Theoretical Overview of the “Sullivan Process”

• Historical Overview
• Intrinsic vs. Extrinsic Sea Quark Distributions
• Contributions to quark distributions, structure functions
  emphasis on qualitative features of quark PDFs
• Asymmetries for intrinsic strange quarks

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Hadron Structure with Tagged Structure Functions
Jefferson Laboratory, Jan 16, 2014

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With Tim Hobbs (IU), Wally Melnitchouk (Jlab)
Shortly following discovery of DIS (1972), in pre-QCD era, Sullivan pointed out that deep inelastic scattering from a virtual meson would also scale with $Q^2$ in the Bjorken limit. Contributions to DIS through scattering from “higher Fock states”

J. D. Sullivan, PR **D5**, 1732 (1972).
Sullivan: Historical Context

1972

Richard Nixon

Disco

Shoulder-length hair
“Sullivan Process”

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

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

Mechanisms for multi-quark states

expansions of nucleon wavefunction

“meson-cloud” or “meson-baryon” models

Look for observables where likely to contribute

flavor symmetry violations, e.g. d\bar{u} \neq u\bar{d}

intrinsic heavy quark probabilities (e.g., s, c)
**Intrinsic vs. Extrinsic Sources of Sea Quarks**

Consider sea quark production from 2 different sources:

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

* asymmetries (mainly 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 distribution moves 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:

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

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:

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

* Brodsky, Hoyer, Peterson & Sakai, PL B93, 451 (1980)
BHPS Model for Intrinsic Sea Quarks:

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

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

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

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

“Meson-Cloud” or “Meson-Baryon” Models of Intrinsic Sea

Expand N Fock state to include transitions to a series of meson-baryon states that include the most important sources of intrinsic quarks:

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

We can calculate a “splitting function” $f_{MB}$ for a nucleon transition to meson $M$ carrying momentum fraction $y$:

$$f_{MB}(y) = \int_0^\infty d^2k_\perp \ |\phi_{MB}(y, k^2_\perp)|^2$$

For inclusive processes the contribution of this meson-baryon state to the parton distribution function is obtained by convoluting the splitting function with the quark probability in meson $M$

$$\delta\bar{q}_M = f_{MB} \otimes \bar{q}_M$$
“Meson-Baryon” Models of Intrinsic Sea Quarks

The 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 the fraction of the total $D$ mass contributed by the $c\bar{c}$.

We can 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 here $m_d$ 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 (not particularly good for pion-cloud).
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 are important to ensure that these constraints are satisfied.
The Gottfried Sum Rule $S_G$ is an excellent “testing ground” for meson-cloud effects:

$$S_G = \left\langle \frac{F_2^{\mu p} - F_2^{\mu n}}{x} \right\rangle = \frac{1}{3} - \frac{2}{3} \langle \bar{d} - \bar{u} \rangle$$

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

See talk by J-C Peng for more on flavor dependence of sea quarks
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 $S_G$

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

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

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 $Q^2 = 4 \text{ GeV}^2$

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

\[ \frac{\sigma_{DY}^{pD}}{2\sigma_{DY}^{pp}} \rightarrow \frac{1}{2} \left[ 1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)} \right] \]

• E866/NuSea Exp’t at FNAL: 450 GeV p on p, D targets

extract \( \bar{d}/\bar{u} \) vs \( x \) at \( Q^2 \sim 54 \text{ GeV}^2 \)

Incorporate E866 flavor asymmetry into global PDF’s

Also HERMES measurements, SIDIS using internal polarized targets at HERA, \( Q^2 = 2.3 \text{ GeV}^2 \)

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

Reviews by:
J.C. Peng and J-W. Qiu, arXiv:1401.0934
Meson-cloud calculation by Nikolaev et al.;
Solid curves: $\pi N$ Fock term with Gaussian form factors
$R_G^2 = 1 \text{ GeV}^2$ (upper curve), and $R_G^2 = 1.5 \text{ GeV}^2$ (lower curve),
Dashed curve: $\pi \Delta$ Fock term with Gaussian form factor $R_G^2 = 2 \text{ GeV}^2$

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

• 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 $\bar{s}_K(y)$.

See talk by J-C Peng on flavor dependence of sea quarks
Quark Asymmetry: 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 B381, 317 (1996)
Strange Quark Distributions: Brodsky-Ma

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

Splitting functions \( f_{\Lambda K}(x) = f_{K\Lambda}(1-x) \)
Convolution with strange parton distribution inside hadron to get intrinsic quark parton distributions

\( s_K(x) \) 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 \( s_{\text{bar}}(x) \).
Strange Quark Asymmetries, 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, $s_{\text{bar}}(x)$ is slightly harder than $s(x)$ in the MBM.

Hobbs/JTL/Melnitchouk, unpublished
Data on Strange Quark Asymmetry:

Determination of $s$, $\bar{s}$ quark PDFs: **Opposite sign dimuons from neutrinos**

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

Strange quark normalization: constrained
(N has zero net strangeness)\[ \langle s - \bar{s} \rangle = 0 \]
Global Analysis of $s$, $\bar{s}$ Quark Dist'n:

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

(D. Mason etal, PRL 99, 192001 (2007))

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

NuTeV: re-analyzed dimuon data, $Q^2 = 16$ GeV$^2$:
- $S^-$ is positive; $s^-$ changes sign at very small $x \sim 0.004$ (lowest $x$ value = 0.015)

- NNPDF2.0*: neural network analysis, di-muon+ DY; very different shape for $s^-$ (peak in $xs^-$ at $x \sim 0.5$ !!)

Global fits of $s$ quark PDFs by: NuTeV, CTEQ, MSTW, NNPDF, AKP:

Strange Quark Asymmetry: Meson-Baryon Models Confront Data

Expt’l data on strange quark asymmetry pose several challenges for meson-baryon models:

- **Sign** of s quark momentum asymmetry $S^-$ opposite to MBM prediction (but same as light-cone result)
- **Crossover** at very small $x < 0.01$ is difficult (impossible?) to achieve in MBM and light-cone models

**NNPDF2.0 result**, $xs^-$ peaks at $x \sim 0.45$, where meson-baryon models give $\sim$ zero.
Conclusions:

✓ Sullivan (1972) demonstrated that “higher-order terms” scale in DIS reactions

✓ “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):

✓ Significant contribution of meson-cloud effects to Gottfried Sum Rule

✓ A number of different complementary precision experiments
  • charged-lepton DIS
  • Drell-Yan
  • neutrino DIS
  • semi-inclusive DIS, polarized internal targets

✓ Strange quarks, neutrino measurements of strange asymmetry

✓ Details of strange quark asymmetry difficult to reconcile with meson-baryon models

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

Expand in series of charmed meson-baryon states
Here, $c$ quark is in baryon, and $c\bar{c}$ 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)
Meson-Baryon Calculation of Intrinsic Charm

Significant uncertainty in intrinsic charm distributions (due to uncertainty in charm production X-sections)
Our $c$, $c\bar{c}$ 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 $c\bar{c}$ harder than $c$; this is due to significantly harder distribution of $c\bar{c}$ in meson than $c$ in baryon ($c\bar{c}$ 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 (together with P. Jimenez-Delgado)
CHANG/PENG: BHPS MODEL FOR INTRINSIC SEA QUARKS:

Use BHPS formula for light (u,d) sea quarks, generate dbar - ubar. Calculate using Monte Carlo integration (Note: extrinsic contrib’n cancels for this combination). Normalize to overall sea quark probability. Dashed curve: dbar - ubar at starting scale. Black curve: QCD evolution from starting scale $\mu = 0.5 \text{ GeV}$ to $Q^2 = 54 \text{ GeV}^2$ of E866 exp’t. Red curve: same but with starting scale $\mu = 0.3 \text{ GeV}$. 

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

W-C Chang and J-C Peng, PRL 106, 252002 (2011)
Chang/Peng conclusion: the BHPS formula when applied to light sea quarks, gives decent agreement with experimental values for dbar - ubar, if we normalize to the overall sea quark probabilities as measured by the E866 Collaboration, and use QCD evolution with starting scale $\mu \sim 0.3$ 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 $s$, $s\bar{b}$ 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 $\rightarrow$ 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>$\Delta R^{\text{total}}$</th>
<th>$\sin^2 \theta_W \pm \text{syst.}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mason et al. [8]</td>
<td>$0.00196 \pm 0.00143$</td>
<td>$-0.0018 \pm 0.0013$</td>
<td>$-0.0063 \pm 0.0018$</td>
<td>$0.2214 \pm 0.0020$</td>
</tr>
<tr>
<td>NNPDF [9]</td>
<td>$0.0005 \pm 0.00086$</td>
<td>$-0.0005 \pm 0.0078$</td>
<td>$-0.0050 \pm 0.0079$</td>
<td>$0.2227 \pm \text{large}$</td>
</tr>
<tr>
<td>Alekhin et al. [31]</td>
<td>$0.0013 \pm 0.0009 \pm 0.0002$</td>
<td>$-0.0012 \pm 0.0008 \pm 0.0002$</td>
<td>$-0.0057 \pm 0.0015$</td>
<td>$0.2220 \pm 0.0017$</td>
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<tr>
<td>MSTW [32]</td>
<td>$0.0016^{+0.0011}_{-0.0009}$</td>
<td>$-0.0014^{-0.0010}_{+0.0008}$</td>
<td>$-0.0059 \pm 0.0015$</td>
<td>$0.2218 \pm 0.0018$</td>
</tr>
<tr>
<td>CTEQ [33]</td>
<td>$0.0018^{+0.0016}_{-0.0004}$</td>
<td>$-0.0016^{+0.0014}_{-0.0004}$</td>
<td>$-0.0061^{+0.0019}_{-0.0013}$</td>
<td>$0.2216^{+0.0021}_{-0.0016}$</td>
</tr>
<tr>
<td>This work (Eq. (10))</td>
<td>$0.0 \pm 0.0020$</td>
<td>$0.0 \pm 0.0018$</td>
<td>$-0.0045 \pm 0.0022$</td>
<td>$0.2232 \pm 0.0024$</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 $\Delta R^s = 0.0 \pm 0.0018$;
- but, **any** of the phenom analyses will give WMA **within 1σ**!
- **world best value** $\sin^2 \theta_W = 0.2229 \pm 0.0004$