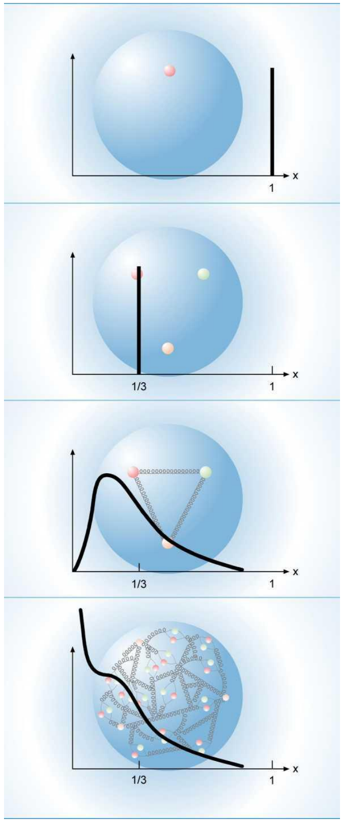
# TIDC Autumn School On EIC

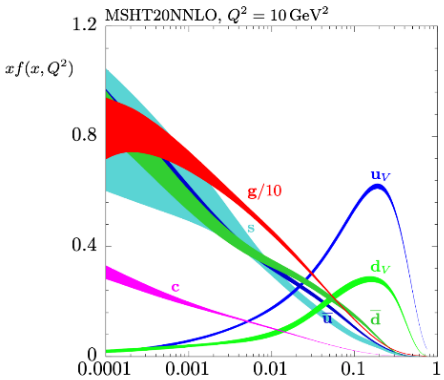
# (NTU, Aug. 29-31, 2023)

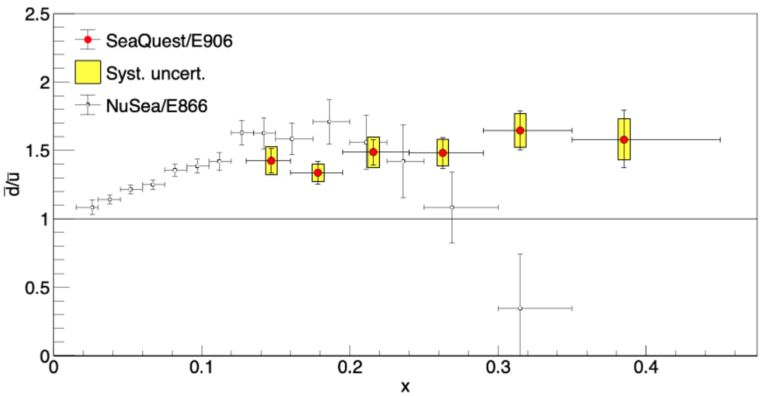
# The 3rd EIC-ASIA Workshop

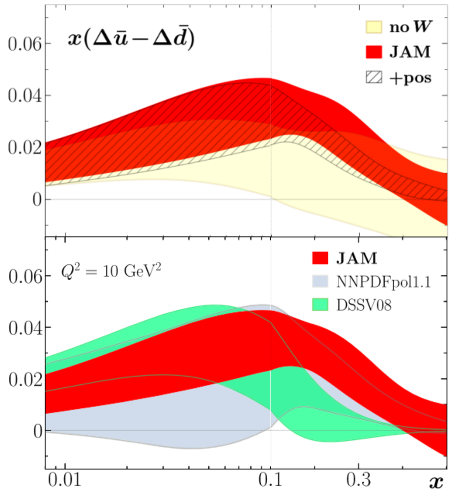
(NCKU, Jan. 29-31, 2024)

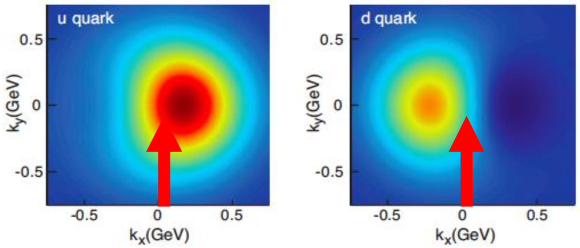
# Summary




- Proton, a fundamental particle, is more than a bound state of 3 static quarks. It contains rich dynamics of valence quarks, sea quarks and gluons therein.
- Mostly due to the non-perturbative effects, interesting flavor dependences of PDFs and TMDs are observed!
- The flavorful aspect of proton partonic structures will be explored in the coming U.S. EIC.