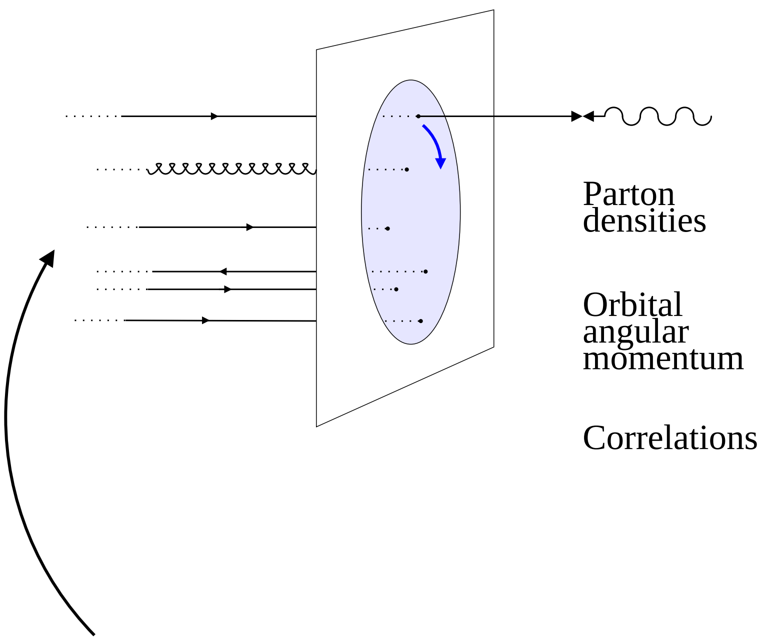
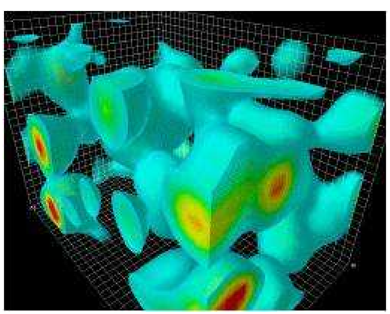
Exploring nucleon structure with longitudinal spin

C. Weiss (JLab), Spin Workshop at RHIC & AGS Users' Meeting, 20–Jun–11





- Nucleon structure in QCD

  Non–perturbative vacuum

  Rest frame vs. parton picture

- Non–singlet sea $\Delta\bar{u} - \Delta\bar{d}, \;\; \Delta\bar{u} + \Delta\bar{d} - 2\Delta\bar{s}$

  Why non-singlets

  Role of chiral dynamics

  Exp. results: SIDIS, $W^{\pm}$ at RHIC

- Gluons and orbital angular momentum

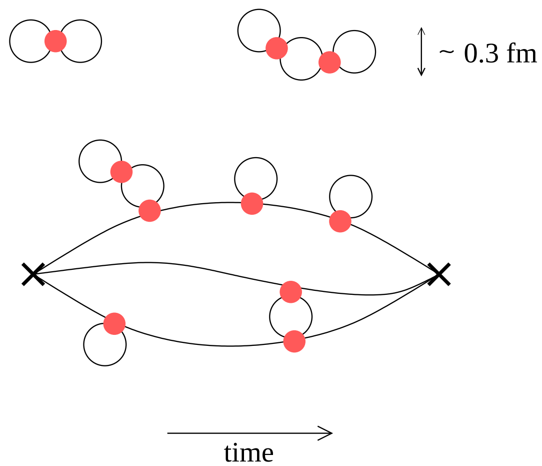
  Status of ΔG

  Comments on OAM challenges

- Beyond densities: Correlations

  Twist–3, 4 from g_1, g_2

Nucleon structure in QCD



- QCD vacuum not empty

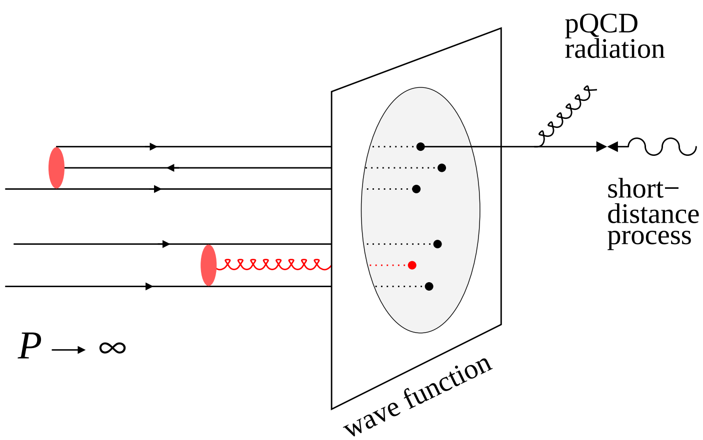
  Strong gluon fields of size $\mu_{\rm vac}^{-1} \ll 1\,{\rm fm}$

  $\bar{q}q$ pair condensate, π as collective excitation

- Nucleon at rest

  $t \rightarrow i\tau$ statistical mechanics Lattice, analytic methods
  $\langle N|O|N\rangle$ from correlation functions

  No concept of "particle content!"



- Nucleon fast–moving $P \gg \mu_{\rm vac}$

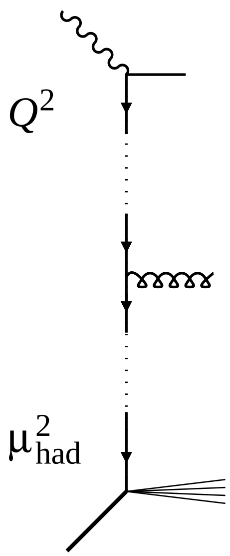
  Closed system: Wave function description,
  components with different particle number
  Feynman, Gribov

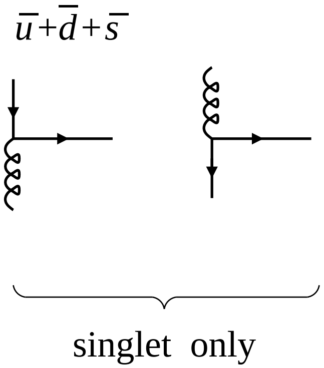
  Short–distance probe: "Snapshot"

  Physical properties: Number densities $f(x)$,
  transverse spatial distributions, orbital motion,
  correlations, . . .

  Correspondence between rest frame and partonic picture is subtle!
  Not all fields project on physical particle states

Non–singlet sea: QCD evolution





- Non-singlets do not mix with gluon

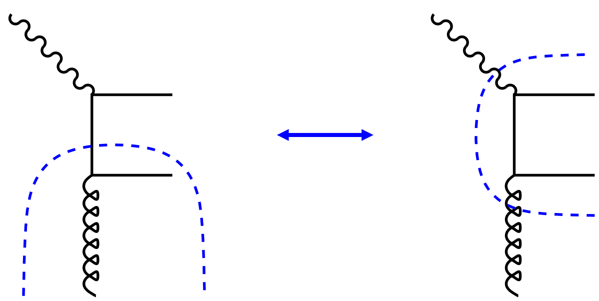
$\bar{u} + \bar{d} + \bar{s}$	singlet
$\bar{u} - \bar{d}$	non-singlet
$\bar{u} + \bar{d} - 2\bar{s}$	non-singlet

- Total numbers conserved in LO

$$\int_0^1 dx\, [\bar{u} - \bar{d}]\, (x, Q^2) \;=\; \text{const} \;+\; O(\alpha_s)$$

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

Must be of non-perturbative origin!



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

- Practically scheme–independent in NLO

Unambiguous matching QCD $\leftrightarrow$ effective models

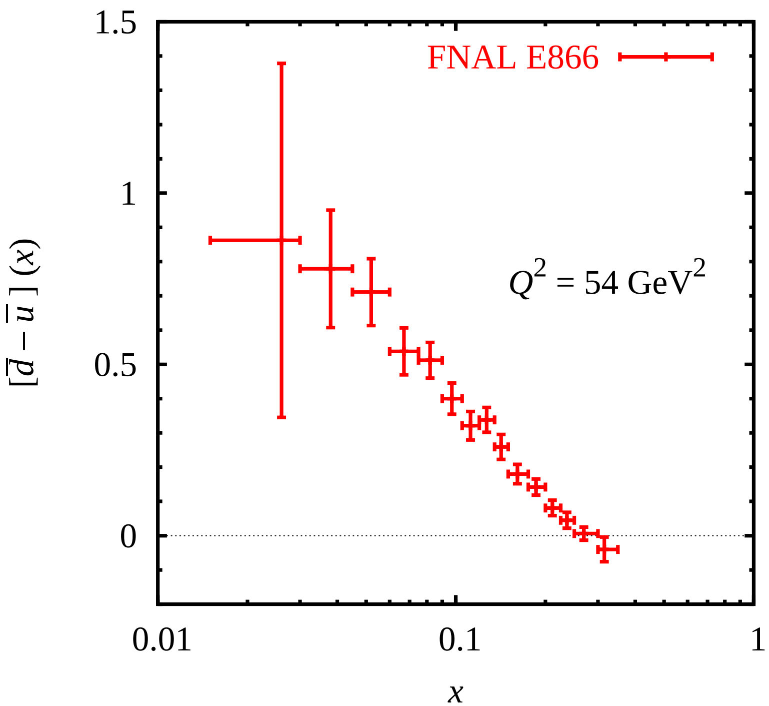
> Non–singlets are "messengers" between short– and long–distance structure

Non–singlet sea: Unpolarized asymmetry

$$I_G \equiv \int_0^1 dx\, \frac{F_2^p - F_2^n}{x}$$

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

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



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

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

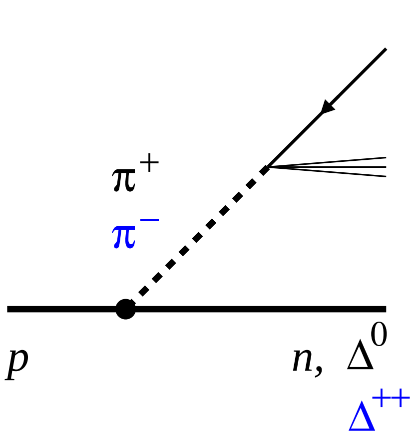
  Very weak scale dependence at NLO
  $\frac{1}{3}[1 + 0.0355\, \alpha_s/\pi + O(\alpha_s^2)]$

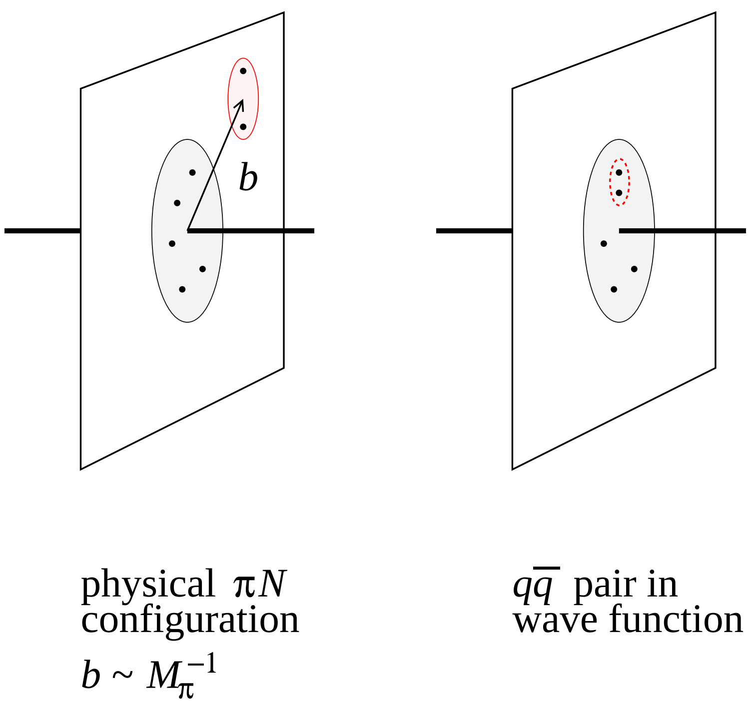
- x–dependence from pp/pD Drell–Yan
  CERN NA51 94, FNAL E866 98/01. Larger x with JPARC?

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

- Semi-inclusive DIS data compatible with Drell–Yan HERMES 98/08

Non–singlet sea: Chiral dynamics





- Pion cloud model Sullivan 72, Thomas 83

  Qualitatively explains why $\bar{d} > \bar{u}$

  Problems with quantitative description: π highly virtual, sits "inside" nucleon

- Consistent formulation based on transverse spatial structure of configs
  cf. GPDs. Strikman, CW, PRD80 (2009) 114029

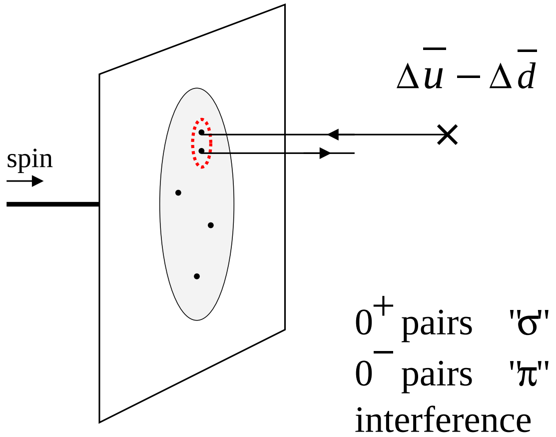
  Large–b component model–independent, calculable from chiral Lagrangian (χPT)

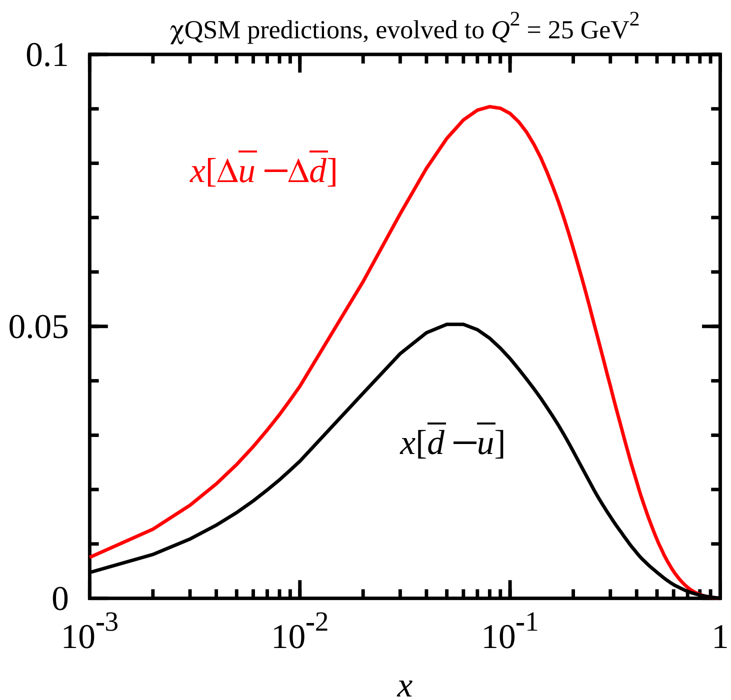
  Distances $b > 0.5\,\text{fm}$ account only for $< 30\%$ of experimental $\bar{d} - \bar{u}$

  Most of asymmetry due to $q\bar{q}$ pairs "deep inside" nucleon!

$\bar{d} - \bar{u}$ tests chiral vacuum structure at distances $\ll 1\,\text{fm}$

Non–singlet sea: Polarized asymmetry





- $\Delta\bar{u} - \Delta\bar{d} > 0$ from interference of 0^+ and 0^- $q\bar{q}$ pairs in wave function
  Dressler et al. EPJ C14 (2000) 147. Cf. π–σ interference in meson cloud model: Fries et al. EPJ A17 (2003) 509

  Supplied by chiral symmetry breaking in QCD vacuum!

- Dynamical realization: Chiral quark–soliton model of nucleon
  Diakonov et al. NPB480 (1996) 341; PRD56 (1997) 4069

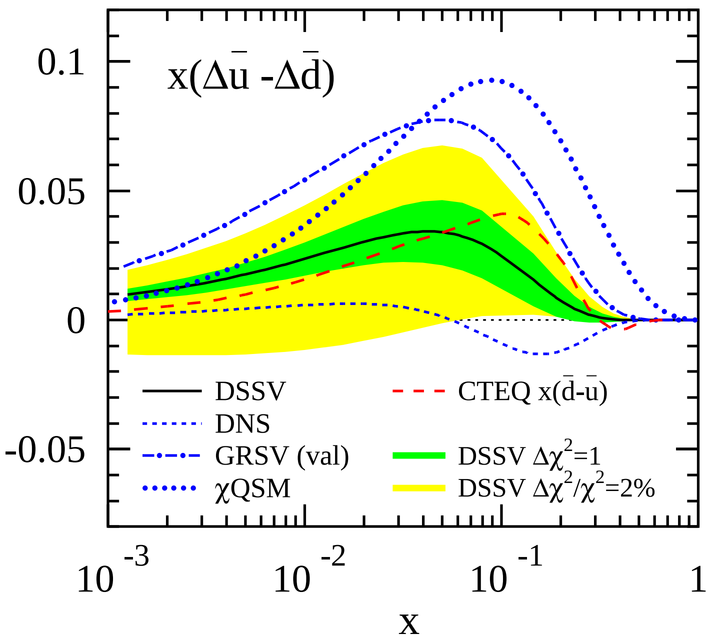
  Relativistic mean–field description based on large–N_c limit of QCD

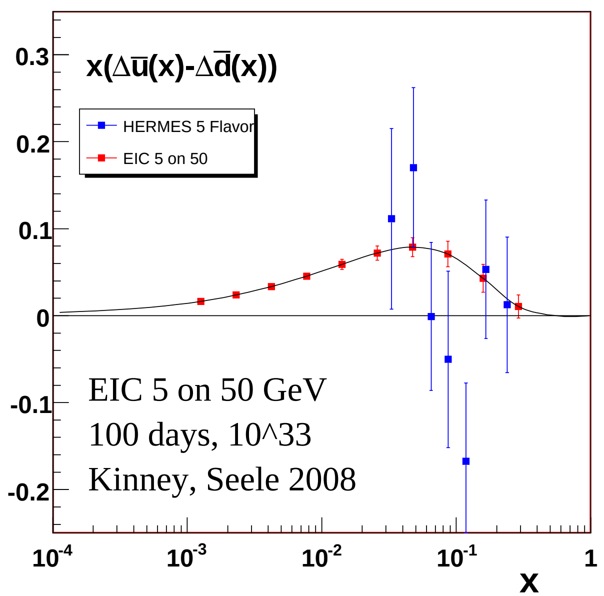
  Matches with soft–pion dynamics (χPT) at large b

  Describes well $\bar{d} - \bar{u}$, parameter–free

$\Delta\bar{u} - \Delta\bar{d}$ from dynamical chiral symmetry breaking in QCD vacuum

Non–singlet sea: Polarized asymmetry from SIDIS





- Indications of $\Delta\bar{u} - \Delta\bar{d} > 0$ in NLO global analysis of DIS/SIDIS data
  De Florian, Sassot,Stratmann Vogelsang 08 (incl. pp);
  Leader, Sidorov, Stamenov 10/11

  DSSV describes also recent COMPASS data, still current Stratmann, DIS2011 Spin WG

  HERMES 04 SIDIS results inconclusive

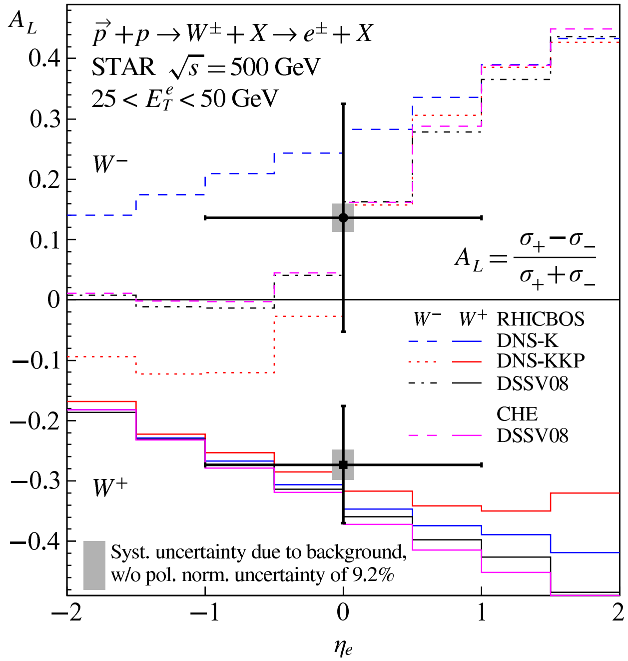
- Planned with JLab 12 GeV
  Hall A proposal: X. Jiang et al.

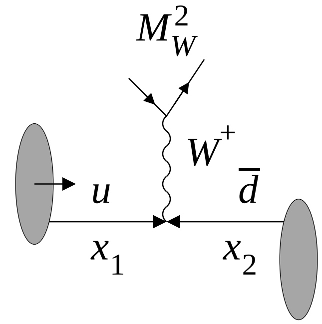
  Need better understanding of production mechanism in limited phase space with $W \sim$ few GeV: Duality, higher–twist

- Excellent prospects with EIC

  Simulations to be updated
  → INT Write–up, Users' Meeting Wednesday

Non–singlet sea: Polarized asymmetry from W



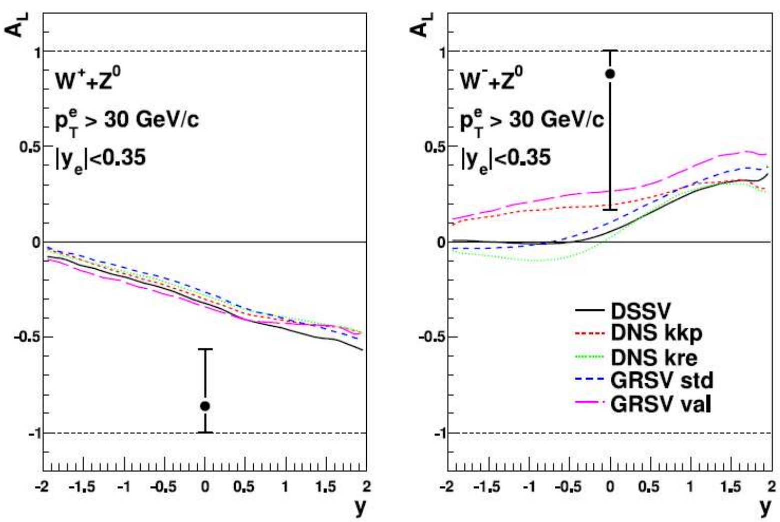


- PV single–spin asymmetry

$$A_L^{W+} = \frac{\Delta u(x_1)\bar{d}(x_2) - \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$$

Sensitive to $\Delta\bar{u} - \Delta\bar{d}$, but also to ΔG
see e.g. Dressler et al. EPJ C18 (2001) 719

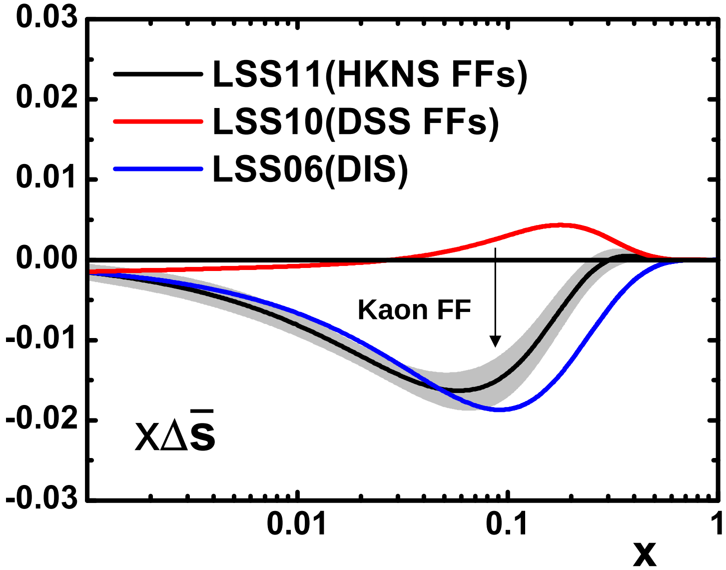
First results reported by STAR, PHENIX
$x_{1,2} = 0.16$ at $\sqrt{s} = 500\,\mathrm{GeV}$, $y = 0$
PRL 106, 062002 (2011); PRL 106, 062001 (2011).
Looking forward to more precise data!



- Unpolarized $\bar{d} - \bar{u}$ at expected from LHC

Measured W^+/W^- ratio + parametrization,
typical $x_{1,2} \sim 10^{-2}$

Non–singlet sea: Strangeness



- Theoretical expectations for $SU(3)$ non–singlet $\Delta\bar{u} + \Delta\bar{d} - 2\Delta\bar{s}$

  $[\Delta\bar{u} + \Delta\bar{d} - 2\Delta\bar{s}](x) = \frac{3F-D}{F+D}\,[\Delta\bar{u} - \Delta\bar{d}](x)$
  with $SU(3)$ symmetry and large–N_c limit
  Numerical value of ratio $\sim$ 0.43–0.6

- $\Delta s + \Delta\bar{s}$ from global fits

  DIS fits "prefer" positive $\Delta\bar{s}$

  SIDIS fits very sensitive to K fragmentation fns
  Leader et al 11: DIS and SIDIS reconciled with HKNS FF's

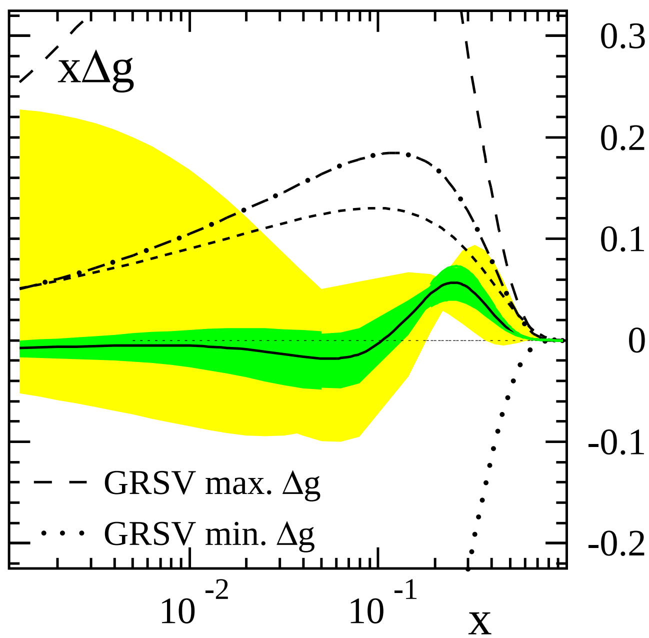
  New HERMES results on π/K multiplicities
  S. Joost, DIS2011; will impact on SIDIS analysis

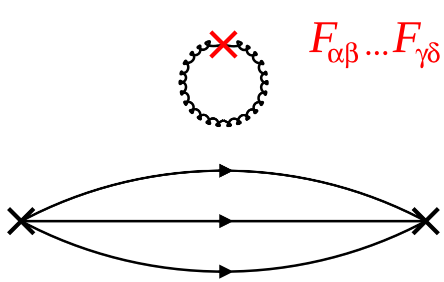
- Possible that $\Delta\bar{s}(x) \neq \Delta s(x)$

  Meson cloud model with $K\Lambda$ not quantitative:
  $b \ll 1\mathrm{fm}$; $K\Lambda$ only small fraction of total $s + \bar{s}$
  Brodsky, Ma 96. Critical discussion: Strikman, CW 09

  Unpolarized CC neutrino DIS discriminates
  s and $\bar{s}$ via $W^{+} + s \to c \to D$ meson

Gluon polarization: Summary





- $\Delta G(x)$ from global fit DIS + SIDIS + pp
  De Florian et al. 08. Summary by M. Stratmann DIS2011

  Small in x–region constrained by data

  RHIC pp data impact on χ^2, esp. at $x < 0.1$

  Future: Jet correlations in pp,
  COMPASS + JLab 12 GeV DIS,
  EIC → INT Write–Up, Users' Meeting Wednesday

- $\Delta G(x)$ and nucleon structure needs more work!

  Connection with non–perturbative vacuum fields still poorly understood
  Instanton vacuum: $G(x)$ subleading in instanton packing fraction

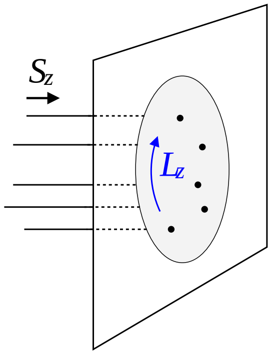
  Gluonic operators challenging for lattice:
  Disconnected diagrams, noise

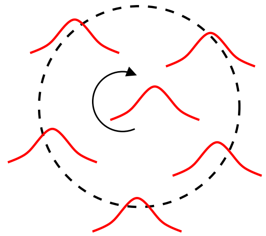
- Spin decomposition: x integrals

  $$\frac{1}{2} \;=\; \frac{1}{2}\Delta\Sigma \;+\; ?$$

  Gluon spin? Orbital angular momentum?

Orbital angular momentum: Concepts





- Formulations of angular momentum

  EM tensor $\langle N | \int d^3 r \, \boldsymbol{r} \times \boldsymbol{T} | N \rangle$ "fields"

  partonic $|N\rangle = \sum |q ... \bar{q} ... g; J_z\rangle$ "particles"

- Questions and challenges Recent summary: Leader 2011

  Separate quark $\leftrightarrow$ gluon angular momentum in interacting theory? Yes, but conventional

  Separate gluon spin and orbital momentum? No

  Complications: Gauge invariance, renormalization

- Different definitions Jaffe, Manohar 90; Ji 97; Chen et al. 08; Wakamatsu 10

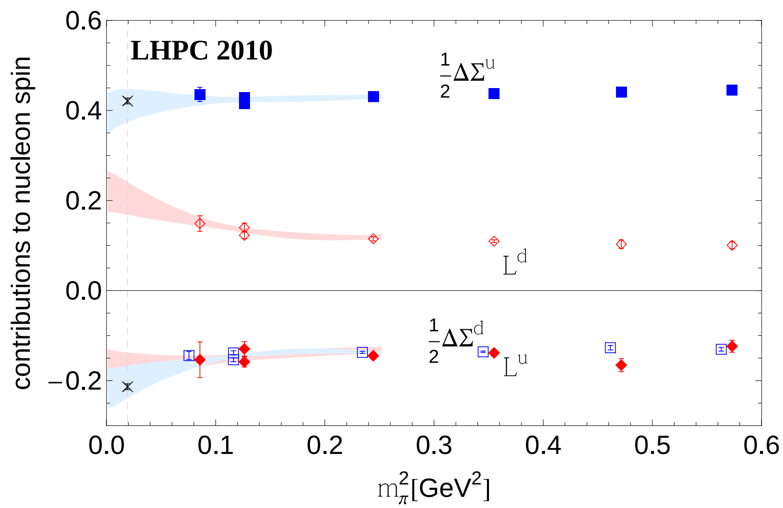
  Ji: Belinfante version of EM tensor; connection with GPDs

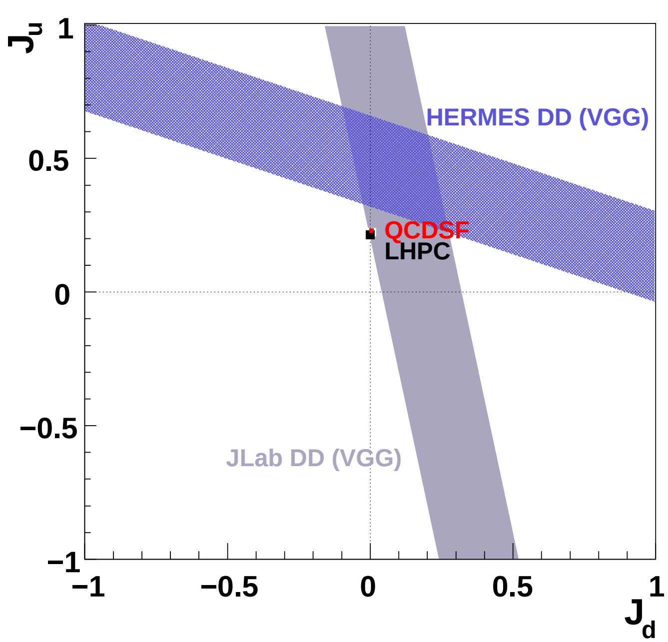
  $$J_{q,g} = \int_0^1 dx \, x \, [H_{q,g} + E_{q,g}](x, \xi, t \to 0)$$

  Integrand not "partonic" density of angular momentum Burkardt, BC 09
  No correspondence: $J_{g,\mathrm{Ji}} \neq \Delta G + L_{g,\text{Jaffe-Manohar}}$

  No simple answers. Much more work needed!

Orbital angular momentum: Nucleon structure





- Large isovector component of OAM

  Lattice results for J_q, Σ_q
  QCDSF, LHPC. Here $L_q \equiv J_q - \Sigma/2$

  Hints at chiral dynamics: πN configs in nucleon light–cone WF have $L = 1$
  $\leftrightarrow$ large sea quark Sivers function at HERMES, COMPASS?

  Models: Chiral quark–soliton model; quark model + pion cloud
  Wakamatsu 05+; Goeke et al. 07. Thomas, Myhrer 08

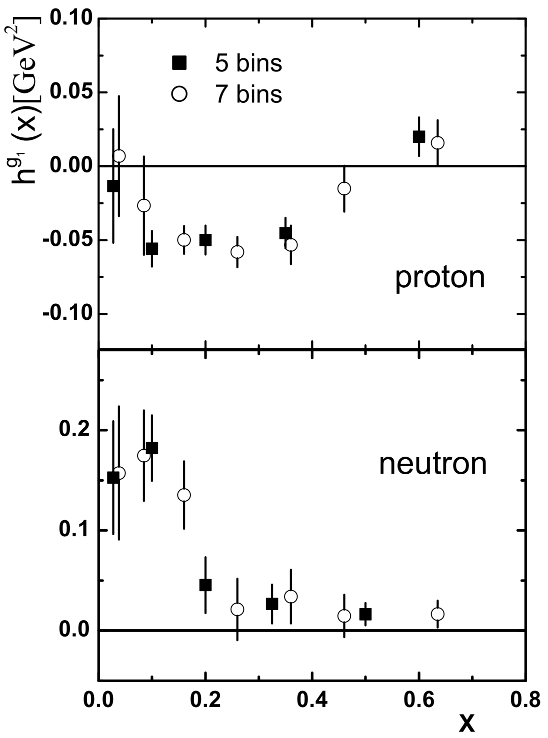
  Model–independent understanding?

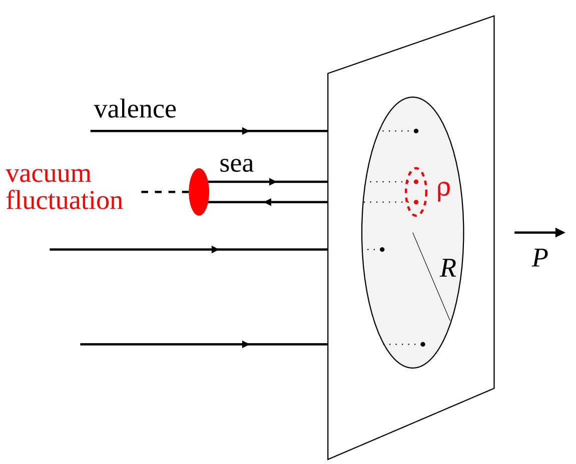
- Future directions

  Ji SR with GPDs constrained by exclusive data?
  DVCS: E_q from neutron and transverse target, charge asymmetry JLab 6/12 GeV, HERMES
  DVMP: E_q from ρ with transverse target, E_g from ϕ? Challenging! Difficult to quantify errors.
  Need 12 GeV data to test reaction models.

  Comprehensive approach using exclusive, semi–inclusive and inclusive observables
  Light–front phenomenology; needs better conceptual understanding!
  Dedicated INT Workshop 6-17 Feb 2012

Beyond densities: Correlations





- Power corrections probe non–perturbative quark–gluon correlations in nucleon

Twist–3 $\langle N | \bar\psi \, \widetilde{F}_{\mu\nu} \, \gamma_\rho \, \psi \, | N \rangle$ $g_2 - g_2^{\text{WW}}$

Twist–4 $\bar\psi \, \widetilde{F}_{\mu\nu} \, \gamma_\nu \, \psi$ g_1

$\rightarrow \bar\psi \gamma_\mu \gamma_5 (-\nabla^2) \psi$ virtuality of polarized quarks

- Large non–singlet twist–4 correlations
Leader et al. 09/10; see also Blümlein, Böttcher 10.

Sits at moderate x; not related to resonances, duality

Average virtuality of sea quarks $k^2 \sim \rho^{-2} \gg R^{-2}$:
Short–range correlations in partonic wave function
Sidorov, CW PRD73 (2006) 074016; Schweitzer et al., in preparation

Quantitative predictions from instanton vacuum:
Twist–3 $\ll$ Twist–4 supported by data
d_2 SLAC E155/E155X; JLab Hall A, C; f_2 CLAS

Footprint of non–pert. QCD vacuum in partonic structure

Other interesting topics

- Nucleon spin structure at $x \to 1$ JLab 12 GeV

  Study properties of 3–quark component of nucleon WF

  Orbital angular momentum important!

- Quark–hadron duality in spin structure functions JLab 6/12 GeV

  Study transition from low to high Q^2
  GDH sum rule for p/D, etc.

- Spin structure with electroweak probes JLab 12 GeV PVDIS, possibly EIC

  Probe with different quantum numbers charge/flavor

Summary

- Learn to discuss non–perturbative nucleon structure in QCD in more model–independent terms!

  Powerful concepts: Vacuum structure, chiral dynamics, large–N_c limit, . . .

  Match tremendous experimental effort!

- Polarized ep/pp data offer many fascinating insights into nucleon structure

Non–singlet sea	$\rightarrow$	chiral vacuum structure
Gluon polarization	$\rightarrow$	orbital angular momentum
Power corrections	$\rightarrow$	quark–gluon correlations

- Orbital angular momentum challenges the very basics of our understanding of partonic structure

Infinite–momentum frame	$\leftrightarrow$	Rest frame
Particles	$\leftrightarrow$	Fields