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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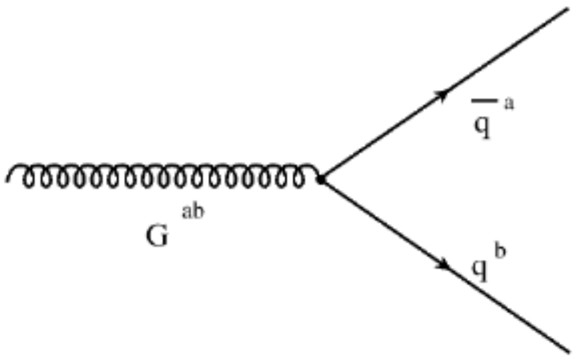
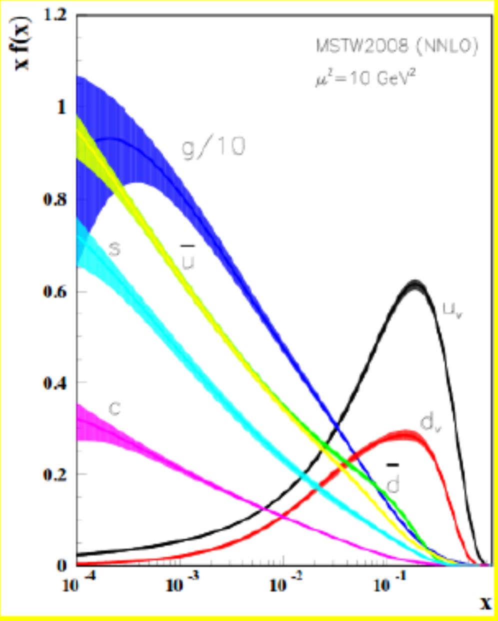
With Tim Hobbs (IU), Wally Melnitchouk (Jlab)

Intrinsic vs. Extrinsic Sources of Sea Quarks





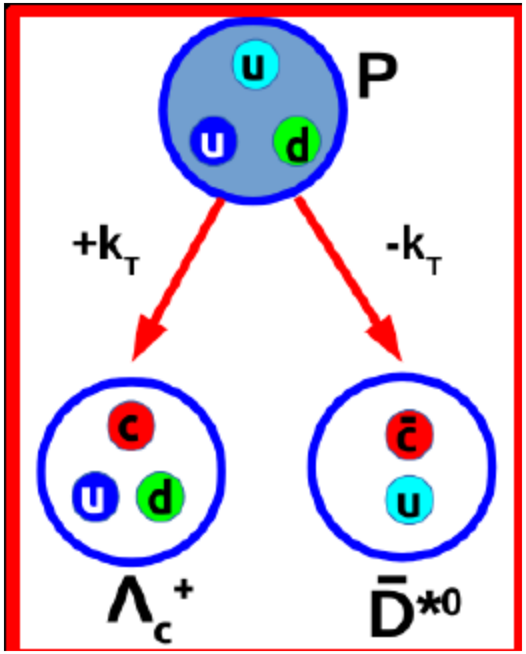
Sea quarks in nucleon arise through 2 different mechanisms:

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

* asymmetries (very small, low-x) arise at NNLO order

Intrinsic vs. Extrinsic Sources of Sea Quarks

- **Intrinsic:** arises from 4q+qbar fluctuations of N Fock state
- at starting scale, peaked at intermediate x; more "valence-like" than extrinsic
- in general, q ≠ qbar 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:

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

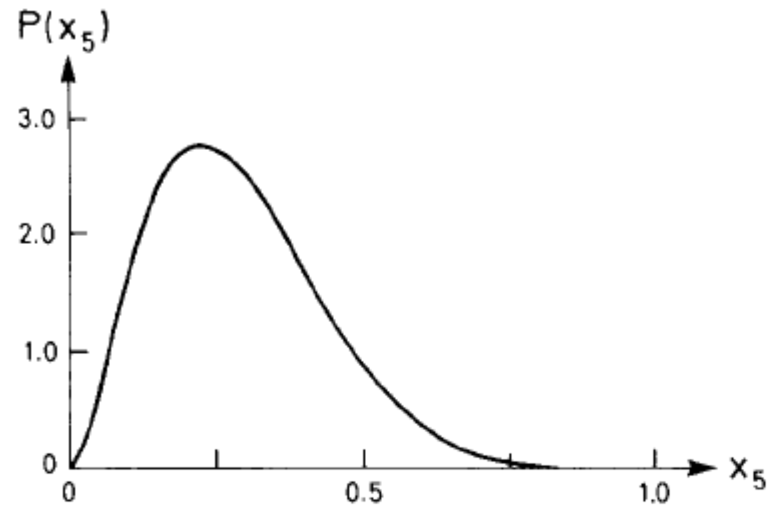
For charm quarks, neglect k_T and assume the charm mass >> any other mass scale. Then obtain analytic expression for probability of charm quark:

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

* Brodsky, Hoyer, Peterson & Sakai, Phys Lett **B93**, 451 (1980)

BHPS Model for Intrinsic Sea Quarks:

Sea quark PDFs peak at relatively large x values.
Normalize to overall quark probability.
BHPS approximation guarantees c = cbar.



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

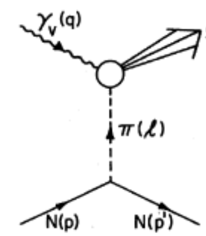
Brodsky, Hoyer, Peterson & Sakai, PL **B93**, 451 (1980)

* W-C. Chang and J.C. Peng, PRL **102**, 252002 (2011).

"Sullivan Process"

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

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



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

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

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

$$f_{MB}(y) = \int_0^{\infty} d^2\boldsymbol{k}_\perp\, |\phi_{MB}(y,k_\perp^2)|^2 \qquad \delta\bar{q}_M = f_{MB}\otimes\bar{q}_M$$

"Meson-Baryon" Models of Intrinsic Sea Quarks

Meson-baryon states contribute to the parton distribution function and structure function for a particular quark flavor q_i

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

$$\delta F_2(x) = \int_x^1 dy f_{MB}(y) F_2^M(\frac{x}{y}) + \int_x^1 dy f_{BM}(y) F_2^B(\frac{x}{y})$$

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 ϕ_{MB} by

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

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

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

Here V_∞ 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

$$s_{MB} = \frac{k_\perp^2 + m_M^2}{y} + \frac{k_\perp^2 + m_B^2}{1-y}$$

E.g., V_∞ for N → Nπ,

$$V_\infty(y, k_\perp^2) = \bar{\psi}^N(k') i\gamma_5 \phi_\pi(k) \psi^N(p)$$

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_{cd} is given by

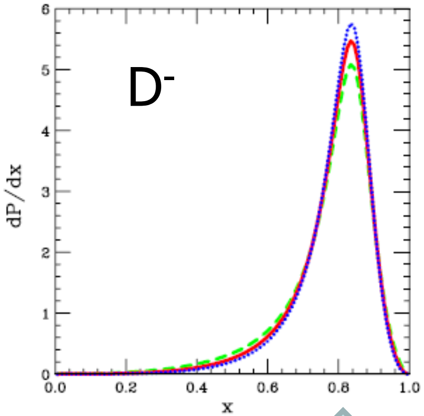
$$s_{\bar{c}d} = \frac{m_c^2 + k_\perp^2}{z} + \frac{m_d^2 + k_\perp^2}{1-z}$$

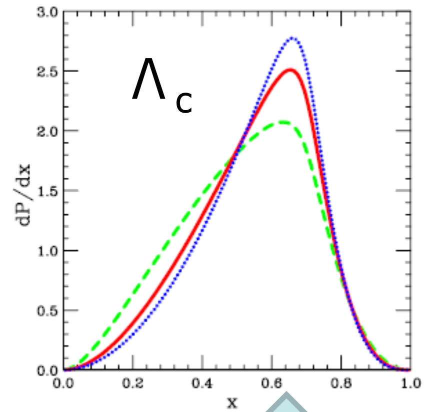
The charm distribution will be strongly peaked at $z \sim \frac{m_c}{m_c + m_d}$ the fraction of the total D mass contributed by the cbar.

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





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

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

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 Λ_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,

$$\langle y \rangle_{MB} + \langle y \rangle_{BM} = \langle n \rangle_{MB}; \quad \langle y \rangle_{MB} = \int_0^1 f_{MB}(y)ydy$$

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

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

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

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

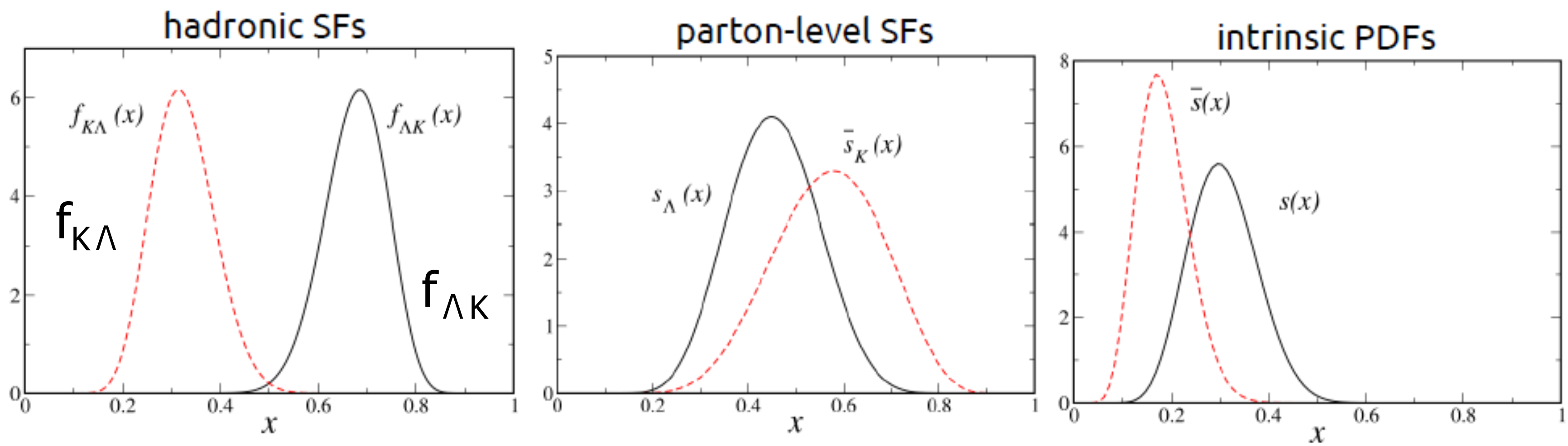
$$\phi_{\Lambda/s}(y, k_\perp^2) = \exp\left[-\frac{s_{sd}}{\Lambda'^2}\right]$$

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

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

S. Brodsky and B-Q Ma, Phys. Lett **B381**, 317 (1996)

Strange Quark Distributions: Brodsky-Ma

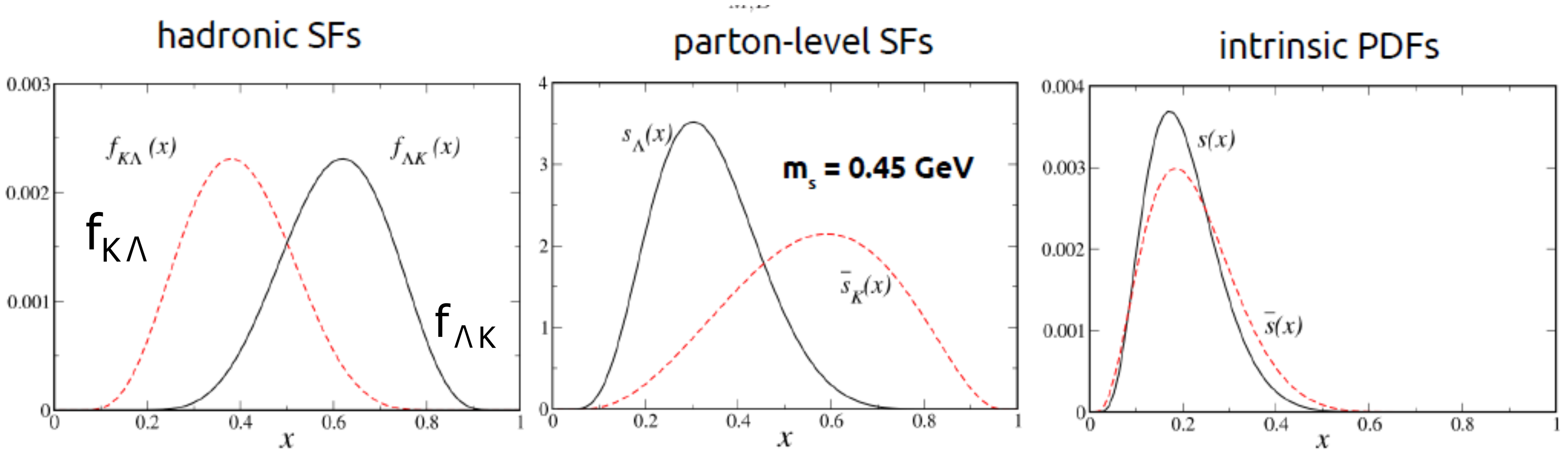


$$\delta s = f_{\Lambda K} \otimes s_\Lambda; \qquad \delta \bar{s} = f_{K\Lambda} \otimes \bar{s}_K$$

Splitting functions $f_{\Lambda K}(x) = f_{K\Lambda}(1\text{-}x)$
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 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, sbar(x) is slightly harder than s(x) in the MBM.

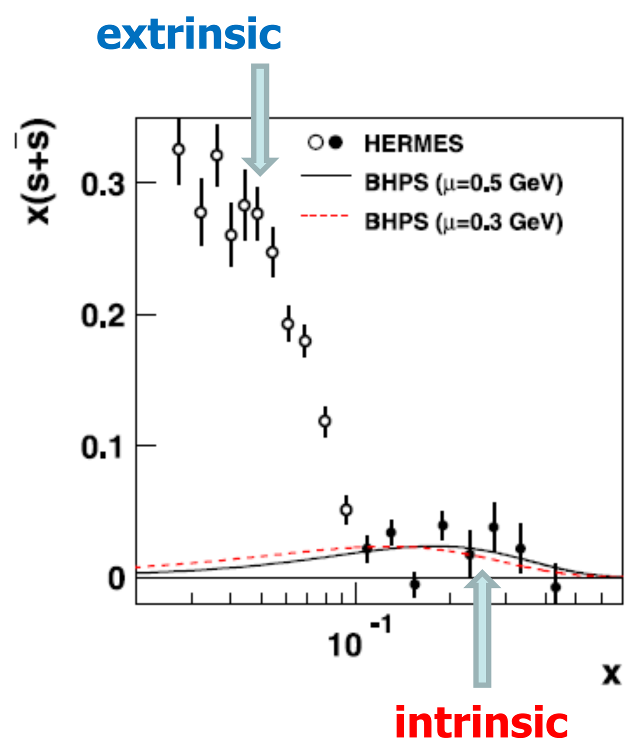
Hobbs/JTL/Melnitchouk, unpublished

Strange Quarks in the Proton

HERMES: Airepetian etal, P Lett B666, 446 (2008)

Extracted x(s + sbar) 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 ~ 0.1
- Chang-Peng: assume distribution is **extrinsic for x ≤ 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)

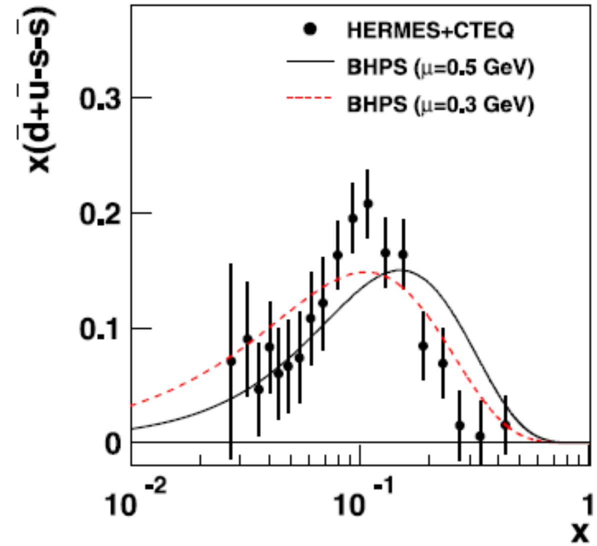
$$\langle s - \bar{s} \rangle = 0$$

Sea Quarks in the Proton

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

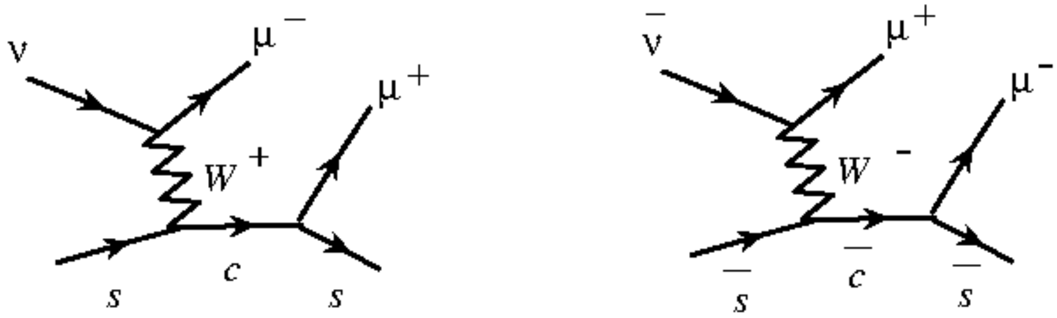
A non-singlet distribution

- No contribution from perturbative effects (extrinsic quarks)
- **combine s quarks from HERMES with light sea from CTEQ6.5**
- evolve from starting scale → 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**

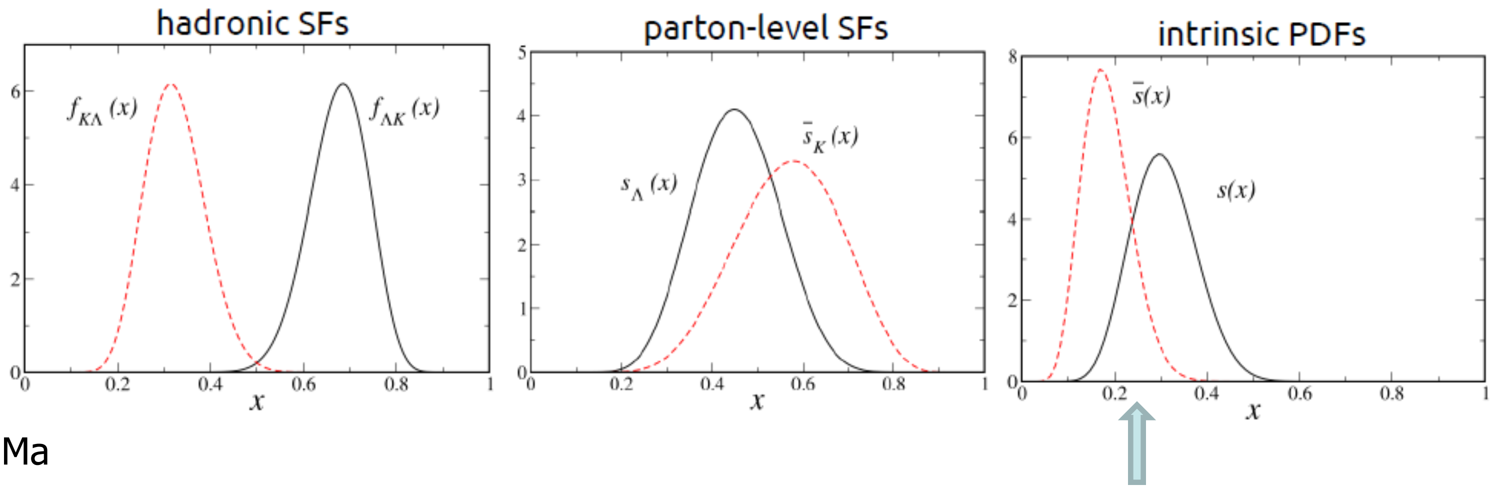


- CCFR: charge of faster muon determines neutrino or antineutrino;
- most precise way to determine s, sbar PDFs→ **NuTeV**
  separate neutrino, antineutrino contributions

Strange quark normalization: constrained
(N has zero net strangeness)

$$\langle s - \overline{s} \rangle = 0$$

Qualitative Strange Quark Asymmetry:



crossover point

Brodsky-Ma

$$S^{-}(x) = x[s(x) - \bar{s}(x)]$$

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

Measure strange quark asymmetry

- The first moment S^{-} measures asymmetry in momentum carried by s and sbar quarks.

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

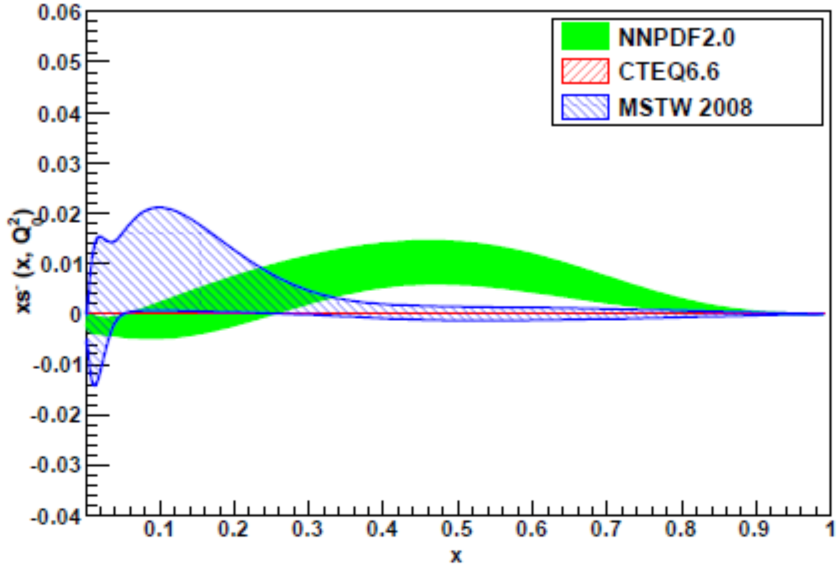
2) **Should have very weak Q^2 dependence**

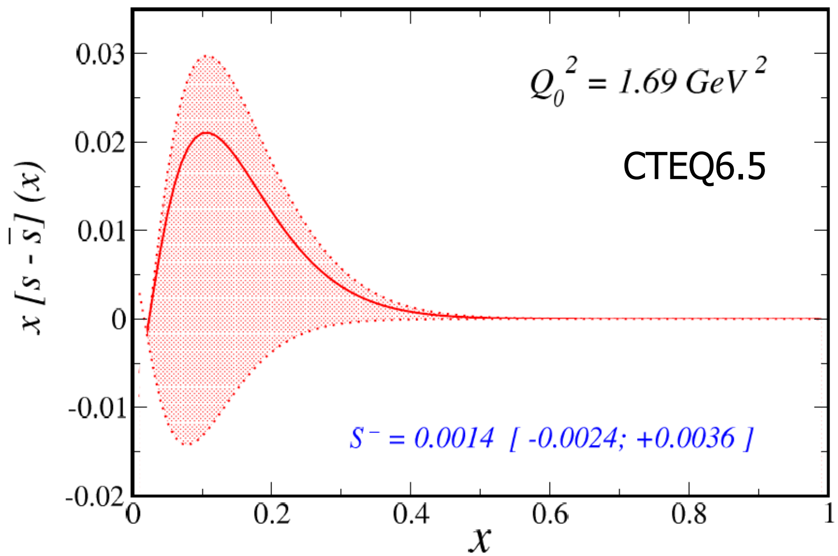
In meson-baryon or light-cone models, $S^{-}(x) = 0$, $x \sim 0.1 - 0.25$

Whether $S^{-} > 0$ or < 0 depends on details of splitting functions, quark dist'ns

s, sbar Distributions in Global Parton Fits

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





MSTW08: global fit of high-energy data, extract s, sbar

s – sbar dominated by opposite-sign dimuon data (NuTeV, CCFR)

- s^- crossover at small x ~ 0.016 (lowest x value =0.015)
- s^{--} ~ 0, x > 0.3 $S^{--} = 0.0024 \pm 0.0020$;

NNPDF2.0: global fit with neural network, no pre-assumed shape for PDFs

s^- crossover at x ~ 0.15 s^- peaks at x = 0.45, extends to x ~ 0.8

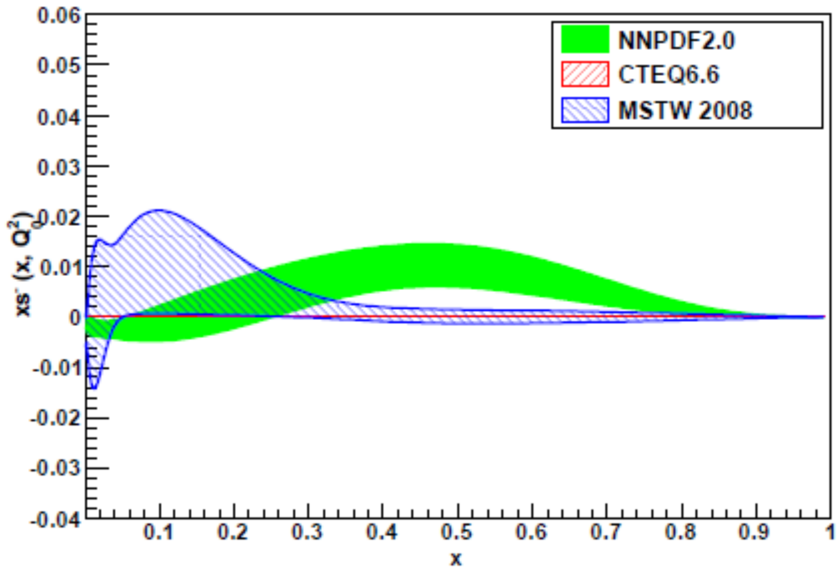
- $S^{--} = 0.0038 \pm 0.0018$;

CTEQ6.5: s^- changes sign at x ~ 0.02; compatible w/MSTW08, NuTeV;

- s^{--} ~ 0, x > 0.3 $S^{--} = 0.0014$ [-0.0024, + 0.0036]

Qualitative Features of s, sbar Distributions

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



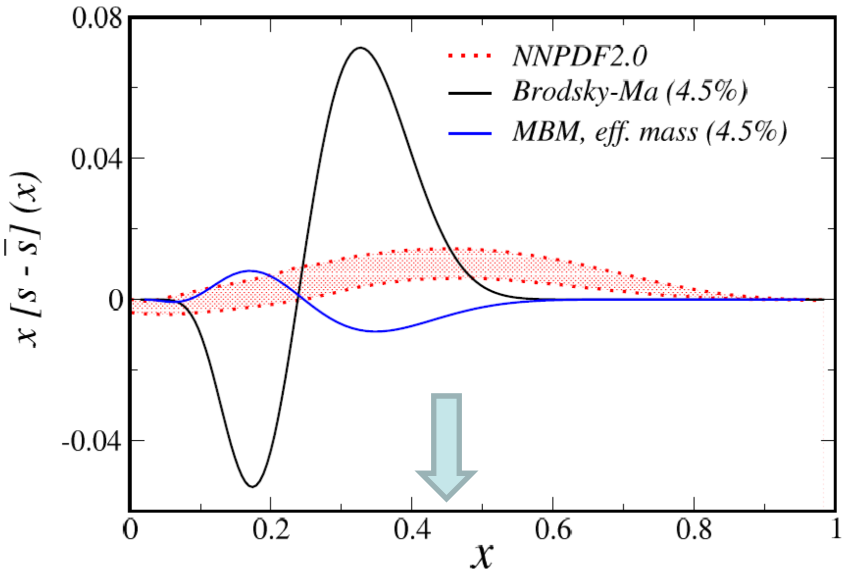
MSTW08, NNPDF2.0: nearly identical global data as input

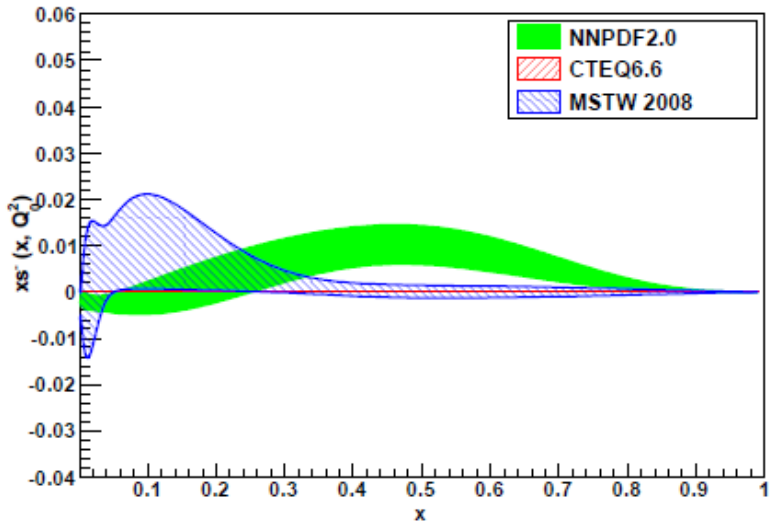
s – sbar dominated by opposite-sign dimuon data (NuTeV, CCFR)

- 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; ν DIS, dimuons; HERA data; Tevatron: jets, W → 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**, xs^- peaks at x ~ 0.45, where models give ~ zero.
- **Strange asymmetry** different from 0 out to x ~ 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 xs^- 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

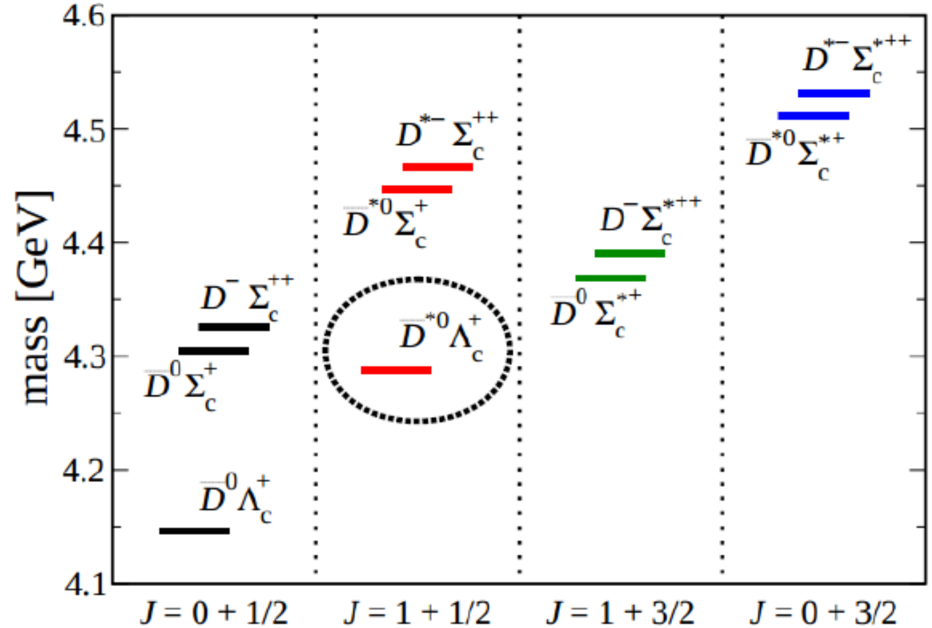
Back-Up Slides

Meson-Baryon Calculation of Intrinsic Charm

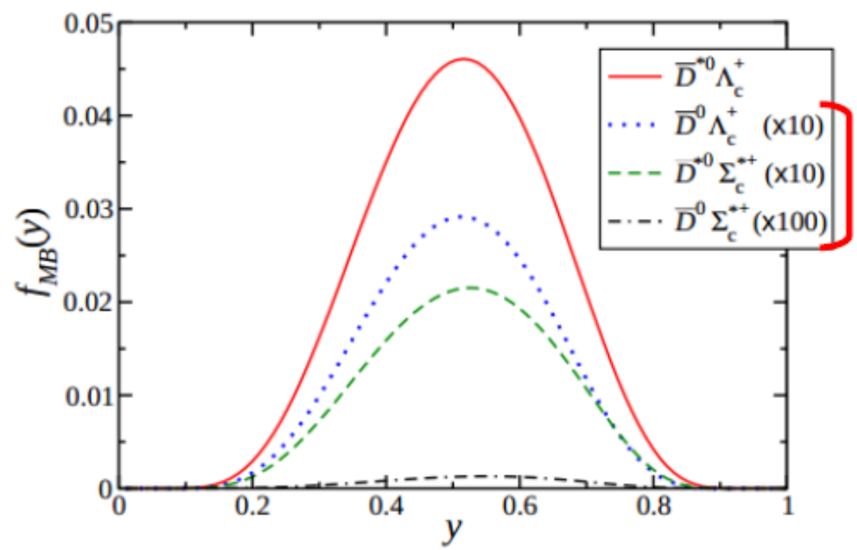
[Hobbs/JTL/Melnitchouk, arXiv:1311.1578]

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

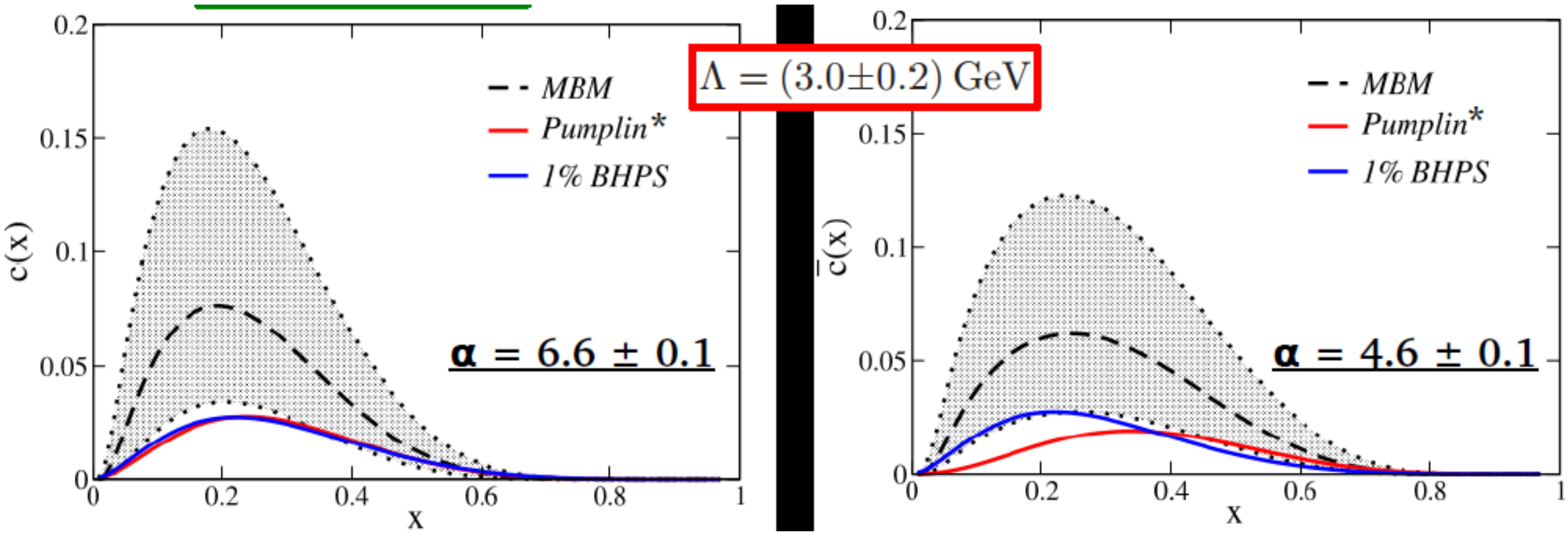
$$p \to \bar{D}^* - \Lambda_c$$



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)



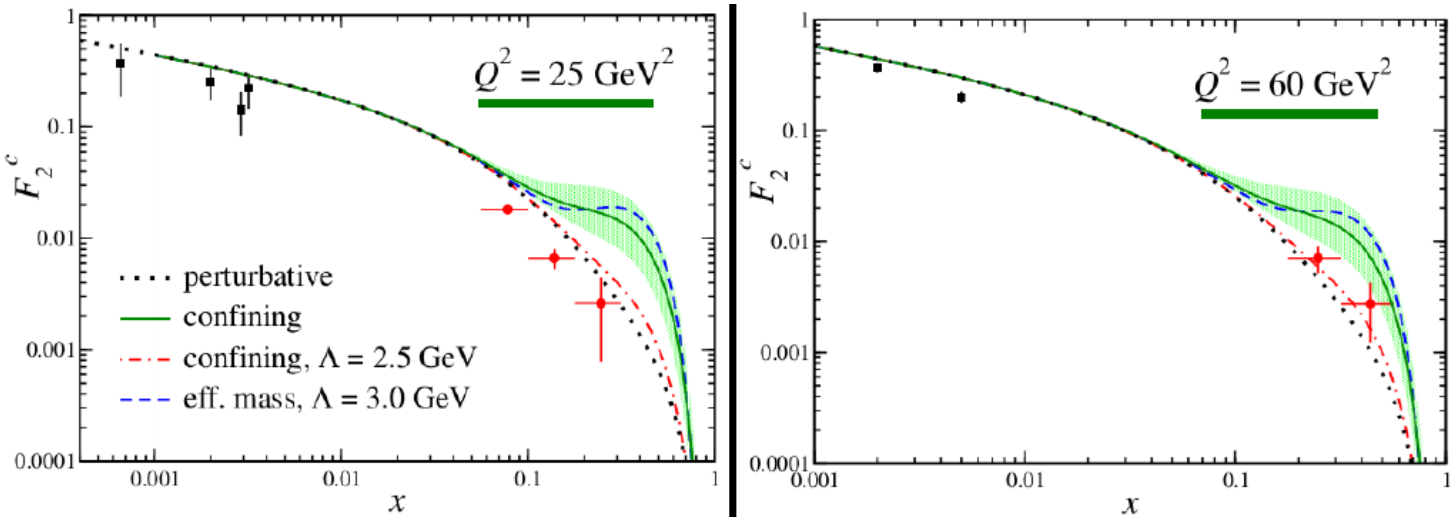
Meson-Baryon Calculation of Intrinsic Charm



Significant uncertainty in intrinsic charm distributions
(due to uncertainty in charm production X-sections)
Our c, 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

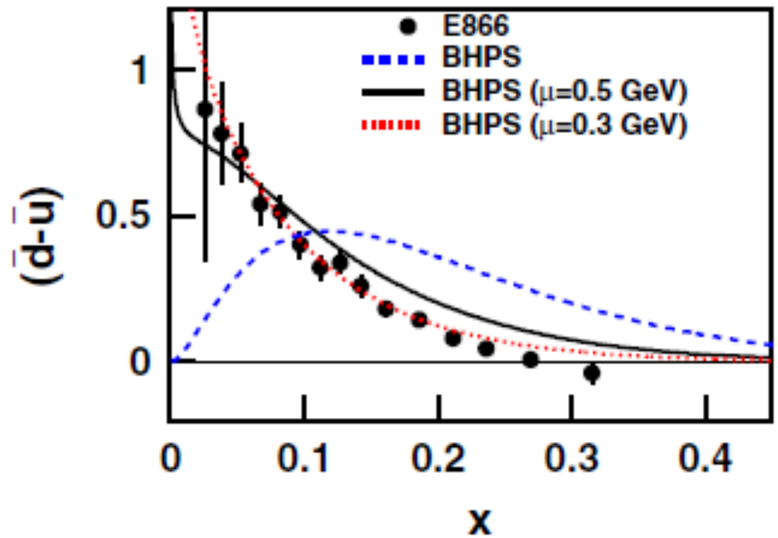


Dotted curve: contribution to F_2^c from extrinsic charm
Shaded curve: additional contribution from intrinsic charm
Black dots: ZEUS data; red squares: EMC charm F_2 data.

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)

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 μ= 0.5 GeV to Q^2 = 54 GeV^2 of E866 exp't.
Red curve: same but with starting scale μ= 0.3 GeV.

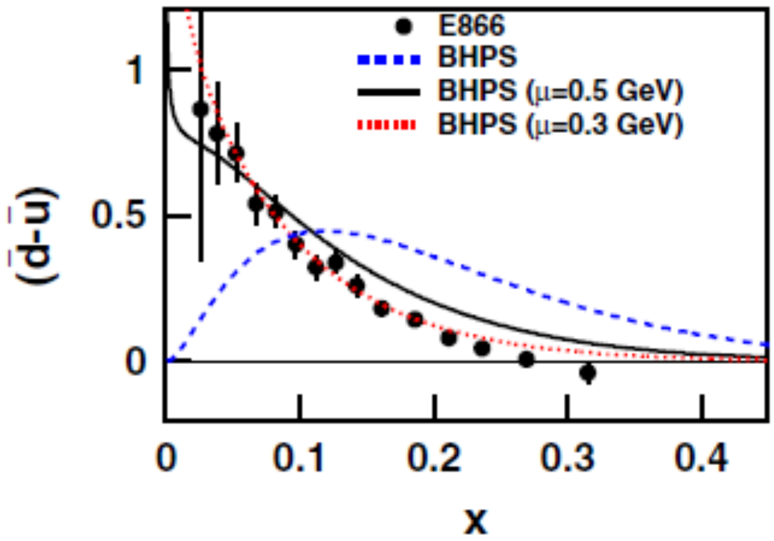


$$\int_0^1 [\bar{d}(x) - \bar{u}(x)]dx = 0.118$$ from E866 exp't

W-C Chang and J-C Peng, PRL **106**, 252002 (2011)

Chang/Peng: 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 dbar – ubar,
if we normalize to the overall sea quark probabilities as measured by the E866 Collaboration,
and use QCD evolution with starting scale μ~ 0.3 GeV.



W-C Chang and J-C Peng, PRL **106**, 252002 (2011)

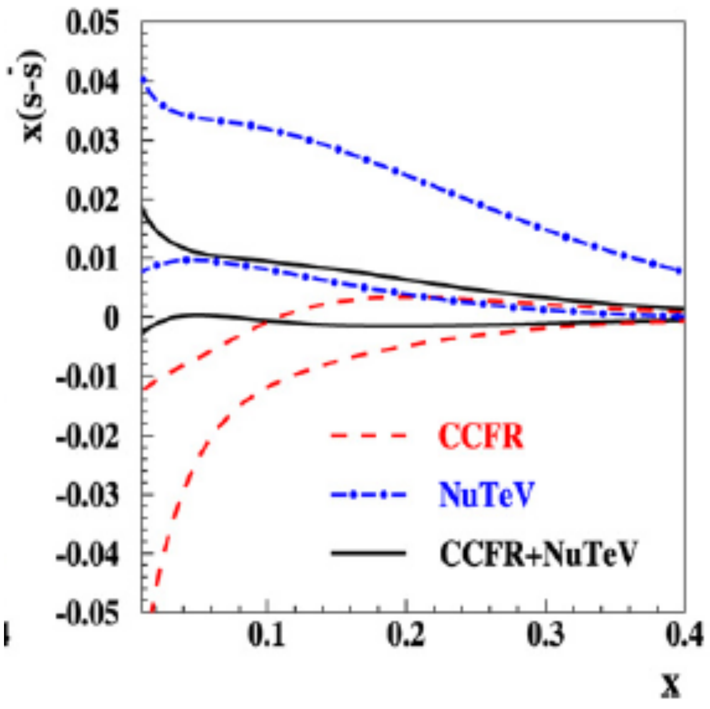
Alekhin Analysis of s, sbar Quark Dist'n:

(S. Alekhin etal, PL **B675**, 433 (2009))

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

Use dimuon data but in addition CHORUS data (better branching ratio)

- S^- is positive
- s^- changes sign at very small $x \le 0.02$



x

$S^- = 0.0013 \pm 0.0009 \pm 0.0002$

Analyses of s quark momentum asymmetry

Two extensive fits of s quark distributions.

CTEQ: [Kretzer etal, PRL **93**, 041802 (04), Olness etal, Eur Phys J C**40**, 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

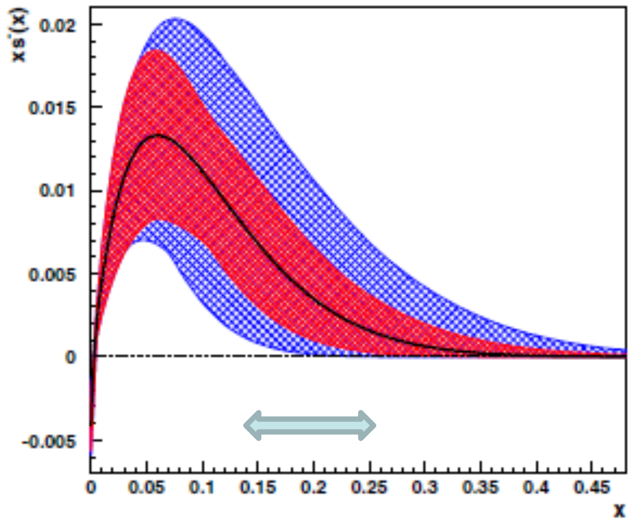
Contributions from s quark asymmetry

	$\langle x\, s^- \rangle$	ΔR^s	$\Delta R^{\mathrm{total}}$	$\sin^2\theta_W \pm$ syst.
Mason *et al.* [8]	0.00196 ± 0.00143	-0.0018 ± 0.0013	-0.0063 ± 0.0018	0.2214 ± 0.0020
NNPDF [9]	0.0005 ± 0.0086	-0.0005 ± 0.0078	-0.0050 ± 0.0079	$0.2227 \pm$ *large*
Alekhin *et al.* [31]	$0.0013 \pm 0.0009 \pm 0.0002$	$-0.0012 \pm 0.0008 \pm 0.0002$	-0.0057 ± 0.0015	0.2220 ± 0.0017
MSTW [32]	$0.0016^{+0.0011}_{-0.0009}$	$-0.0014^{-0.0010}_{+0.0008}$	-0.0059 ± 0.0015	0.2218 ± 0.0018
CTEQ [33]	$0.0018^{+0.0016}_{-0.0004}$	$-0.0016^{+0.0014}_{-0.0004}$	$-0.0061^{+0.0019}_{-0.0013}$	$0.2216^{+0.0021}_{-0.0016}$
This work (Eq. (10))	0.0 ± 0.0020	0.0 ± 0.0018	-0.0045 ± 0.0022	0.2232 ± 0.0024

- 5 phenomenological analyses of s quark dist' ns
- All dominated by dimuon data
- NuTeV (Mason etal '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 etal, 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 1 σ !**
- world best value $\sin^2 \theta_W = 0.2229 \pm 0.0004$

NuTeV Analysis of s, sbar Quark Dist'ns

$x(s - \overline{s})$ (D. Mason etal, PRL **99**, 192001 (2007))

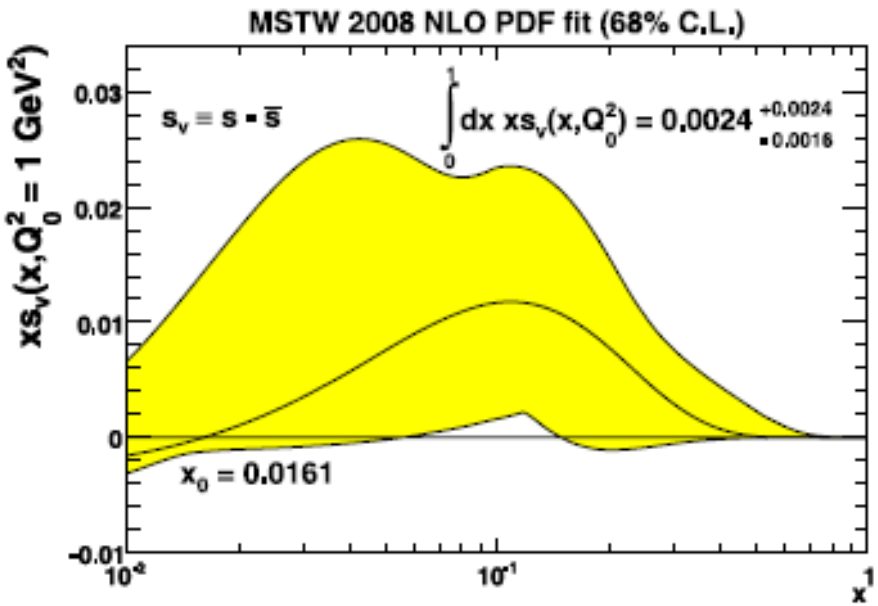


$$S^- \equiv \langle x[s(x) - \bar{s}(x)]\rangle = 0.00196 \pm 0.00143$$

NuTeV: re-analyzed dimuon data, $Q^2 = 16\ GeV^2$:
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 ~ 0.004 (lowest x value =0.015)
- Crossover x << any result from MBM or light-cone models

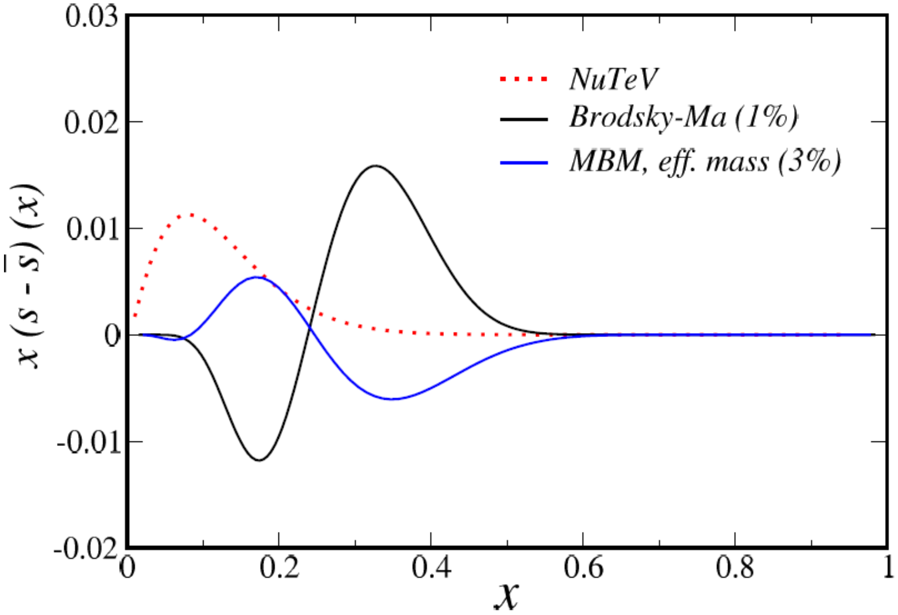
Global fits of s quark PDFs by: NuTeV, CTEQ, MSTW, NNPDF, AKP:



MSTW 2008 NLO PDF fit (68% C.L.)
$xs_v(x,Q_0^2 = 1\ \mathrm{GeV}^2)$
$s_v = s - \bar{s}$
$\int_0^1 dx\ xs_v(x,Q_0^2) = 0.0024^{+0.0024}_{-0.0016}$
$x_0 = 0.0161$
0.03
0.02
0.01
0
-0.01
10^{-2}
10^{-1}
1
x

NuTeV Analysis of s, sbar Quark Dist'ns

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

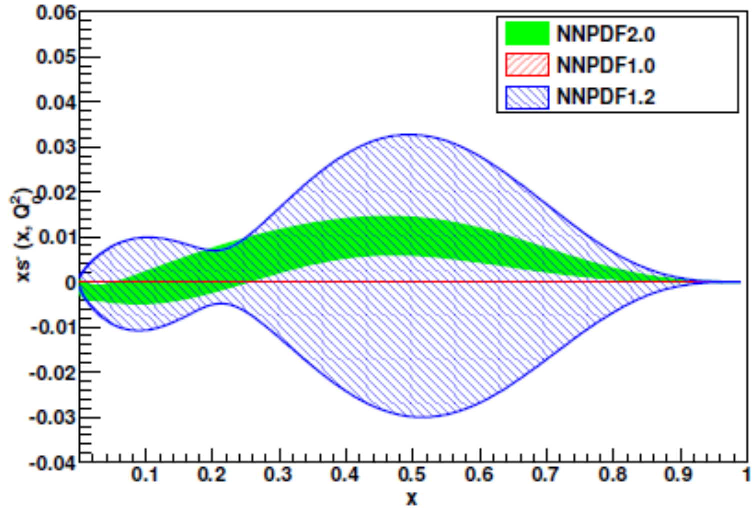


NuTeV: crossover point too small for any of these models

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 Strange Quark Asymmetry



$$S^{-} = 0.0038 \pm 0.0018$$

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!

Example: Meson-Cloud Contributions to the Gottfried Sum Rule

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

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

- 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 $\pi^- = (d\bar{u})$.

Flavor Asymmetry in the Quark Sea

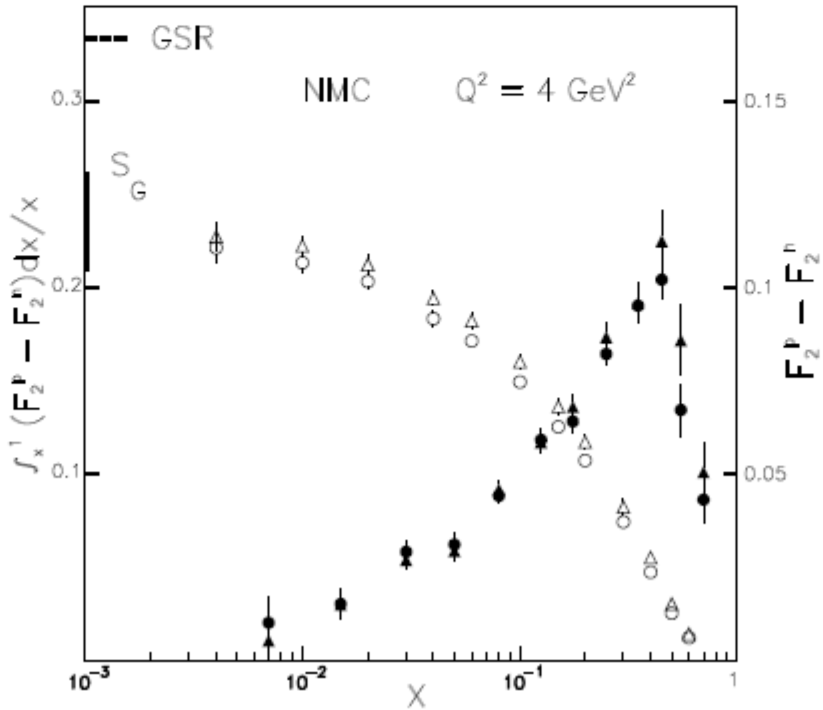
NMC Expt (Amaudruz etal, PRL66, 2712 (91)): measured F_2 in μ-p, μ-D reactions
Constructed the Gottfried Sum Rule S_G

$$S_G = < \frac{F_2^{\mu p} - F_2^{\mu n}}{x} > = \frac{1}{3} - \frac{2}{3} < \bar{d} - \bar{u} >$$
$$= 0.235 \pm 0.026 \Rightarrow < \bar{d} - \bar{u} > \approx 0.147 \pm 0.039$$

Strong evidence for flavor asymmetry in proton sea (a **4-** σ 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

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

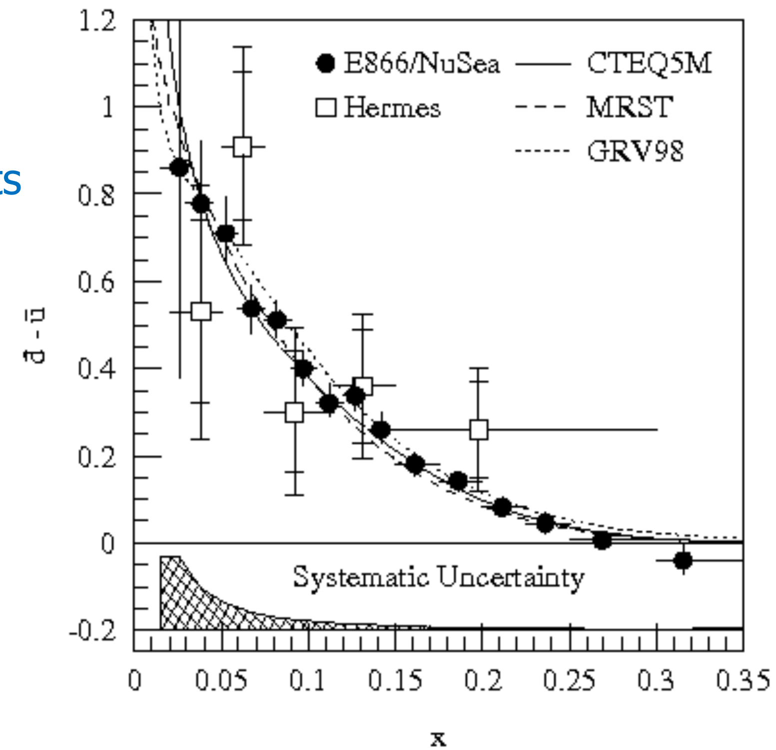
- E866/NuSea Exp't at FNAL: 450 GeV p on p, D targets

extract $\bar{d}/\bar{u}$ vs x at $Q^2 \sim 54$ 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

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



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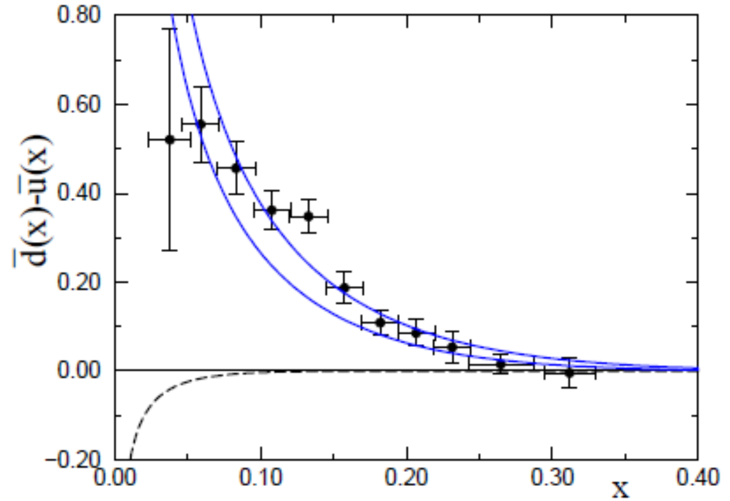
S. Kumano, Phys. Rept. **303**, 183 (1998).
J. Speth and A.W. Thomas, Adv. Nucl. Phys. **24**, 83 (1998)
G.T. Garvey and J.C. Peng, Prog. Part. Nuc. Phys. **47**, 203 (2001)
J.C. Peng and J-W. Qiu, arXiv:1401.0934

Meson-Cloud Calculation of $\bar{d} - \bar{u}$.

Meson-cloud calculation by Nikolaev etal;
Solid curves: πN 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: πΔ 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 etal, J Phys **G22**, 1741 (1996);
Chiral soliton model, Pobylitsa etal, PR **D59**, 034024 (1999);
Instanton model, Dorokhev & Kochelev, P Lett **B259**, 335 (1991);
BHPS model, Chang & Peng, PRL **106**, 252002 (2011).

N.N. Nikolaev, W. Schaefer, A. Szczurek and J. Speth, PR **D60**, 014004 (1999).