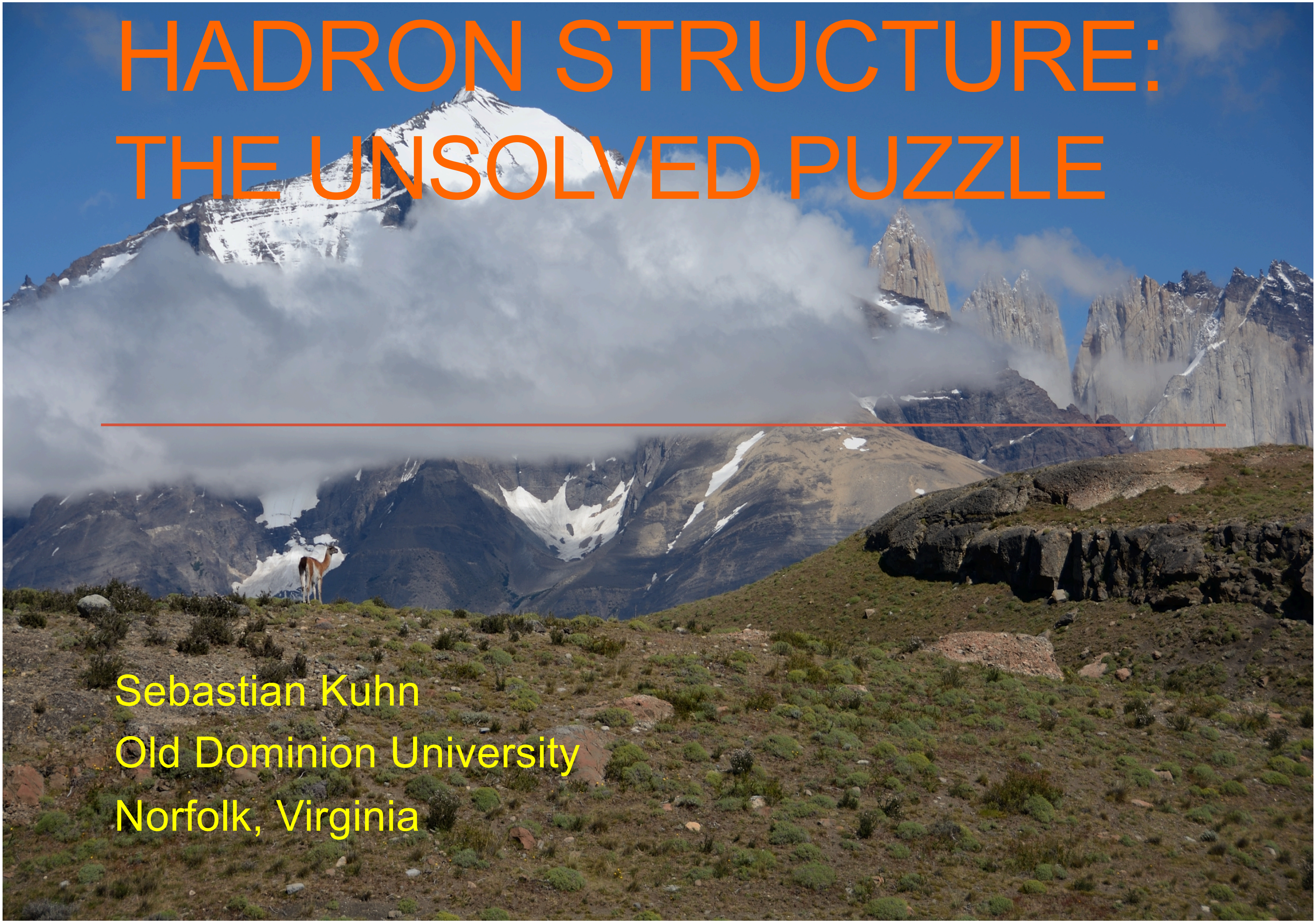

HADRON STRUCTURE: THE UNSOLVED PUZZLE

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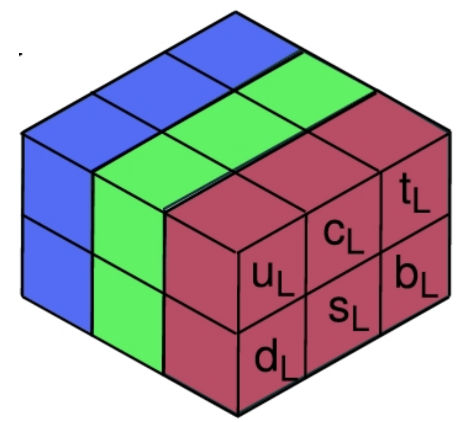
Fundamental Problem of Nuclear and Hadronic Physics

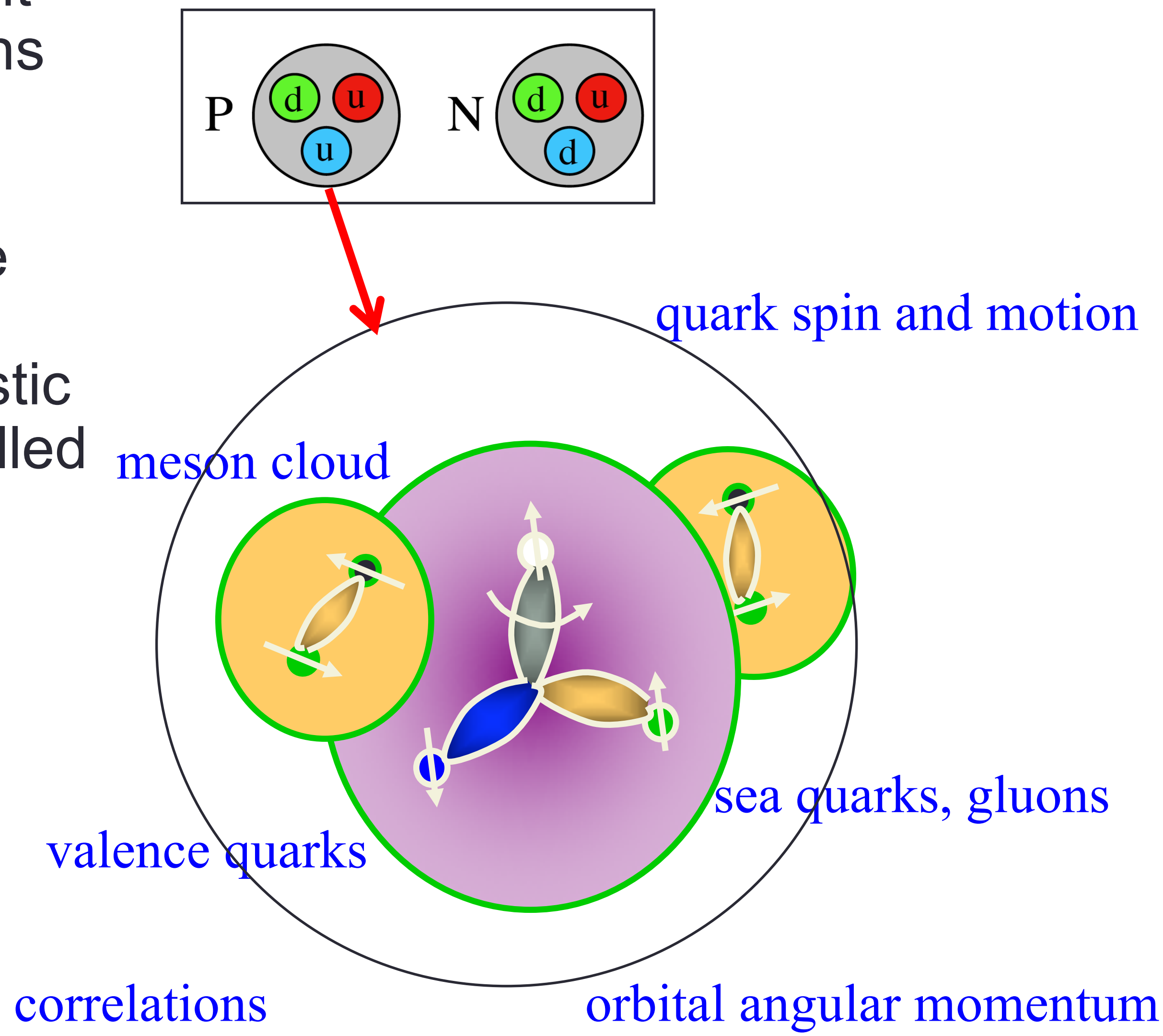
- Nearly all well-known ("visible") mass in the universe is due to hadronic matter
- Fundamental theory of hadronic matter exists since the 1960's: Quantum Chromo Dynamics
  - "Colored" quarks (u,d,c,s,t,b) and gluons; Lagrangian
- BUT: knowing the ingredients doesn't mean we know how to build hadrons and nuclei from them!
  - akin to the question: "Given bricks and mortar, how do you build a house?"



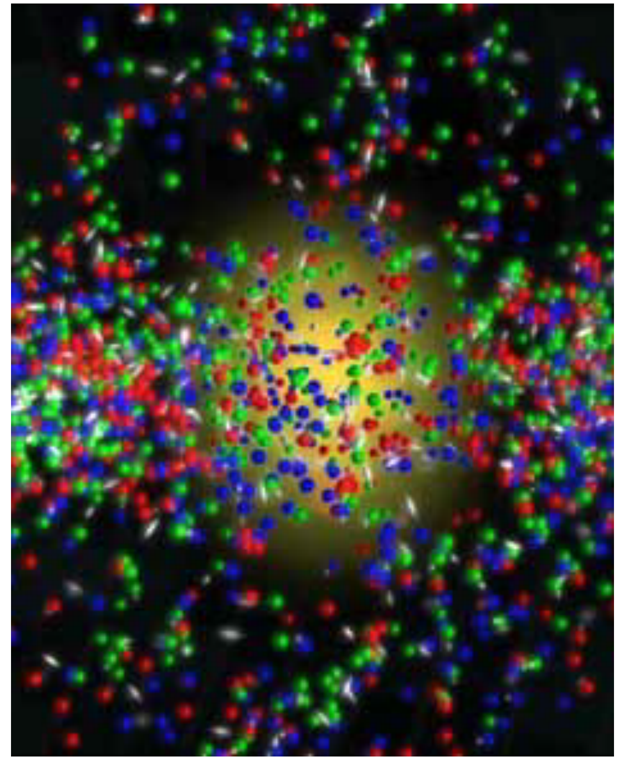
- Four related puzzles:
  - What is the "quark-gluon wave function" of known hadrons?
  - How are hadrons (nucleons) bound into nuclei? Does their quark-gluon wave function change inside a nucleus?
  - How do fast quarks and gluons propagate inside hadronic matter?
  - How do fast quarks and gluons turn back into observable hadrons?

Hadron Structure

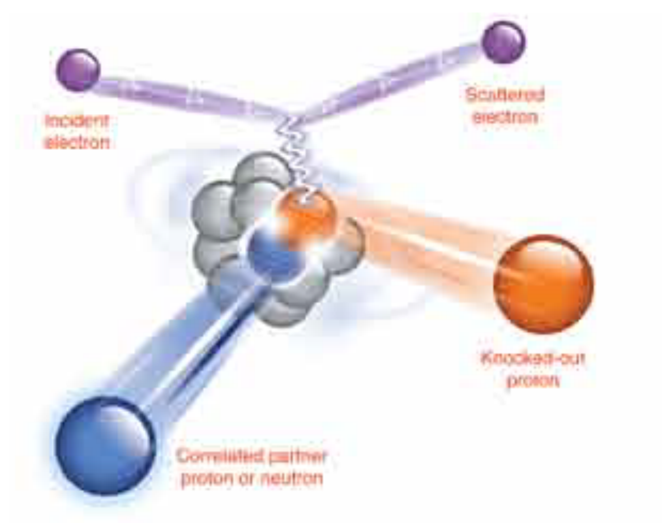
- Simple-most (constituent quark) model of nucleons (protons and neutrons)
- … becomes much more complicated once we consider the full relativistic quantum field theory called QCD
- Effective theories: Quark model, χPT, sum rules, …
- and Lattice QCD!



Nuclear Structure



- Even more complicated!
- Effective degrees of freedom: nucleons, mesons, nucleon resonances… augmented by phenomenological NN potentials
- Effective theories: low-energy EFT, χPT, relativistic and non-relativistic potential models, shell model,…
- and Lattice QCD???

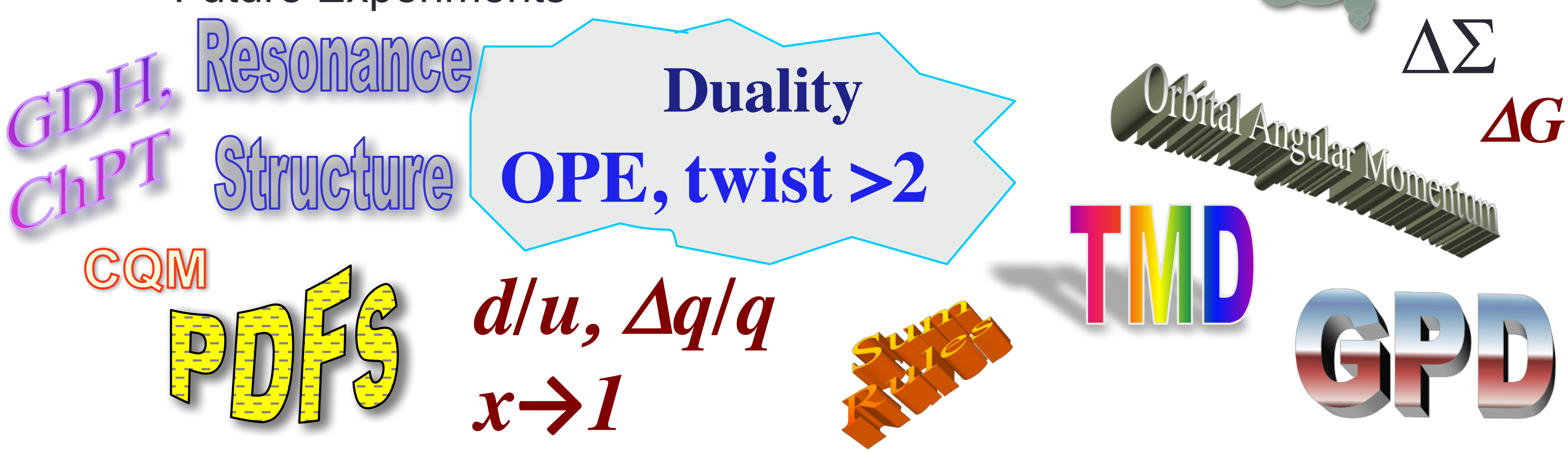


How Do We Study Hadron/Nuclear Structure?

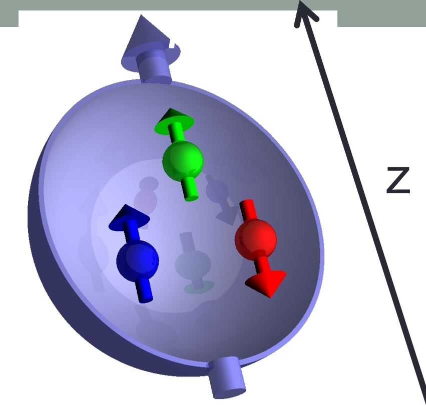
- Energy levels: Nuclear and particle (baryon, meson) masses, excitation spectra, excited state decays ->
  Spectroscopy *(What exists?)*
- Elastic and inelastic scattering, particle production
  Reactions *(Relationships?)*
- Probing the internal structure directly
  Imaging *(Shape and Content?)*
- Particular way to encode this: Structure Functions
  - *"Parton wave function"?*
    5(6)-dim. Wigner distribution ➔ …

Overview

- Partonic Structure of the Nucleon
- Polarized and Unpolarized Structure Functions
- Recent Results
  - Spin-Averaged Structure Functions
  - Spin-Dependent Structure Functions
  - Nuclear Structure Functions
- Outlook
  - From 1D to 3D
  - Future Experiments

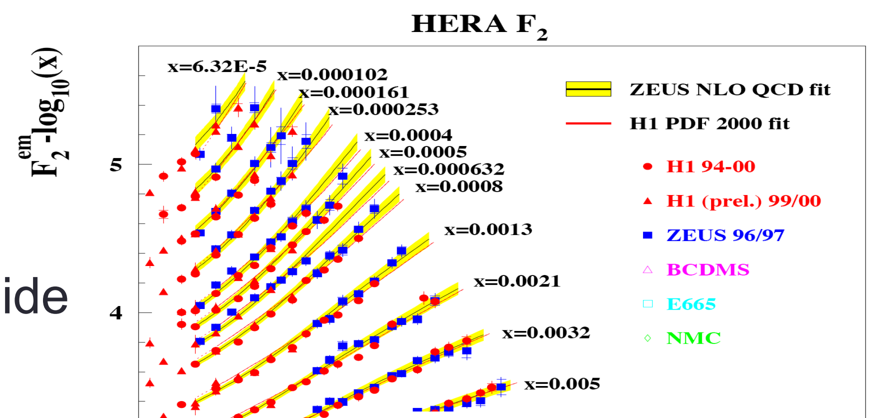


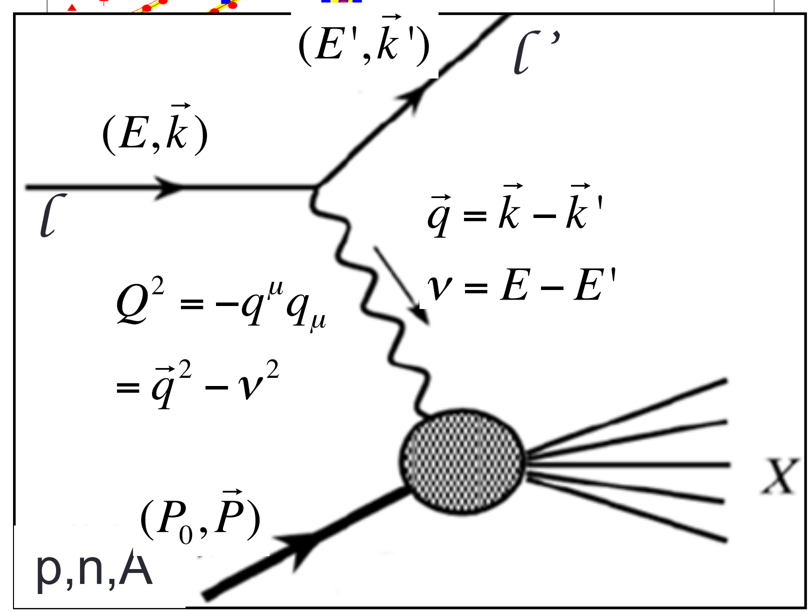
Parton Distribution Functions



- The 1D world of nucleon/nuclear collinear structure:
  - Take a nucleon/nucleus
  - Move it real fast along z
    ⇒ light cone momentum
    $P_+ = P_0 + P_z$ (>>M)
  - Select a "parton" (quark, gluon) inside
  - Measure **its** l.c. momentum
    $p_+ = p_0 + p_z$ (m≈0)
  - ⇒ Momentum Fraction x = p_+/P_+ *)
  - In DIS **): $p_+/P_+ \approx \xi = (q_z - \nu)/M$
    $\approx x_{Bj} = Q^2/2M\nu$
  - Probability: $f_1^i(x), i = u, d, s, \ldots, G$

In the following, will often write "$q_i(x)$" for $f_1^i(x)$

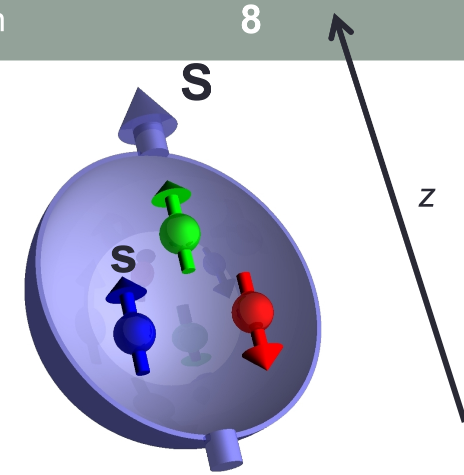




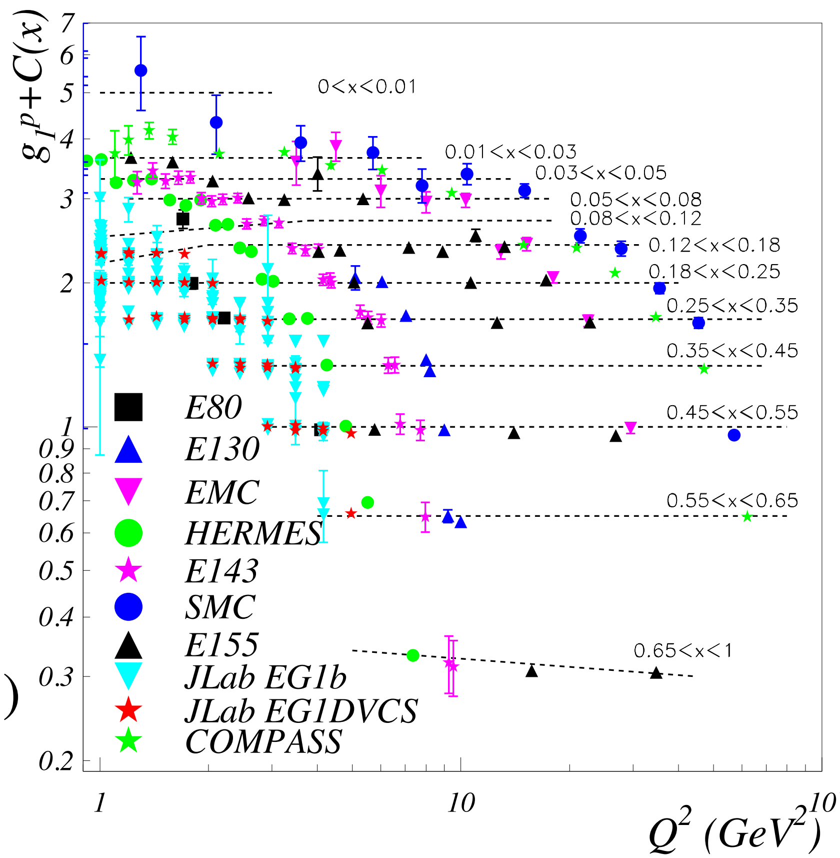
*) Advantage: Boost-independent along *z*

**) DIS = "Deep Inelastic (Lepton) Scattering

Polarized Parton Distribution Functions



- Introduce two more quantities of interest:
  - Proton spin **S**
  - Parton spin **s**
  - Now we have 3 vectors: $\hat{z}, \vec{S}, \vec{s}$
  - **But**: Every observable must be a scalar
  - **And**: Spins are axial vectors!
  - **Finally**: Must treat longitudinal and transverse directions differently (boost)
  - 2 Pseudoscalars: $H = \vec{S} \cdot \hat{z}, h = \vec{s} \cdot \hat{z}$
  - 2 transverse (2D) axial vectors: $\vec{S}_\perp, \vec{s}_\perp$
  - 2nd Structure function



$$g_1^i(x) = \langle hH \rangle q_i(x) \text{ or } \langle hH \rangle G(x) = \Delta q_i(x) \text{ or } \Delta G(x)$$

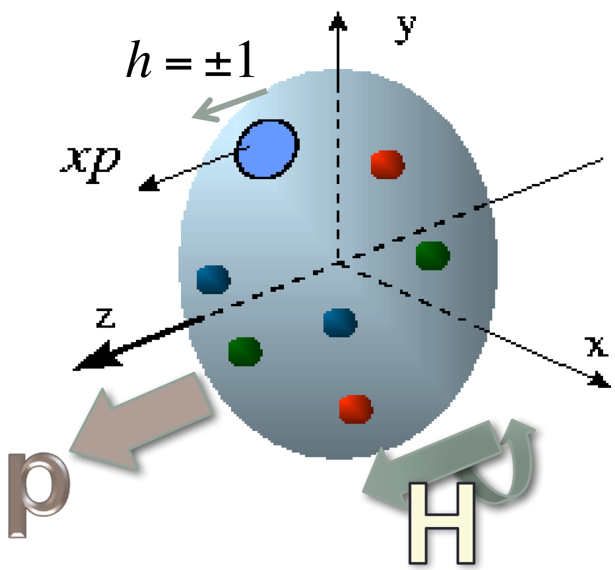
$$\Delta q_i = \quad q \Uparrow\uparrow(x) - q \Uparrow\downarrow(x)$$

Can also form one more scalar: $T = \vec{S}_\perp \cdot \vec{s}_\perp$ (not measurable in DIS) → Transversity $h_1(x)$

Inclusive lepton scattering

Parton model: DIS can access $F_1(x) = \frac{1}{2}\sum_i e_i^2 q_i(x)$ (and $F_2(x) \approx 2xF_1(x)$) — Callan-Gross

$g_1(x) = \frac{1}{2}\sum_i e_i^2 \Delta q_i(x)$ $\left(\text{and } g_2(x) \approx -g_1(x) + \int_x^1 \frac{g_1(y)}{y} dy\right)$ — Wandzura-Wilczek



$q(x;Q^2), \langle h \cdot H \rangle q(x;Q^2)$

Traditional "1-D" Parton Distributions (PDFs)
(integrated over many variables)

At finite Q²: pQCD evolution ($q(x,Q^2)$, $\Delta q(x,Q^2)$ ⇒ DGLAP equations), and gluon radiation

$$g_1(x,Q^2)_{pQCD} = \frac{1}{2}\sum_q^{N_f} e_q^2[(\Delta q + \Delta\bar{q}) \otimes (1 + \frac{\alpha_s(Q^2)}{2\pi}\delta C_q) + \frac{\alpha_s(Q^2)}{2\pi}\Delta G \otimes \frac{\delta C_G}{N_f}]$$

⇒ access to gluons. $\delta C_q, \delta C_G$ – *Wilson* coefficient functions

SIDIS: Tag the flavor of the struck quark with the leading FS hadron ⇒ separate $q_i(x,Q^2)$, $\Delta q_i(x,Q^2)$

Jefferson Lab kinematics: $Q^2 \approx M^2$ ⇒ target mass effects, higher twist contributions and resonance excitations

- Non-zero $R = \frac{F_2}{2xF_1}\left(\frac{4M^2x^2}{Q^2}+1\right)-1$, $g_2^{HT}(x) = g_2(x) - g_2^{WW}(x)$
- Further Q^2-dependence (power series in $\frac{1}{Q^n}$)

⇒ Our 1D View of the Nucleon

(depends on x and the resolution of the virtual photon ~ $1/Q^2$)

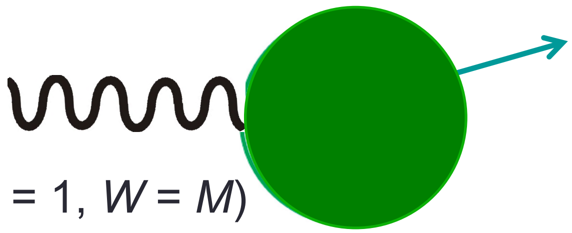
W = final state invariant mass = $\sqrt{M^2 + \left(\frac{1}{x} - 1\right)Q^2}$

Low Q^2:
ChPT
CQM
OPE

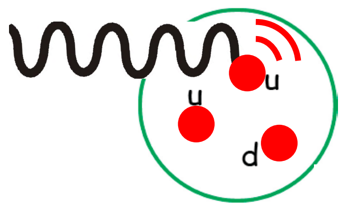
JLab

DIS

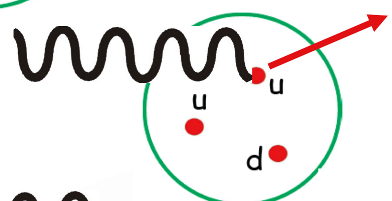
- Elastic scattering
  (Whole system recoils, $x = 1$, $W = M$)



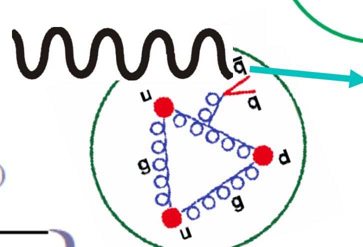
- Resonances
  ($x < 1$, $W < 2$ GeV)



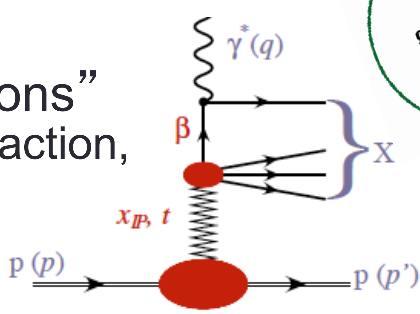
- Valence quarks
  ($x \geq 0.3$, $W > 2$ GeV)

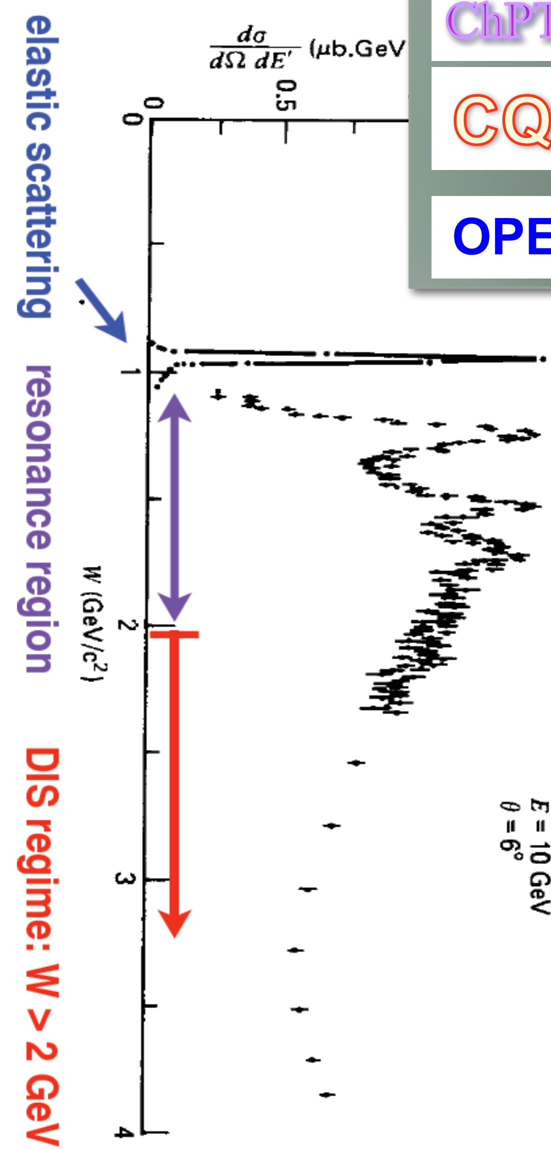


- Sea quarks, gluons
  ($x < 0.3$)

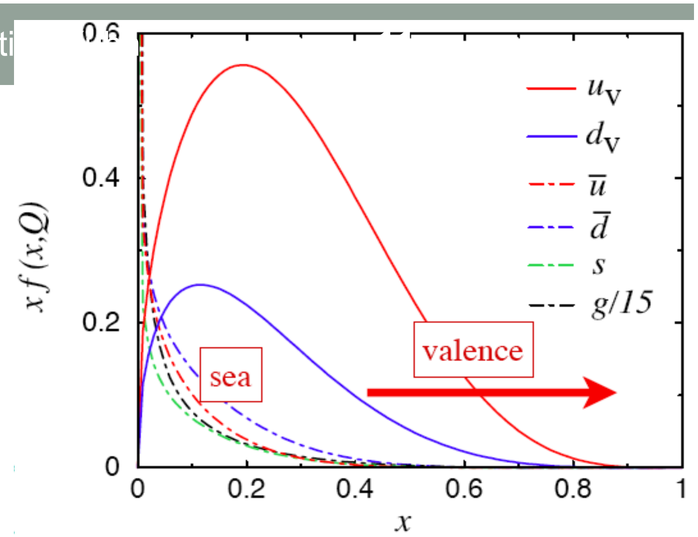


- "Wee Partons"
  ($x \to 0$, Diffraction, Pomerons)

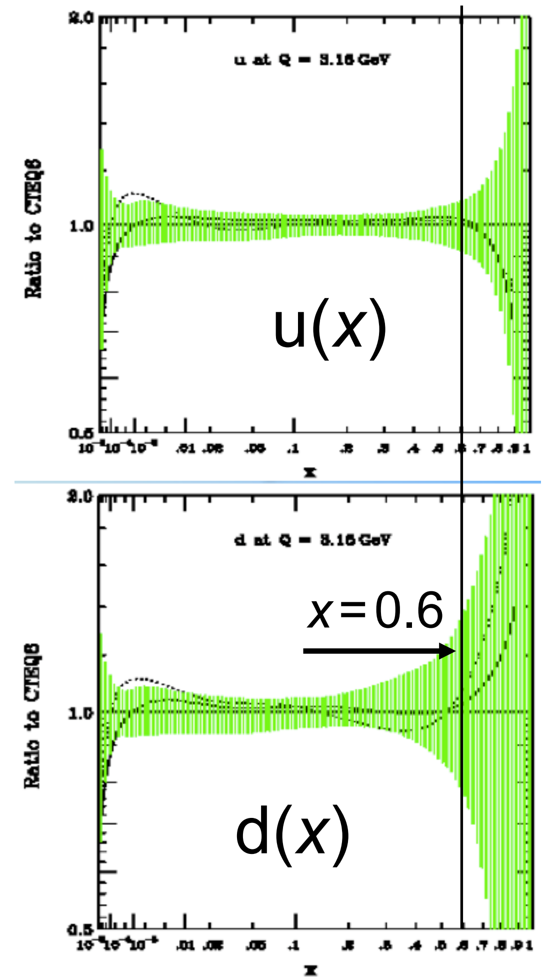




Valence PDFs



- Behavior of PDFs still unknown for $x \to 1$
  - SU(6): d/u = 1/2, Δu/u = 2/3, Δd/d = -1/3 for all x
  - Relativistic Quark model: Δu, Δd reduced
  - Hyperfine effect (1-gluon-exchange): Spectator spin 1 suppressed, d/u → 0, Δu/u → 1, Δd/d → -1/3
  - Helicity conservation: d/u → 1/5, Δu/u → 1, Δd/d → 1
  - Orbital angular momentum: can explain slower convergence to Δd/d → 1
- Plenty of data on proton → mostly constraints on u and Δu
- Knowledge on d limited by lack of free neutron target (nuclear binding effects in d, ^{3}He)
- Large x requires very high luminosity and resolution; binding effects become dominant uncertainty for the neutron



Moments of Structure Functions

Related to matrix elements of local operators (OPE) - in principle accessible to lattice QCD calculations

Sum rules relate moments to the total spin carried by quarks in the nucleon (and β-decay matrix elements), sea quark asymmetries etc.

At low Q^2: Higher Twist, Parton-Hadron Duality, Chiral Perturbation Theory, GDH Sum Rule

Bjorken Sum Rule: $\Gamma_1^p - \Gamma_1^n = \frac{g_A}{6} + \text{ QCD corr.}$

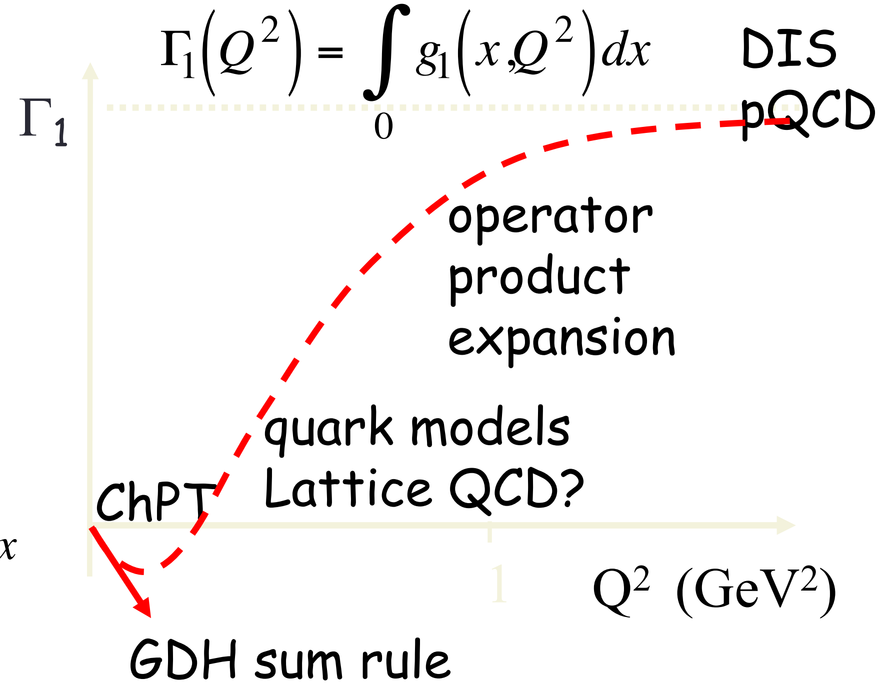
GDH Sum Rule: $\Gamma_1\left(Q^2 \to 0\right) \to -\frac{Q^2}{2M^2}\frac{\kappa^2}{4}$

…and γ_0, δ_{LT}

Gottfried Sum Rule:

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

$$\Gamma_1\left(Q^2\right) = \int_0^1 g_1\left(x,Q^2\right)dx$$



Experimental Facilities