Parton Distributions in Hadrons

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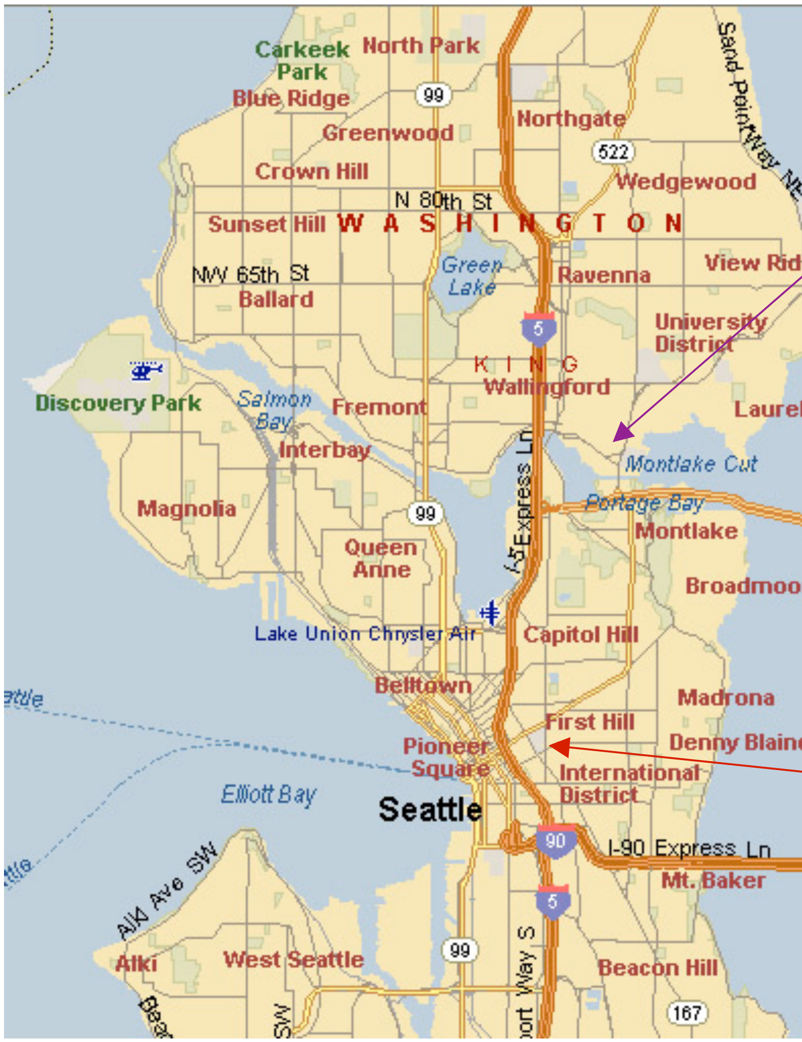
HUGS 2008

Seattle University ≠ University of Washington



University of Washington

– public research university
- ~ 36,000 students
- ~ 60 physics faculty
- ~ 200 undergraduate physics majors

Masters, PhD programs

Institute for Nuclear Theory

Seattle University

– private Jesuit university
- ~ 7,000 students
- 6 physics faculty
- 21 undergraduate physics majors

no graduate physics students

Anacapa Society

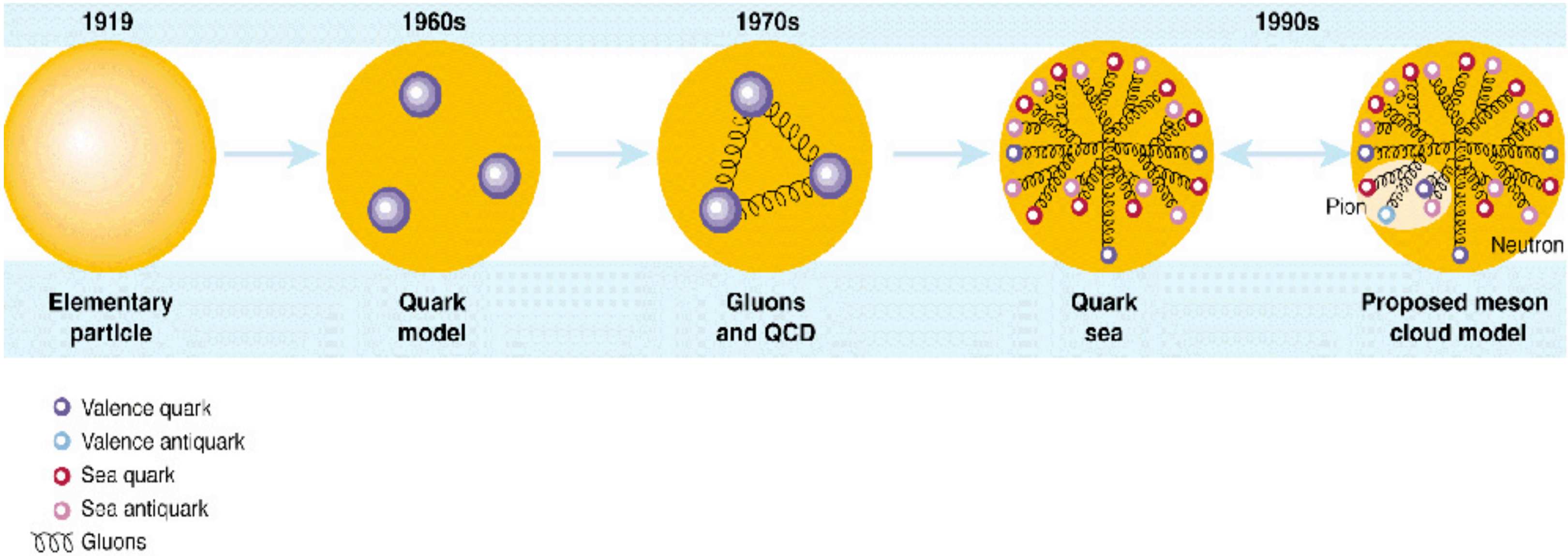
- With support of David Gross, formed last summer at Kavli Institute for Theoretical Physics, UC Santa Barbara
- To promote theoretical and computational physics research at PUI (Primarily Undergraduate Institutions)
- Resources (e.g. KITP Scholars program), mentoring, information on nature of careers at PUI, best preparation for, etc
- Membership (free!) open to grad students, postdocs, faculty in PUI or supportive thereof (e.g. advisors looking for jobs for students or postdocs)
- http://anacapasociety.org

Motivation

- A fundamental challenge for strong interaction physics is to determine how the properties of a hadron arise from its constituents.

- How are energy, momentum, spin and angular momentum distributed among quarks, antiquarks and gluons?

Resolving the proton



"Exploring the Proton Sea", Andrew Watson, Science 283, 472 -474 (1999)

- SLAC experiments analogous to Rutherford's
- Resolution depends on wavelength $\lambda \sim 1/Q$
- Scaling of structure functions $F_1(x,Q^2)$ and $F_2(x,Q^2)$

Feynman's Parton Model

- Infinite momentum frame - use impulse approximation
- Proton constituents are non-interacting, point-like objects
- Virtual photon is absorbed by parton of momentum fraction x

$$F_1(x) = \tfrac{1}{2}\sum_i e_i^2 f_i(x)$$

$$F_2(x) = 2xF_1(x) = x\sum_i e_i^2 f_i(x)$$

in which $f_i(x)$ is the number density of partons of type i which have momentum fraction x.

Structure Functions for nucleons

For the proton, assuming only a light sea:

$$F_2^p(x) = x\left[\tfrac{4}{9}\left(u(x) + \bar{u}(x)\right) + \tfrac{1}{9}\left(d(x) + \bar{d}(x)\right)\right]$$

and for the neutron,

$$F_2^n(x) = x\left[\tfrac{4}{9}\left(d(x) + \bar{d}(x)\right) + \tfrac{1}{9}\left(u(x) + \bar{u}(x)\right)\right],$$

in which charge symmetry has been assumed,

$$u(x) \equiv u^p(x) = d^n(x), \text{ and } d(x) \equiv d^p(x) = u^n(x)$$

Valence distributions:

$$u_v(x) = u(x) - \bar{u}(x) \qquad d_v(x) = d(x) - \bar{d}(x)$$

Evolution

- Radiative corrections due to gluon emission before/after scattering
- Use perturbative QCD to calculate variation of structure functions with Q^2

e.g.

$$F_2^p(x,Q^2) = x\left[\tfrac{4}{9}\left(u(x,Q^2)+\overline{u}(x,Q^2)\right)+\tfrac{1}{9}\left(d(x,Q^2)+\overline{d}(x,Q^2)\right)\right]$$

Use DGLAP equations to determine Q^2 evolution of flavor non-singlet (e.g. valence quark) and singlet (e.g. gluon) distributions.

Sum rules

For the proton, total numbers of valence quarks are fixed

$$\int_0^1 u_v(x,Q^2)dx = \int_0^1 \left[u(x,Q^2) - \bar{u}(x,Q^2) \right] dx = 2$$

$$\int_0^1 d_v(x,Q^2)dx = \int_0^1 \left[d(x,Q^2) - \bar{d}(x,Q^2) \right] dx = 1$$

which leads to the Gross-Llewellyn-Smith and Adler sum rules:

$$\mathrm{S}_{\mathrm{GLS}}\left(Q^2\right) \equiv \int_0^1 \left[u(x,Q^2) - \bar{u}(x,Q^2) + d(x,Q^2) - \bar{d}(x,Q^2) \right] dx = 3,$$

$$\mathrm{S}_{\mathrm{A}}\left(Q^2\right) \equiv \int_0^1 \left[\left(u(x,Q^2) - \bar{u}(x,Q^2) \right) - (d(x,Q^2) - \bar{d}(x,Q^2)) \right] dx = 1$$

Gottfried sum rule

$$S_G(Q^2) = \int_0^1 \left[\left(F_2^p(x,Q^2) - F_2^n(x,Q^2) \right) / x \right] dx$$

$$= \frac{1}{3} - \frac{2}{3} [\bar{d}(x,Q^2) - \bar{u}(x,Q^2)]$$

- If we assume a flavor-symmetric sea, S_G should be 1/3.

- Any violation of this symmetry is due to non-perturbative physics.

Flavor asymmetry

- New Muon Collaboration at CERN - DIS on proton and deuteron targets
- range in x was (0.004, 0.8)
- NMC found 0.235 ± 0.026 at $Q^2 = 4\ \text{GeV}^2$ (1990)

$$\tfrac{2}{3}(\bar{u} - \bar{d}) = -0.098$$

$$\bar{d} - \bar{u} = 0.147$$

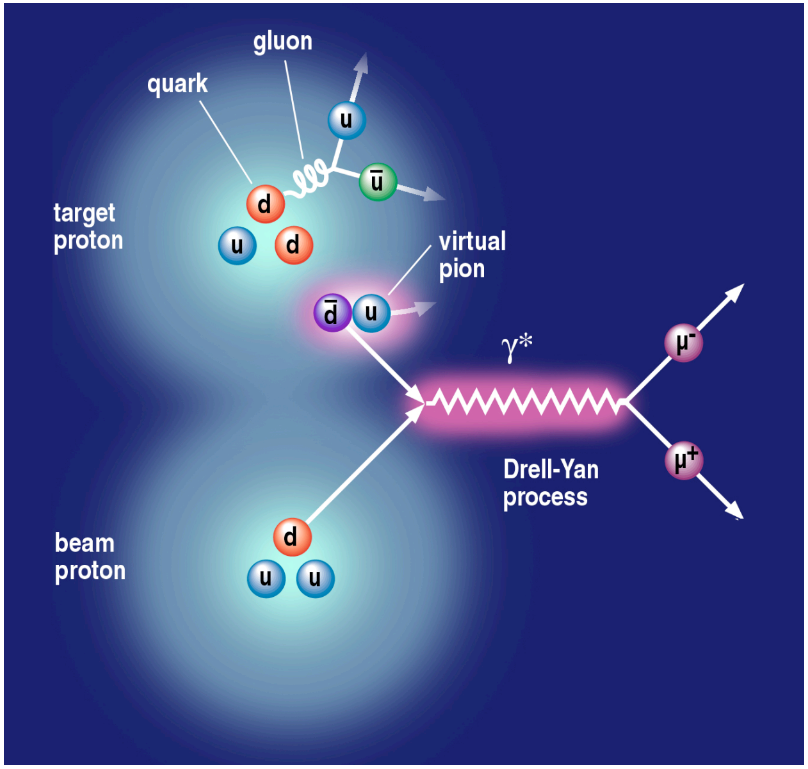
an excess of $d\bar{d}$ pairs in the sea!

Momentum distributions

- Drell-Yan production of $\mu^+\mu^-$ pairs
  - NA51 at CERN (1994) - at $x \sim 0.18$
  - E866/NuSea at Fermilab (1998) - x range (0.02, 0.345)
- Hermes - DIS

Asymmetry is x - dependent

E866 Drell-Yan Experiment

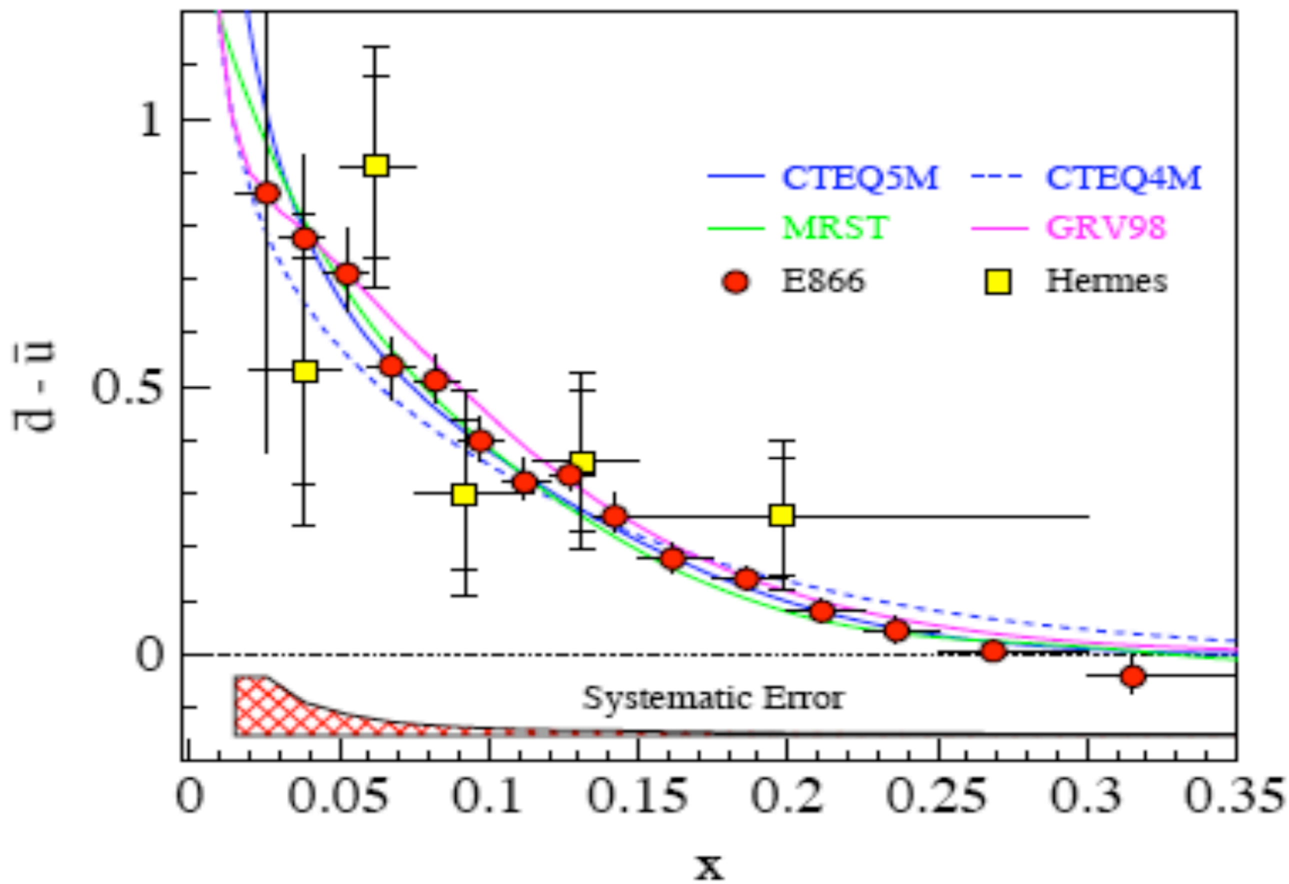


determined $\bar{d}(x), \bar{u}(x)$

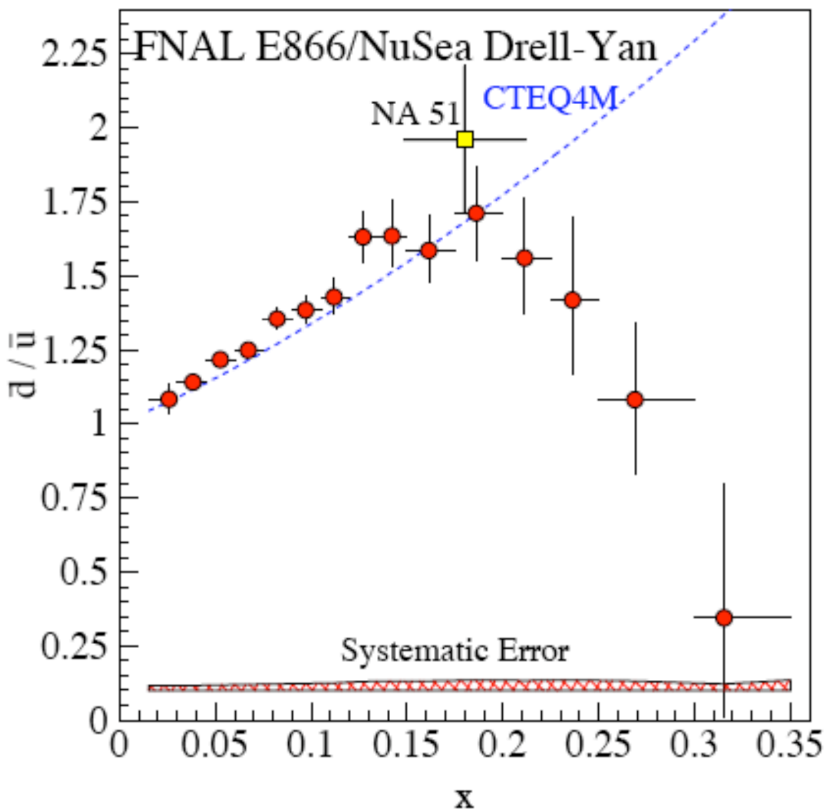
$$\bar{d} = \int_0^1 \bar{d}(x)dx, \quad \bar{u} = \int_0^1 \bar{u}(x)dx$$

$$\bar{d} - \bar{u} = 0.118 \pm 0.012$$

dbar - ubar



Difference decreases with increasing *x*

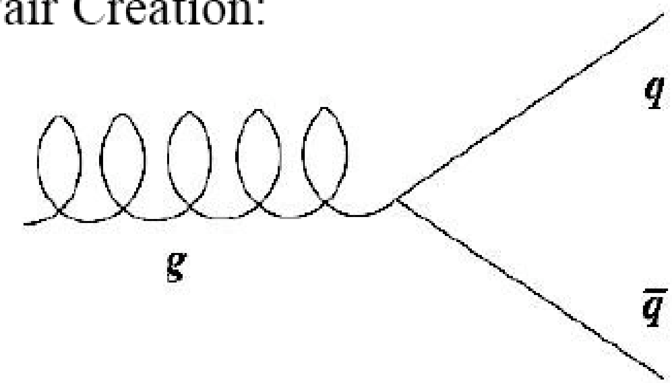


Ratio drops below 1 for $x > 0.3$

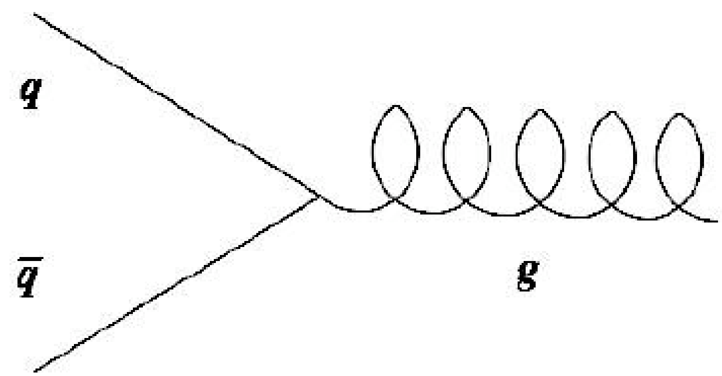
Light sea flavor asymmetry

- Why a surprise? Expect a symmetric light sea
- Gluon splitting is flavor blind
- Mass difference of u, d too small to explain this

Pair Creation:



Pair Annihilation:



On reflection - not a surprise

Field/Feynman - 1977 – Pauli exclusion principle suppresses uubar creation relative to ddbar

Thomas – importance of pion cloud

$p(uud) \rightarrow n(udd) + \pi^{+}(u\bar{d})$ creates an excess of $\bar{d}$ over $\bar{u}$

Models

- Not QCD - but "QCD-inspired"
  - Meson cloud
  - Statistical
- Will discuss these two in detail

Motivation

- Accessible to undergraduates
- Heuristic - helpful in understanding asymmetries
- Incorporate pion - essential for nucleon structure and interactions

Meson-Baryon Model

The wave function of the proton is written in terms of a Fock State expansion

$$| p\rangle = \sqrt{Z}\, | p\rangle_{\mathrm{bare}} + \sum_{MB} \int dy\, d^2\vec{k}_\perp\, \phi_{BM}(y, k_\perp^2)\, | B(y, \vec{k}_\perp) M(1-y, -\vec{k}_\perp)\rangle$$

Here Z is a wavefunction renormalization constant, $\phi_{BM}(y, k_\perp^2)$ is the probability amplitude for finding a physical nucleon in a state consisting of a baryon, B with longitudinal momentum fraction y and meson M of momentum fraction (1-y) and squared transverse relative momentum $k_\perp^2$.

For a review, see Speth and Thomas (1997)

Distribution functions

Bare distribution + contribution from meson-baryon splitting

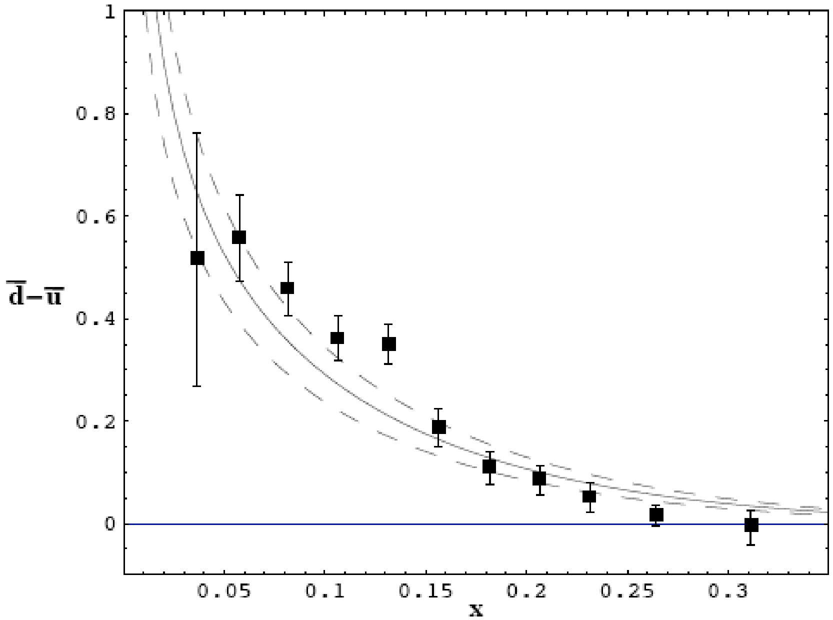
$$q(x) = q^{\mathrm{bare}}(x) + \delta q(x) \ ,$$

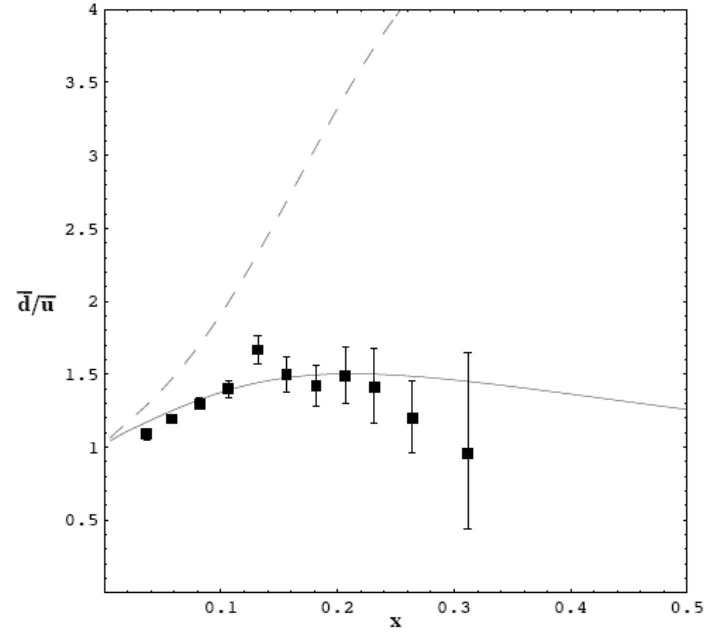
$$\delta q(x) = \sum_{MB} \left(\int_x^1 f_{MB}(y) q_M(\frac{x}{y}) \frac{dy}{y} + \int_x^1 f_{BM}(y) q_B(\frac{x}{y}) \frac{dy}{y} \right) ,$$

$$f_{MB}(y) = f_{BM}(1-y) \ ,$$

$$f_{BM}(y) = \int_0^\infty \mid \phi_{BM}(y, k_\perp^2) \mid^2 \ d^2 k_\perp \ .$$

Role of ω





difference fit well by many models

ω, an isoscalar, has no effect

fit to ratio improved by including ω in Fock state expansion