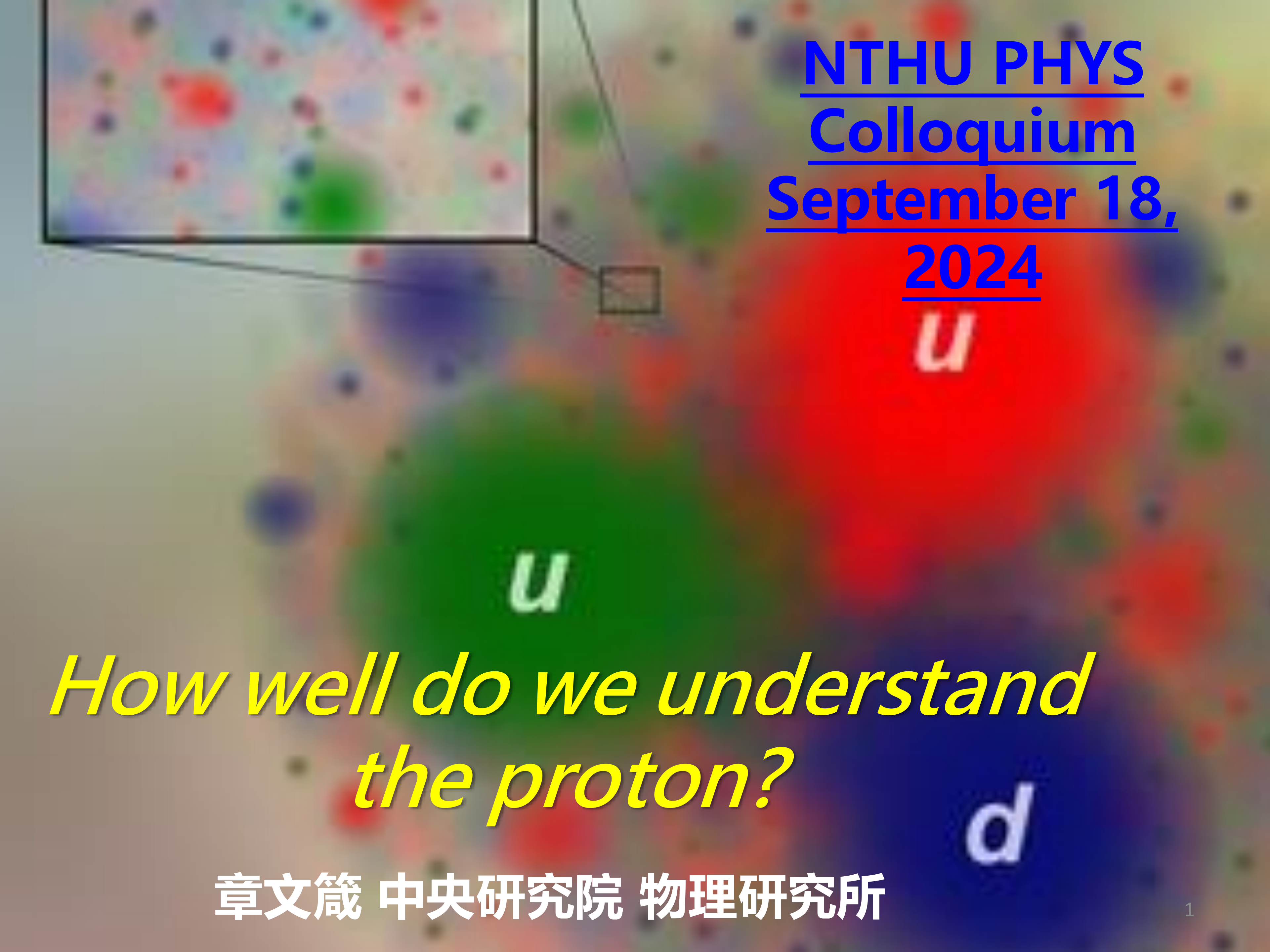


NTHU PHYS Colloquium September 18, 2024

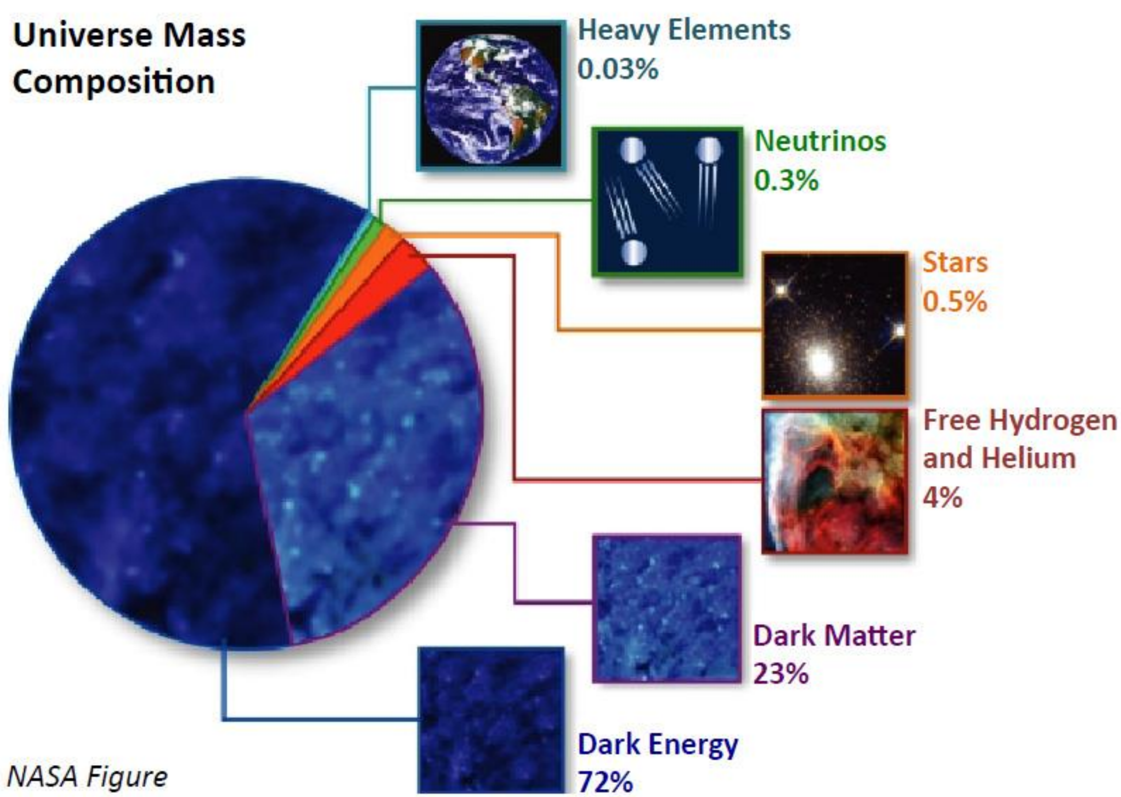
How well do we understand the proton?

章文箴 中央研究院 物理研究所

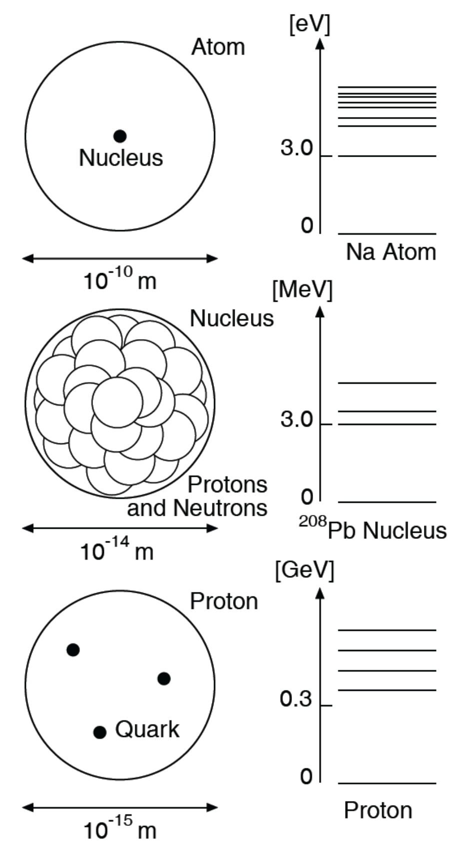
Outline

- Proton as an composite fundamental particle: constituent quark model, parton model and QCD.
- Drell-Yan process:
  - E906/SeaQuest at FNAL: PDFs
  - COMPASS at CERN: TMDs
  - E50 at J-PARC: GPDs
- U.S. EIC program
- Summary

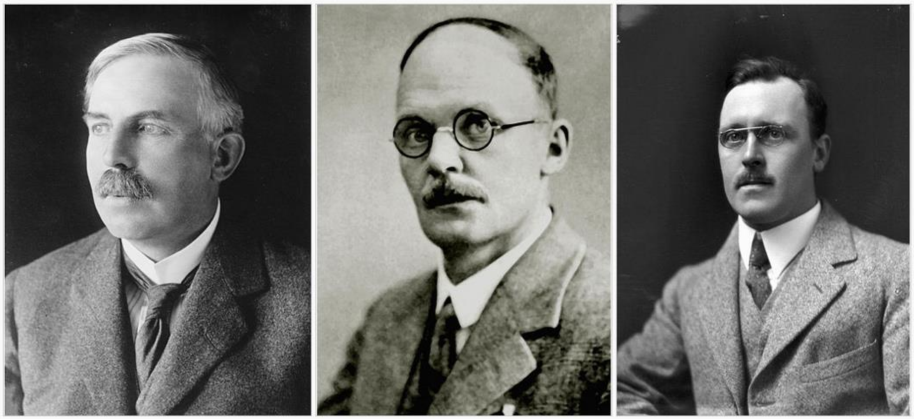
Composition of the Universe



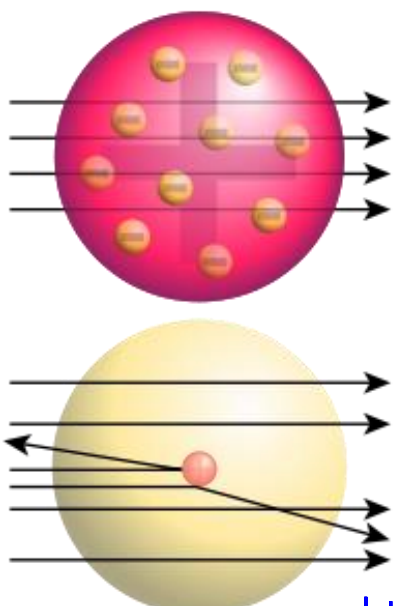
Bound states of QCD

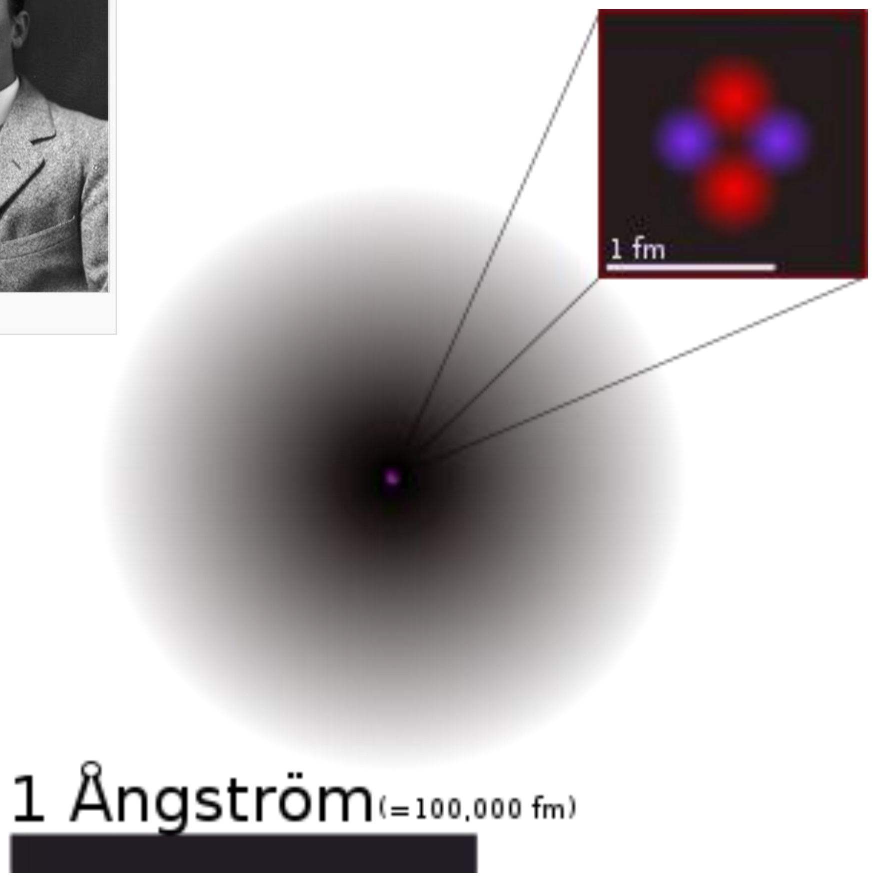


Rutherford experiment (1913)
: Nucleus and Sub-atomic Structure



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

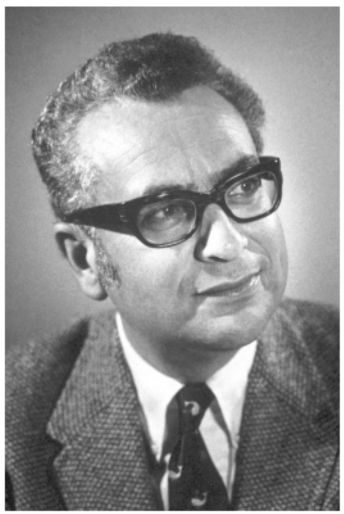
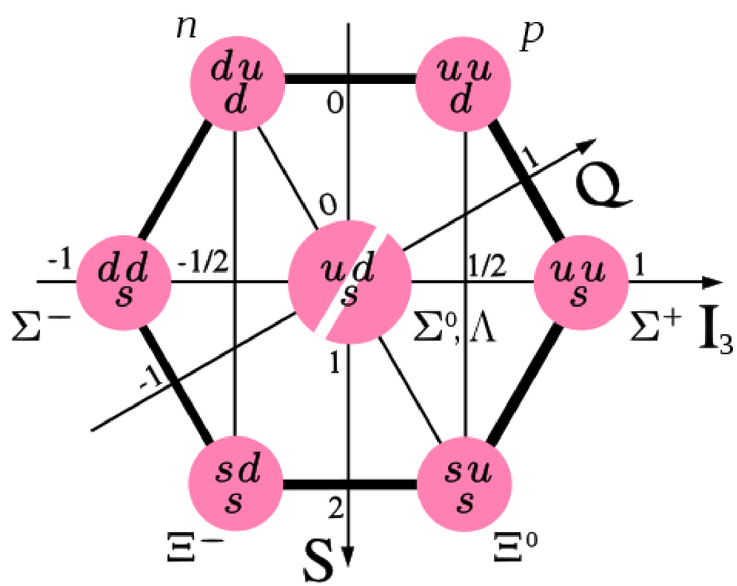
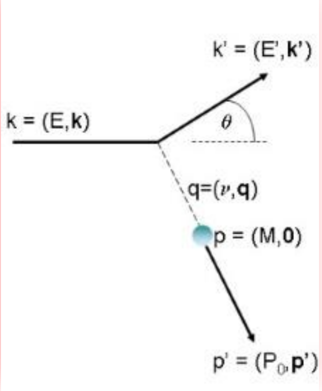


Photo from the Nobel Foundation archive.

Murray Gell-Mann



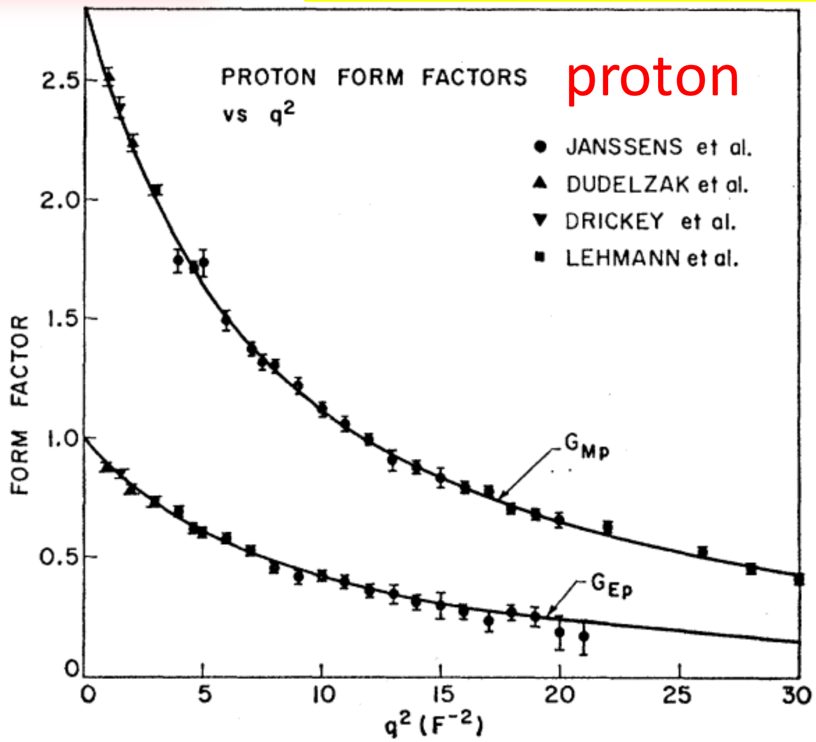
"for his contributions and discoveries concerning the classification of elementary particles and their interactions"

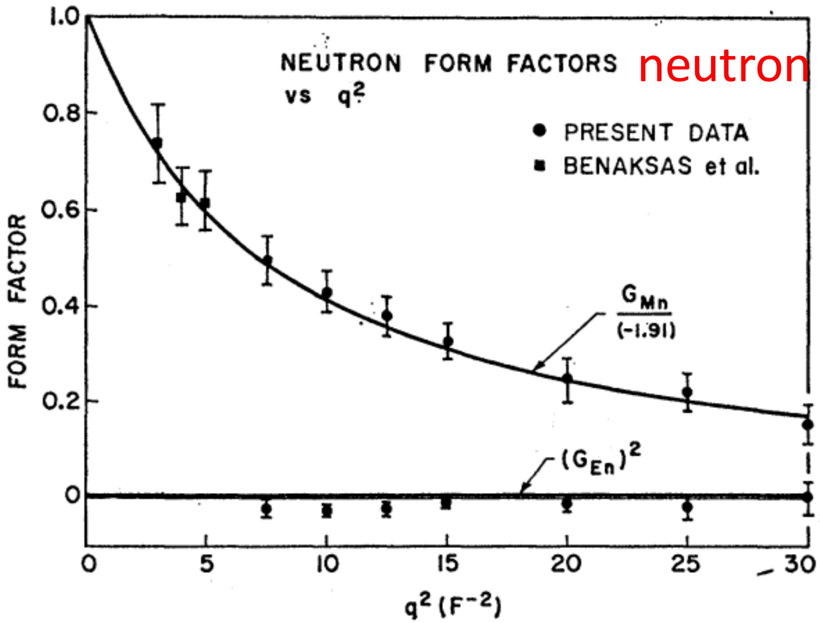


e-N Elastic Scattering

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

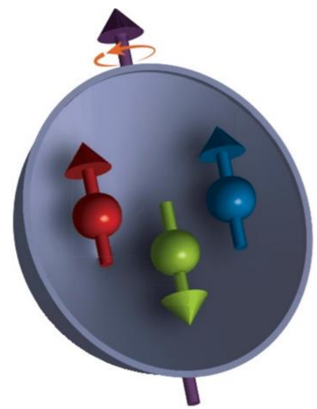
$G_E^p(Q^2=0)=1 \qquad G_E^n(Q^2=0)=0$

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

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

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

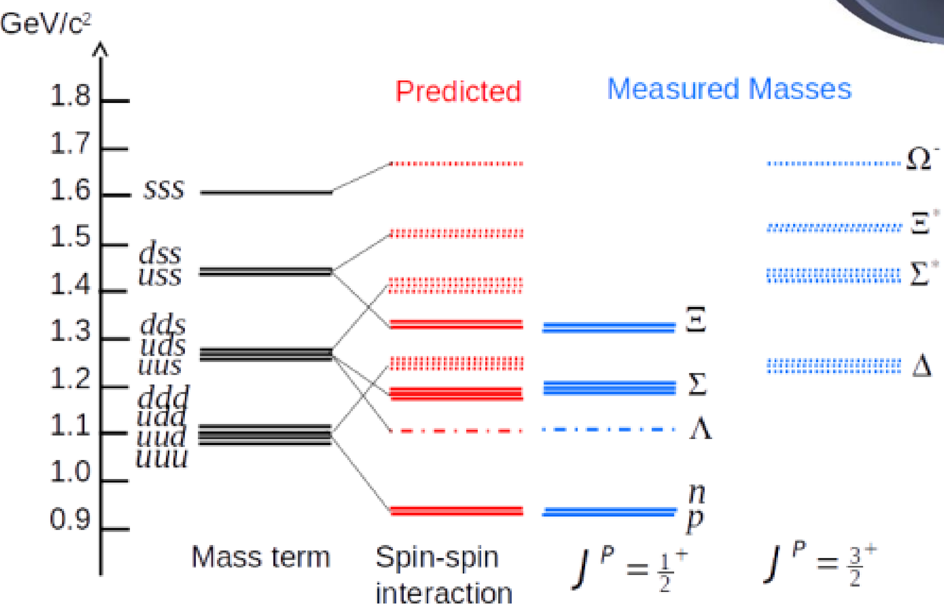
Constituent Quark Model



Anomalous magnetic moment
Otto Stern, Nobel Prize 1943

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

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



Baryon	μ_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
Λ (uds)	μ_s	−0.61	-0.614 ± 0.005
Σ^+ (uus)	$\frac{4}{3}\mu_u - \frac{1}{3}\mu_s$	+2.68	$+2.46 \pm 0.01$
Ξ^0 (ssu)	$\frac{4}{3}\mu_s - \frac{1}{3}\mu_u$	−1.44	-1.25 ± 0.014
Ξ^- (ssd)	$\frac{4}{3}\mu_s - \frac{1}{3}\mu_d$	−0.51	-0.65 ± 0.01
Ω^- (sss)	$3\mu_s$	−1.84	-2.02 ± 0.05

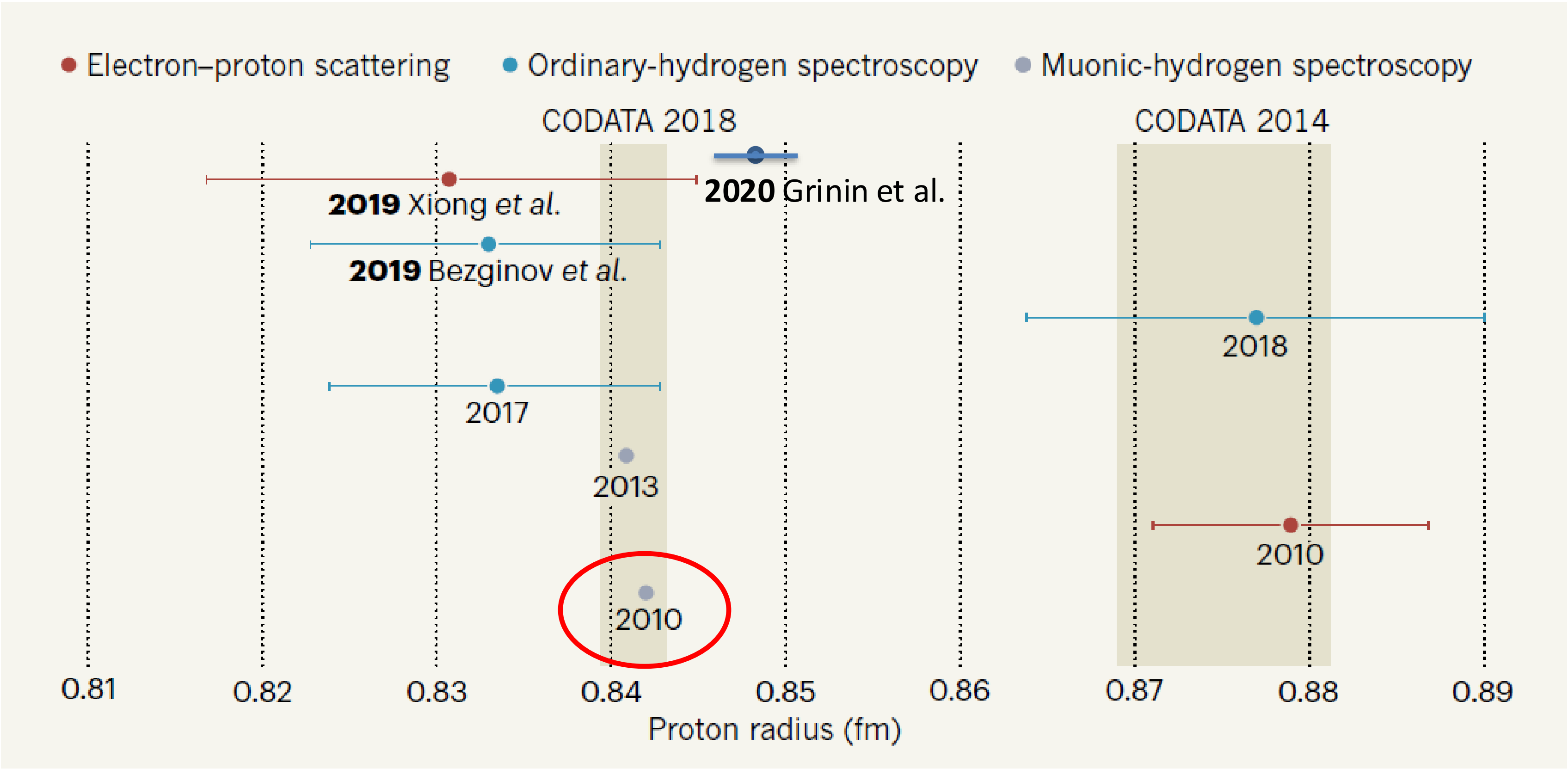
$$\mu_u = \frac{2}{3}\frac{e\hbar}{2m_u}, \qquad \mu_d = -\frac{1}{3}\frac{e\hbar}{2m_d}, \qquad \mu_s = -\frac{1}{3}\frac{e\hbar}{2m_s}$$

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

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

Proton Electric 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

https://inspirehep.net/literature/1861691

https://pos.sissa.it/413/005/pdf

Proton in PDG

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

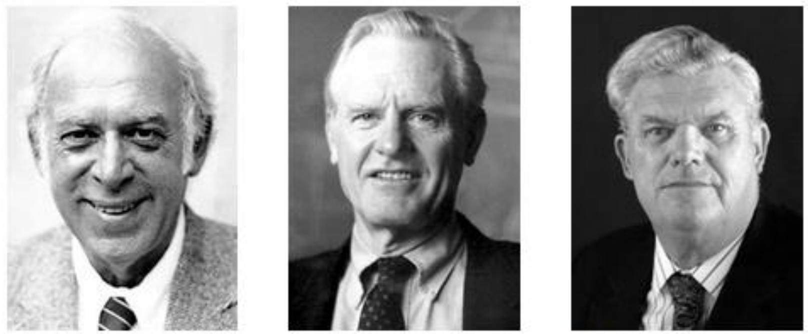
PDGID:S016 JSON INSPIRE

p $I(J^P) = 1/2(1/2^+)$ 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 α_p	0.00112 ± 0.00004 fm^3
p MAGNETIC POLARIZABILITY β_p	$(2.5 \pm 0.4) \times 10^{-4}$ fm^3 (S = 1.2)
p CHARGE RADIUS	0.8409 ± 0.0004 fm
p MAGNETIC RADIUS	0.851 ± 0.026 fm
p MEAN LIFE	$> 9 \times 10^{29}$ years CL=90.0%
$\overline{p}$ MEAN LIFE	

Deep Inelastic Scattering (~1970)

The Nobel Prize in Physics 1990

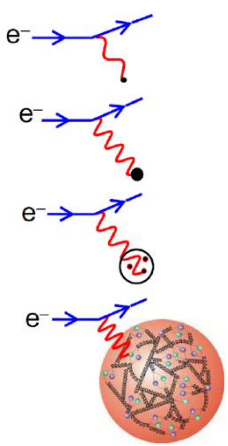


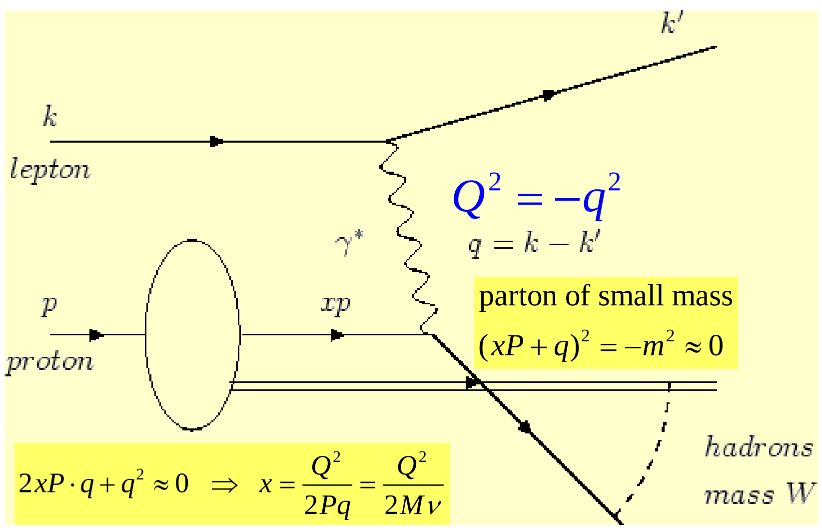
Jerome I. Friedman
Prize share: 1/3

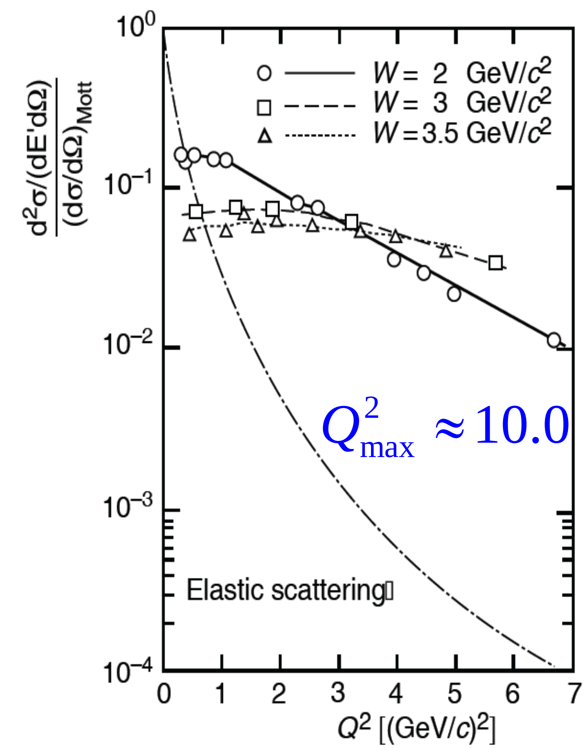
Henry W. Kendall
Prize share: 1/3

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"







$Q^2_{max} \approx 10.0$ GeV^2

Quantum Chromo-Dynamics (QCD)

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

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

Color index: α, β=1, 2, 3, N_c=3; a, b, c = 1,2,…,8 for SU(3)

Lorentz index: μ, ν=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

Asymptotic Freedom of QCD

The Nobel Prize in Physics 2004

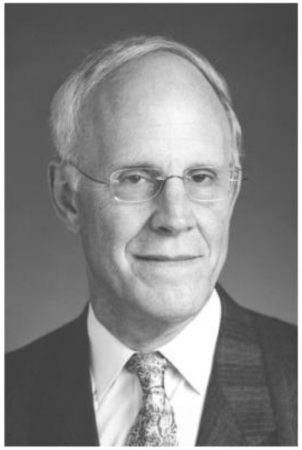


Photo from the Nobel Foundation archive.

David J. Gross

Prize share: 1/3

Photo from the Nobel Foundation archive.

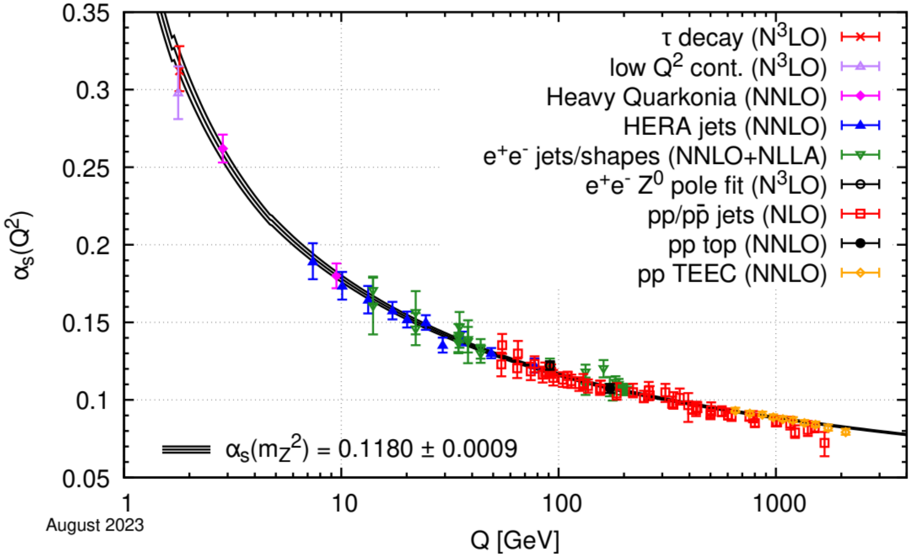
H. David Politzer

Prize share: 1/3

Photo from the Nobel Foundation archive.

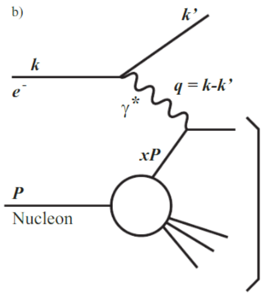
Frank Wilczek

Prize share: 1/3



https://pdg.lbl.gov/2024/reviews/rpp2024-rev-qcd.pdf

The Nobel Prize in Physics 2004 was awarded jointly to David J. Gross, H. David Politzer and Frank Wilczek "for the discovery of asymptotic freedom in the theory of the strong interaction"

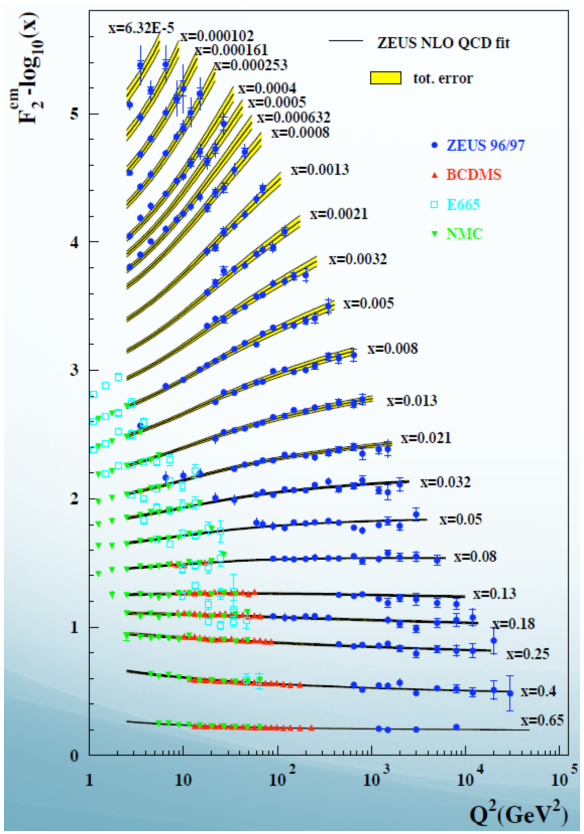


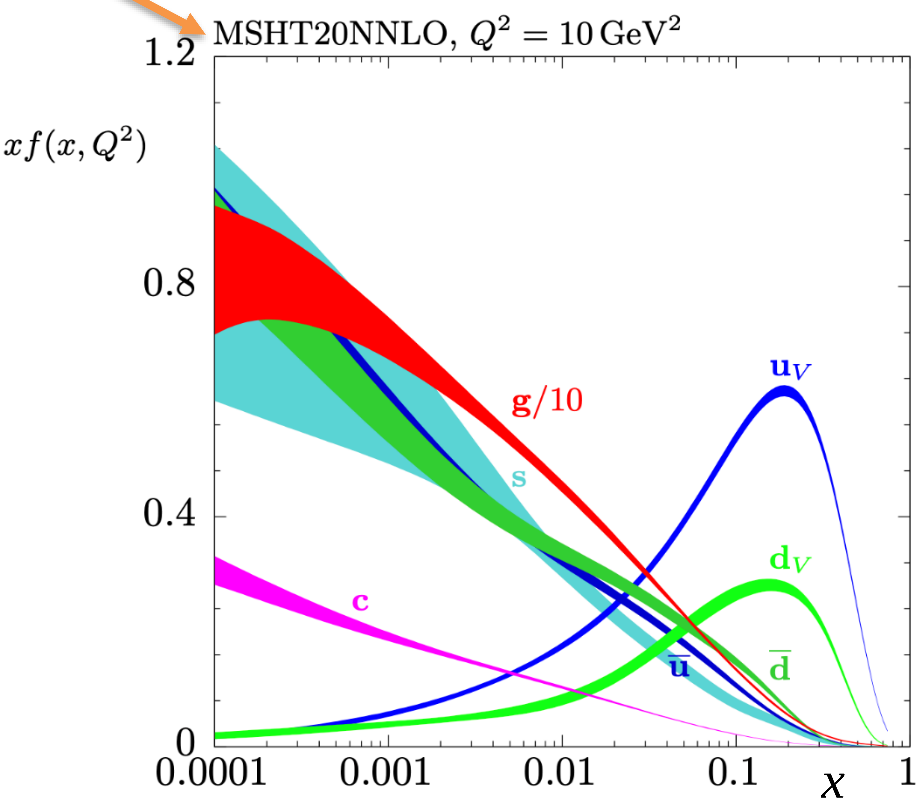
Factorization

and Parton Density Functions (PDFs)

$$\sigma_{\text{proton}}(Q) = f_{\text{parton}}(x, Q) \otimes \hat{\sigma}_{\text{parton}}(Q)$$

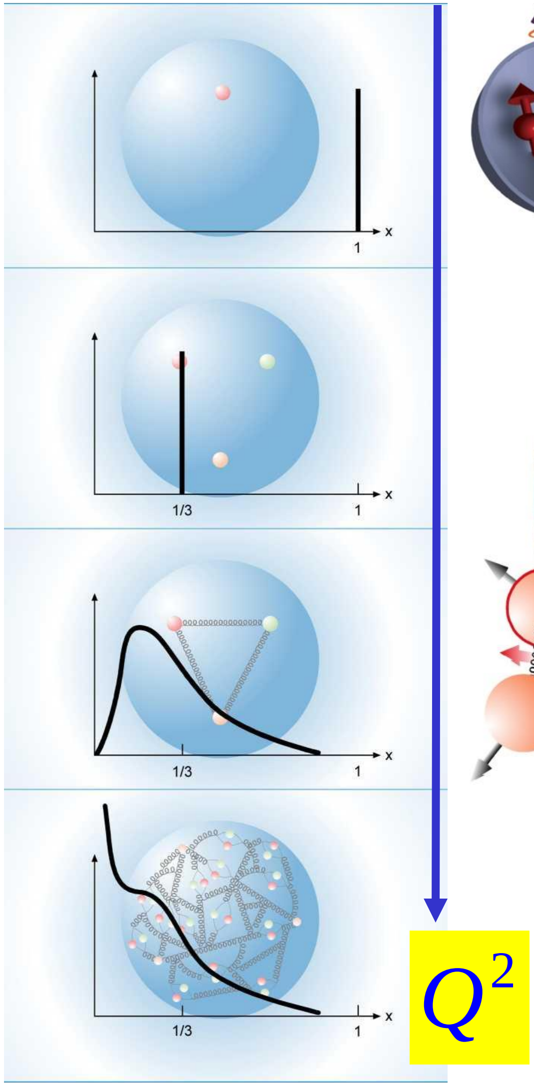
Calculable by pQCD

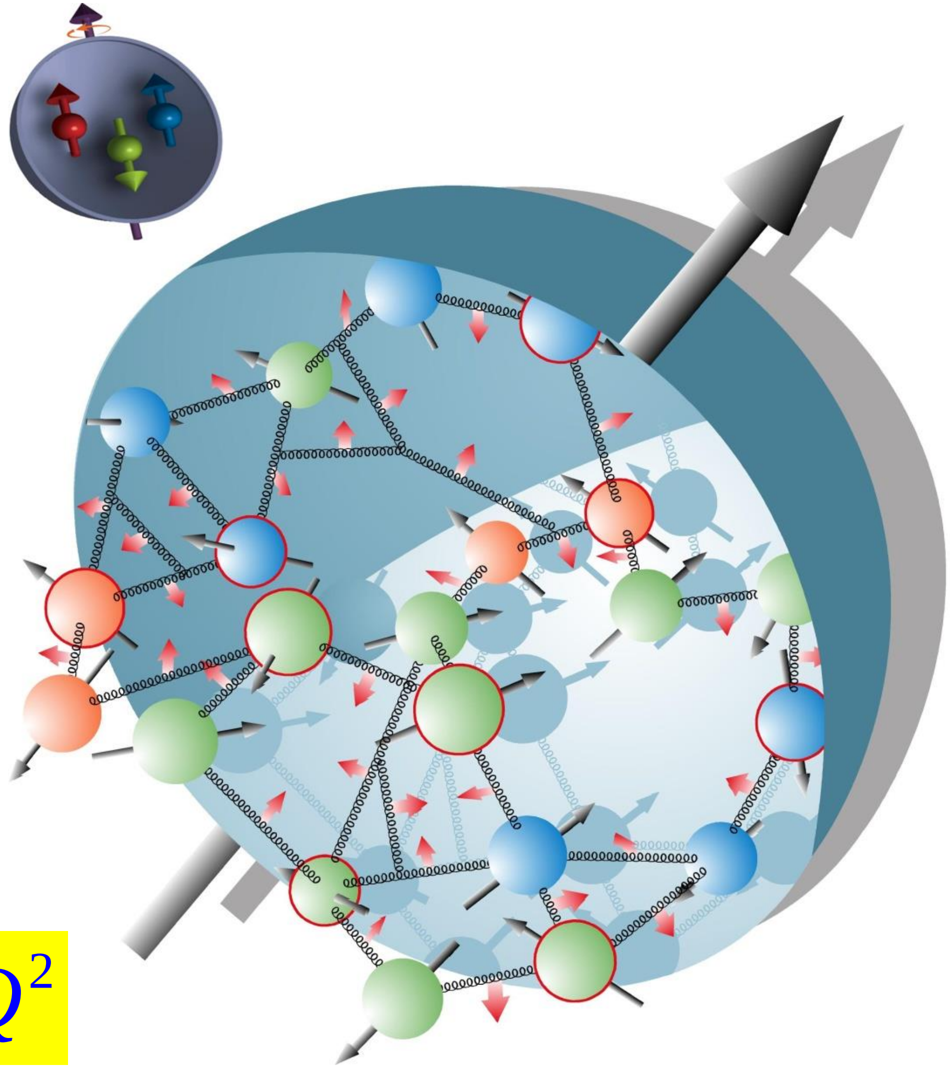


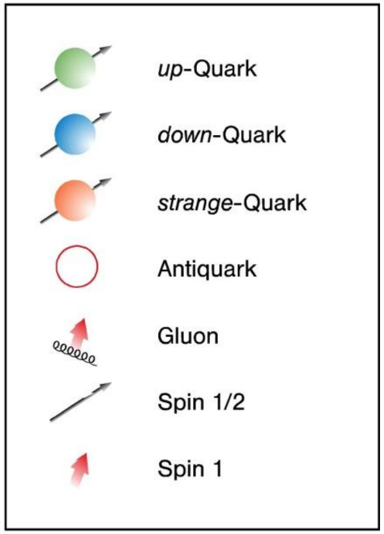


MSHT20: https://arxiv.org/abs/2012.04684

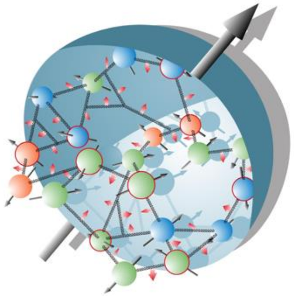
Evolving Understanding of Protons



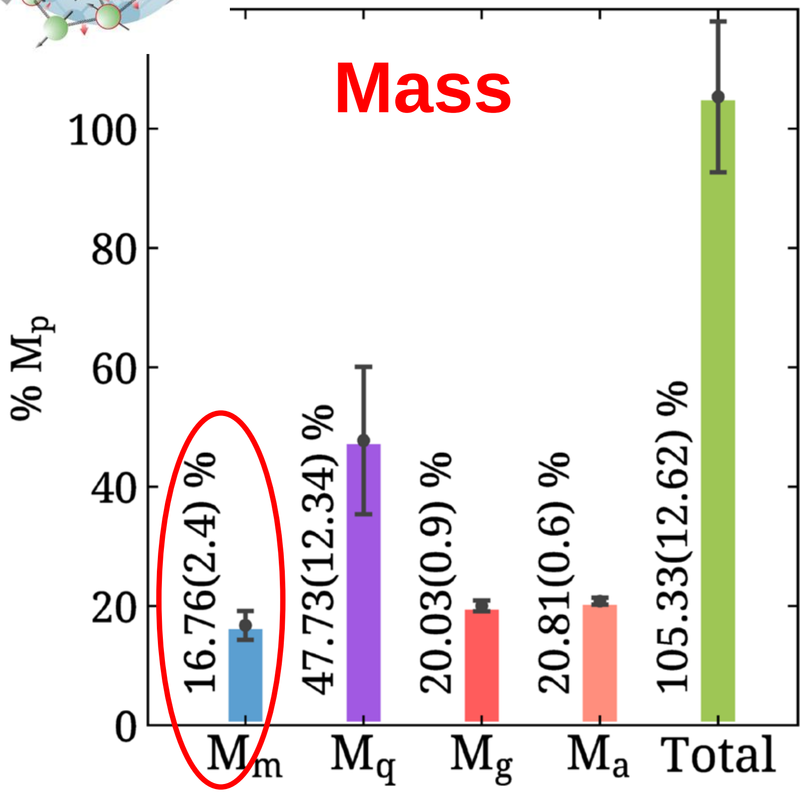




Mass/Spin Decomposition of Proton (Lattice QCD)



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



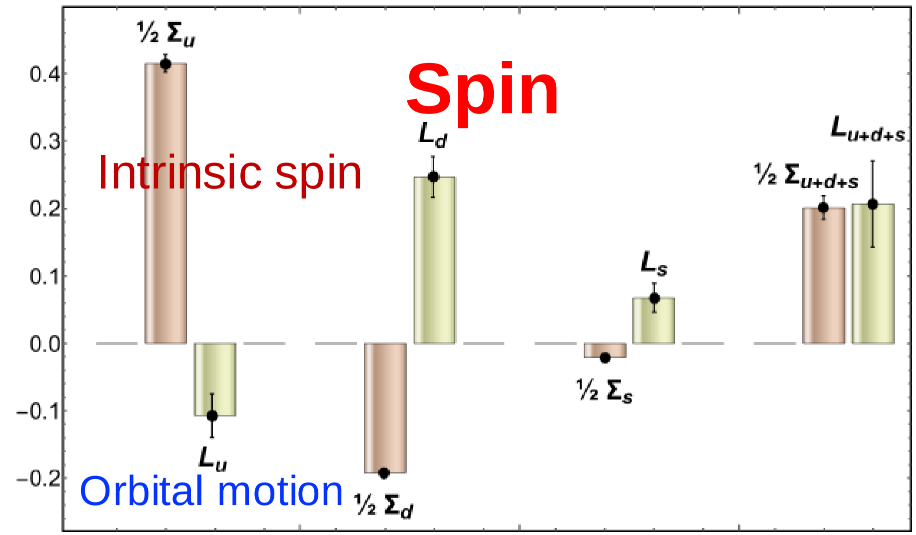
Quark mass

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)

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

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

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

$d_1(t)$: gravitational form factor

$p(r)$: radial pressure distribution

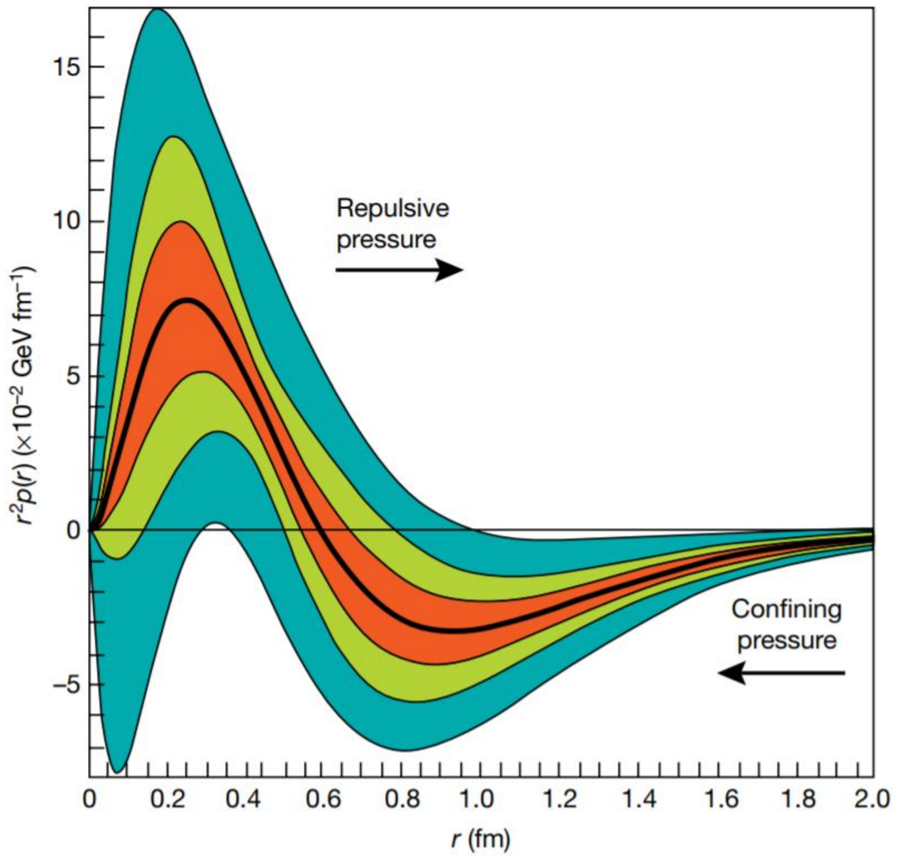
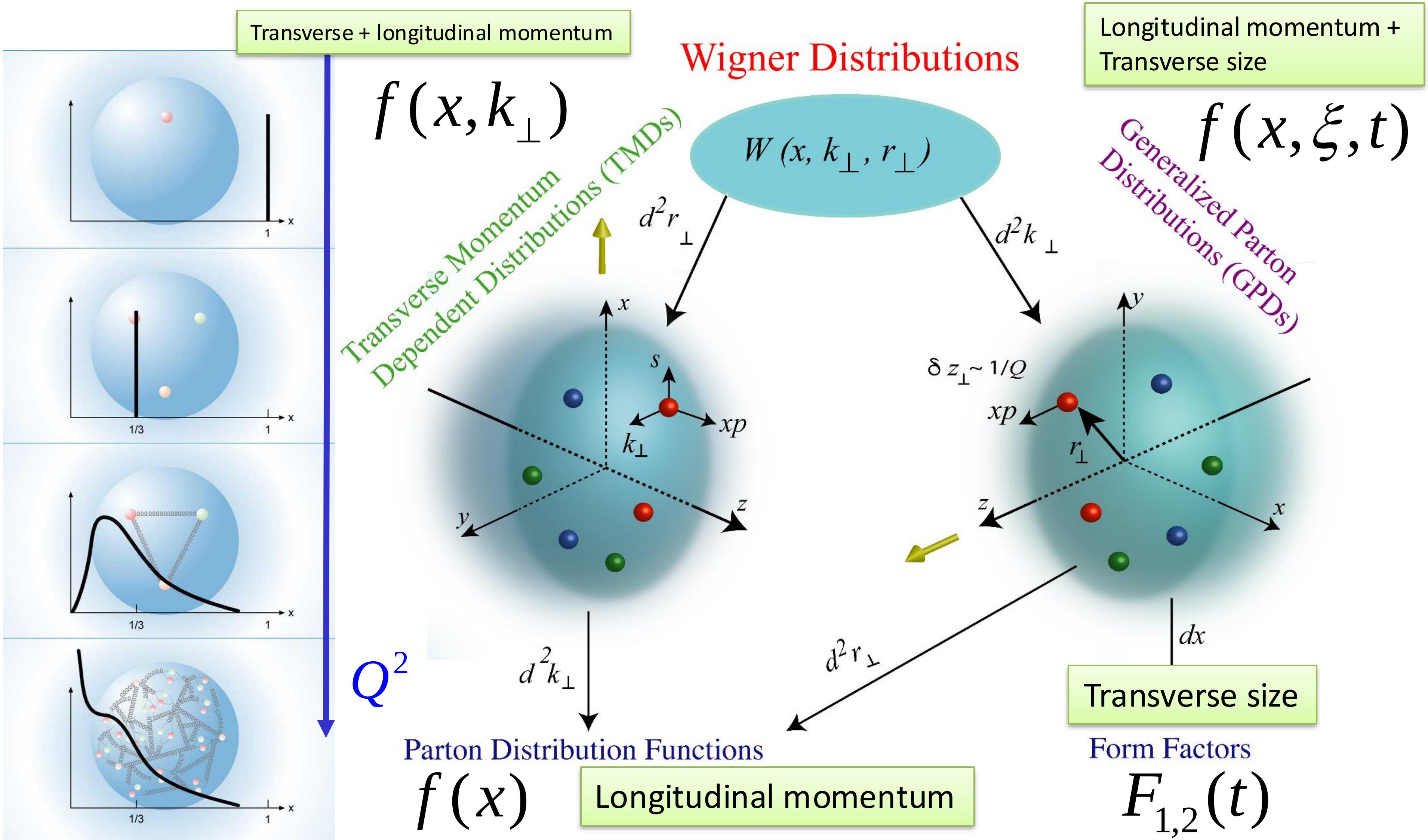


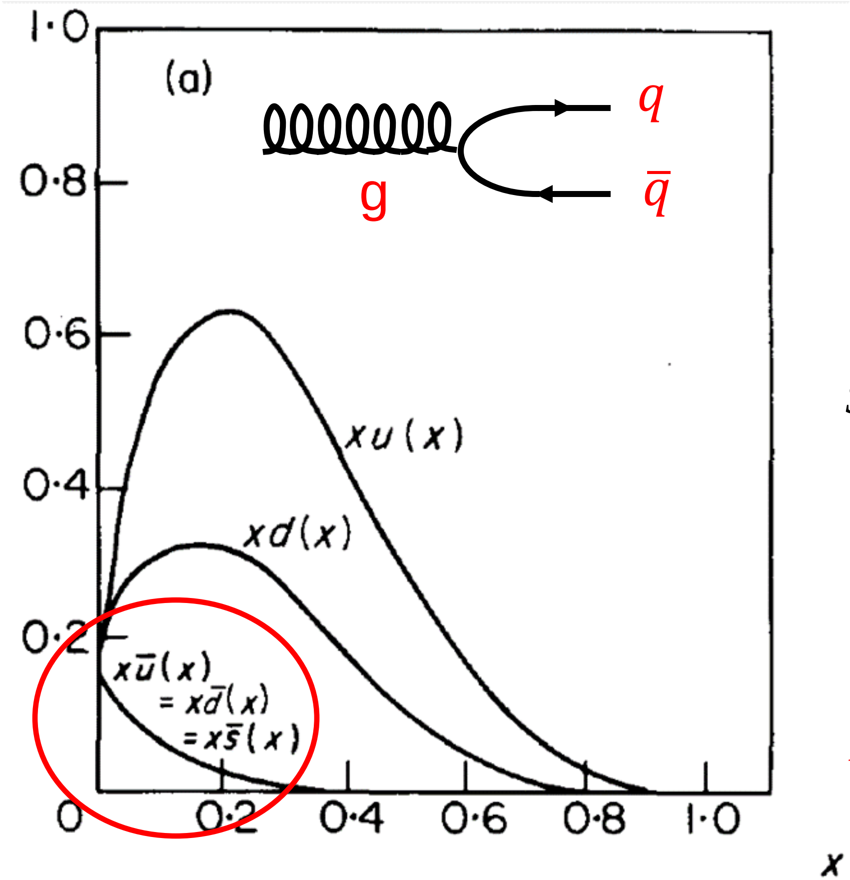
Fig. 1 | Radial pressure distribution in the proton. The graph shows the pressure distribution $r^2p(r)$ that results from the interactions of the

Multi-dimensional Partonic Structures



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

Naïve Expectation of Nucleon Sea: SU(3) Symmetric



Gottfried Sum Rule

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

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

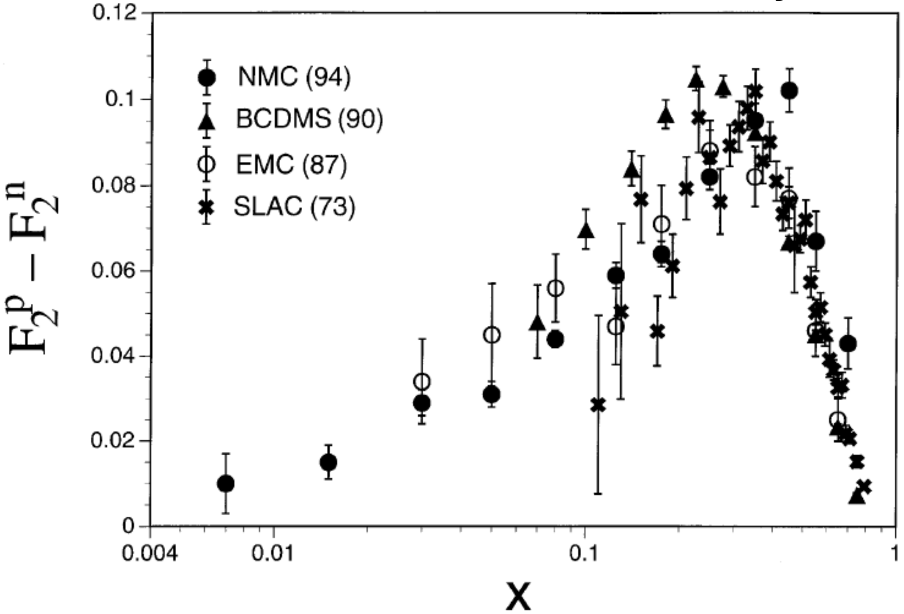
$$= \frac{1}{3} \quad (\text{if } \bar{u}(x) = \bar{d}(x))$$

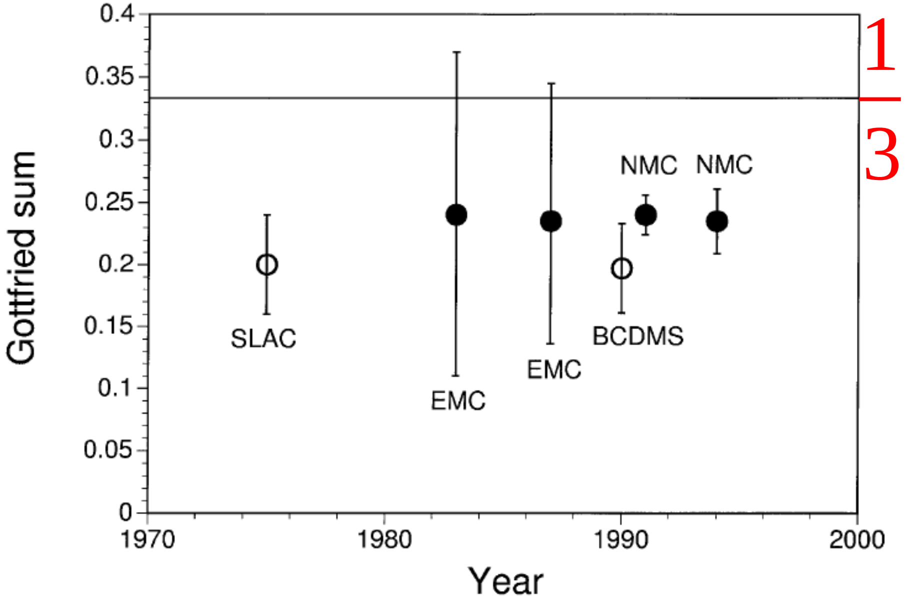
F_2^p, F_2^n : Structure functions of proton and neutron from DIS

F.E. Close, "An Introduction to Quarks and Partons"

Gottfried Sum

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





$\frac{1}{3}$

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

$$S_G = 0.235 \pm 0.026$$

(Significantly lower than 1/3 !)

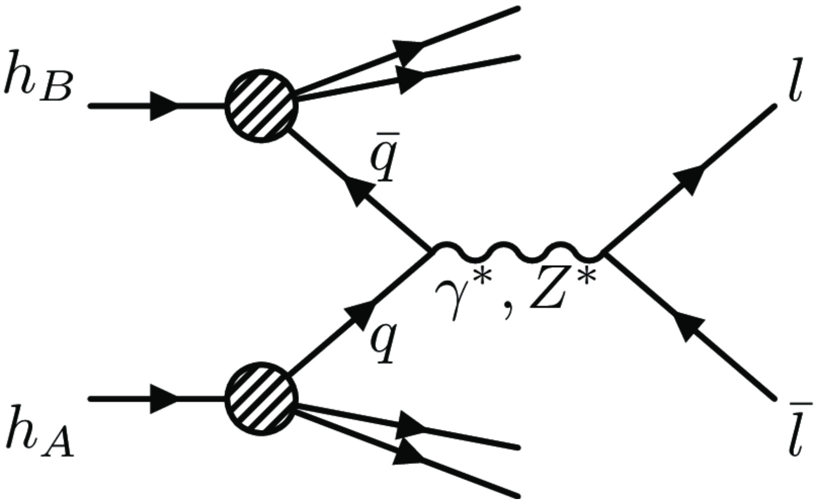
Drell-Yan Process

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

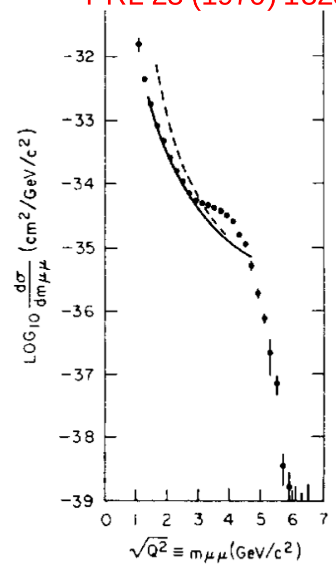
MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES*

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 νW_2 near threshold.

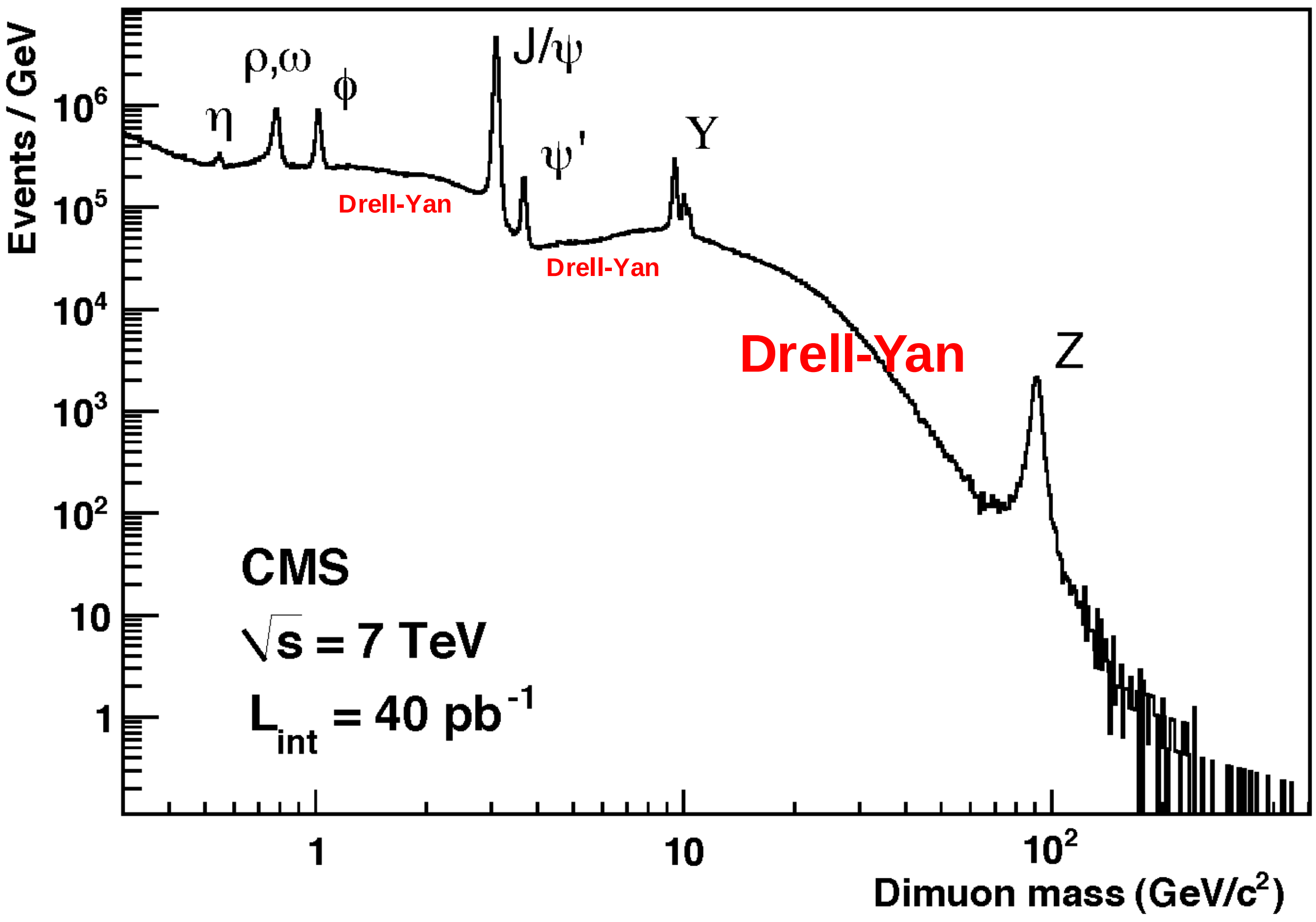


PRL 25 (1970) 1523



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

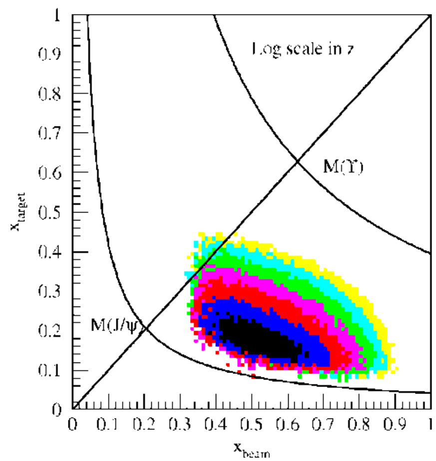
Dimuon Invariant Mass Spectrum

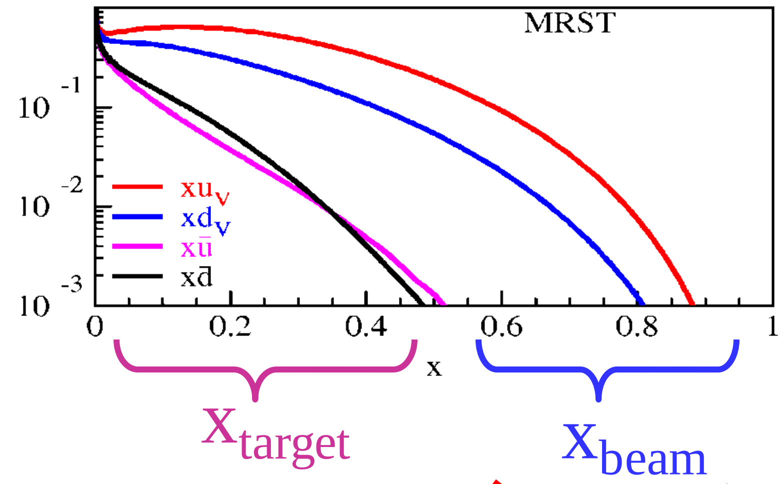


x-dependence of Sea Quarks

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):

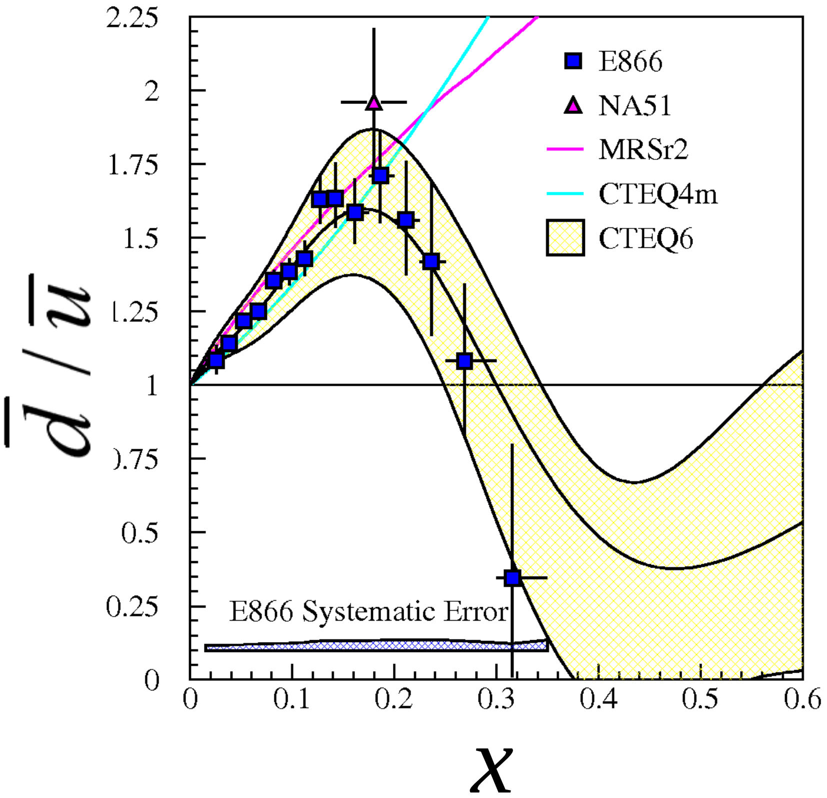
$$\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] dx \neq 0$$

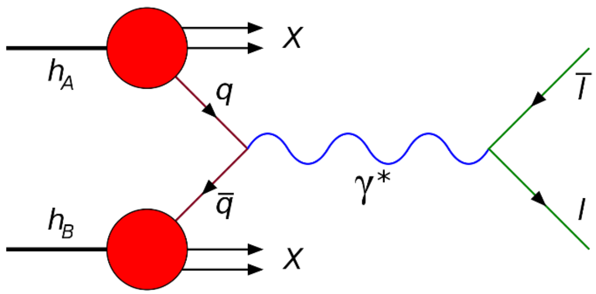
- NA51 (Drell-Yan, 1994):

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

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

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





Pauli Exclusive Principle

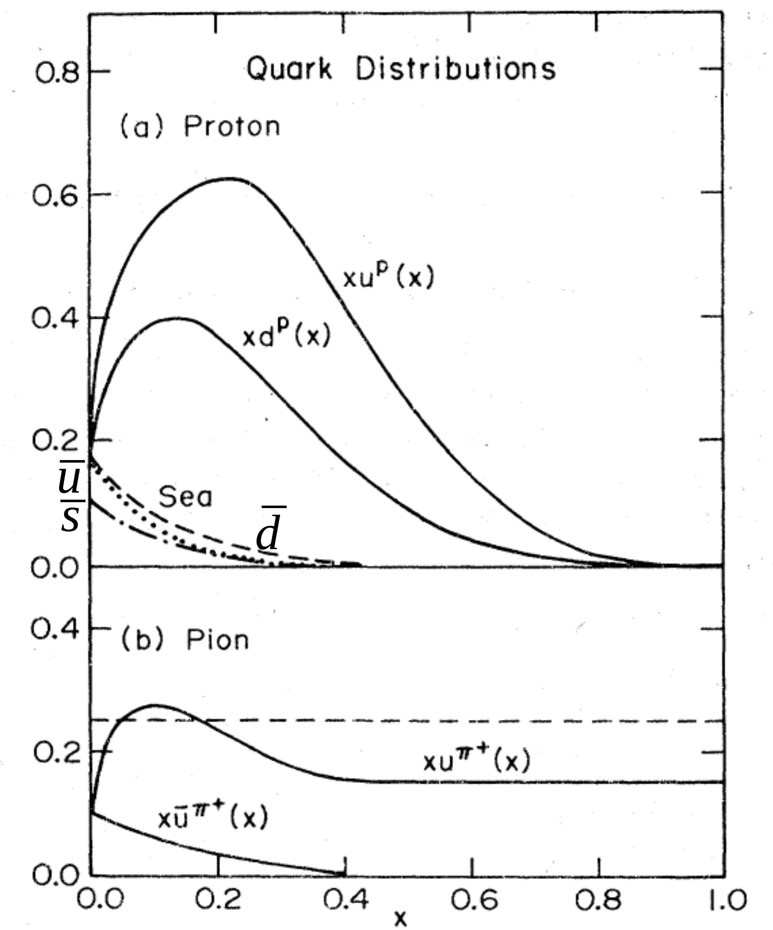
Field and Feynman, PRD 15, 2590 (1977)

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

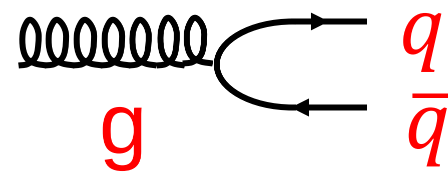
$$\int_0^1 [\nu W_2^{ep}(x) - \nu W_2^{en}(x)]\frac{dx}{x} = \int_0^1 \tfrac{1}{3}(u+\bar{u}-d-\bar{d})dx$$

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

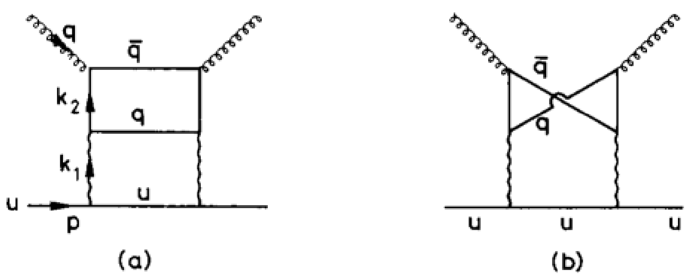
using the sum rules (2.2). Experimentally this integral is hard to determine for it depends on small differences near $x=0$. It seems, however, to be distinctly less than $\frac{1}{3}$[8] (from the data of Figs. 2 and 3(b) one gets about 0.27), indicating $\bar{u}<\bar{d}$ (although, of course, they 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

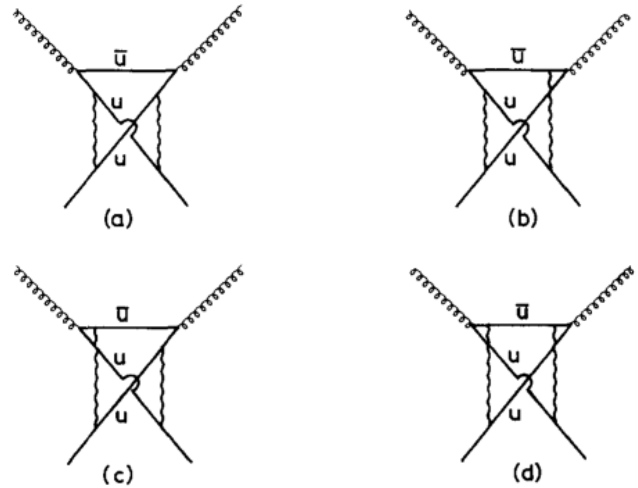


Origin of $\bar{u}(x) \neq \bar{d}(x)$: pQCD effect?



- 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*)



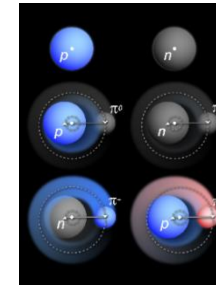


$$\int \frac{dx}{x} \{[\nu W_2^{ep}(x, q^2) - \nu W_2^{en}(x, q^2)] - [\nu W_2^{ep}(x, q_0^2) - \nu W_2^{en}(x, q_0^2)]\}$$

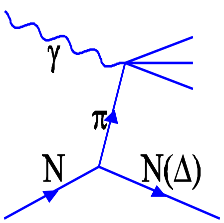
$$\simeq 0.01(\alpha_s(q^2) - \alpha_s(q_0^2)) ,$$

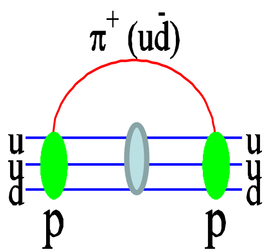
The perturbative effect is too small to explain the antiquark asymmetry!

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.

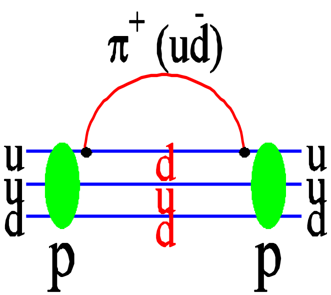




$$|p\rangle = \sqrt{Z}\,|p_0\rangle + a_{N\pi/p}\left[-\sqrt{\frac{1}{3}}|p_0\pi^0\rangle + \sqrt{\frac{2}{3}}|n_0\pi^+\rangle\right] + a_{\Delta\pi/p}\left[\sqrt{\frac{1}{2}}|\Delta_0^{++}\pi^-\rangle - \sqrt{\frac{1}{3}}|\Delta_0^{+}\pi^0\rangle + \sqrt{\frac{1}{6}}|\Delta_0^{0}\pi^+\rangle\right]$$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

n

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

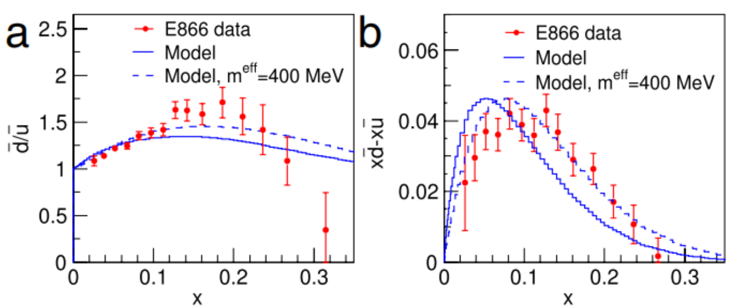


$$|U\rangle = \sqrt{Z}|u\rangle + \sqrt{\frac{1}{3}}a_{\pi/U}|u\pi^0\rangle + \sqrt{\frac{2}{3}}a_{\pi/U}|d\pi^+\rangle + a_{K/U}|sK^+\rangle + \cdots$$

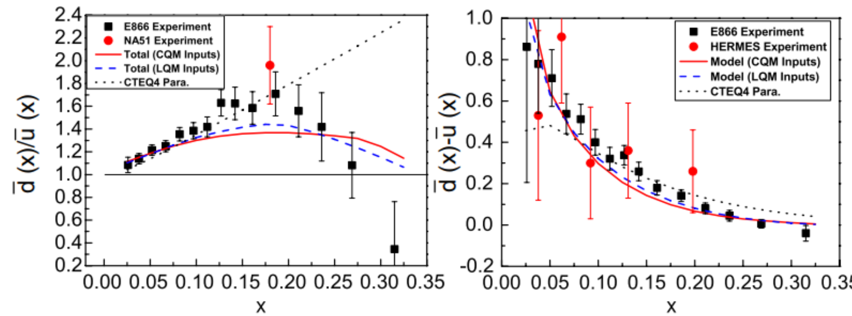
$$|D\rangle = \sqrt{Z}|d\rangle + \sqrt{\frac{1}{3}}a_{\pi/D}|d\pi^0\rangle + \sqrt{\frac{2}{3}}a_{\pi/D}|u\pi^-\rangle + a_{K/D}|sK^0\rangle + \cdots,$$

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

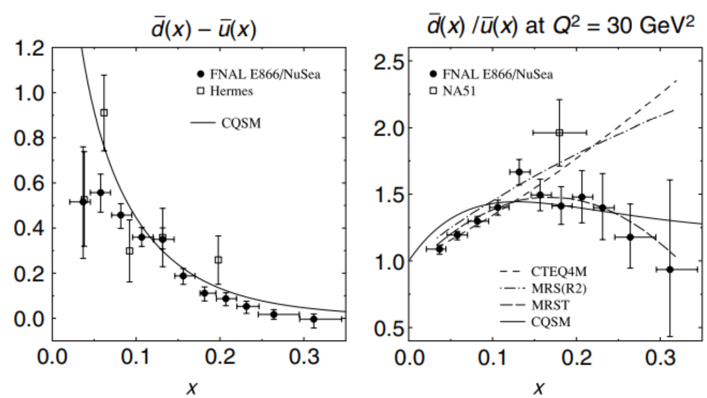
Flavor structure of nucleon sea



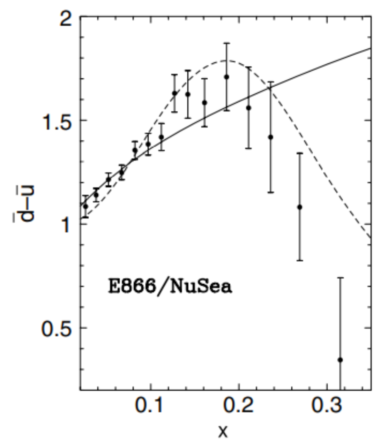
(a) Meson cloud model. Figure from [34].



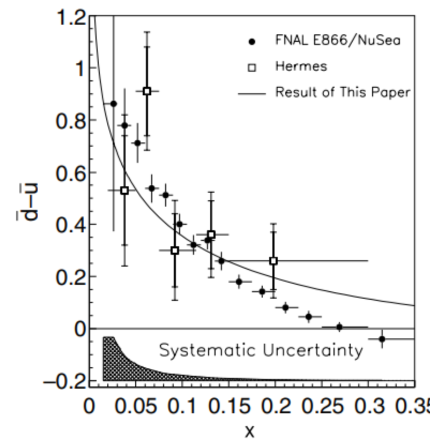
(b) Chiral quark model. Figure from [37].



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



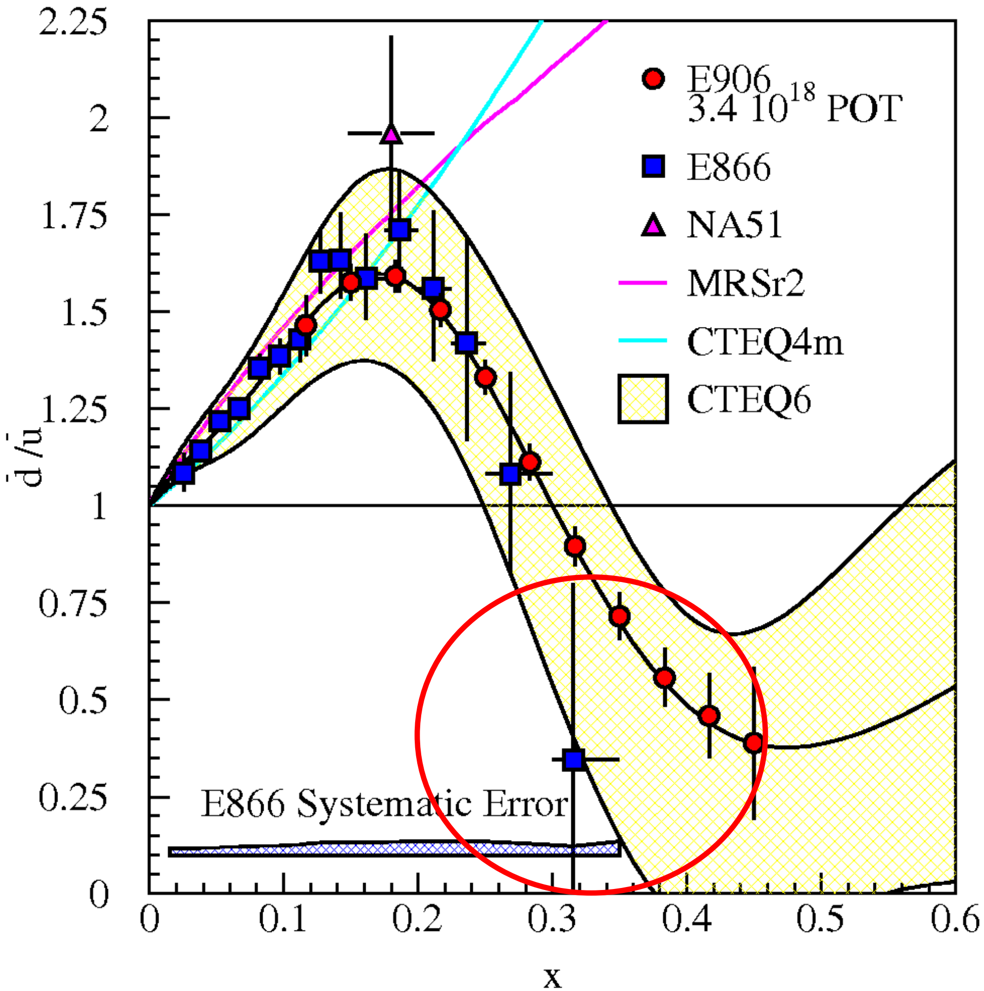
(d) Chiral quark model. Figure from [37].



(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

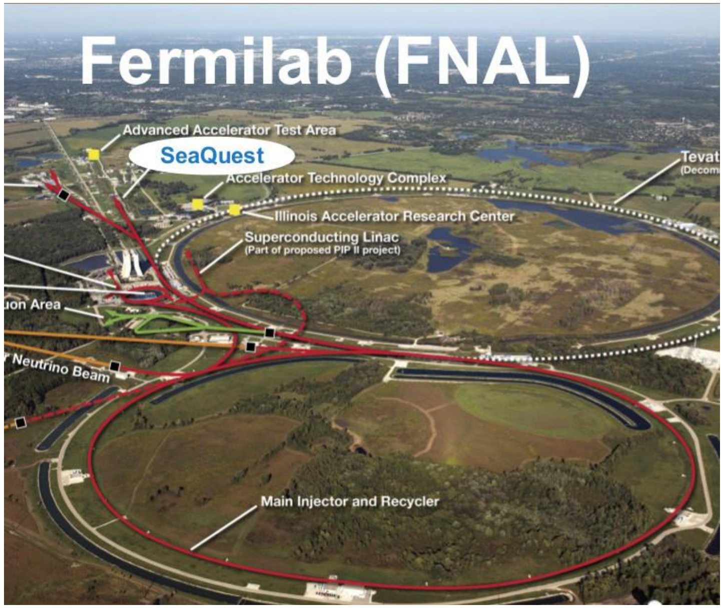
$\bar{d}(x)/\bar{u}(x)$ Measured by FNAL E906/SeaQuest Experiment



$(\bar{d}(x)/\bar{u}(x))$ up to x_T : 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
- ^{1}H, ^{2}H, 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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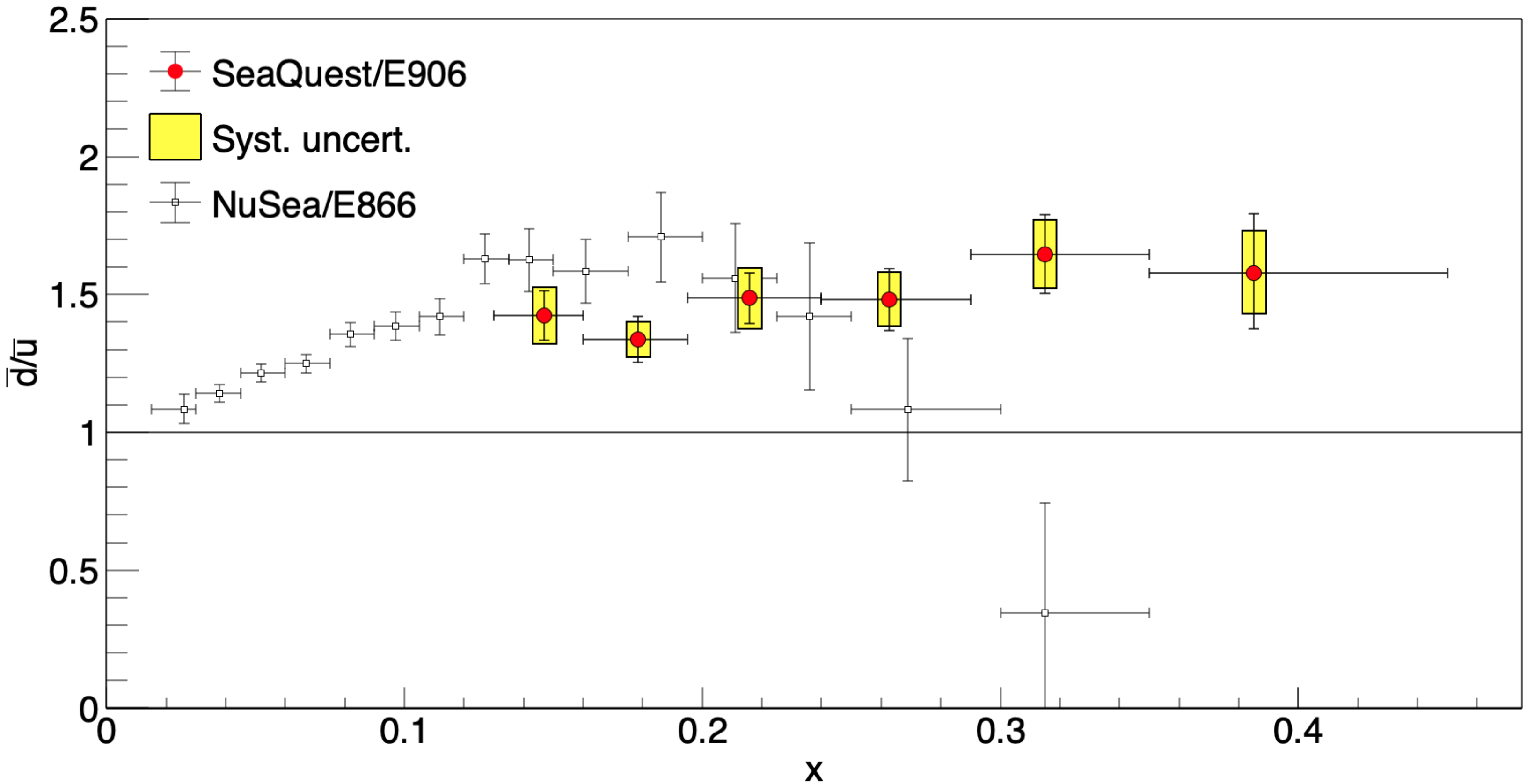
Check for updates

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

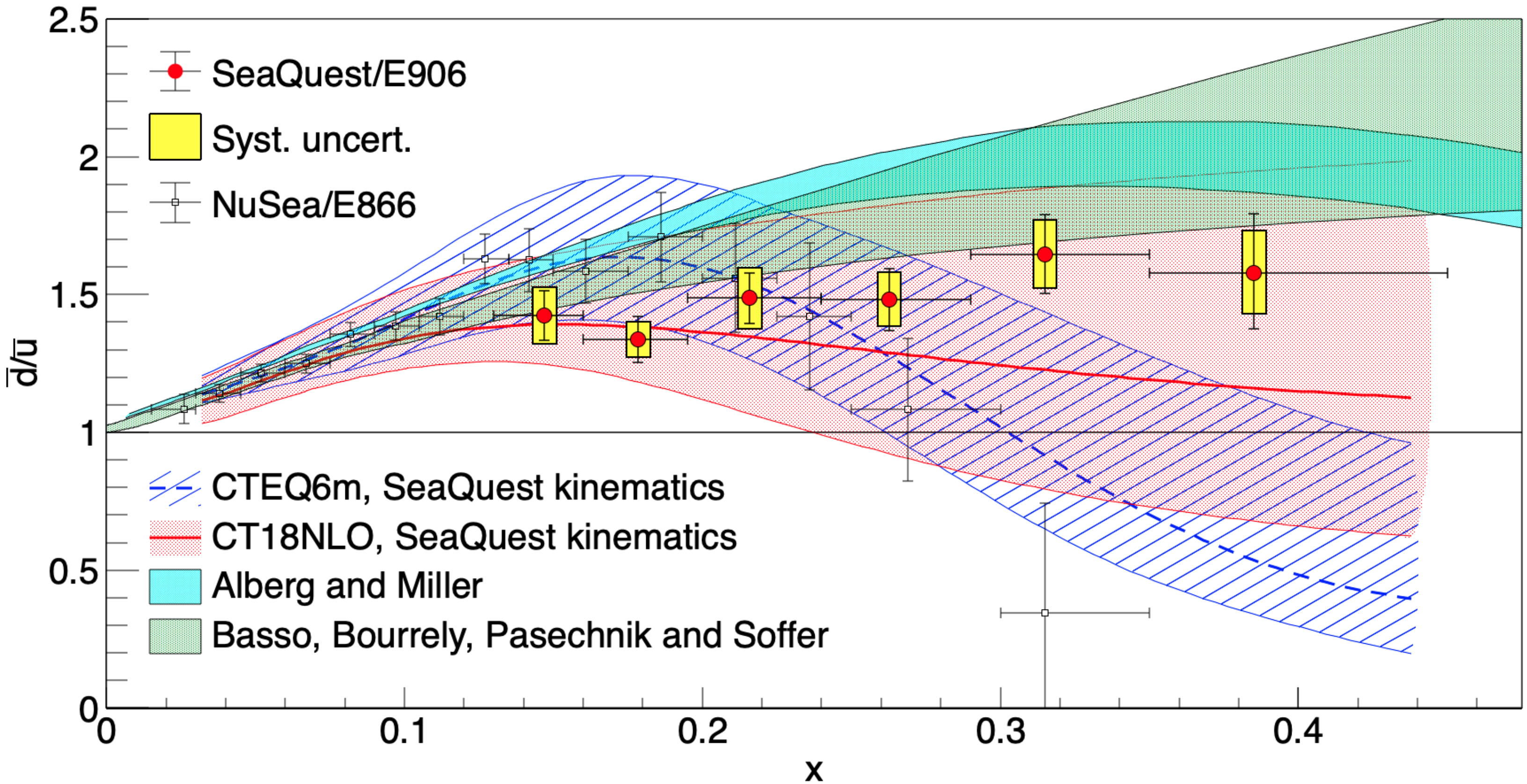
$\bar{d}/\bar{u}(x)$

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



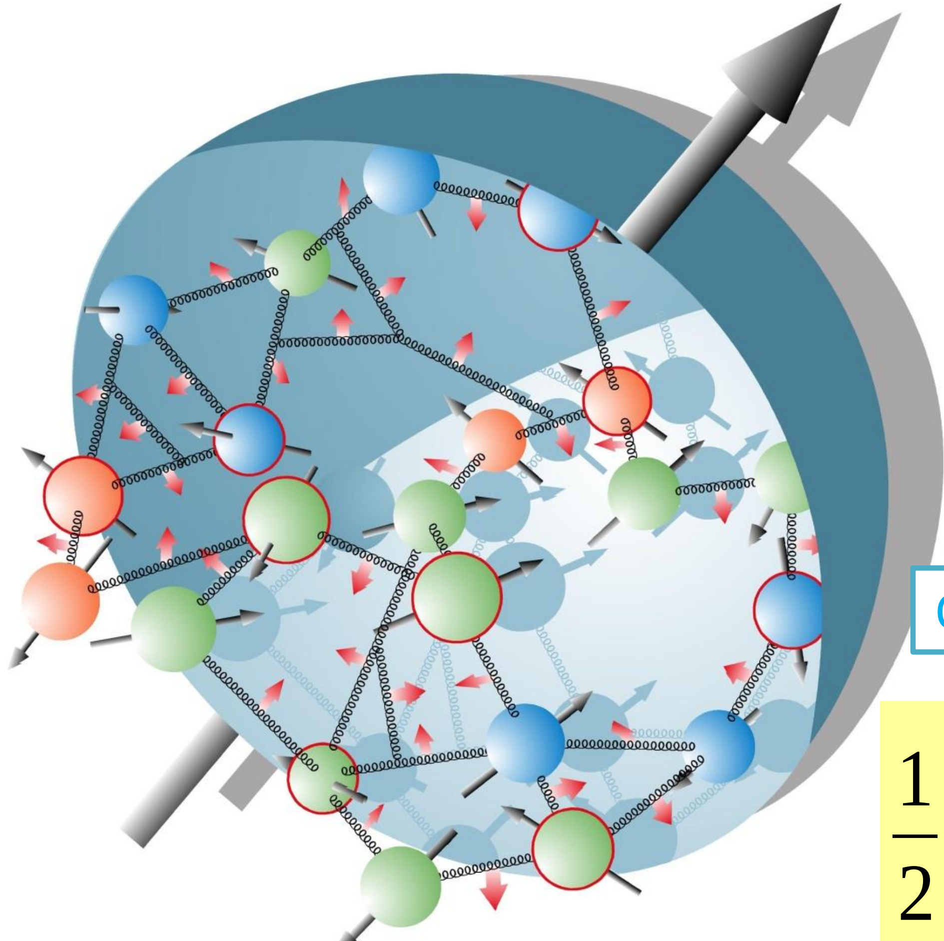
The trends between SeaQuest and NuSea at large x are quite different.
No explanation is found for these differences.

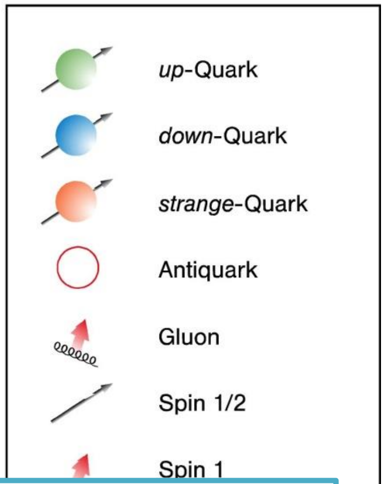
$\bar{d}/\bar{u}(x)$



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

Decomposition of Proton Spin





$$L_Z = \vec{r}_T \times \vec{P}_T$$

Quark spin (~30%)

Gluon spin (~0)

$$\frac{1}{2}\bigg|^{proton} = \frac{1}{2}\Delta\Sigma + \Delta g + L_q$$

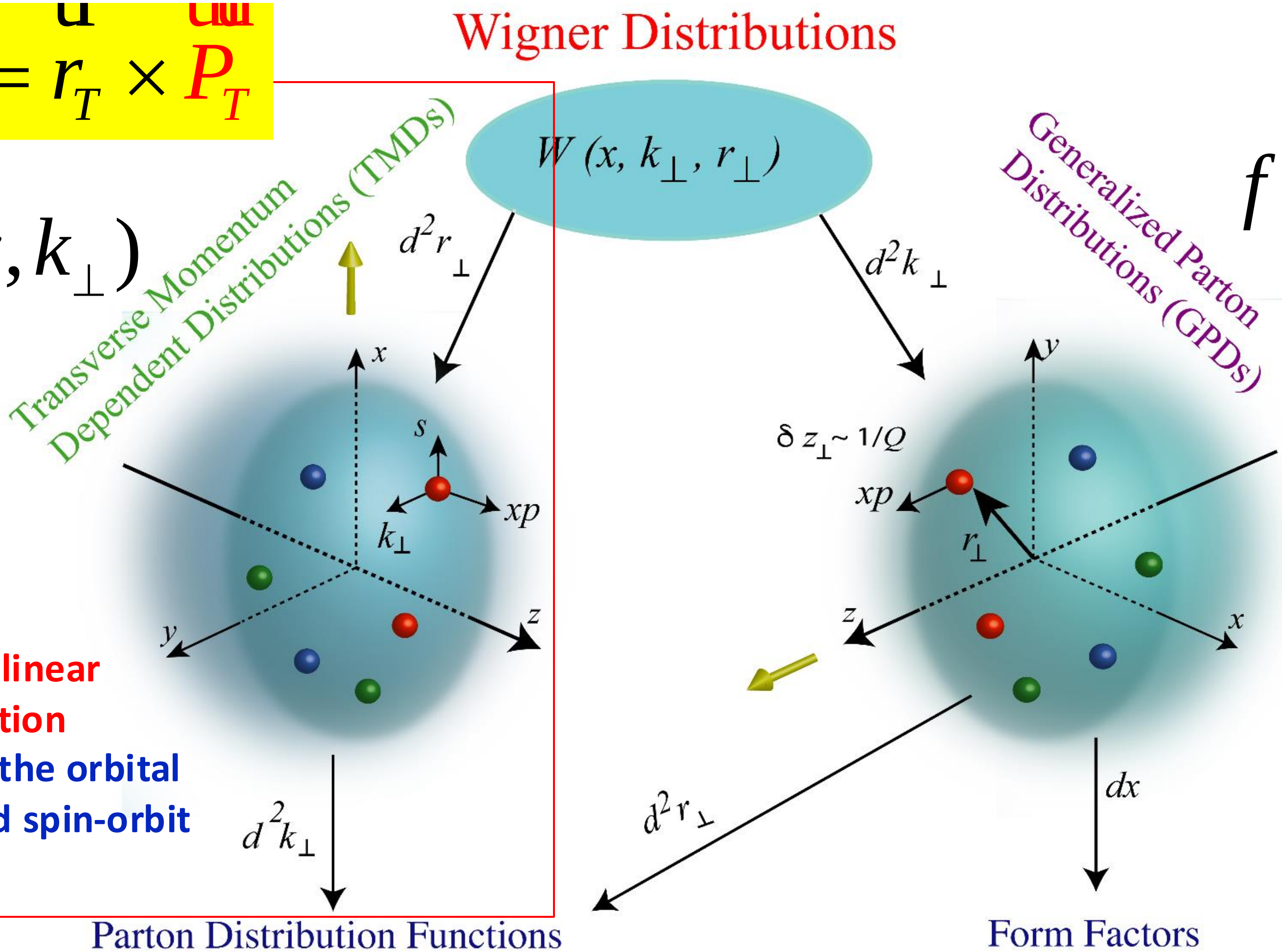
Orbital angular momentum

Multi-dimensional Partonic Structures

$$L_Z = r_T \times P_T$$

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

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



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

$$f(x)$$

$$F_{1,2}(t)$$

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

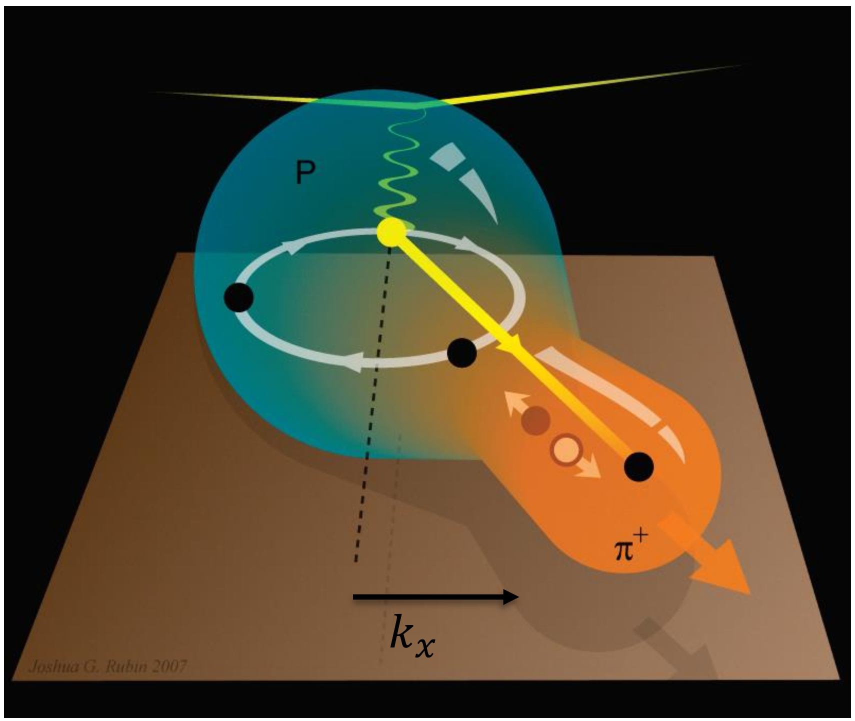
Leading-Twist Transverse-momentum Dependent **Parton Density Function** (TMDs)

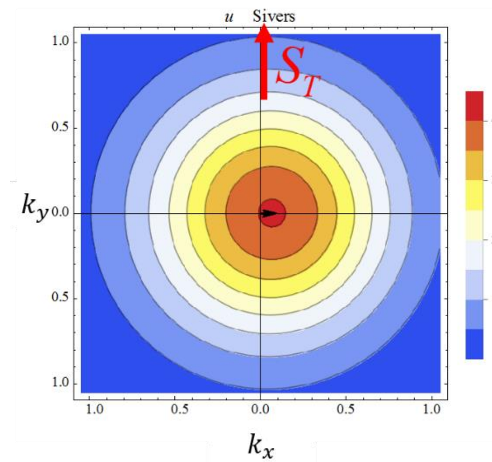
- spin of the nucleon
- spin of the parton
- k_T of the parton

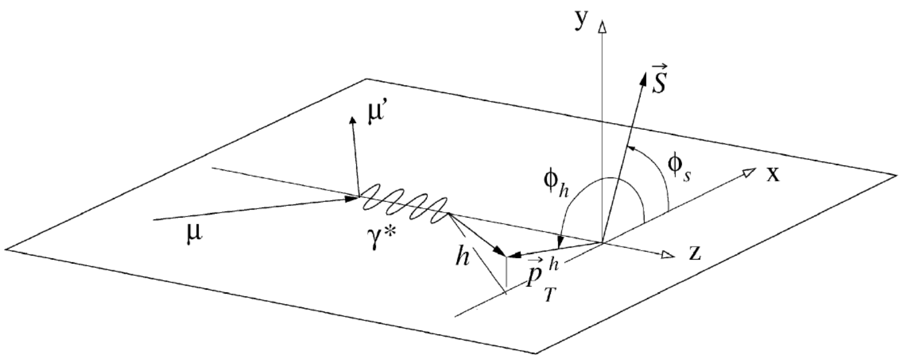
Quark / Nucleon	U	L	T
U	number density $f_1^{q,g}(x, k_T^2)$		Boer-Mulders $h_1^{\perp q,g}(x, k_T^2)$
L		Helicity $g_{1L}^{q,g}(x, k_T^2)$	worm-gear L $h_{1L}^{\perp q,g}(x, k_T^2)$
T	Sivers $f_{1T}^{\perp q,g}(x, k_T^2)$	Kotzinian-Mulders worm-gear T $g_{1T}^{\perp q,g}(x, k_T^2)$	Transversity $h_1^{q,g}(x,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

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.





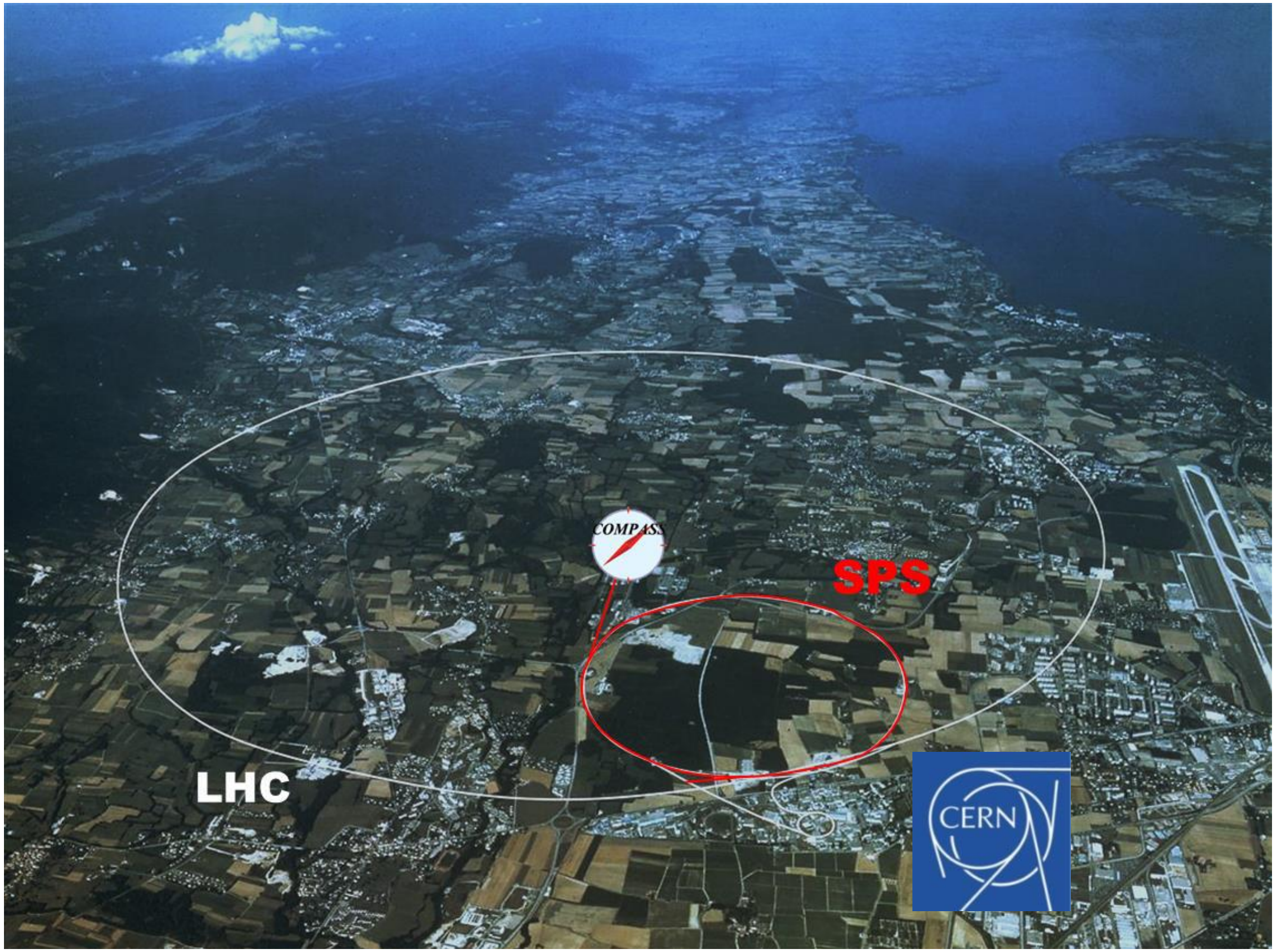


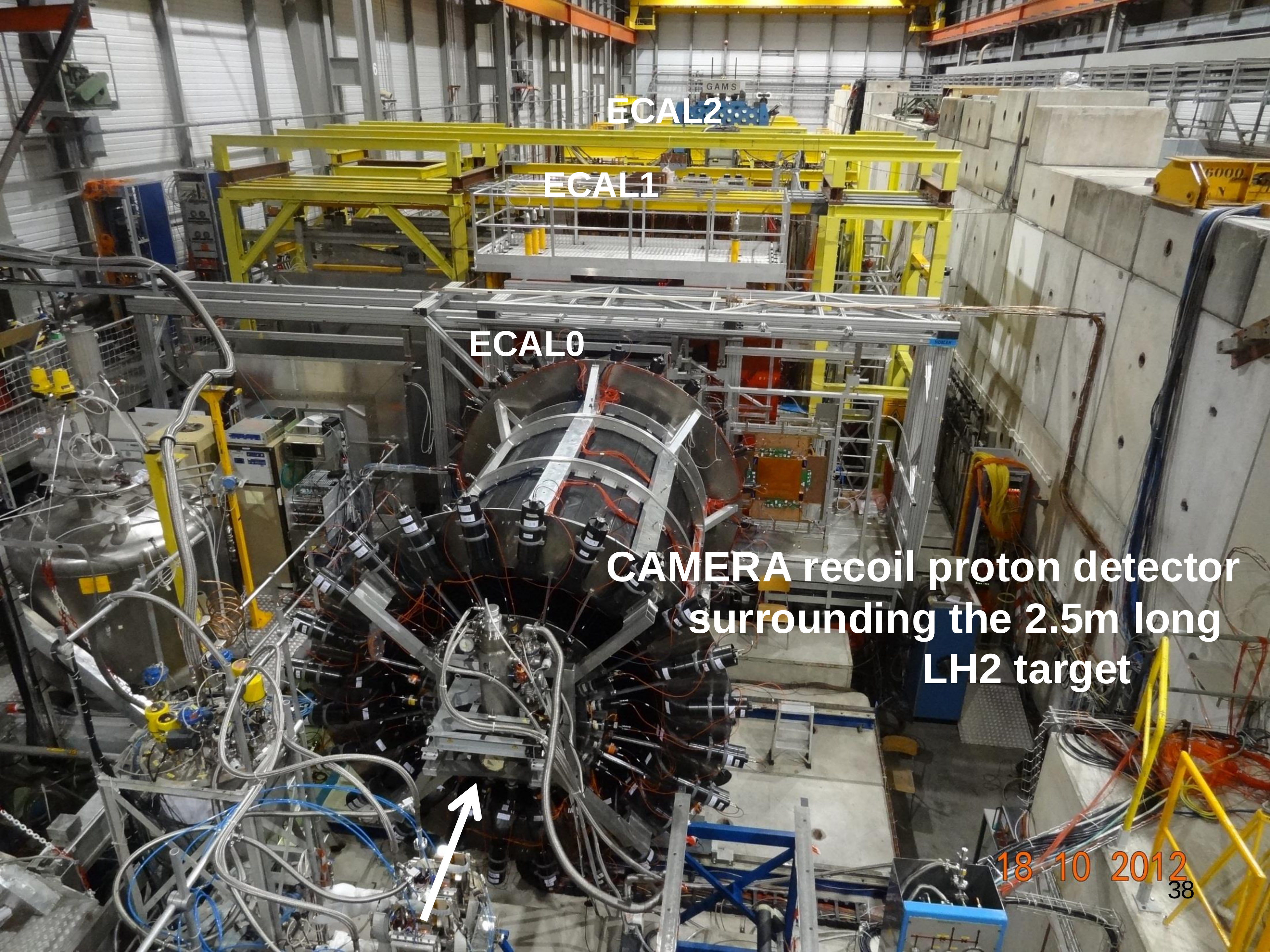
$$A_T^h \equiv \frac{d\sigma(\vec{S}_T) - d\sigma(-\vec{S}_T)}{d\sigma(\vec{S}_T) + d\sigma(-\vec{S}_T)} = \left|\vec{S}_T\right| \cdot \left[D_{NN} \cdot A_{Coll} \cdot \sin(\phi_h + \phi_S - \pi) + A_{Siv} \cdot \sin(\phi_h - \phi_S)\right]$$

COMPASS Collaboration

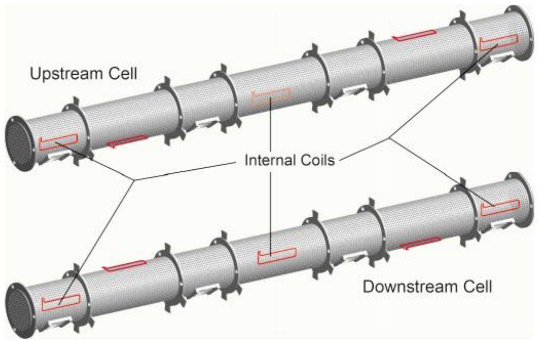
(Common Muon and Proton Apparatus for Structure and Spectroscopy)

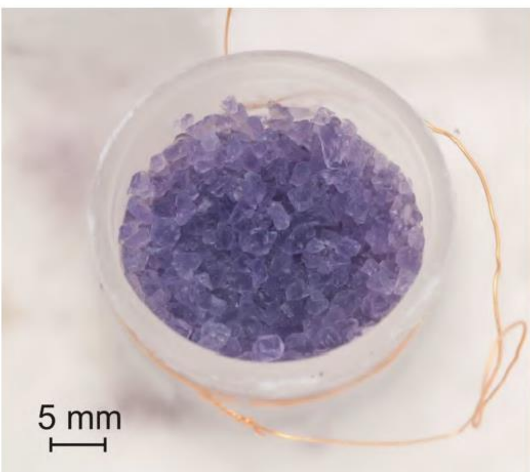
- 24 institutions from 13 countries – nearly 250 physicists
- Fixed-target experiment at SPS north area
- Physics programs:
  - Nucleon spin and partonic structures
  - Hadron spectroscopy

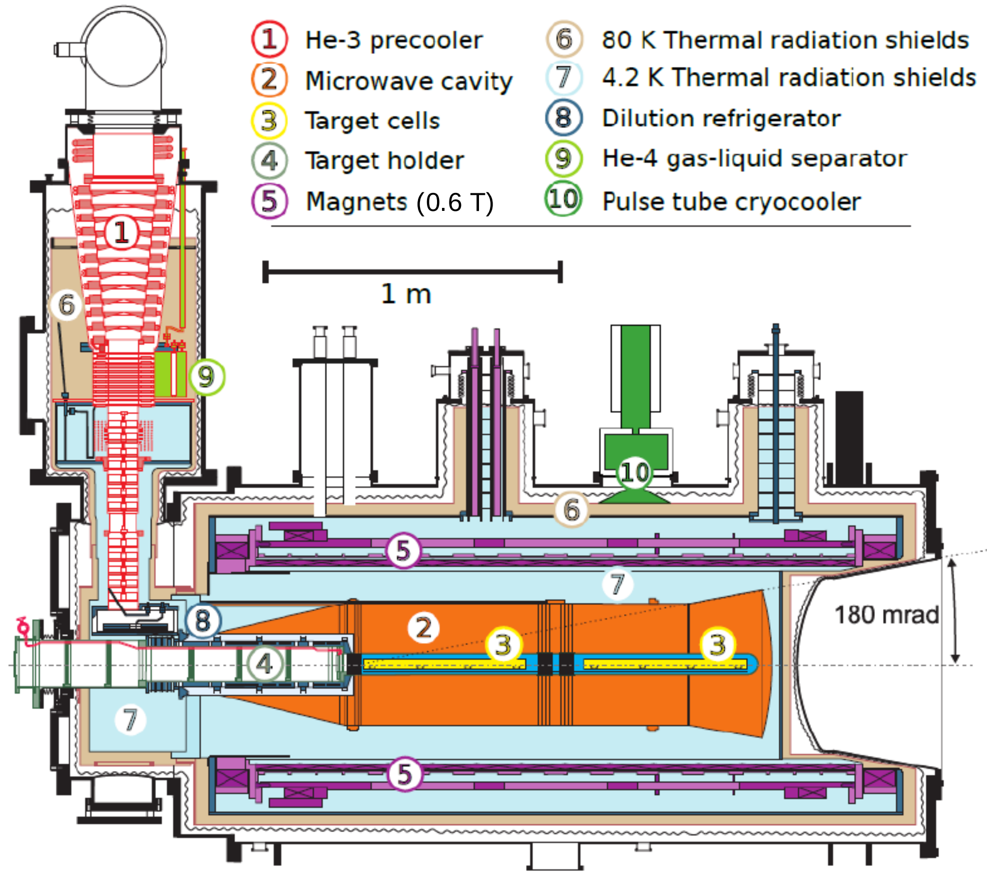



GAMS
ECAL2
ECAL1
ECAL0
CAMERA recoil proton detector
surrounding the 2.5m long
LH2 target
18 10 2012

Polarized NH_3 Target

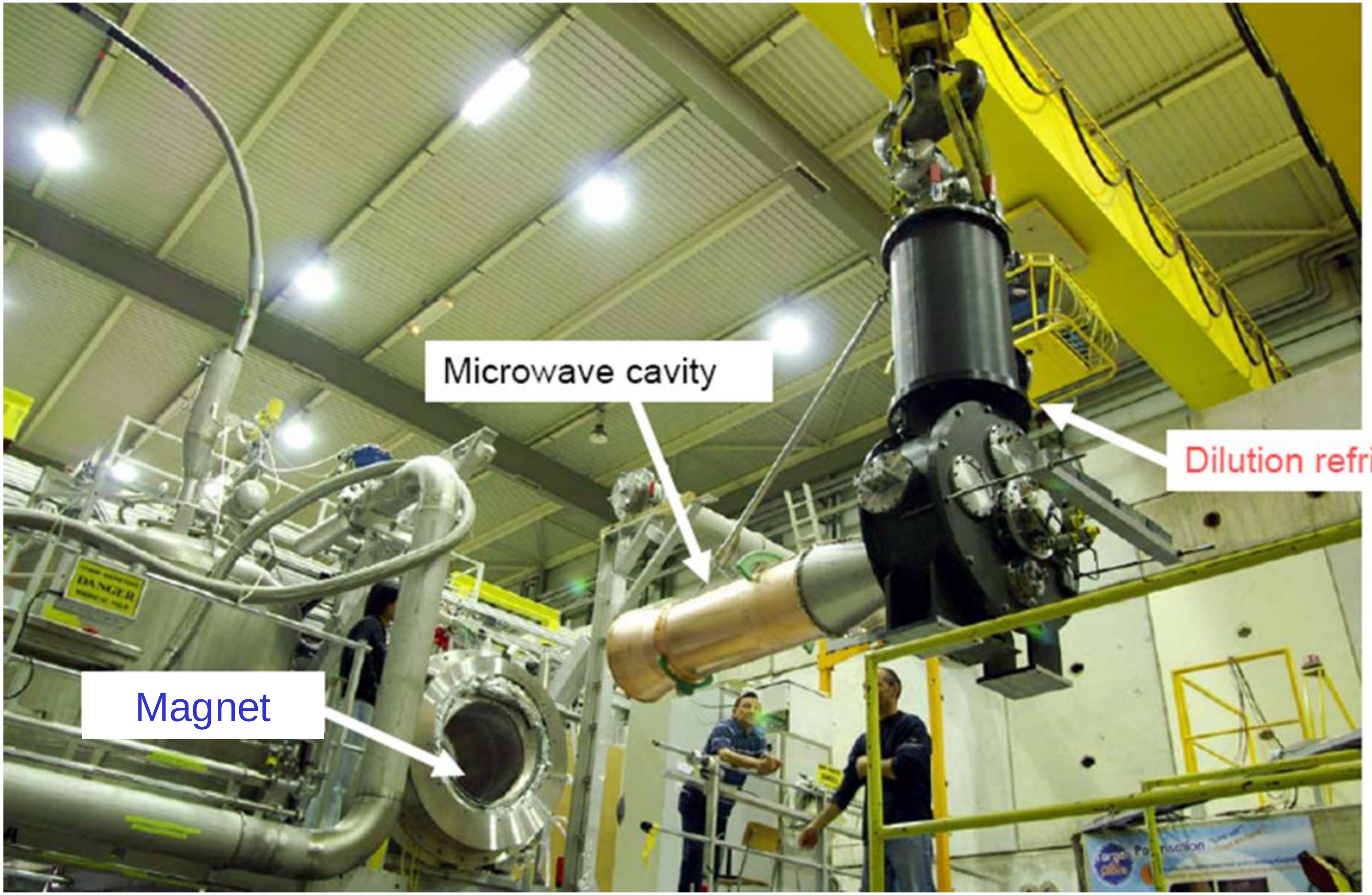




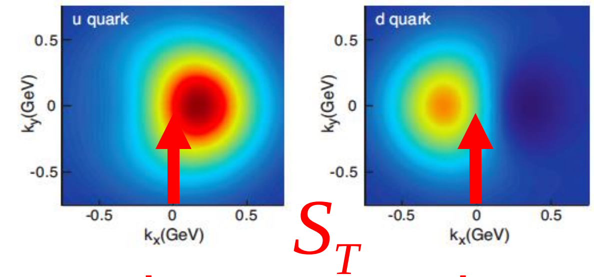


Polarization: 70%
Relaxation time: 1000 hrs

Polarized NH_3 Target

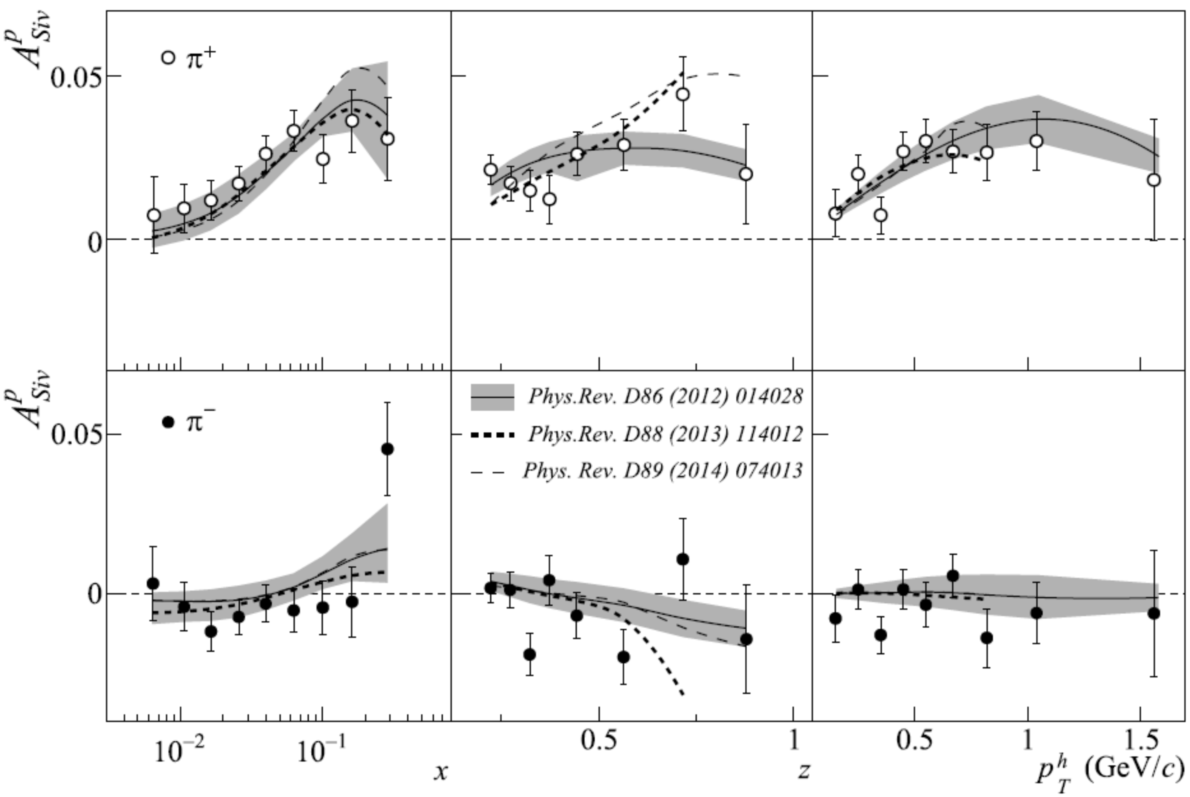


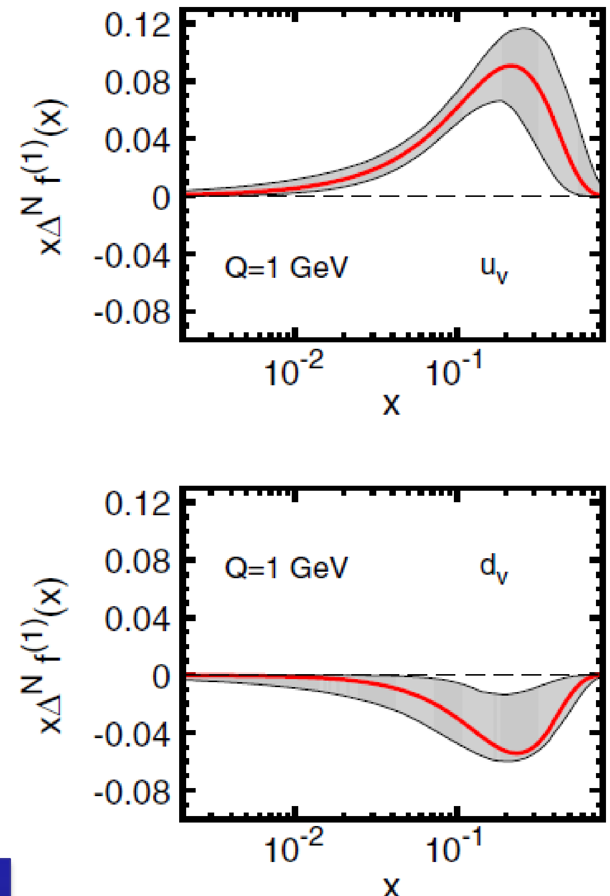
Sivers Asymmetries



Sivers Functions

COMPASS, PLB 744 (2015) 250





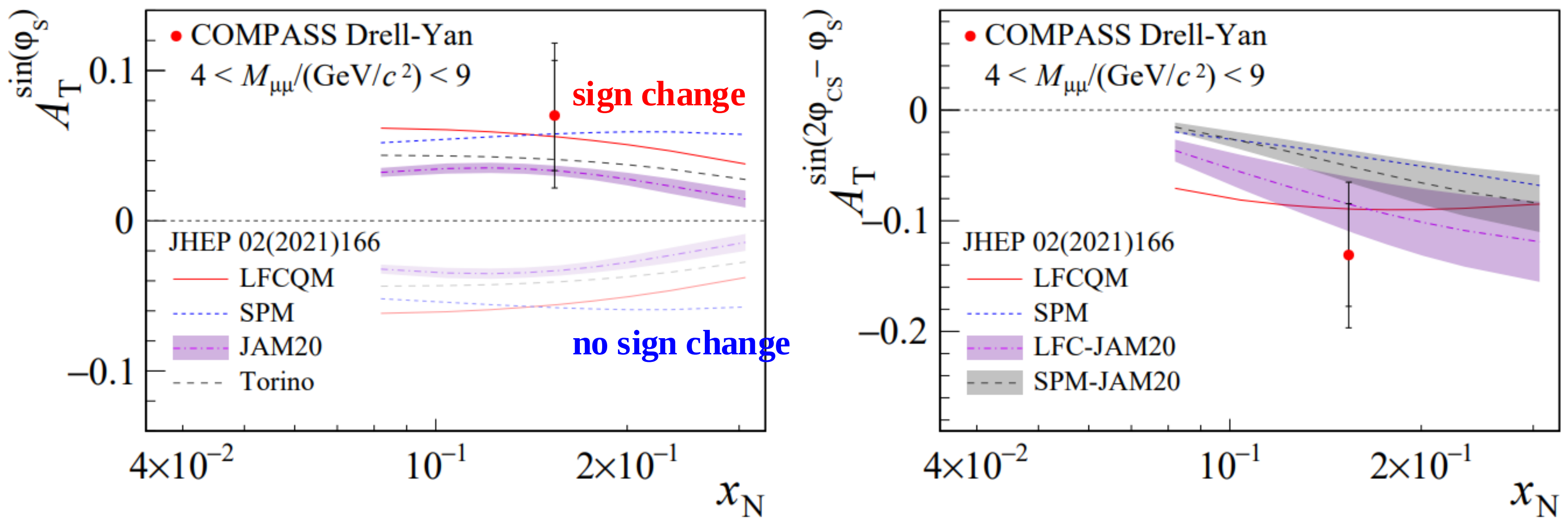
Signals of Sivers functions in SIDIS.
Flavor dependence.

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

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

Statistics:
2015: 35K
2018: 37K

COMPASS, PRL 133, 071902 (2024)



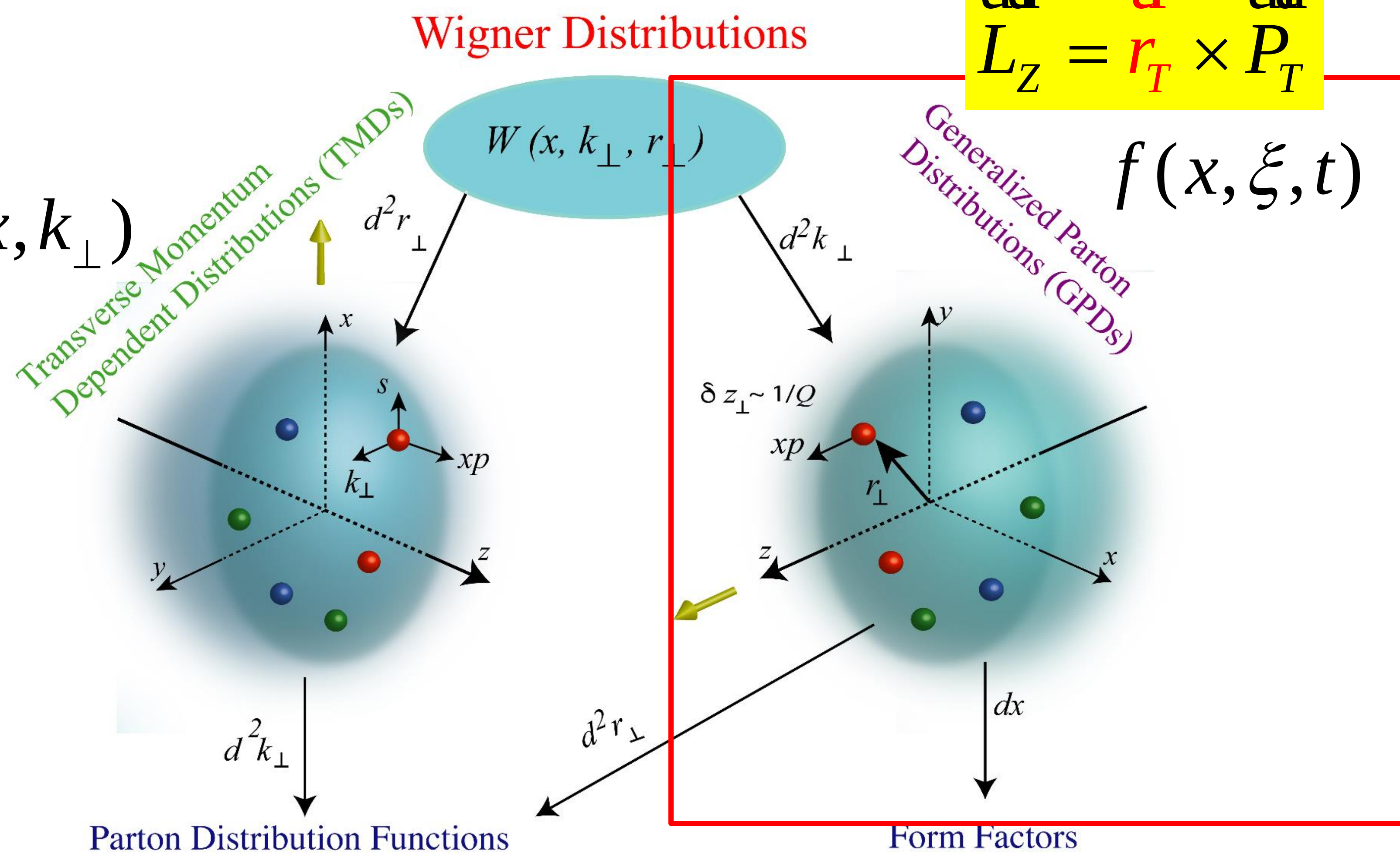
Agreeing with the sign-change hypothesis

Negative transversity TSA

Our results supports the general validity of the TMD approach!

Multi-dimensional Partonic Structures

$$L_Z = r_T \times P_T$$



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

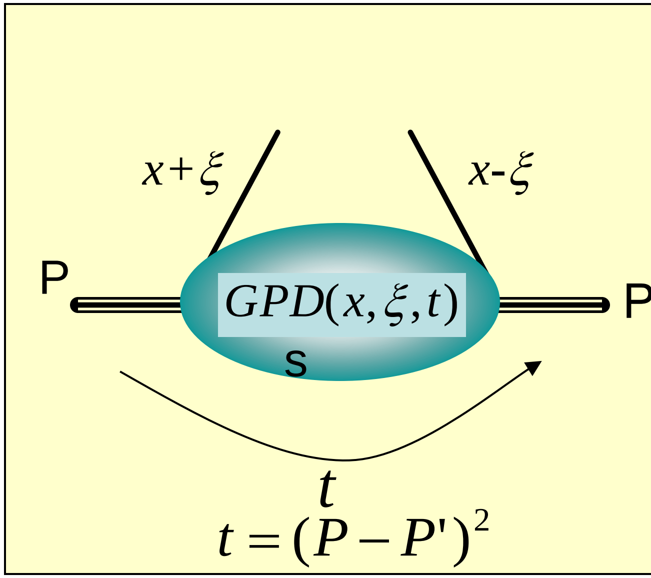
$$f(x, \xi, t)$$

$$f(x)$$

$$F_{1,2}(t)$$

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

Generalized Parton Distribution (GPD)



$t = \xi = 0$

$$H_f(x,0,0) = q_f(x) = -\bar{q}_f(-x)$$

$$\tilde{H}_f(x,0,0) = \Delta q_f(x) = -\Delta\bar{q}_f(-x)$$

First moment

$$\int_{-1}^{1} dx \sum_f H_f(x,\xi,t) = F_1(-t)$$

Dirac FF

$$\int_{-1}^{1} dx \sum_f E_f(x,\xi,t) = F_2(-t)$$

Pauli FF

$$\int_{-1}^{1} dx \sum_f \tilde{H}_f(x,\xi,t) = g_A(-t)$$

axial FF

$$\int_{-1}^{1} dx \sum_f \tilde{E}_f(x,\xi,t) = g_p(-t)$$

pseudoscalar FF

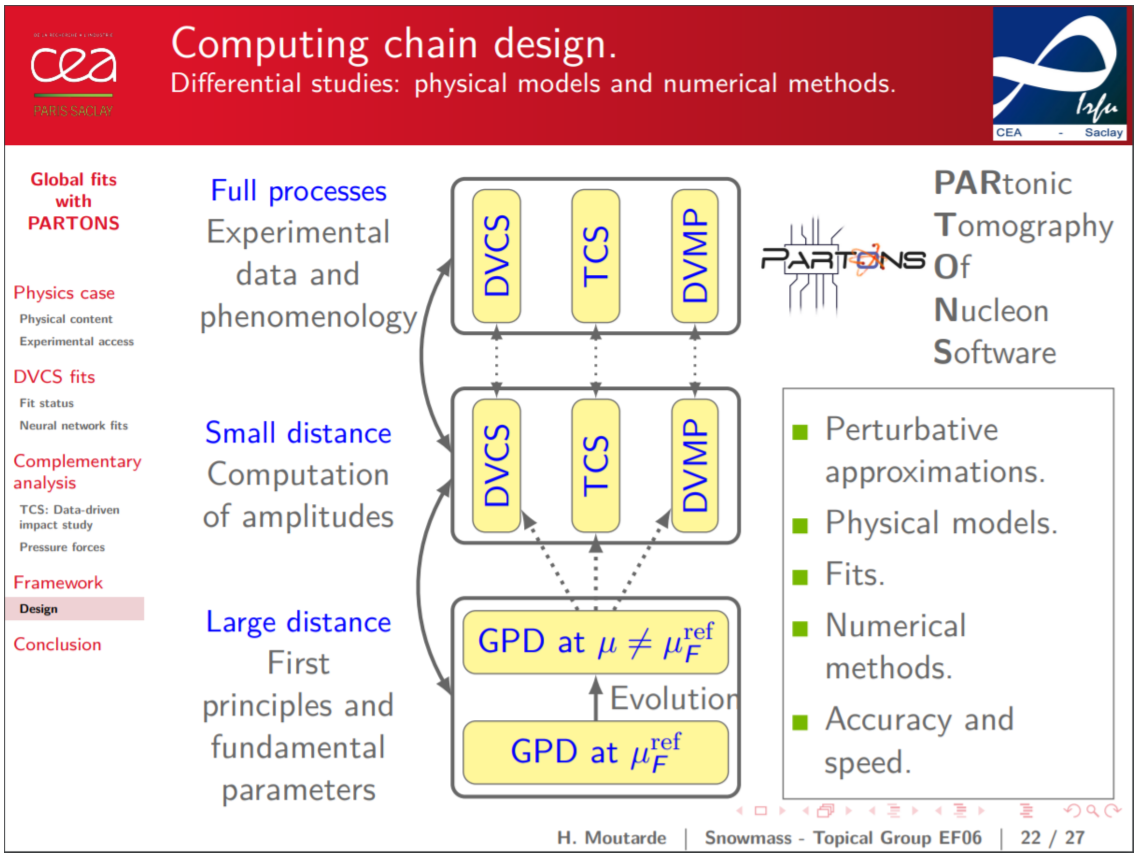
	γ^μ	$\gamma^\mu\gamma^5$
no spin flip	$H_f(x,\xi,t)$	$\tilde{H}_f(x,\xi,t)$
spin flip	$E_f(x,\xi,t)$	$\tilde{E}_f(x,\xi,t)$

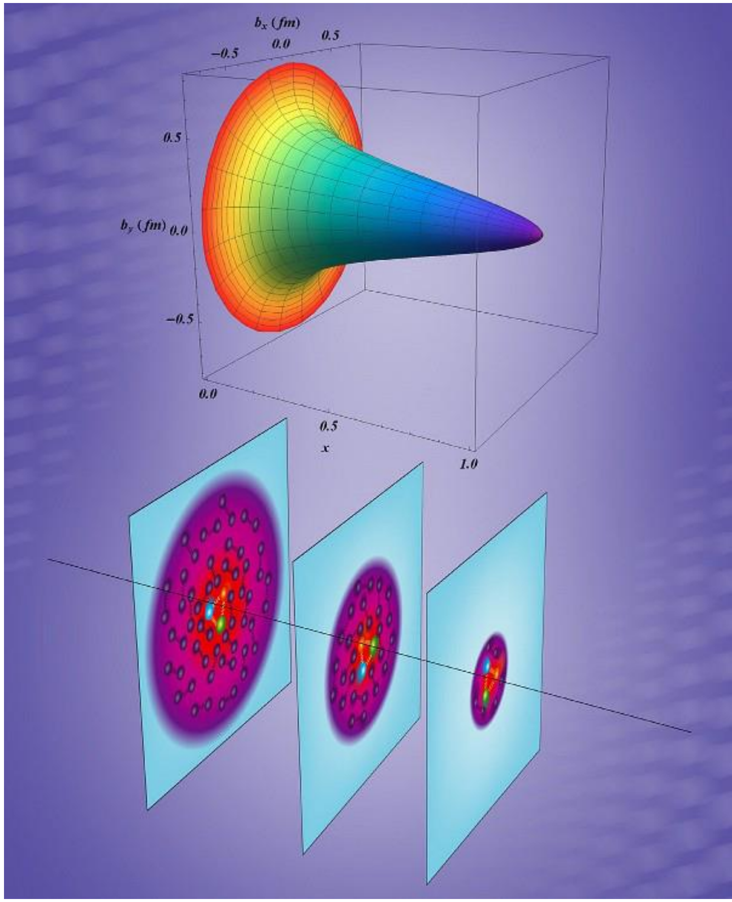
Ji's sum rule

$$J_f = \frac{1}{2}\Delta\Sigma^f + L^f = \frac{1}{2}\int_{-1}^{1} x\,dx\,[H_f(x,\xi,0) + E_f(x,\xi,0)]$$

Global Analysis of GPDs

http://partons.cea.fr/partons/doc/html/index.html



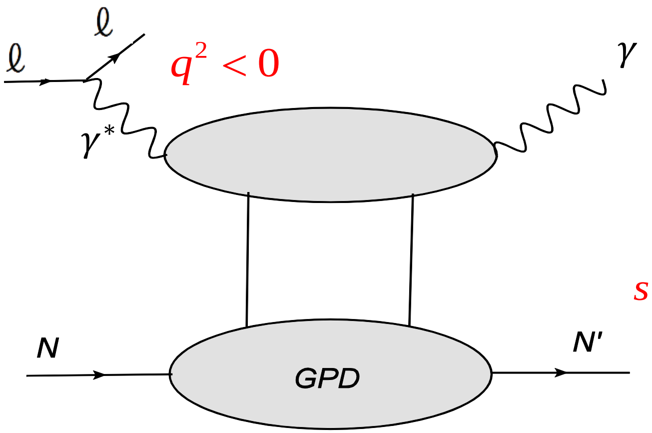


https://indico.fnal.gov/event/44147/contributions/192194/attachments/133262/164302/moutarde-snowmass-2020-08-19.pdf

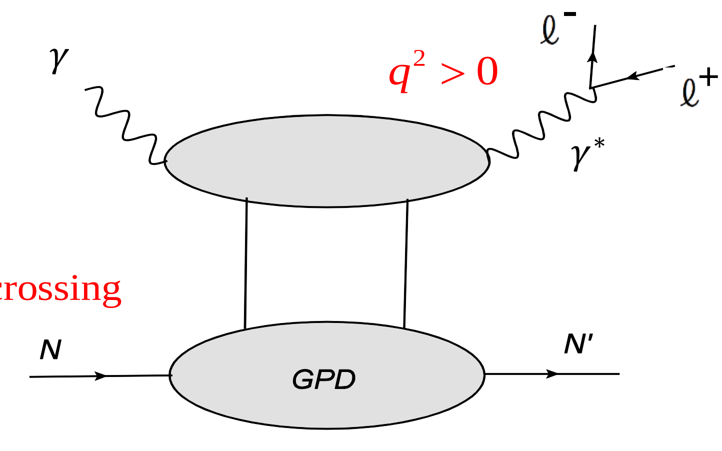
Generalized Parton Distributions

Muller et al., PRD 86 031502(R) (2012)

Deeply Virtual Compton Scattering



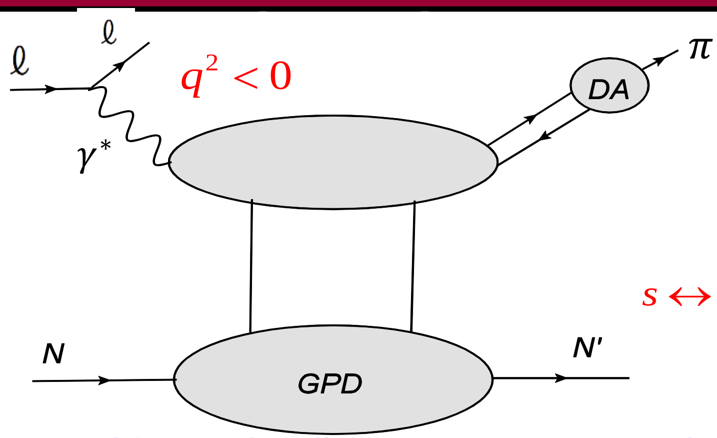
Time-like Compton Scattering



$s \leftrightarrow u$ channel crossing

Ji, PRL 78, 610 (1997); Radyushkin, PLB 380, 417 (1996)

Deeply Virtual Meson Production



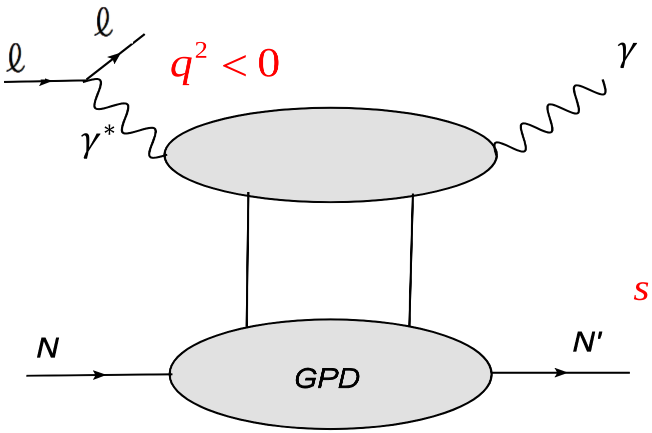
$s \leftrightarrow u$ channel crossing

Collins, Frankfurt and Strikman, PRD 56, 2982 (1997)

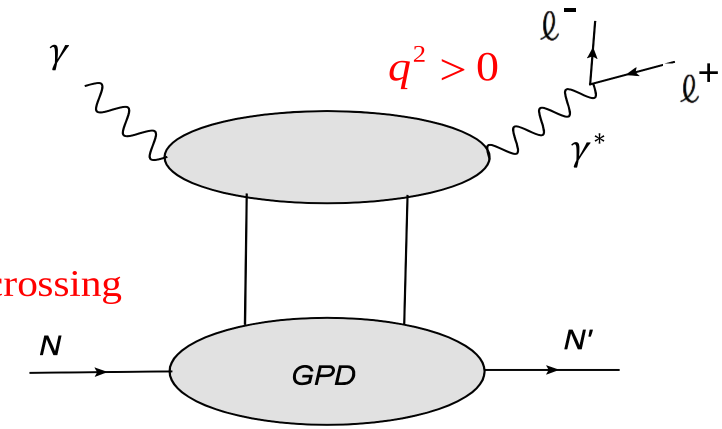
Generalized Parton Distributions

Muller et al., PRD 86 031502(R) (2012)

Deeply Virtual Compton Scattering



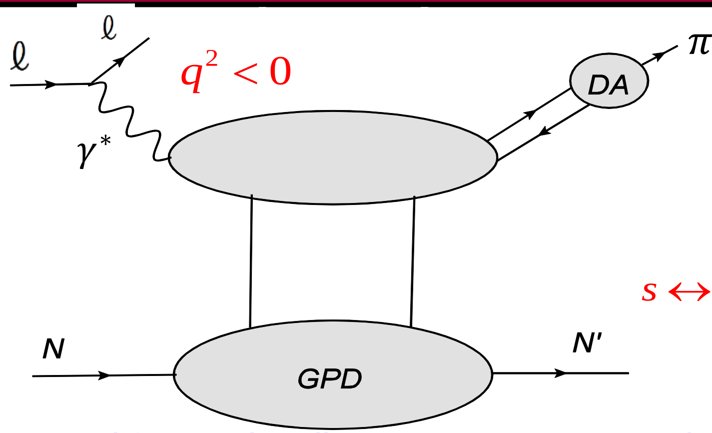
Time-like Compton Scattering



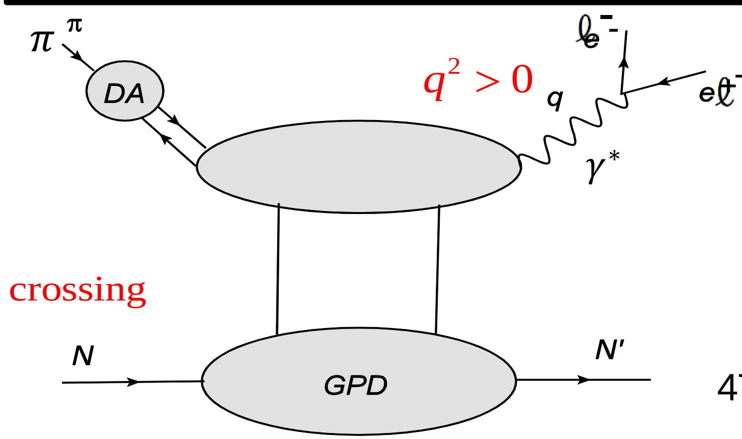
$s \leftrightarrow u$ channel crossing

Ji, PRL 78, 610 (1997); Radyushkin, PLB 380, 417 (1996)

Deeply Virtual Meson Production



Exclusive meson-induced DY

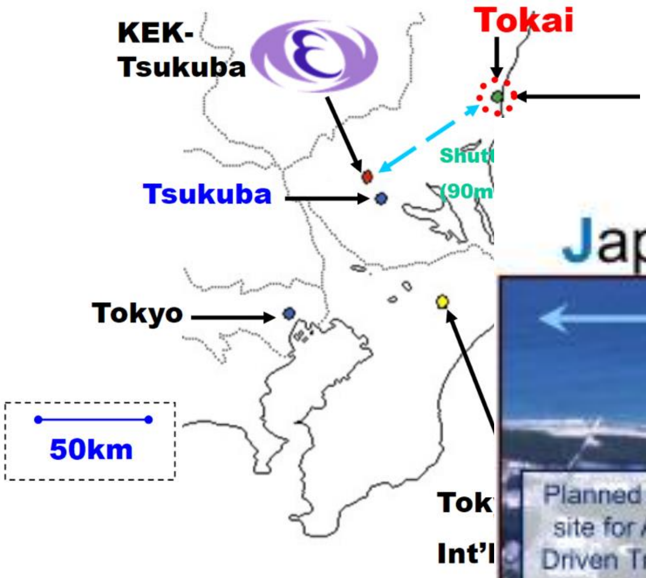


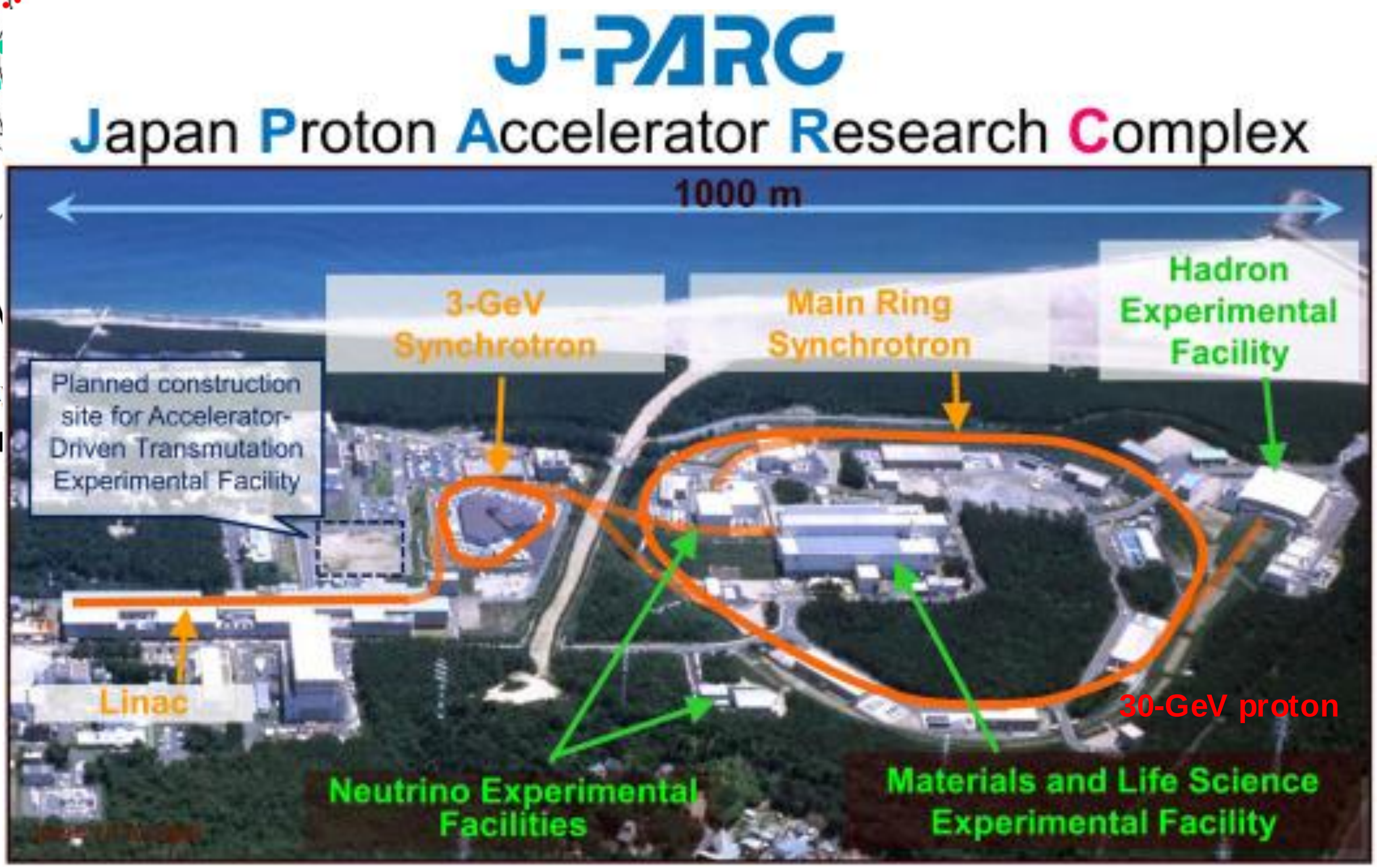
$s \leftrightarrow u$ channel crossing

Collins, Frankfurt and Strikman, PRD 56, 2982 (1997)

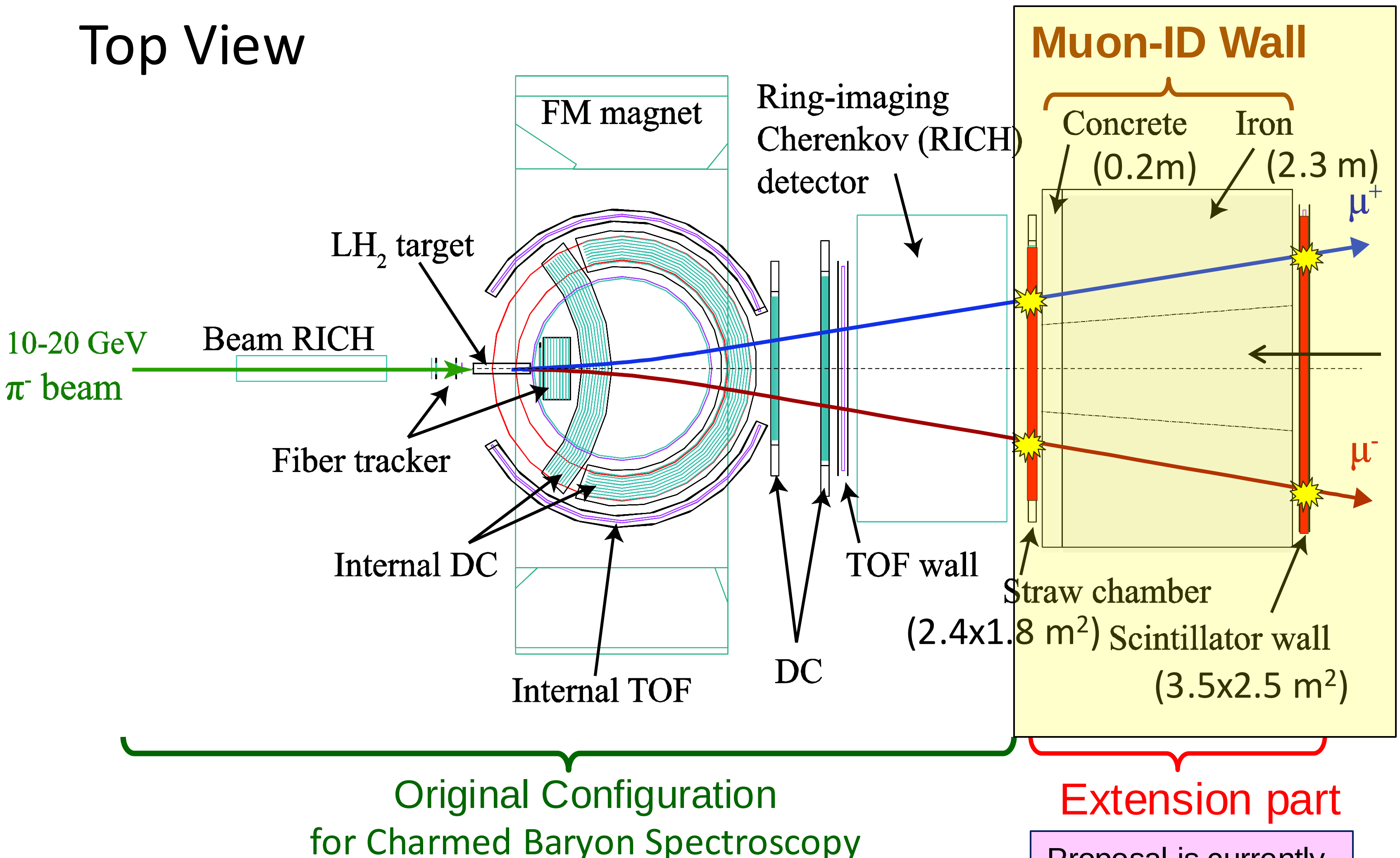
J-PARC

Japan Proton Accelerator Research Complex





Extension of J-PARC E50 Experiment for Drell-Yan measurement



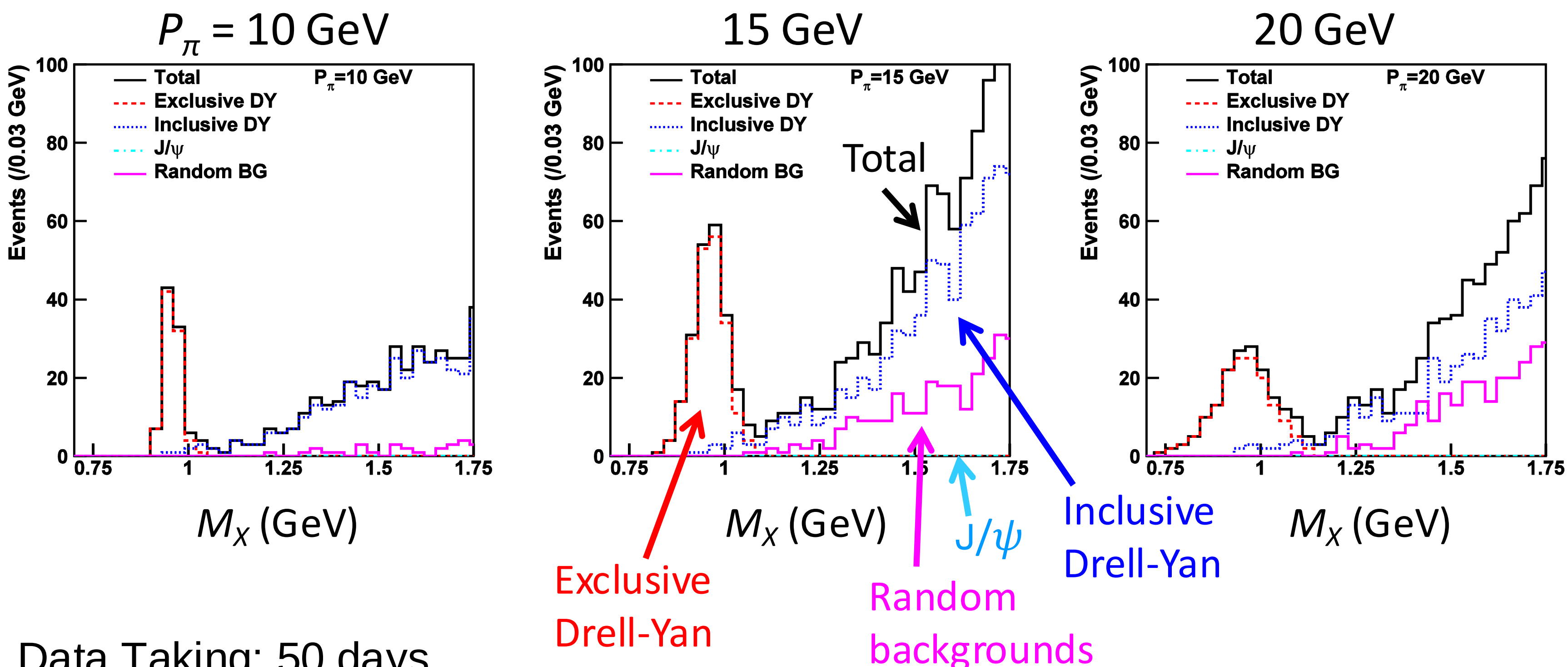
Stage-1 approved by J-PARC PAC-18, August 12, 2014.

Proposal is currently being prepared.

$\pi^- N \rightarrow l^+ l^- X$ Missing-mass M_X

Takahiro Sawada, Wen-Chen Chang, Shunzo Kumano, Jen-Chieh Peng, Shinya Sawada, Kazuhiro Tanaka, PRD 93 (2016) 114034

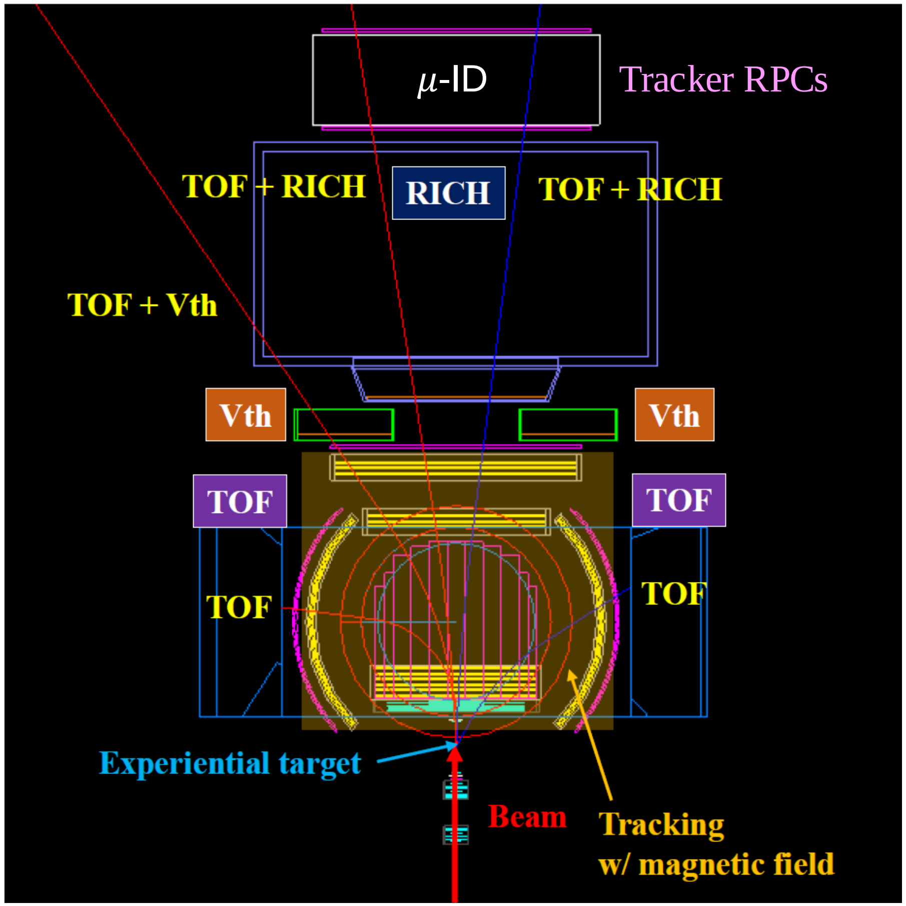
π^- Beam Momentum



- Data Taking: 50 days
- $1.5 < M_{\mu^+\mu^-} < 2.9$ GeV
- $|t - t_0| < 0.5$ GeV^2
- “GK2013” GPDs

The exclusive Drell-Yan events could be identified by the signature peak at the nucleon mass in the missing-mass spectrum for all three pion beam momenta.

Proposal to Complete

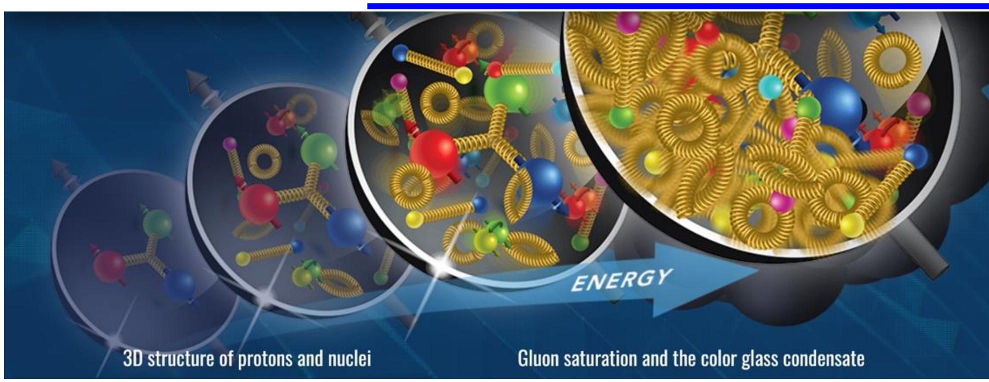


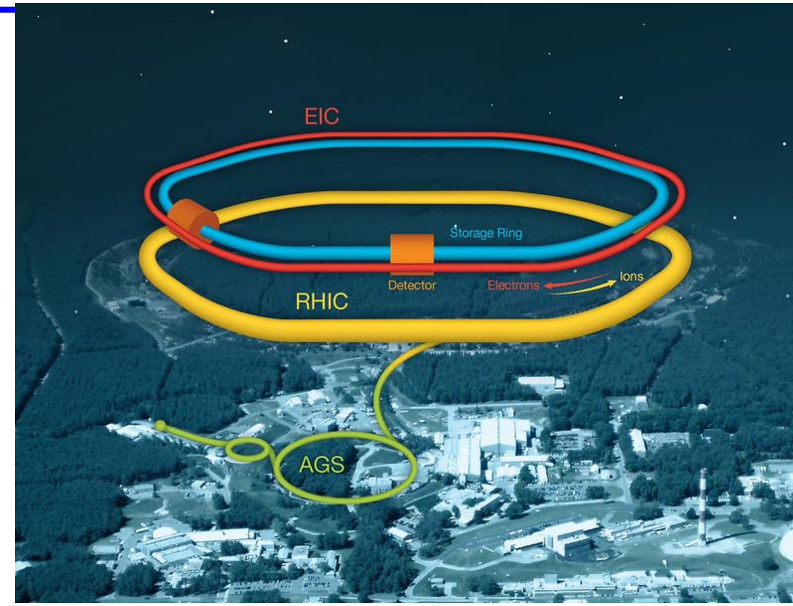
- The μ-ID system:
  - Tracker RPCs: rejection of muons from the decay-in-flight pions and kaons.
  - Material of hadron absorber: concrete and steel
- Updating the GPD modeling.
- Simulate the expected signal-to-background and yields of exclusive DY events.
- Optimize the design of μ-ID system and dimuon trigger.

Commission: **2030** (expected)

Natsuki Tomida (RCNP, Osaka University), ***Takahiro Sawada (***Osaka City University), ***Chia-Yu Hsieh, Po-Ju Lin, Ming-Lee Chu , Wen-Chen Chang (***Academia Sinica)

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





NTU

AS

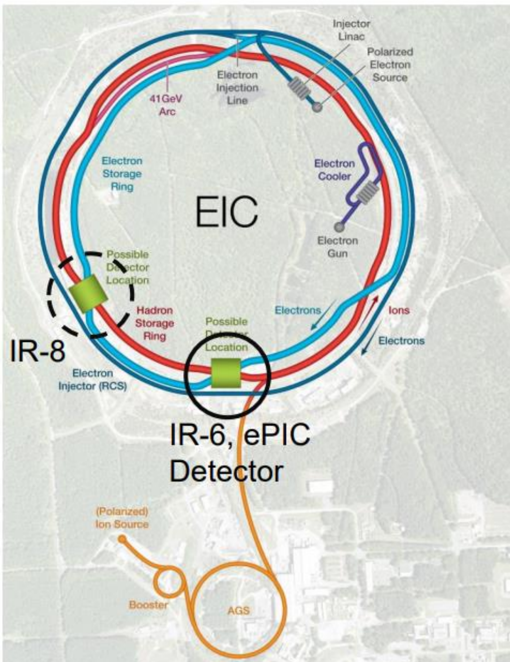
NCU

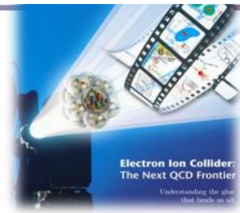
NTHU

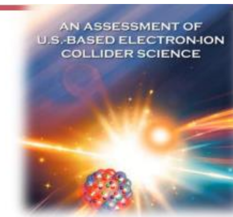
Physics Goals

- 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

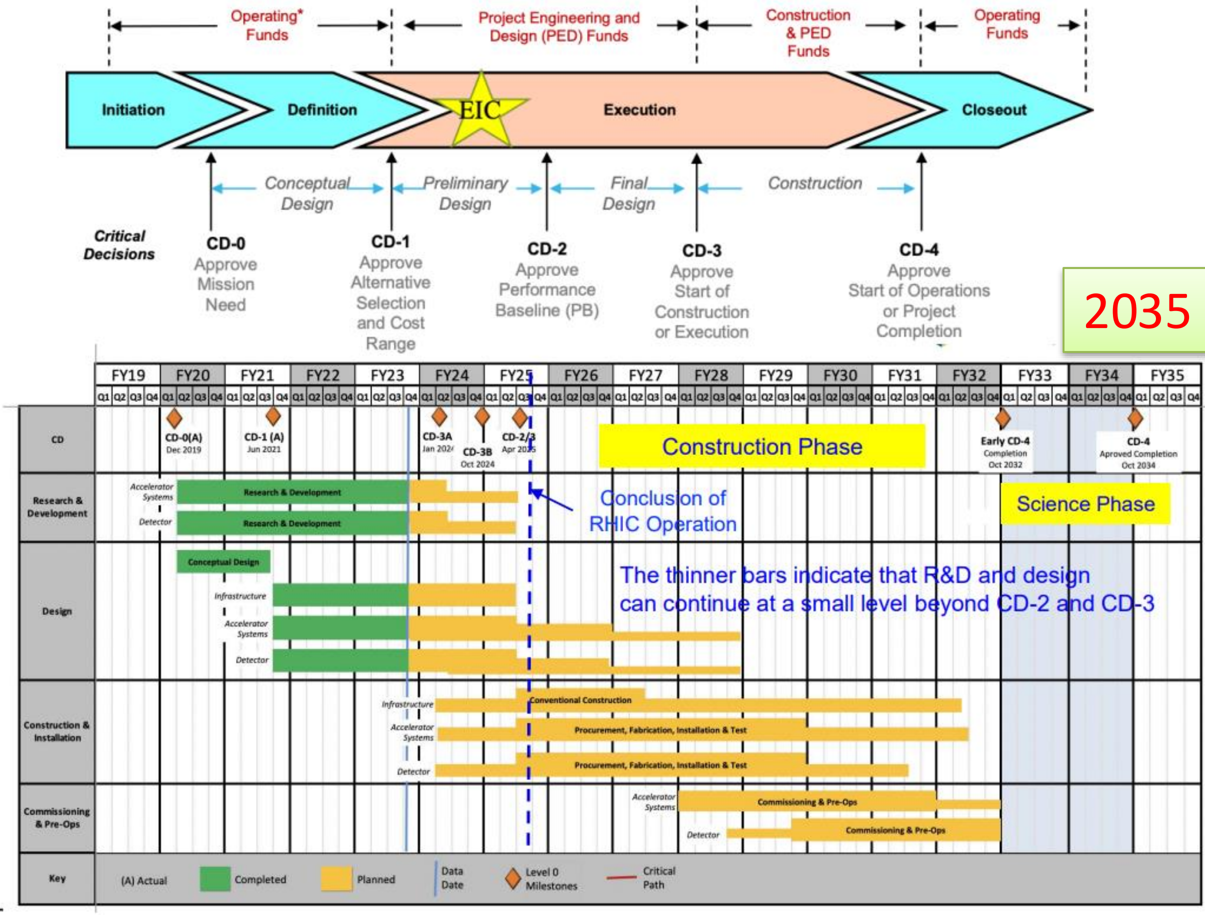
EIC Schedule

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**

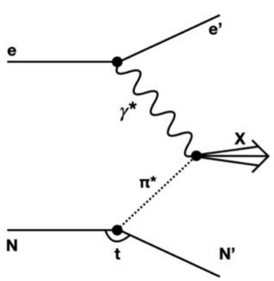
CD-2:
Approve preliminary design for all subdetectors
Design Maturity: >60%
Need "pre-"TDR (or draft TDR)
Baseline project in scope, cost, schedule

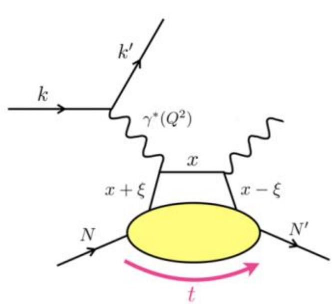
CD-3:
Approve final design for all subdetectors
Design Maturity: ~90%
Need full TDR

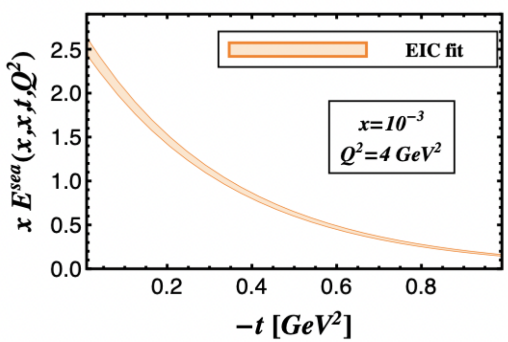


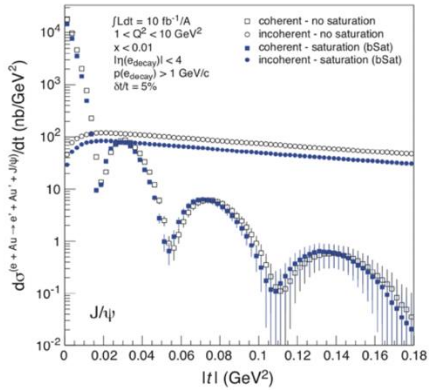
Interests of EIC Physics Programs

- **Pion and Kaon PDFs** (tagged-DIS; Sec. 7.1.3 of YR):
  W.C. Chang, J.W. Chen, C.W. Kao, D. Lin
- **GPDs** (DVCS, TCS, DVMP; Sec. 7.2.2 of YR):
  P.J. Lin, J.W. Chen, C.W. Kao
- **CGC** (di-jet, di-hadron DIS; Sec. 7.3.1 of YR):
  C.M. Kuo, H.N. Li
- **Hard Probe** (jet, heavy quarks; Sec. 7.3.9 of YR):
  Y. Yang









EIC yellow report (YR): https://arxiv.org/abs/2103.05419

EIC Detectors

- Asymmetric beam energies
  - requires an asymmetric detector with electron and hadron endcap
  - tracking, particle identification, EM calorimetry and hadronic
    calorimetry functionality in all directions
  - very compact Detector, Integration will be key
- Imaging science program with protons and nuclei
  - requires specialized detectors integrated in the IR over 80 m
- Momentum resolution for EIC science
  - requires a large bore 2T magnet
    (1.7 T magnet operation point, stretch goal 2T
    that has same geometry as the BaBAR magnet).
- Highest scientific flexibility
  - requires Streaming Readout electronics model

hadronic calorimeters (HCAL)

Solenoidal Magnet

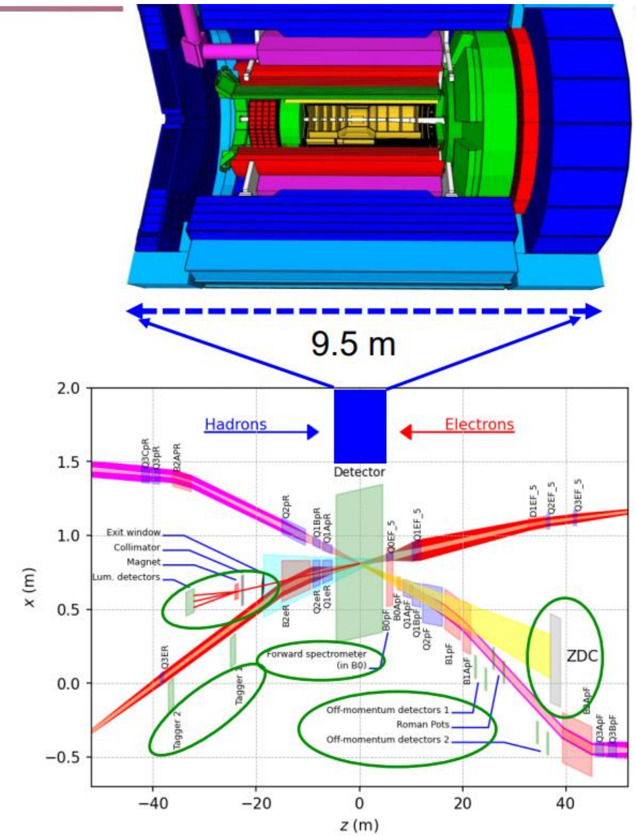
e/m calorimeters (ECal)

Time.of.Flight (ToF), DIRC, RICH detectors

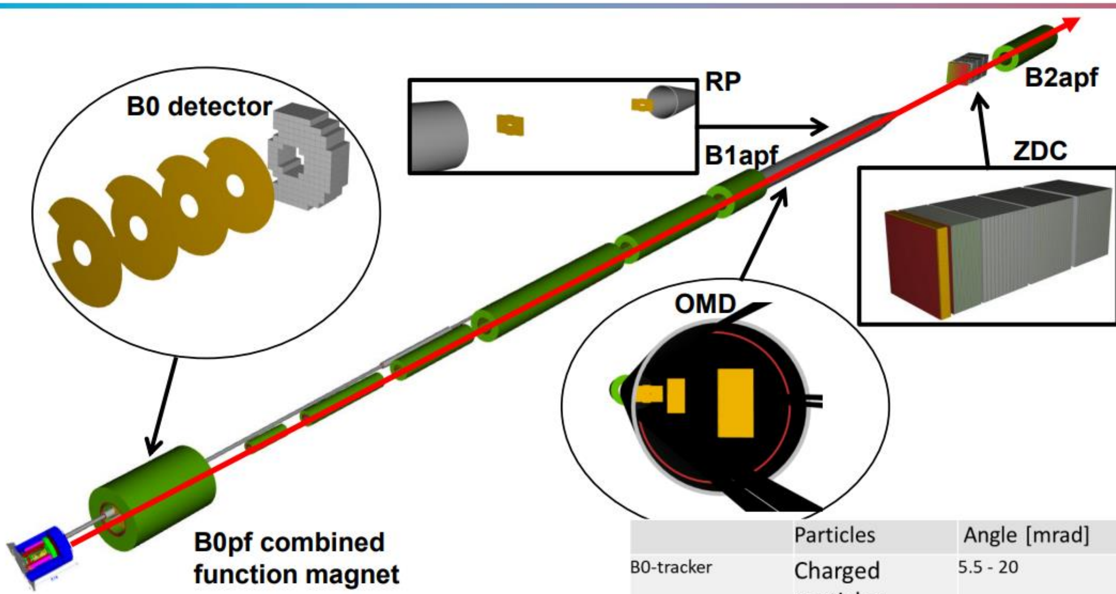
MPGD trackers

MAPS tracker

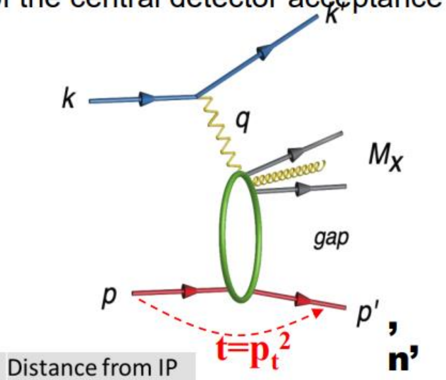
23 Subdetectors incl. Polarimeters + Electronics + Data Acquisition



Far-Forward detectors



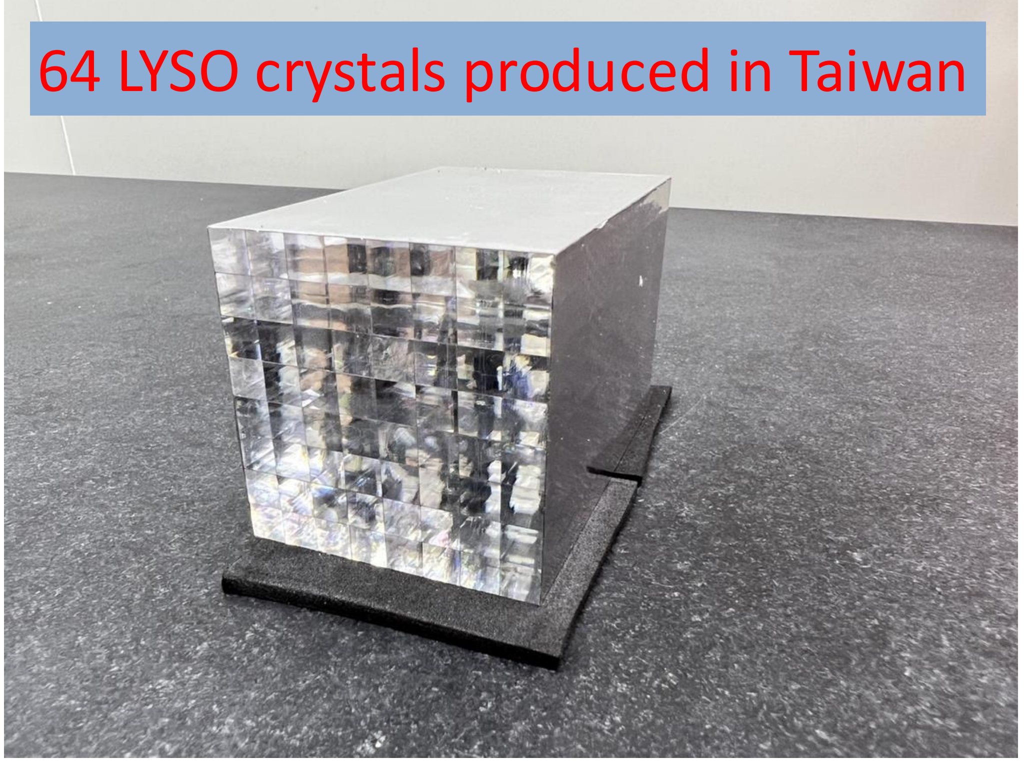
Exclusive /diffractive reactions driving the design of FF area -> reconstruction of particles outside of the central detector acceptance



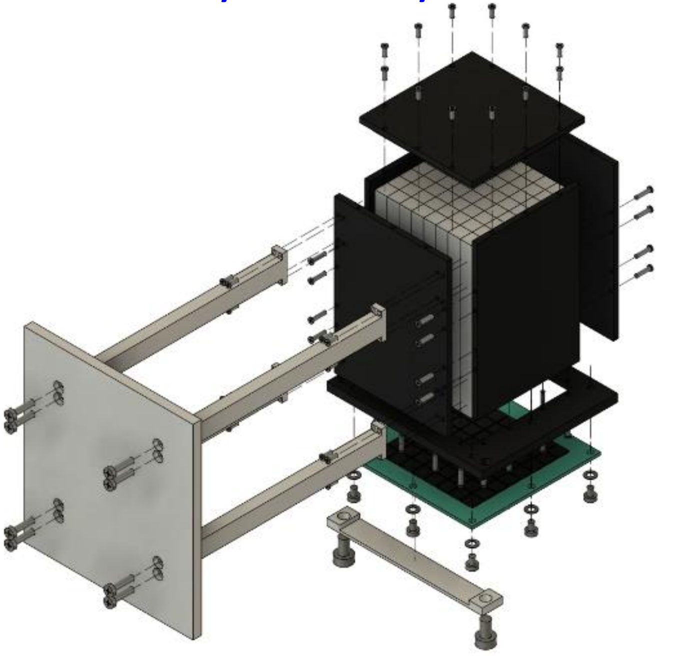
	Particles	Angle [mrad]		Distance from IP
B0-tracker	Charged particles Photons (tagged)	5.5 - 20		ca 6-7 m
Off-momentum	Charged particles	0-5.0	0.4< xL< 0.65	ca 23-25 m
Roman Pots	Protons Light nuclei	0*-5.0	0.6 < xL< 0.95	ca 27-30 m
ZDC	Neutrons Photons	0-4.0 (5.5)		ca 35 m

✓protons at wide range of p_T^2
✓protons with **different rigidity**
✓**neutrons and photons**

ePIC ZDC Prototype with LYSO Crystals (Taiwan, Japan, Korea)



8x8 LYSO crystal array



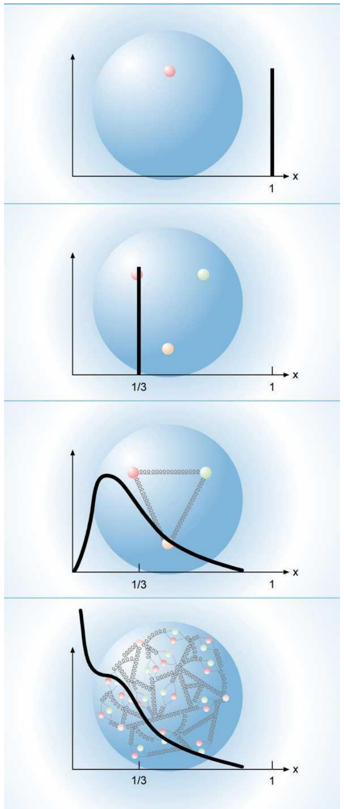
- A beam test at <u>Tohoku University</u> in February 2024 to compare the performance between the LYSO and $PbWO_4$ crystals

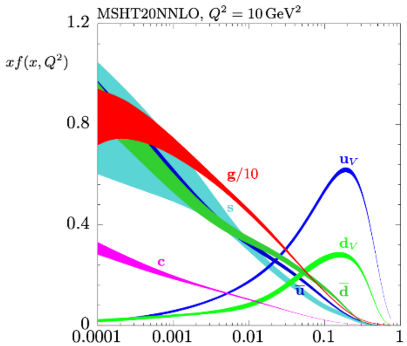
TIDC Autumn School On EIC
(NTU, Aug. 29-31, 2023)

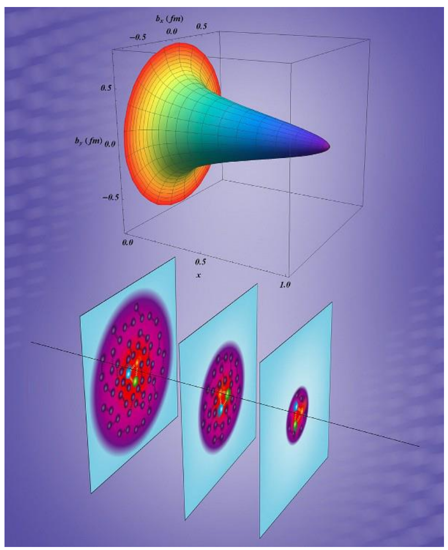
The 3rd EIC-ASIA Workshop

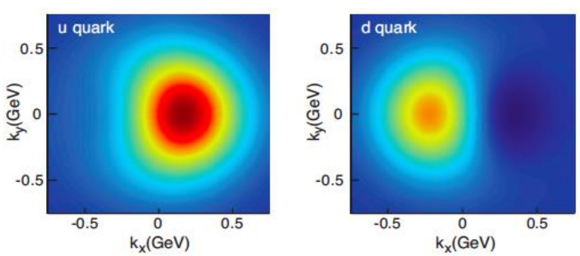
(NCKU, Jan. 29-31, 2024)

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.
- Drell-Yan process has been a powerful approach to extract proton PDFs and TMDs and will be used for GPDs.
- In the coming U.S. EIC, a deeper understanding of the origin of proton’s mass and spin is anticipated.