Intrinsic Quark Distributions in the Nucleon

- Intrinsic vs. Extrinsic Sea Quark Distributions
- Contributions to quark distributions, structure functions
  emphasis on qualitative features of quark PDFs
- Asymmetries for intrinsic strange quarks
- Experimental challenges for theory

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With Tim Hobbs (IU), Wally Melnitchouk (Jlab)
**Intrinsic vs. Extrinsic** Sources of Sea Quarks

Sea quarks in nucleon arise through 2 different mechanisms:

- **Extrinsic**: arises from gluon radiation to q-qb pairs
  - included in QCD evolution
  - strongly peaked at low x; grows with $Q^2$
  - extrinsic sea quarks require $q = \bar{q}\ast$

* asymmetries (very small, low-x) arise at NNLO order
Intrinsic vs. Extrinsic Sources of Sea Quarks

- **Intrinsic**: arises from $4q + q\bar{q}$ fluctuations of N Fock state

- at starting scale, peaked at intermediate $x$; more “valence-like” than extrinsic

- in general, $q \neq q\bar{q}$ for intrinsic sea

- intrinsic parton distributions move to lower $x$ under QCD evolution
**A Simple Model for Intrinsic Sea Quarks:**

**BHPS**: in IMF, transition probability for p to 5-quark state involves energy denominator of the form:

\[
P(p \to uudQ\bar{Q}) \sim \left[ M^2 - \sum_{i=1}^{5} \frac{k_i^2 + m_i^2}{x_i} \right]^{-2}
\]

For charm quarks, neglect \( k_T \) and assume the charm mass \( \gg \) any other mass scale. Then obtain analytic expression for probability of charm quark:

\[
P(x_5) = \frac{N x_5^2}{2} \left[ \frac{(1 - x_5)}{3} (1 + 10x_5 + x_5^2) + 2x_5(1 + x_5) \ln(x_5) \right]
\]

BHPS Model for Intrinsic Sea Quarks:

Sea quark PDFs peak at relatively large $x$ values.
Normalize to overall quark probability.
BHPS approximation guarantees $c = c_{\text{bar}}$.

Can calculate for any quark flavor (use Monte Carlo integration)*

"valence-like" PDF at starting scale ($Q \sim m_c$); moves in to smaller $x$ with increasing $Q^2$ through QCD evolution.

Brodsky, Hoyer, Peterson & Sakai, PL B93, 451 (1980)

Expand “bare” 3-quark valence state of nucleon to include multi-quark states. These will contribute to parton distribution functions, structure functions

\[
|p\rangle = \sqrt{Z} |p\rangle_{bare} + \sum |uudQ\bar{Q}\rangle + \ldots
\]

“Meson-baryon” models: expand nucleon state in a series of meson-baryon states that include the most important sources of intrinsic quarks:

\[
|N\rangle = \sqrt{Z} |N\rangle_0 + \sum_{M,B} \int dy \, d^2k_\perp \phi_{MB}(y, k_\perp^2) |M(y, k_\perp); B(1 - y, -k_\perp)\rangle
\]

 Contribution of a meson-baryon state to parton dist’n function = convolution of splitting function with quark probability in hadron

\[
f_{MB}(y) = \int_0^\infty d^2k_\perp |\phi_{MB}(y, k_\perp^2)|^2
\]

\[
\delta \bar{q}_M = f_{MB} \otimes \bar{q}_M
\]
Meson-baryon states contribute to the parton distribution function and structure function for a particular quark flavor $q_i$.

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

\[
\delta F_2(x) = \int_x^1 dy f_{MB}(y) F_2^M \left( \frac{x}{y} \right) + \int_x^1 dy f_{BM}(y) F_2^B \left( \frac{x}{y} \right)
\]
The Splitting Function in Meson-Baryon Models

The splitting function $f_{MB}$ for nucleon to state with meson $M$, baryon $B$ is related to the wave function $\phi_{MB}$ by

$$f_{MB}(y) = \int d^2k_\perp |\phi_{MB}(y, m^2_\perp)|^2$$

Calculate in the infinite-momentum frame (IMF), where the wave function is given by

$$\phi_{MB}(y, k^2_\perp) = \frac{1}{2\pi \sqrt{y(1-y)}} \frac{V_\infty(y, k^2_\perp) F(s)}{m^2_N - s_{MB}}$$

Here $V_\infty$ is the N-MB coupling, $F(s)$ is a form factor to damp out contributions from very large energies, and $s_{MB}$ is the energy in the IMF

$$s_{MB} = \frac{k^2_\perp + m^2_M}{y} + \frac{k^2_\perp + m^2_B}{1-y}$$

E.g., $V_\infty$ for $N \rightarrow N\pi$,

$$V_\infty(y, k^2_\perp) = \bar{\psi}^N(k') i\gamma_5 \phi_\pi(k) \psi^N(p)$$
Quark Distribution in a Meson or Baryon

To obtain the meson-baryon contribution, we need the quark distribution in a meson or baryon. Also working in the IMF, we obtain the quark distribution in a meson, e.g., $D^- = \bar{c}d$

$$\bar{c}(z) = \int dk_\perp^2 \frac{|V_{\bar{c}d}(z, k_\perp^2)|^2 F(s)^2}{4\pi^2 z(1 - z)(m_D^2 - s_{\bar{c}d})^2}$$

where the energy $s_{\bar{c}d}$ is given by

$$s_{\bar{c}d} = \frac{m_c^2 + k_\perp^2}{z} + \frac{m_d^2 + k_\perp^2}{1 - z}$$

The charm distribution will be strongly peaked at $z \sim \frac{m_c}{m_c + m_d}$

We use an analogous argument for the $c$ distribution in $\Lambda_c^+ = (udc)$

In a quark-diquark picture the $c$ distribution should peak at

$$z = \frac{m_c}{m_c + m_d}$$

where $m_d$ is the diquark mass
Examples: Charm, Anticharm Distributions in Hadrons

Calculations of charm distributions in hadrons by Pumplin, who used point-like vertices. Left: $\bar{c}$ in $D^{-} = (\bar{c}d)$. Right: $c$ in $\Lambda_{c}^{+} = (udc)$. The $\bar{c}$ distribution is harder than the $c$ distribution because the $\bar{c}$ is a larger fraction of the $D$ mass than the $c$ quark is of the $\Lambda_{c}$.

Peak shifts and broadening occur when hadron internal structure is included; this approximation works best for heavy quarks (a bad approximation for pion-cloud).

J. Pumplin, PR D73, 114015 (2006)
Constraints on Meson-Baryon Models:

Meson-baryon models must satisfy constraints that reflect conservation of charge and momentum. A first and obvious constraint is:

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

If a proton splits into a meson + baryon and the meson carries momentum fraction $y$, then baryon must carry momentum fraction $1 - y$. Integrating the splitting function over $y$ gives the charge conservation constraint,

$$\langle n \rangle_{MB} = \langle n \rangle_{BM}; \quad \langle n \rangle_{MB} = \int_{0}^{1} f_{MB}(y) dy$$

The momentum conservation constraint is obtained by multiplying the splitting functions by $y$ and integrating over $y$,

$$\langle y \rangle_{MB} + \langle y \rangle_{BM} = \langle n \rangle_{MB}; \quad \langle y \rangle_{MB} = \int_{0}^{1} f_{MB}(y) y dy$$

Use of IMF kinematics and form factors depending on energy help to ensure that these constraints are satisfied.
Intrinsic Quark-Antiquark Asymmetries

- Meson-baryon models typically produce intrinsic parton distributions with $q_i \neq \bar{q}_i$.

- What is the expected shape of $s(x), \bar{s}(x)$ distributions, and what is the strange quark asymmetry?

- How do calculated $s$ quark asymmetries compare with those extracted from global fits?

Assume meson-baryon state $p \rightarrow \Lambda \bar{K}$.

Then $\delta s(x) = f_{\Lambda K} \otimes s_\Lambda$; $\delta \bar{s}(x) = f_{K \Lambda} \otimes \bar{s}_K$.

Quark distributions will depend on splitting functions $f_{\Lambda K}(y) = f_{K \Lambda}(1 - y)$, and quark distributions in hadrons, $s_\Lambda(y)$ and $\bar{s}_K(y)$.
Intrinsic s Quarks: light-cone model of Brodsky & Ma

\[ f_{K\Lambda}(y) = \int dk_\perp^2 |\phi_{K\Lambda}(y, k_\perp^2)|^2 \]

\[ s_\Lambda(y) = \int dk_\perp^2 |\phi_{\Lambda/s}(y, k_\perp^2)|^2 \]

Brodsky-Ma assumed light-cone wave functions for splitting functions

\[ \phi_{p/K\Lambda}(y, k_\perp^2) = \exp \left[ -\frac{s_{K\Lambda}}{\Lambda^2} \right] \]

\[ s_{K\Lambda} = \frac{m_K^2 + k_\perp^2}{y} + \frac{m_\Lambda^2 + k_\perp^2}{1 - y}; \]

\[ \phi_{\Lambda/s}(y, k_\perp^2) = \exp \left[ -\frac{s_{sd}}{\Lambda^{'2}} \right] \]

\[ s_{sd} = \frac{m_s^2 + k_\perp^2}{y} + \frac{m_d^2 + k_\perp^2}{1 - y} \]

With these assumptions, \( f_{p/K\Lambda}(y) \) and \( s_\Lambda(y) \) can be calculated analytically.

S. Brodsky and B-Q Ma, Phys. Lett \textbf{B381}, 317 (1996)
Strange Quark Distributions: Brodsky-Ma

hadronic SFs

parton-level SFs

intrinsic PDFs

\[ \delta s = f_{\Lambda K} \otimes s_\Lambda; \quad \delta \bar{s} = f_{K\Lambda} \otimes \bar{s}_K \]

Splitting functions \( f_{\Lambda K}(x) = f_{K\Lambda}(1-x) \)

Convolution with strange parton distribution inside hadron to get intrinsic quark parton distributions

\( s_\Lambda(x) \) is harder than \( s_\Lambda(x) \), but light-cone splitting function \( f_{\Lambda K} \) is much harder than \( f_{K\Lambda} \), resulting in \( s(x) \) substantially harder than \( sbar(x) \).
Intrinsic Strange Quarks, meson-baryon model

Qualitative similarity with Brodsky-Ma calculation, however in the meson-baryon model the asymmetry in the splitting functions $f_{\Lambda K}$ and $f_{K\Lambda}$ is smaller than Brodsky-Ma. As a consequence, $s_{\Lambda}(x)$ is slightly harder than $s(x)$ in the MBM.

Hobbs/JTL/Melnitchouk, unpublished
Strange Quarks in the Proton

Extracted $x(s + s\bar{b})$ from SIDIS involving charged K photo-production
- measured $0.02 \leq x \leq 0.5$, $Q^2 = 2.5$ GeV$^2$
- values of $s$ have striking feature:
  - sharp transition in shape at $x \sim 0.1$
- Chang-Peng: assume distribution is extrinsic for $x \leq 0.1$, intrinsic for $x > 0.1$.

W. Chang & J.C. Peng, PRL 102, 026001 (2011)

Strange quark normalization: constrained
(N has zero net strangeness)  
$\langle s - s\bar{b} \rangle = 0$
Sea Quarks in the Proton

\[ \bar{u}(x) + \bar{d}(x) - s(x) - \bar{s}(x) \]

A non-singlet distribution
- No contribution from perturbative effects (extrinsic quarks)
- **combine s quarks from HERMES with light sea from CTEQ6.5**
- evolve from starting scale \( \rightarrow \) HERMES \( Q^2 \)
- experiment in good agreement with estimates of intrinsic sea
Data on Strange Quark Asymmetry:

Determination of s, sbar quark PDFs: **Opposite sign dimuons from neutrinos**

- CCFR: charge of faster muon determines neutrino or antineutrino;
- most precise way to determine s, sbar PDFs→ **NuTeV**
  separate neutrino, antineutrino contributions

Strange quark normalization: constrained
(N has zero net strangeness) \[ \langle s - \bar{s} \rangle = 0 \]
Measure strange quark asymmetry

- **The first moment** $S^-$ measures asymmetry in momentum carried by $s$ and $\bar{s}$ quarks.

1) $S^-(x)$ is a non-singlet quantity, thus no contributions from gluon radiation

2) **Should have very weak $Q^2$ dependence**

In meson-baryon or light-cone models, $S^-(x) = 0$, $x \sim 0.1 - 0.25$

Whether $S^- > 0$ or $< 0$ depends on details of splitting functions, quark dist’ns
MSTW08: global fit of high-energy data, extract $s$, $\bar{s}$ interchangeabilities
- $s$ – $\bar{s}$ dominated by opposite-sign dimuon data (NuTeV, CCFR)
  - $s$ crossover at small $x \sim 0.016$ (lowest $x$ value = 0.015)
  - $s \sim 0, x > 0.3$ \quad $S^- = 0.0024 \pm 0.0020$;

NPDF2.0: global fit with neural network, no pre-assumed shape for PDFs
- $s$ crossover at $x \sim 0.15$ \quad $s$ peaks at $x = 0.45$, extends to $x \sim 0.8$
  - $S^- = 0.0038 \pm 0.0018$;

CTEQ6.5: $s$ changes sign at $x \sim 0.02$; compatible w/MSTW08, NuTeV;
- $s \sim 0, x > 0.3$ \quad $S^- = 0.0014 [-0.0024, + 0.0036]$
Qualitative Features of $s$, $s\bar{s}$ Distributions

$$x(s - \bar{s})$$

**MSTW08, NNPDF2.0:** nearly identical global data as input
- $s - s\bar{s}$ dominated by opposite-sign dimuon data (NuTeV, CCFR)
- almost no similarity between $s$ in 2 fits.
- crossover point, shape of distribution completely different
- large-$x$ behavior of NNPDF2.0 totally different from MSTW08
- hard to imagine more different shapes.

**Global Fit data:** lepton DIS; Drell-Yan; $\nu$ DIS, dimuons; HERA data; Tevatron: jets, $W \rightarrow$ lepton asymmetry, $Z$ rapidity
Models Confront Global Fit Strange Asymmetry

Meson-baryon, light-cone models look nothing like either parton dist'n

- **NNPDF2.0 result**, $x s$ peaks at $x \sim 0.45$, where models give $\sim$ zero.
- **Strange asymmetry** different from 0 out to $x \sim 0.8$, far above region where model results are non-zero.
- **MSTW08**: crossover at $x = 0.016$; not possible for either light-cone or meson-baryon model to reproduce
  - Largest values for $x s$ below $x = 0.2$
  - **Very difficult** for either model to replicate qualitative features of either $s$ quark asymmetry distribution.
Conclusions:

✓ “Meson-Cloud” or “Meson-baryon” effects can make significant contributions to parton distributions, structure functions

✓ “Intrinsic” vs. “Extrinsic” sources of sea quarks

- Intrinsic parton distributions are convolution of splitting function for p to meson-baryon, with distribution of quark inside baryon

- Qualitative pictures of splitting functions, quark distributions
Conclusions (cont’d):

- Strange quarks: dimuon X-sections in neutrino reactions can give strange asymmetry

- Details of strange quark asymmetry difficult
- 2 different global fits → need to be reconciled!
- Difficult (impossible?) to fit either distribution with meson-baryon, light-cone models (NJL, ....)

- Important to have independent measurements of sea quark distributions!
  - light intrinsic sea quarks
  - strange, charm distributions
  - asymmetry of s, c quarks
Back-Up Slides
Meson-Baryon Calculation of Intrinsic Charm

[Hobbs/JTL/Melnitchouk, arXiv:1311.1578]

Expand in series of charmed meson-baryon states
Here, c quark is in baryon, and cbar in meson
One state is dominant:

\[ p \rightarrow \bar{D}^* - \Lambda_c \]

NOT the lowest-mass state!
Splitting function for this state dominates all others:
A result of large tensor coupling (arising from assumption of SU(4) symmetry for coupling constants)
Significant uncertainty in intrinsic charm distributions (due to uncertainty in charm production X-sections)
Our c, cbar PDFs larger than those of BHPS, Pumplin (which are normalized to 1% charm probability – charm carries 0.57% of proton momentum).

Our best fit $P_c = 1.34\%$ of proton momentum.
We obtain cbar harder than c; this is due to significantly harder distribution of cbar in meson than c in baryon (cbar represents larger fraction of total mass in meson, than c in baryon).
**Intrinsic Charm Contribution to Structure Function**

Dotted curve: contribution to $F_2^c$ from extrinsic charm

Shaded curve: additional contribution from intrinsic charm

Black dots: ZEUS data; red squares: EMC charm $F_2$ data.

At lower $Q^2$, intrinsic charm contribution insignificant at low $x$, but well above EMC data

Higher $Q^2$, intrinsic charm still somewhat above EMC data

Currently undertaking global fit of high-energy data, including EMC charm structure function data, to determine upper limits on intrinsic charm contribution (collab with P. Jimenez-Delgado)
Use BHPS formula for light (u,d) sea quarks, generate $d\bar{u} - u\bar{d}$.
Calculate using Monte Carlo integration (Note: extrinsic contrib’ n cancels for this combination).
Normalize to overall sea quark probability.
Dashed curve: $d\bar{u} - u\bar{d}$ at starting scale.
Black curve: QCD evolution from starting scale $\mu = 0.5$ GeV to $Q^2 = 54$ GeV$^2$ of E866 exp’t.
Red curve: same but with starting scale $\mu = 0.3$ GeV.

$$\int_0^1 \left[ \bar{d}(x) - \bar{u}(x) \right] dx = 0.118 \quad \text{from E866 exp’t}$$

W-C Chang and J-C Peng, PRL 106, 252002 (2011)
Chang/Peng: BHPS Model for Intrinsic Sea Quarks:

Chang/Peng conclusion: the BHPS formula when applied to light sea quarks, gives decent agreement with experimental values for d-bar - u-bar, if we normalize to the overall sea quark probabilities as measured by the E866 Collaboration, and use QCD evolution with starting scale $\mu \sim 0.3 \text{ GeV}$.

W-C Chang and J-C Peng, PRL 106, 252002 (2011)
Use dimuon data but in addition CHORUS data (better branching ratio)
- $S^-$ is positive
- $s^-$ changes sign at very small $x \leq 0.02$

Alekhin Analysis of $s$, $s\bar{b}$ar Quark Dist'n:
(S. Alekhin etal, PL B675, 433 (2009))

$$x(s - \bar{s})$$

$$S^- = 0.0013 \pm 0.0009 \pm 0.0002$$
Analyses of s quark momentum asymmetry

Two extensive fits of s quark distributions.

**CTEQ:** [Kretzer et al, PRL 93, 041802 (04), Olness et al, Eur Phys J C40, 145 (05)]

- Global analysis of parton PDFs → CTEQ6
- Includes CCFR, NuTeV dimuon data
- (includes expt’l cuts on dimuons)
- Extract “best fit” for s, sbar dist’ns
  [enforce s normalization cond’n]

**NuTeV:** analyzed s, sbar for small \(0 < x \leq 0.3\)

- Initially, reported best fit \(S^- < 0\)
  (opposite to CTEQ)
- CTEQ, NuTeV **collaborated on analysis**
- Qualitative differences persisted, until this year
Contributions from s quark asymmetry

<table>
<thead>
<tr>
<th></th>
<th>\langle x s^- \rangle</th>
<th>\Delta R^s</th>
<th>\Delta R^{total}</th>
<th>sin^2 \theta_W ± syst.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mason et al. [8]</td>
<td>0.00196 ± 0.00143</td>
<td>−0.0018 ± 0.0013</td>
<td>−0.0063 ± 0.0018</td>
<td>0.2214 ± 0.0020</td>
</tr>
<tr>
<td>NNPDF [9]</td>
<td>0.0005 ± 0.0086</td>
<td>−0.0005 ± 0.0078</td>
<td>−0.0050 ± 0.0079</td>
<td>0.2227 ± large</td>
</tr>
<tr>
<td>Alekhin et al. [31]</td>
<td>0.0013 ± 0.0009 ± 0.0002</td>
<td>−0.0012 ± 0.0008 ± 0.0002</td>
<td>−0.0057 ± 0.0015</td>
<td>0.2220 ± 0.0017</td>
</tr>
<tr>
<td>MSTW [32]</td>
<td>0.0016±0.00011 -0.0009</td>
<td>−0.0014−0.0010 <em>0.0008</em></td>
<td>−0.0059 ± 0.0015</td>
<td>0.2218 ± 0.0018</td>
</tr>
<tr>
<td>CTEQ [33]</td>
<td>0.0018±0.0016 -0.0004</td>
<td>−0.0016±0.0014 -0.0004</td>
<td>−0.0061±0.0019 <em>0.0013</em></td>
<td>0.2216±0.0021 <em>0.0016</em></td>
</tr>
<tr>
<td>This work (Eq. (10))</td>
<td>0.0 ± 0.0020</td>
<td>0.0 ± 0.0018</td>
<td>−0.0045 ± 0.0022</td>
<td>0.2232 ± 0.0024</td>
</tr>
</tbody>
</table>

- 5 phenomenological analyses of s quark dist’ ns
- All dominated by dimuon data
- NuTeV (Mason et al. ‘07), collaborated with CTEQ (‘07)
- MSTW & Alekhin (‘09) also include CHORUS data – help w/branching ratios
- NNPDF neural network (‘09); main interest in $V_{ud}$; big errors;
- Bentz et al., assume zero s quark asymmetry
- We chose $\Delta R^s = 0.0 ± 0.0018$ ;
- but, any of the phenom analyses will give WMA within 1σ!
- World best value $\sin^2 \theta_W = 0.2229 ± 0.0004$
NuTeV Analysis of $s$, $\bar{s}$ Quark Dist'ns

\[ x(s - \bar{s}) \quad \text{(D. Mason et al., PRL 99, 192001 (2007))} \]

\[ S^- \equiv \langle x[s(x) - \bar{s}(x)] \rangle = 0.00196 \pm 0.00143 \]

NuTeV: reanalyzed dimuon data, $Q^2 = 16 \text{ GeV}^2$: non-strange PDFs taken from CTEQ global fits, analysis done in collaboration with CTEQ group.

- $S^-$ is positive; $s^-$ changes sign at very small $x \sim 0.004$ (lowest $x$ value = 0.015)
- Crossover $x <<$ any result from MBM or light-cone models

Global fits of $s$ quark PDFs by: NuTeV, CTEQ, MSTW, NNPDF, AKP:
MSTW 2008 NLO PDF fit (68% C.L.)

\[ s_v = s = \bar{s} \]

\[ \int_0^1 dx \, x s_v(x, Q^2) = 0.0024^{+0.0024}_{-0.0016} \]

\[ x_0 = 0.0161 \]
NuTeV Analysis of $s$, $\bar{s}$ Quark Dist’ns

Compare MSTW08, NNPDF2.0 with meson-baryon, light-cone models

NuTeV: crossover point too small for any of these models
Meson-baryon & light-cone models give different sign, shape for $S^{-}$
Neither of these models looks anything like the NuTeV analysis
NNPDF2.0 analysis of s-quark asymmetry: neural network analysis

- No a priori assumption of shape of parton distribution
- Global fit to data including especially NuTeV, CHORUS dimuon data, Drell-Yan data [E605, E866], HERA low-x data
- Very different result from NuTeV (although much the same data!)
- Very small errors on strange asymmetry!

\[ S^- = 0.0038 \pm 0.0018 \]
Example: Meson-Cloud Contributions to the Gottfried Sum Rule

The Gottfried Sum Rule $S_G$ is an excellent “testing ground” for meson-cloud effects:

$$S_G = \frac{1}{3} - \frac{2}{3}\langle \bar{d} - \bar{u}\rangle$$

- $S_G$ is purely non-perturbative: no contribution from perturbative effects or extrinsic quarks.
- a ”natural” contribution to $S_G$ from $p \rightarrow n\pi^+$ with scattering from $\pi^+ = (u\bar{d})$.
- obtain opposite contribution from $p \rightarrow \Delta^{++}\pi^-$ with $\pi^- = (d\bar{u})$. 
Flavor Asymmetry in the Quark Sea

NMC Expt (Amaudruz et al, PRL66, 2712 (91)): measured $F_2$ in $\mu - p$, $\mu - D$ reactions

Constructed the Gottfried Sum Rule $S_G$

$$S_G = \frac{F_2^{\mu p} - F_2^{\mu n}}{x} = \frac{1}{3} - \frac{2}{3} < \bar{d} - \bar{u} >$$

$$= 0.235 \pm 0.026 \Rightarrow < \bar{d} - \bar{u} > \approx 0.147 \pm 0.039$$

Strong evidence for flavor asymmetry in proton sea (a 4-$\sigma$ effect!)

Measurements of $F_2^p - F_2^n$ vs $x$ (solid), and the integral of this difference/x vs $x$ (open), at $Q^2 = 4$ GeV$^2$

Small-$x$ measurements crucial to establishing $S_G$
Flavor Asymmetry: Drell-Yan, SIDIS Data

Drell-Yan Measurement of Flavor Asymmetry

- DY measurements for protons on p, D
  \[
  \frac{\sigma_{pD}^{DY}}{2\sigma_{pp}^{DY}} \to \frac{1}{2} \left[ 1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)} \right]
  \]

- E866/NuSea Exp’t at FNAL: 450 GeV p on p, D targets
  
  extract $\bar{d}/\bar{u}$ vs $x$ at $Q^2 \sim 54$ GeV$^2$

Incorporate E866 flavor asymmetry into global PDF’s

Also HERMES measurements, SIDIS using internal polarized targets at HERA, $Q^2 = 2.3$ GeV$^2$

\[
\langle \bar{d} - \bar{u} \rangle = 0.118 \pm 0.012
\]

Reviews by:
J.C. Peng and J-W. Qiu, arXiv:1401.0934
Meson-Cloud Calculation of $\bar{d} - \bar{u}$.

Meson-cloud calculation by Nikolaev et al;
Solid curves: $\pi N$ Fock term with Gaussian form factors
$R_G^2 = 1$ GeV$^2$ (upper curve), and $R_G^2 = 1.5$ GeV$^2$ (lower curve),
Dashed curve: $\pi \Delta$ Fock term with Gaussian form factor $R_G^2 = 2$ GeV$^2$

- Obtain semi-quantitative post-diction of E866, NMC results
- Strong dependence on assumed N-MB vertex form factors

See also: chiral quark model, Szczurek et al, J Phys G22, 1741 (1996);
Chiral soliton model, Pobylitsa et al, PR D59, 034024 (1999);
Instanton model, Dorokhev & Kochelev, P Lett B259, 335 (1991);