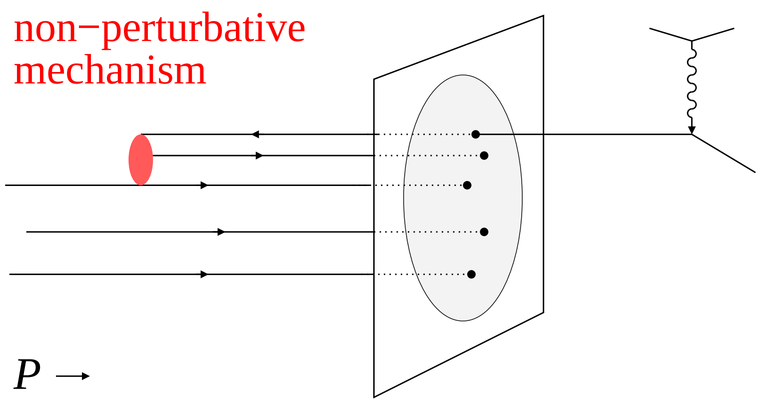
Antiquark flavor asymmetries: Origin and probes

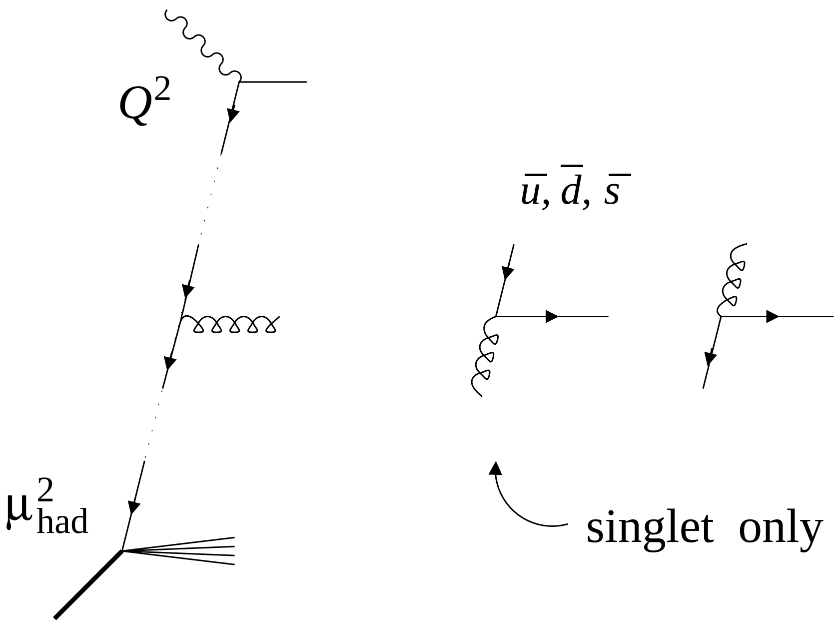
C. Weiss (JLab), "High-energy hadron physics," KEK Japan, 06–Jan-10



- $\rightarrow$ Nucleon as a many-body system: $3q, 5q \ldots$
- $\rightarrow$ QCD vacuum structure: Non-pert. fields, $q\bar{q}$ pairs, cf. Euclidean approaches
- $\rightarrow$ Chiral dynamics

- Sea quarks: Why non-singlets
  - QCD evolution, non-pert. origin
  - Experimental status of $\bar{d} - \bar{u}$ etc.
- Non-singlet sea and nucleon structure
  - Quark models: Pauli blocking
  - Pion cloud model
  - QCD: Chiral dynamics, large–N_c limit **NEW**
- Polarization and strangeness
  - $\Delta\bar{u} - \Delta\bar{d}$ in SIDIS, $W^{\pm}$ in pp
  - $s - \bar{s}$ from charm
- Future studies
  - $\bar{d}/\bar{u}$ at LHC, SIDIS with EIC
  - $k_{\perp}$ dependence, transverse spatial structure

Non-singlet sea: QCD evolution



$\bar{u} + \bar{d} + \bar{s}$ singlet

$\bar{u} - \bar{d}$ non-singlet

$\bar{u} + \bar{d} - 2\bar{s}$ non-singlet

- Non-singlet sea quark distributions do not mix with gluon
  cf. valence $q - \bar{q}$

- Total numbers conserved in LO

$$\int dx \left[\bar{u} - \bar{d} \right] (x, Q^2) \quad = \quad \text{const}$$

$$\Delta\bar{u} - \Delta\bar{d} \quad \text{etc.}$$

NLO: Weak Q^2–dependence

- Non-singlet sea distributions are of non-perturbative origin!

“Creation, not evolution”

Non-singlet sea: Higher–order QCD corrections

$$I_G \equiv \int_0^1 \frac{dx}{x} \left[F_2^p - F_2^n\right](x, Q^2)$$

$$= \frac{1}{3} + \frac{2}{3}\int_0^1 dx\, \left[\bar{u} - \bar{d}\right] \quad \text{LO}$$

↓ NNLO

$$\frac{1}{3}\left[1 + 0.0355\,\frac{\alpha_s}{\pi} - 0.811\left(\frac{\alpha_s}{\pi}\right)^2\right]$$

- Example: Gottfried sum

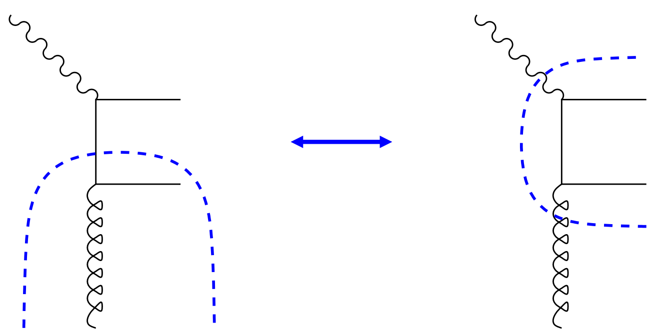
  $$q + \bar{q} \;\rightarrow\; (q - \bar{q}) + 2\bar{q}$$

- Higher–order QCD corrections small

  Corrections for flavor–symmetric sea computed to order α_s^2 Kataev, Parente 03

- Deviation from $1/3$ must be of non-perturbative origin

Non-singlet sea: Scheme dependence



$C_q \times \bar{q}(x)$ $C_g \times G(x)$

- NLO: PDFs generally depend on factorization scheme

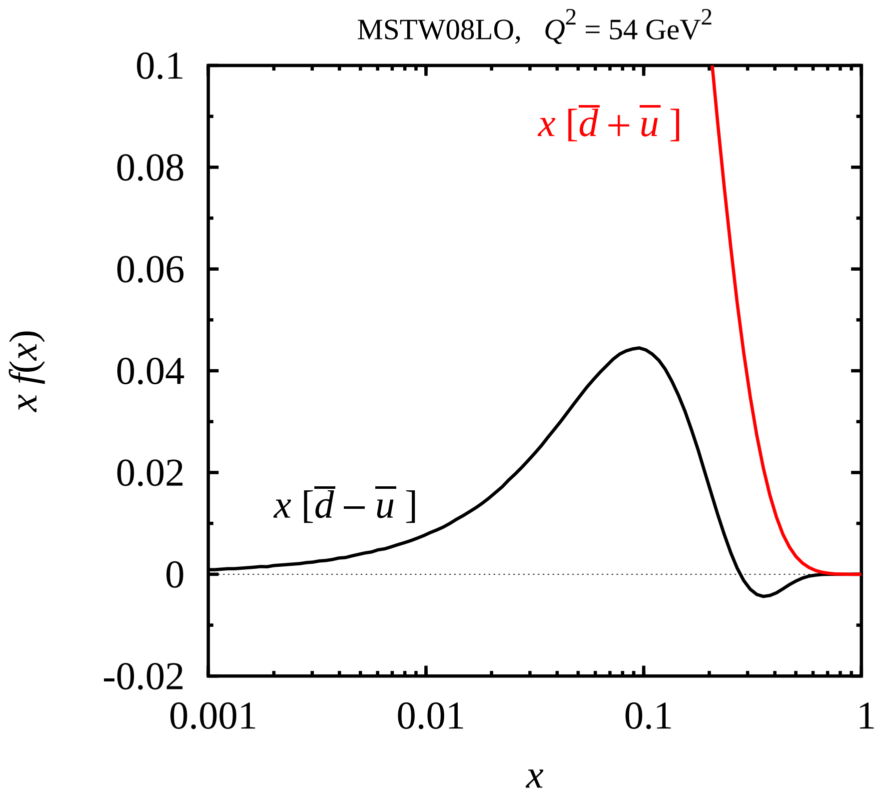
  Particularly $\Delta\bar{q} \leftrightarrow \Delta G$

- Non-singlets much less affected than singlets

- Unambiguous matching pQCD $\leftrightarrow$ non-perturbative models in non-singlet sector

Non-singlet sea quarks “messengers” between small–distance and large–distance structure

Non-singlet sea: x dependence



- Non–singlets not affected by rise of gluon density at small x
- Main strength at $0.01 < x < 0.3$ ($Q^2 \sim$ few 10 GeV^2)

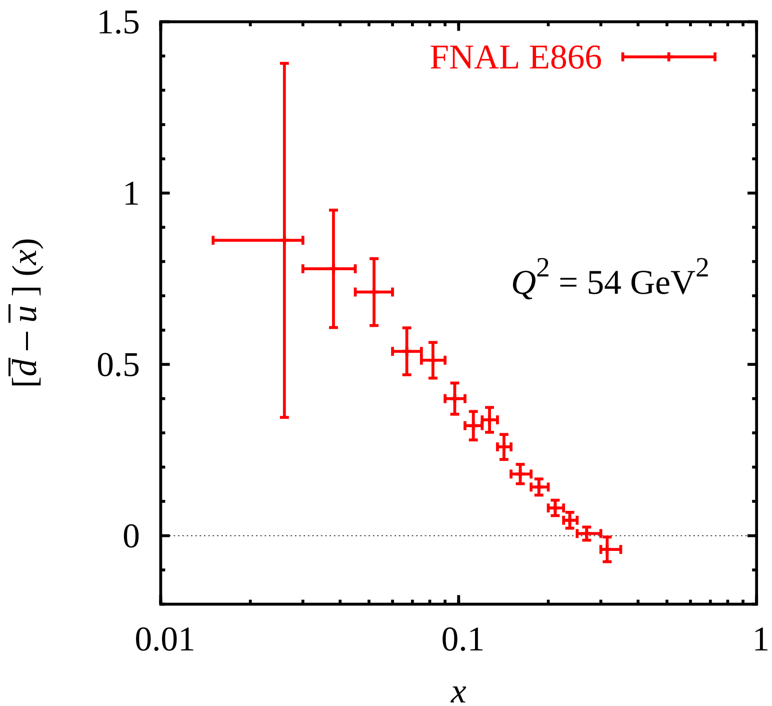
Similar for $\Delta\bar{u} - \Delta\bar{d}$ predictions → later

Non-singlet sea: Experimental data on $\bar{d} - \bar{u}$

$$I_G \equiv \int_0^1 \frac{dx}{x} \left[F_2^p - F_2^n\right]$$

$$= \frac{1}{3} + \frac{2}{3} \int_0^1 dx \, \left[\bar{u} - \bar{d}\right] \quad \text{LO}$$

$$= 0.235 \pm 0.026 \quad \text{NMC, } Q^2 = 4 \text{ GeV}^2$$



- Gottfried integral from $eN/\mu N$ DIS
  SLAC 75, EMC 87, BCDMS 90, NMC 94

  Higher–order QCD corrections Kataev, Parente 03

  Nuclear corrections? Guzey et al. 01

- x–dependence from pp/pD Drell–Yan
  CERN NA51 94, FNAL E866 98/01

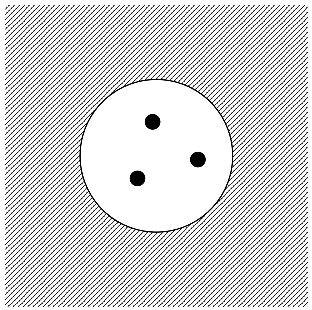
  $\bar{d} - \bar{u}$ extracted from measured $\bar{d}/\bar{u}$ with help of PDF parametrization

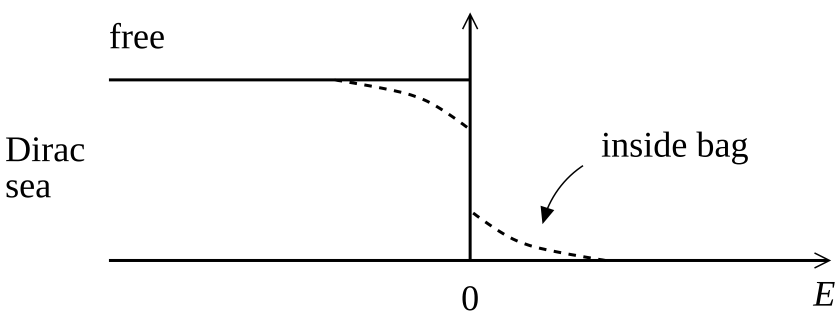
  Does it turn negative at $x > 0.3$?

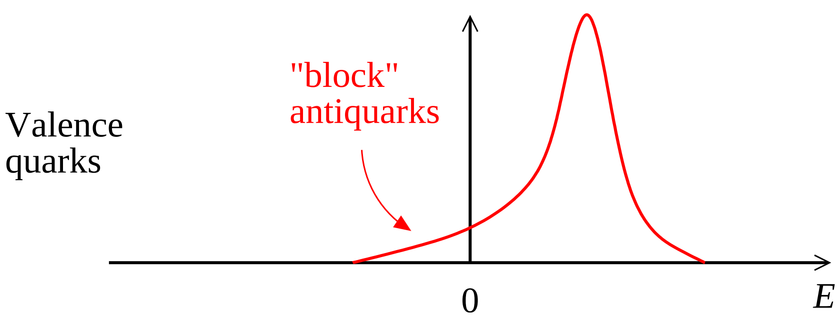
- Semi-inclusive DIS $eN \rightarrow e' + h + X$
  HERMES 98/08

  $\bar{d} - \bar{u}$ compatible with Drell–Yan data

Nucleon structure: Quark models







- “Pauli blocking” of $q\bar{q}$ pairs by valence quarks qualitatively explains $\bar{d} > \bar{u}$
  Feynman, Field 77

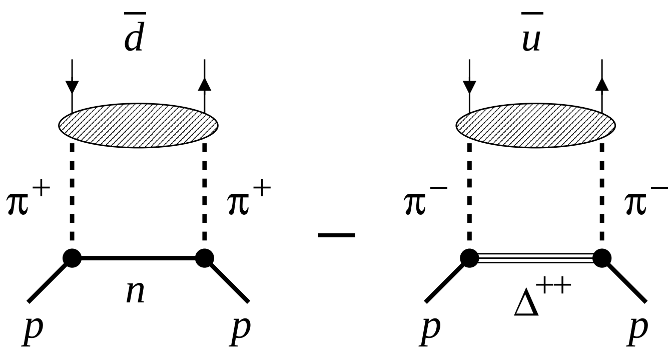
  Details model–dependent!

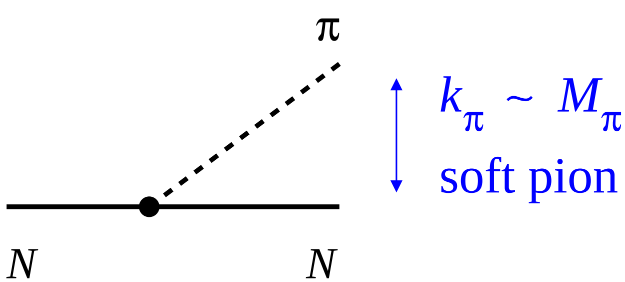
- Bag model: Cavity creates non-pert. sea of $\bar{q}q$ pairs, cf. temperature $T \neq 0$
  Signal, Thomas 88; Schreiber et al. 91; see also: Bourrely, Soffer 95

- Dirac wave functions of confined valence quarks have negative–energy components, block antiquarks: $\bar{d} > \bar{u}$

- Polarization: Model–dependent, $\Delta\bar{u} > \Delta\bar{d}$ from spin–0 pairs
  Bhalerao et al. 99; Glück, Reya 00; Cao, Signal 01

Nucleon structure: Pion cloud model





- Qualitatively explains why $\bar{d} > \bar{u}$
  Sullivan 72, Thomas 83

- Quantitative modeling: Extensive work
  Jülich Group 90's. Reviews Kumano 98; Garvey, Peng 01

  Realistic soft πN formfactors give at most 50% of exp. $\bar{d} - \bar{u}$

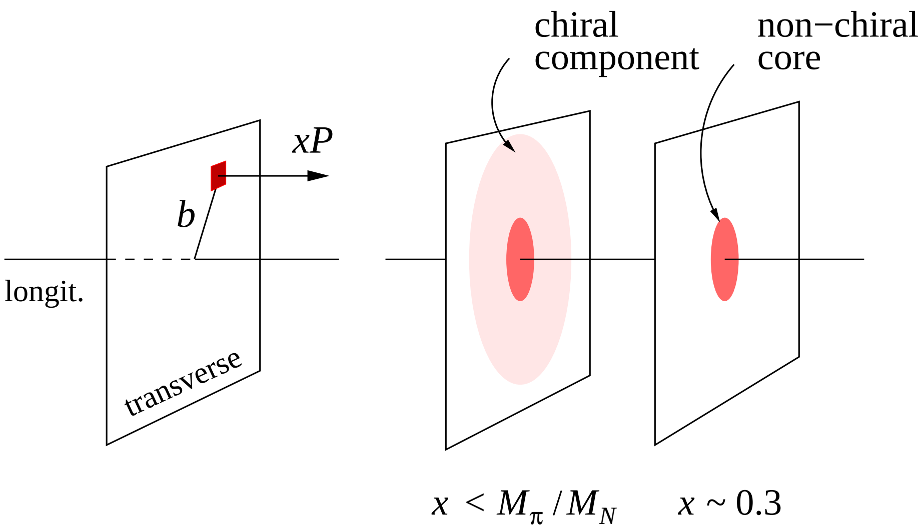
  Strong cancellations between N and Δ intermediate states

- Principal theoretical questions

  How to formulate concept of "pion cloud" in partonic structure consistently with chiral dynamics?

  How to interpret/handle cancellations between N and Δ?

Nucleon structure: Chiral dynamics

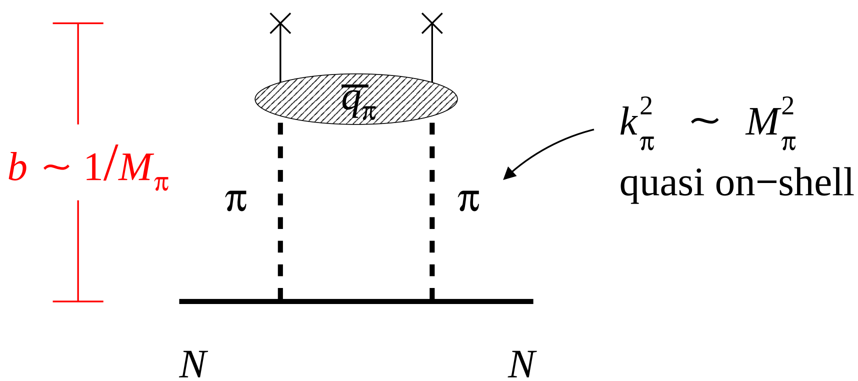


- Impact parameter–depend. PDF

$$q(x) \; = \; \int d^2 b \; q(x, b)$$

- Chiral dynamics generates unique large–distance component

$$b \sim 1/M_\pi$$
$$x < M_\pi / M_N$$



- Calculable from soft–pion exchange

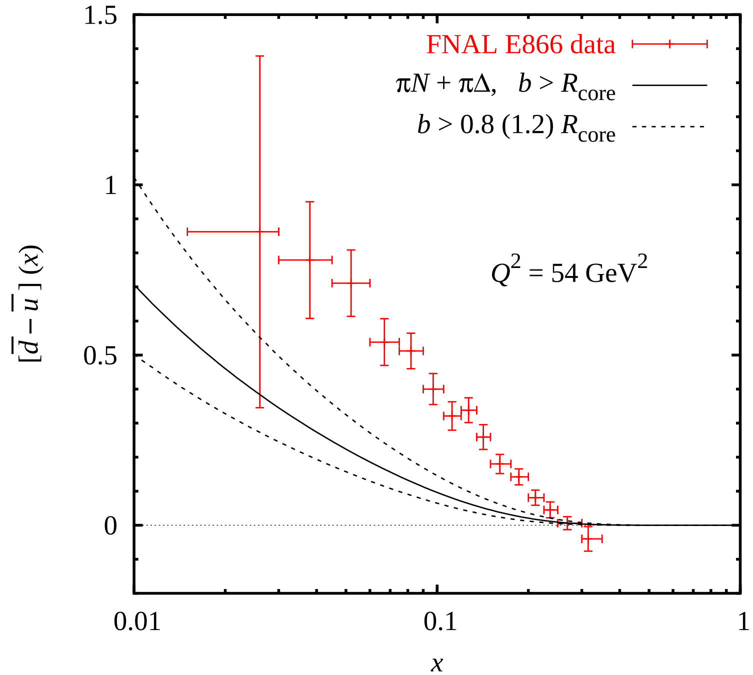
  Independent of short–distance dynamics, no πN form factors

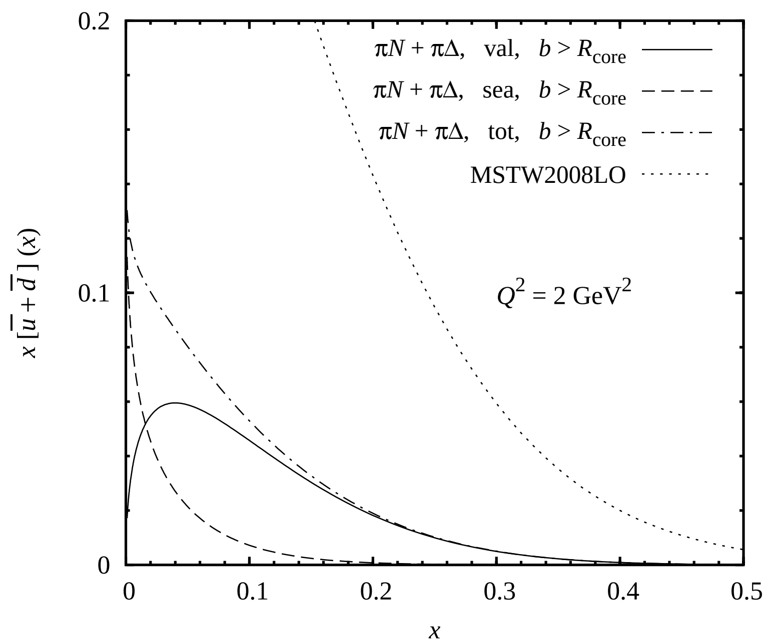
  Yukawa tail with x–dependent range of order $1/(2M_\pi)$

Model–independent formulation, consistent with chiral dynamics

Strikman, CW PRD **69**, 054012 (2004); PRD 2009, in press

Nucleon structure: Chiral dynamics





- Quantify contribution of large–b region to sea quark densities in nucleon

  $R_{\text{core}} \sim 0.55\,\text{fm}$ estimated from transverse axial charge radius

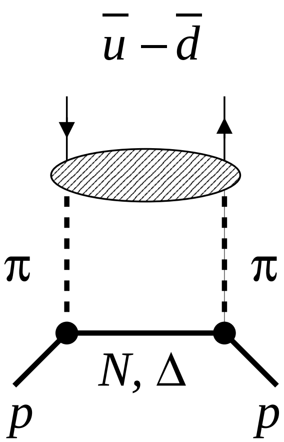
- Chiral component accounts for only $\sim 1/3$ of observed $\bar{d} - \bar{u}$!

  Singlet $\bar{u} + \bar{d}$ in chiral component only $\sim 1/5$ of observed value

Flavor asymmetry sits mostly in core, at transverse distances $b < 0.55\,\text{fm}$

Strikman, CW 09

Nucleon structure: Large–N_c limit of QCD



- General N_c–scaling of PDFs in QCD Diakonov et al. 96

$$\bar{u} - \bar{d} \sim N_c \times \text{function}(N_c x), \quad x \sim 1/N_c$$

- Nucleon intermediate state alone gives

$$\bar{u} - \bar{d} \sim N_c^2 \times \text{function}(N_c x)$$ ↯ too high!

- But N and Δ degenerate at large N_c:

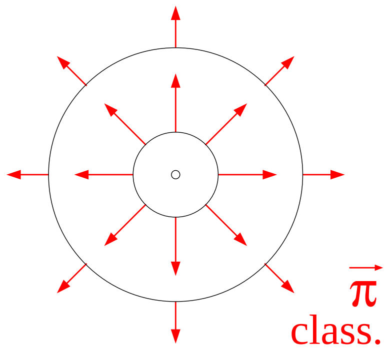
$$M_N - M_\Delta \sim 1/N_c, \quad g_{\pi N \Delta} = \frac{3}{2} g_{\pi NN}$$

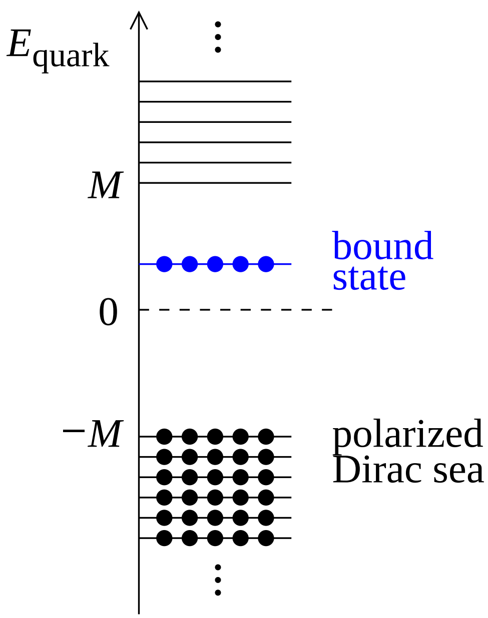
Cancellation restores proper N_c scaling!

Δ essential for proper N_c scaling of pion cloud clontribution

Strikman, CW 03/09

Nucleon structure: Chiral quark–soliton model





- Generic model of nucleon based on

  Large–N_c limit of QCD
  Effective non-linear chiral dynamics

- Quarks move independently in self–consistent classical pion field ("soliton")

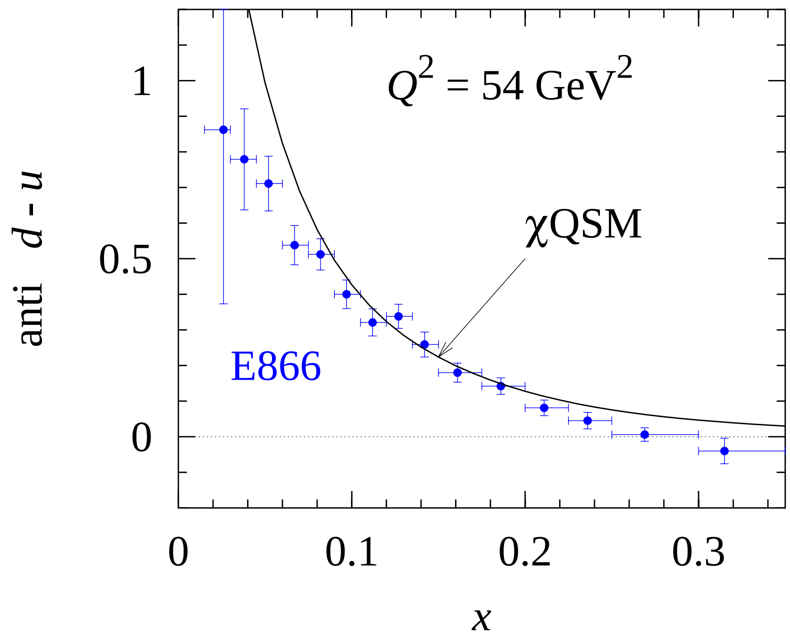
- Fully relativistic, field–theoretical description: Completeness of states

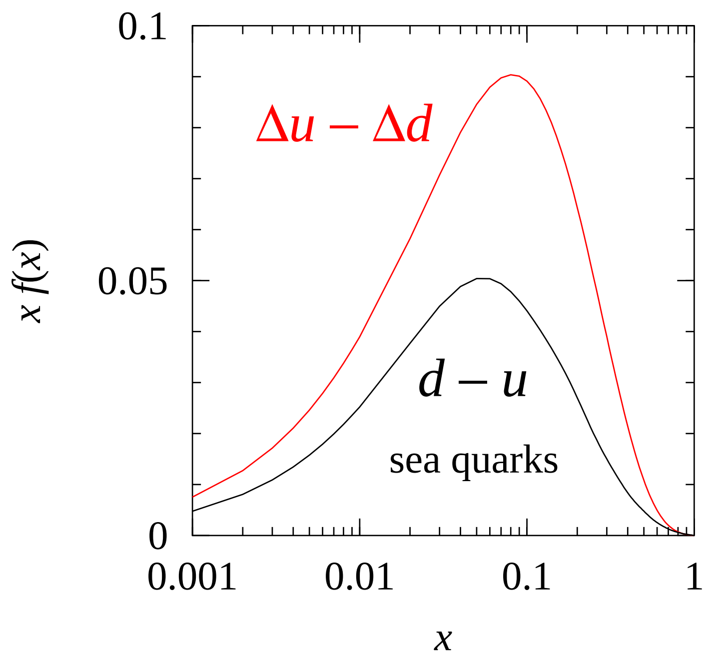
  Partonic sum rules
  Positivity $q(x), \bar{q}(x) > 0$

- Describes PDFs at scale $\mu \sim 0.6\,\text{GeV}$ ("cutoff" of chiral symmetry breaking)

Basics: Diakonov, Petrov, Pobylitsa 88; PDFs: Diakonov et al. 96+

Nucleon structure: Chiral quark–soliton model

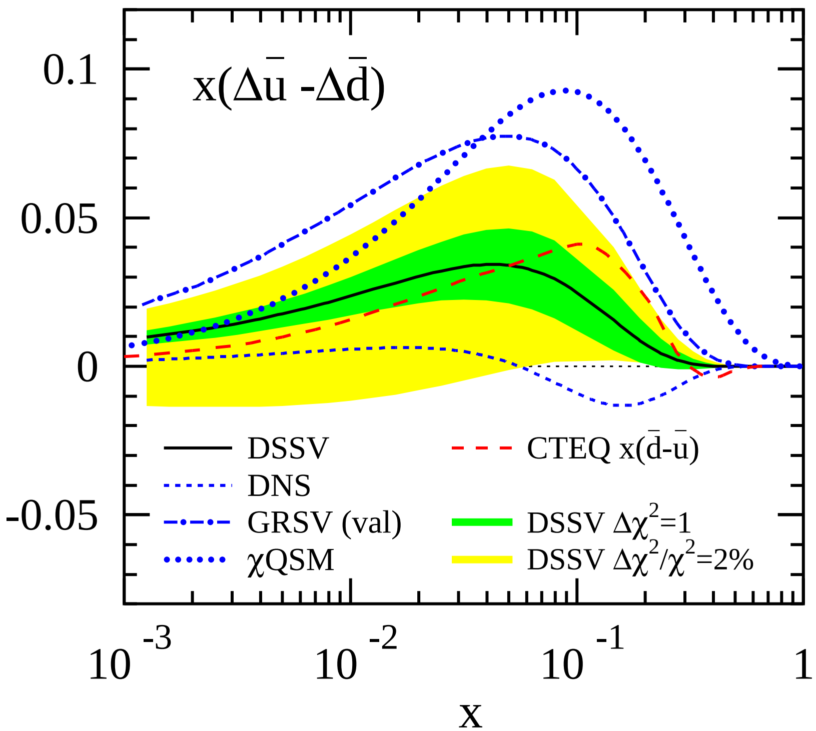


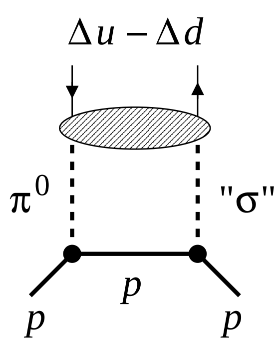


- Describes $\bar{d} - \bar{u}$ data parameter–free!
- Predicts large $\Delta\bar{u} - \Delta\bar{d} > 0$
- SU(3) symmetry: $\Delta\bar{u} + \Delta\bar{d} - 2\Delta\bar{s} \; = \; \dfrac{3F - D}{F + D}(\Delta\bar{u} - \Delta\bar{d})$ [num: 5/9]

Diakonov et al. 96, Pobylitsa et al. 98

Polarized asymmetry: Theory and SIDIS results





- $1/N_c$ expansion of QCD

  $\Delta\bar{u} - \Delta\bar{d}$ leading cf. $g_A^{(3)} \sim N_c$

  $\bar{d} - \bar{u}$ subleading $I_3 \sim 1$

- Chiral quark–soliton model predicts large $\Delta\bar{u} - \Delta\bar{d} > 0$
  Diakonov et al. 96/97; Wakamatsu 97

- Meson cloud picture: π-σ interference
  Fries, Schäfer, CW 03

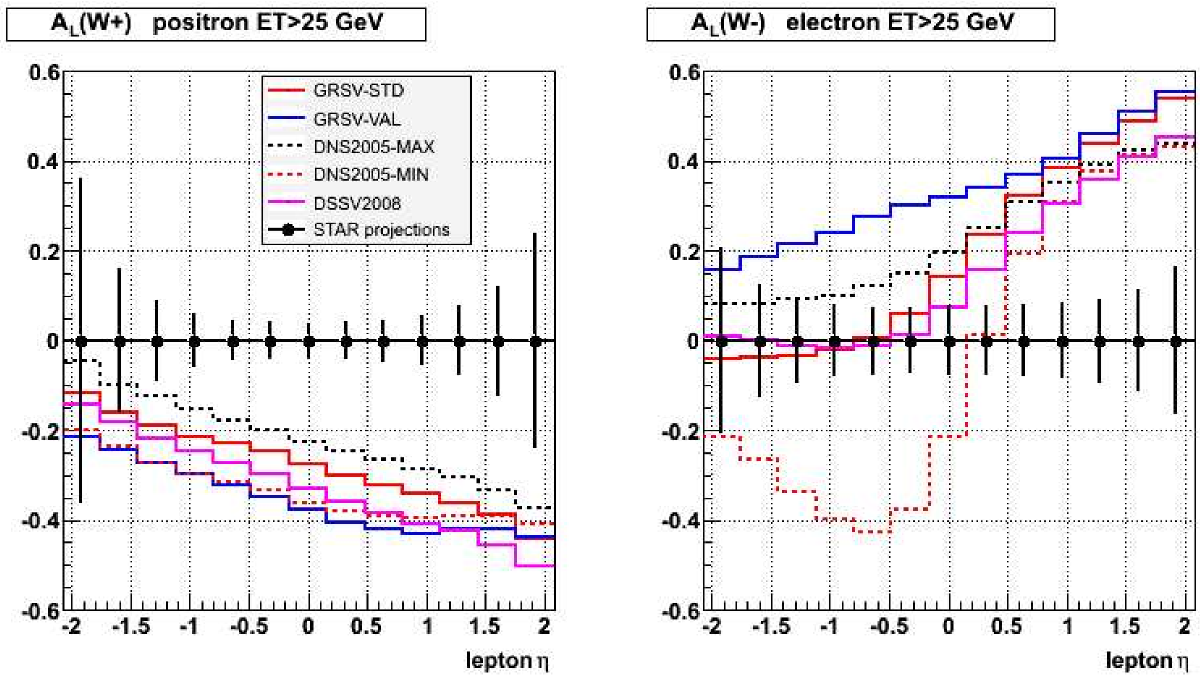
  Not a serious model, but explains why large $\Delta\bar{u} - \Delta\bar{d}$ natural

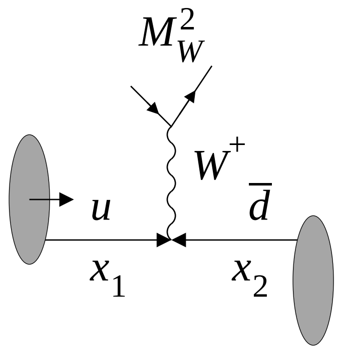
  Vector mesons ρ negligible

- First sign of $\Delta\bar{u} - \Delta\bar{d} > 0$ in global analysis of DIS/SIDIS data
  De Florian, Sassot,Stratmann Vogelsang 08

  HERMES 04 SIDIS results inconclusive

Polarized asymmetry: $W^{\pm}$ at RHIC



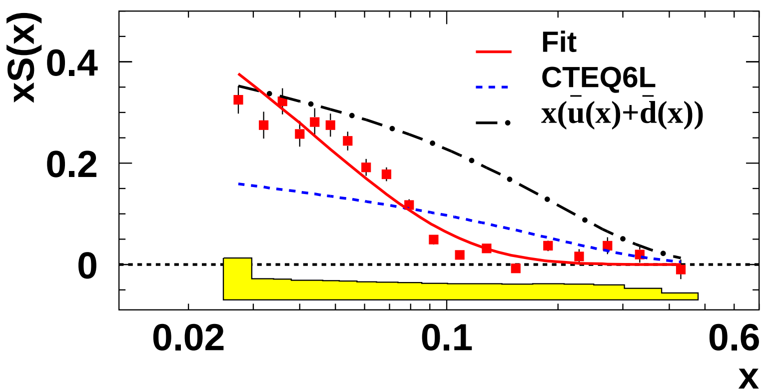


Projected STAR results for 300 pb^{-1} from J. Sowinski, arXiv:0901.4581 [hep-ex].
Based on RHICBOS generator of Nadolsky, Yuan 03

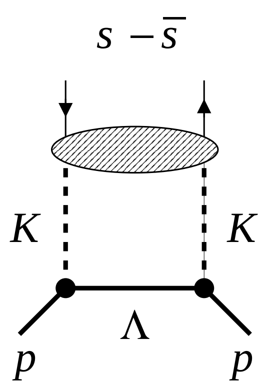
- Single–spin asymmetry $A_L^{W+} = \dfrac{\Delta u(x_1)\bar{d}(x_2) - \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$

High sensitivity to $\Delta\bar{u} - \Delta\bar{d}$, but also to ΔG

Strangeness: $SU(3)$ nonsinglet and $s \neq \bar{s}$



HERMES 08 semi-inclusive DIS analysis



- $SU(3)$ non-singlet $\bar{u} + \bar{d} - 2\bar{s}$ extracted from $eN + \nu N$ DIS assuming $s = \bar{s}$

- HERMES SIDIS results suggest large $SU(3)$ non-singlet at $x > 0.1$

  Kaon fragmentation still poorly understood

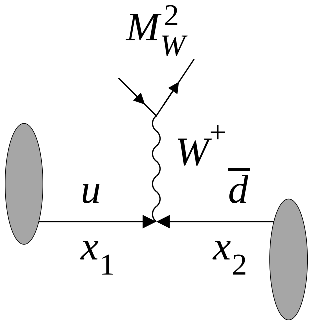
  Strong correlation $x \leftrightarrow Q^2$

- Speculations that $s(x) \neq \bar{s}(x)$

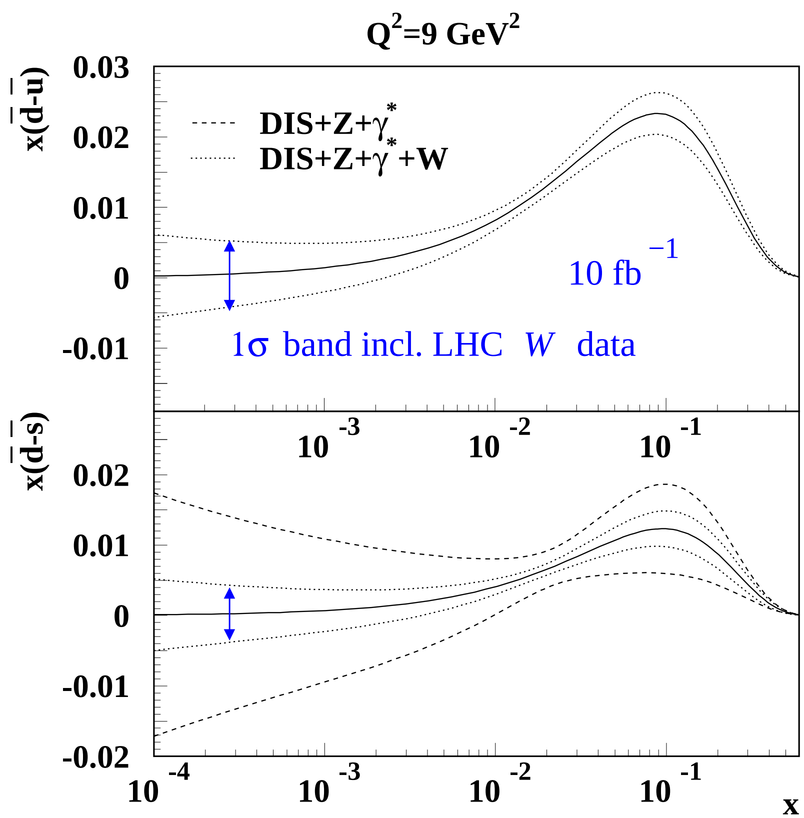
  CC neutrino DIS can discriminate between s and $\bar{s}$ via $W^+ + s \to c \to D$ meson

  Meson cloud model with $K\Lambda$ not quantitative: No separation between K and Λ; model describes only small fraction of total $s + \bar{s}$.
  Brodsky, Ma 96

Future studies: Antiquarks from W, Z at LHC



$$x_{1,2} = \frac{M^2}{\sqrt{s}} e^{\pm y}$$



M. Dittmar et al., HERA LHC Workshop Proceedings; hep-ph/0511119

- PDFs are crucial infrastructure for particle physics at LHC

- LHC measurements will dramatically enlarge data set for PDF fits

  Small x $\rightarrow$ resummation, saturation

  Very high masses $M \sim$ few TeV at large x

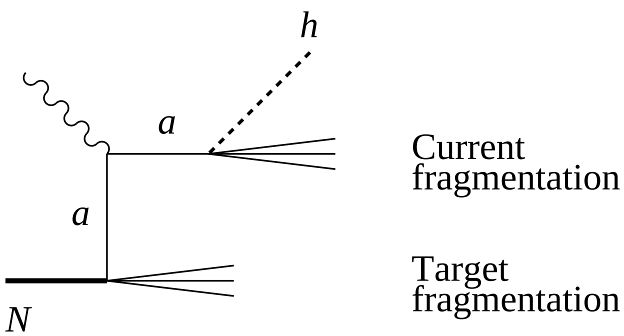
  Flavor through W, Z

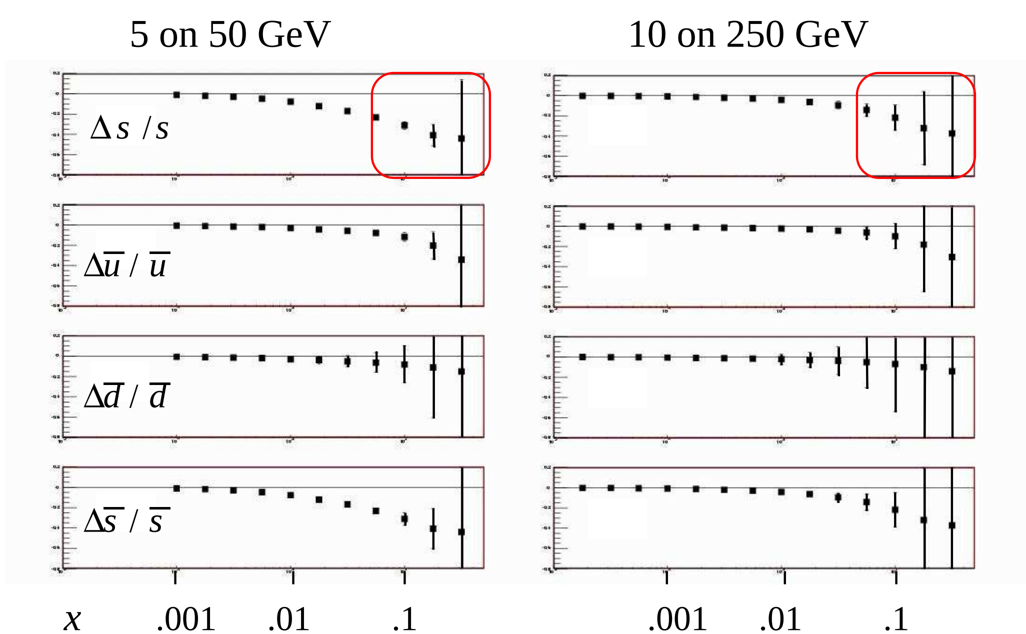
- d/u and $\bar{d}/\bar{u}$ from $W^{\pm}$

  Rates of 200 W/sec before cuts!

  Acceptance $|y| < 2.5, \ 10^{-3} < x < 10^{-2}$

Future studies: SIDIS with EIC





E. Kinney, J. Seele, 07–09

- JLab 12 GeV: SIDIS in valence region. Spin/flavor separation of sea a major objective for EIC

- Want sensitivity at $x > 0.1$

  Non-singlets $\bar{d} - \bar{u}, s - \bar{s}, \ldots$

  Relative polarization $\Delta q / q$

- Ideal w. lower–energy, more symmetric collider, e.g. 5/50–10/50 GeV

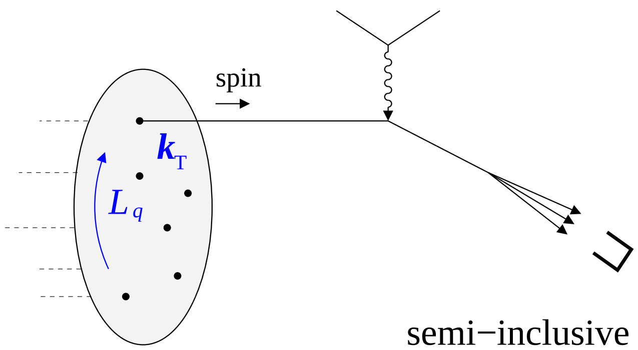
  Constraint $Q^2 > sxy_{\rm min}$ allows for wide range of Q^2 above 1 GeV^2

  Good particle ID for low–energy π, K

- Interesting: Target fragmentation and flavor correlations

  K in current, Λ in target FR, . . .

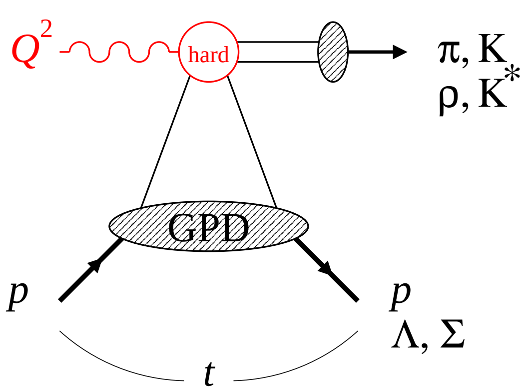
Outlook: k_T dependence, spatial distribution

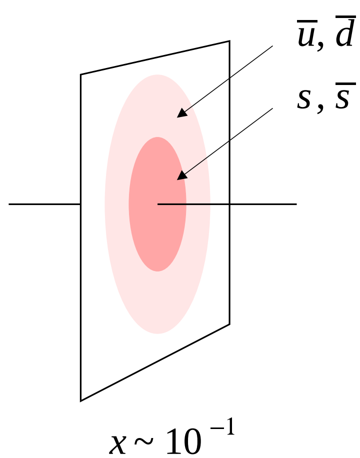


- k_T dependence of sea quarks from SIDIS

  Additional information about non-perturbative origin

  Indications of large sea quark Sivers function





- Transverse spatial distribution of sea quarks from exclusive processes

  Area$(q + \bar{q})$ > Area(gluons) at $x < 0.1$ from chiral dynamics, cf. HERA data
  Strikman, CW 09

  Individual flavor distributions from exclusive π, ρ^+, K, K^*

Summary

- Non-singlet sea particularly interesting for nucleon structure: Non-perturbative origin, weak scale/scheme dependence

- Concept of “pion cloud” formulated consistently with chiral dynamics; accounts for only $\sim 1/3$ of observed asymmetry $\bar{d} - \bar{u}$

- Polarization and strangeness–related asymmetries will test dynamical models in much greater detail