The Flavor Structure of Nucleon Sea
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Sea Quark Flavor Asymmetries from Chiral Symmetry Breaking

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Overview:

- QCD and dynamical chiral symmetry breaking
- practical tool: chiral quark soliton model
- examples: $M_N(m_\pi)$, GPDs, q PDFs
- sea quark flavor asymmetries
- what gives rise to them?
- conclusions

motivation

- **perturbative QCD** powerful tool!
  establish factorization, provide definitions of non-perturbative objects
  tells us how a non-perturbative object looks at $Q > \mu_0$ if it is known at μ_0

  but how does a non-perturbative object look like at initial scale?
  how to compute it? Beyond pQCD.

- **non-perturbative methods** needed

  lattice QCD: great!
  gives us the correct answer (42!)
  but we do not not why (that's what QCD says)

  models:
  give an approximate result (41 ...)
  but we know exactly why we got it (because we did $\int_1^{10} \mathrm{d}y \, \frac{N_c(N_c+2)}{N_c+1+y} - 1 = 41$)
  can be insightful (if model well-motivated,
  and if it provides predictions we can test)

global symmetries of QCD

- $\mathcal{L}_{\rm QCD} = \mathcal{L}_{\rm QCD}(\bar{\psi}_q, \psi_q, A_\mu)$

  with $m_q \ll M_{\text{hadronic}}$ for $q = u, d, s$ $M_{\text{hadronic}} \sim \mathcal{O}(M_\rho, M_N) \sim (0.77{-}0.94)$ GeV ~ 1 GeV

- chirality $\psi_{q,L} = \frac{1}{2}(1 - \gamma_5)\,\psi_q$ and $\psi_{q,R} = \frac{1}{2}(1 + \gamma_5)\,\psi_q$

  vector symmetry $V = L + R$, axial symmetry $V = L - R$

  global symmetry $U(3)_L \otimes U(3)_R = \underbrace{U(1)_V}_{\text{baryon number}} \otimes \underbrace{U(1)_A}_{\text{axial anomaly}} \otimes \underbrace{SU(3)_V}_{SU(n_f)\text{ flavor symmetry}} \otimes \underbrace{SU(3)_A}_{\text{spontanuous breaking}}$

$J^\pi = \frac{1}{2}^+$ p, n
$J^\pi = 1^+$ ρ^+, ρ^0, ρ^-
$J^\pi = \frac{3}{2}^+$ Δ^{++}, Δ^+, Δ^0, Δ^-
SU(3) octets and decuplets
small $m_q \neq 0 \to$ mass splittings
$\Downarrow$
symmetry is realized in hadron spectrum

$J^\pi = \frac{1}{2}^+$ $N(940)$ vs
$J^\pi = \frac{1}{2}^-$ $N(1535)$ so
nucleon's chiral partner much heavier
$\Downarrow$
symmetry not realized spontaneously broken

spontaneous chiral symmetry breaking

- $N_f^2 - 1$ **Goldstone bosons**
  π, K, η with $m_h \ll 1$ GeV

- implemented in $\mathcal{L}_{\chi PT}$ with degrees of freedom $N, \Delta, \pi, \ldots$
  powerful effective field theory

- **key feature of strong interaction**
  fundamental for light hadron spectrum
  crucial for structure of nucleon $\in$ light hadron spectrum

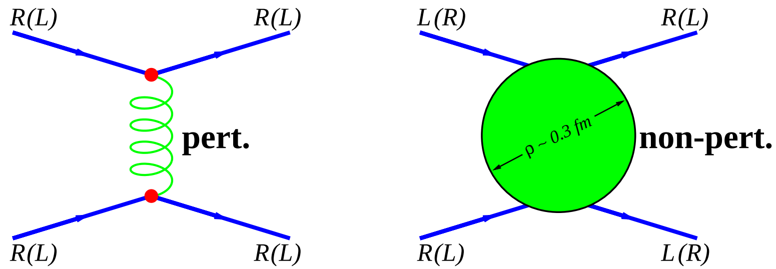
- **how to apply to parton structure of nucleon?**

- **dynamical microscopic theory** needed which:
  – has partonic and Goldstone boson degrees of freedom
  – provides insights in non-perturbative regime(!)
  – is well-motivated, founded on QCD
  – consistent, effective, reliable
  – solvable*

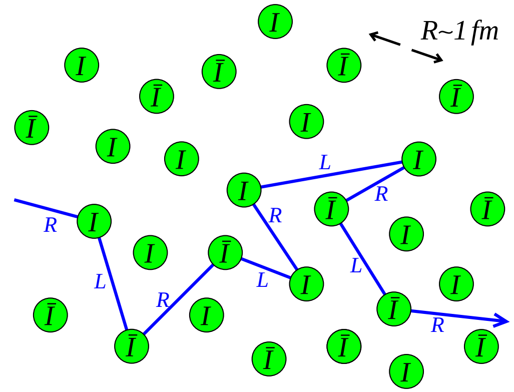
* more easily than lattice QCD, otherwise just do lattice QCD

dynamical chiral symmetry breaking

Shuryak; Diakonov, Petrov (1980s)

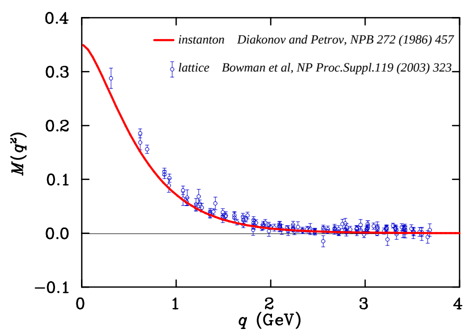


- perturb. interactions preserve quark chirality
  non-perturbative gluon fields can flip it
  topological gauge fields, instantons



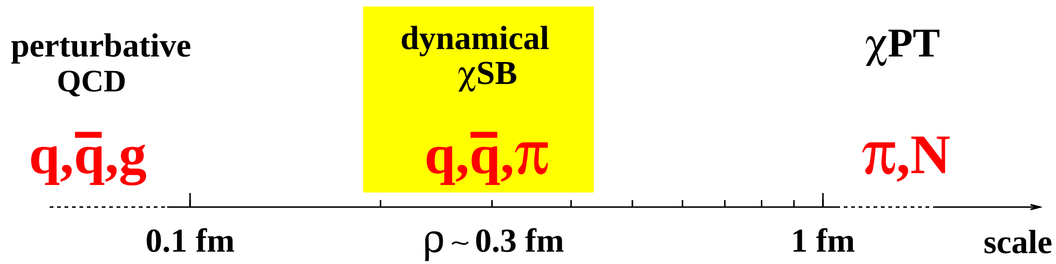
- I, $\bar{I}$ form dilute strongly-interacting medium
  which stabilizes at $\rho \sim 0.3$ fm and $R \sim 1$ fm
  non-trivial small parameter $\sim c_0\,(\rho/R)^4/N_c \sim \frac{1}{20}$
  instanton liquid model of QCD vacuum

- light quarks acquire momentum-dependent mass
  QCD vacuum structure (quark condensate)
  $\langle 0|\bar{\psi}\psi|0\rangle = \langle 0|\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L|0\rangle \neq 0$
  order parameter of symmetry breaking



- **Goldstone** boson π collective excitation
  $m_\pi^2 f_\pi^2 = -m_q \langle 0|\bar{\psi}\psi|0\rangle$ Gell-Mann–Oakes–Renner

- **effective ("constituent") q, $\bar{q}$** with
  dynamical mass $M(0) \sim 0.35$ GeV
  for $p \ll \Lambda_{\text{cut}} = \rho^{-1} \sim 0.6$ GeV



- chiral symmetry breaking
  occurs at **scale $\rho \sim 0.3$ fm**

tool: chiral quark soliton model

Diakonov, Eides 1983; Diakonov, Petrov 1986

$$\mathcal{L}_{\text{eff}} = \overline{\Psi}\Big(i\,\partial\!\!\!/ + M\,U^{\gamma_5}\Big)\Psi$$

- constituent $q, \bar{q}$ degrees of freedom
  with **dynamical mass** $M \sim 350\,\text{MeV}$
  at energies $\lesssim \rho^{-1} \simeq 600\,\text{MeV}$ (cutoff)

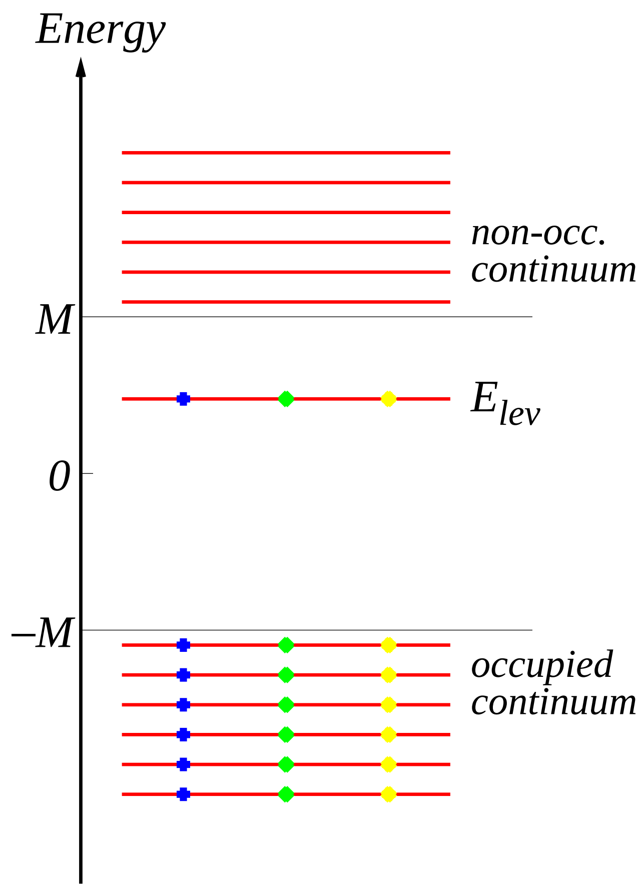
- coupled to chiral field $U^{\gamma_5} = \exp(i\gamma_5\tau^a\pi^a/F_\pi)$
  coupling constant $g_{\pi q\bar{q}} = M/F_\pi \sim 4$ is large!

- $\langle N'|\dots|N\rangle = \int \mathcal{D}\bar{\Psi}\,\mathcal{D}\Psi\,\mathcal{D}U\;\langle 0|J_N(\frac{T}{2})\dots J_N^\dagger(-\frac{T}{2})|0\rangle\, e^{-iS_{\text{eff}}}$
  solve limit $T\to\infty$ on paper, integration over $\bar{\Psi}$, Ψ exact
  path integral over U non-perturbatively in **$1/N_c$ expansion**
  $M_N = \min\limits_U E_{\text{sol}}[U]$, quantize zero modes (large N_c picture, Witten 1979)

- **chiral quark-soliton model** (no free parameters!)
  Diakonov, Petrov, Pobylitsa 1986; Kahana, Ripka 1984

- full Dirac sea, no Fock space truncation:
  consistent, theoretically appealing!
  (completeness, locality, analyticity)

- **successful phenomenology!** useful accuracy (10-30)%
  systematic $1/N_c$ expansion: mass spectrum, form factors, PDFs, GPDs
  TMDs (Goeke et al, Diakonov et al, Reinhardt et al, Wakamatsu et al)



$$H\psi_n = E_n\psi_n$$

$$\langle N'|\overline{\Psi}\dots\Psi|N\rangle = A\sum_n \bar{\psi}_n\dots\psi_n$$

applications of effective theory

- **vacuum sector:** $\frac{\langle F^2 \rangle}{32\pi^2} \simeq (200\,\text{MeV})^4$ **gluon condensate** QCD sum rules

  $= \text{instanton density} \Rightarrow R \sim 1\,\text{fm}$

  $\langle \bar{\Psi}\Psi \rangle \simeq -(250\,\text{MeV})^3$ **quark condensate**

  $= \text{const}\, N_c/(\rho R^2) \Rightarrow \rho \sim \frac{1}{3}\,\text{fm}$

- **meson sector:** **chiral Lagrangian** integrate out $\int \mathcal{D}\bar{\Psi}\,\mathcal{D}\Psi\, e^{-iS_{\text{eff}}} =$

$$\mathcal{L}_\pi(U) = \frac{1}{4} f_\pi^2 \partial^\mu U \partial_\mu U^\dagger + \text{Gasser-Leutwyler-terms} + \ldots$$

$$f_\pi^2 = \int \frac{\mathrm{d}^4 p}{(2\pi)^4} \frac{4 N_c M^2}{(p^2 + M^2)^2} = (93\,\text{MeV})^2 \Rightarrow \Lambda_{\text{cut}}$$

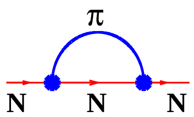
  low energy coefficients predicted, consistent
  Schüren, Ruiz Arriola, Goeke 1991

- **baryon sector:** parameter-free results/predictions, no tuning!
  $M = 350\,\text{MeV}$ and $\Lambda_{\text{cut}} \sim \rho^{-1} \sim 600\,\text{MeV}$
  determined in vacuum + meson sector
  examples: M_N, GPDs, PDFs of q
  main topic: asymmetries of $\bar{q}$

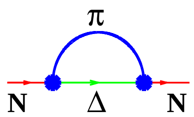
nucleon mass $M_N = N_c \sum_{\mathrm{occ}} (E_n - E_n^{(0)})_{\mathrm{reg}} \; + \; \mathcal{O}(N_c^0)$

- at physical point: about 25% too large, spurious soliton center of mass motion ✓
  N_c^0-correction ~ -300 MeV Pobylitsa et al. 1992
  $\hookrightarrow$ **model accuracy $\sim$ (10–30)%**

- in chiral limit: $M_N(m_\pi) = M_N(0) + A\, m_\pi^2 + k \times \frac{3\, g_A^2}{32\pi f_\pi^2}\, m_\pi^3 +$ higher orders ✓
  $k = 1$ at finite N_c
  $k = 3$ large–N_c limit
  limits do not commute
  the role of Δ-resonance
  leading non-analytic terms



$m_\pi \to 0$

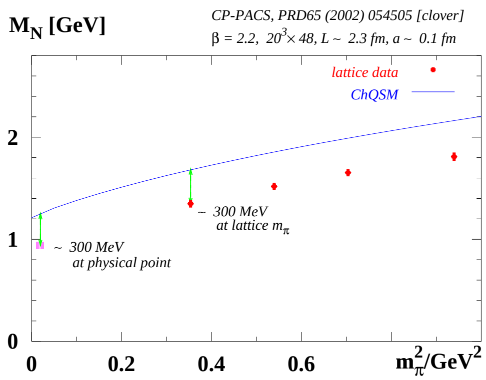


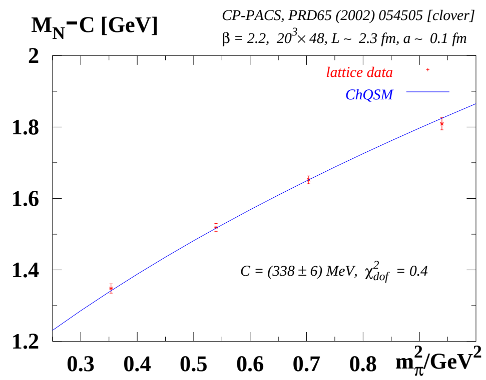
$m_\pi \to M_\Delta - M_N \to 0$ in large-N_c
Cohen, Broniowski 1992

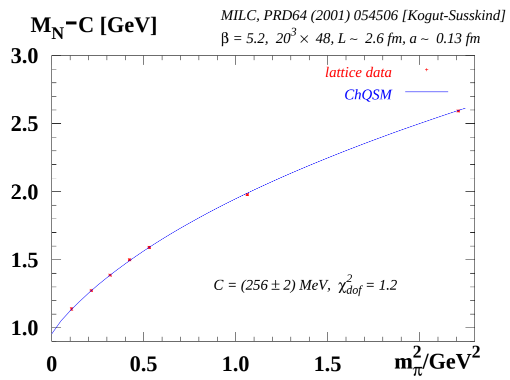
- heavy quark limit: $\lim_{m_q \to M_Q} M_N = N_c M_Q$ formal proof ✓ Goeke et al, EPJA27 (2006) 77

- test with lattice ✓

$\Rightarrow$ no precision tool but does what it is expected: chiral physics!







historical plot $\rightarrow$ model describes well **variation of M_N with m_π** (chiral physics)

EPJA (2006)

see Tony Thomas et al, FRR approach

GPDs most demanding for models!

(i) **forward limit** $H^q(x,\xi,t) \to f_1^q(x)$ ✓ all models

(ii) **form factors** $\to \int \mathrm{d}x\, H^q(x,\xi,t) = F_1^q(t) \neq F(\xi,t)$ ✓ not all models!

(i) **positivity** $\to f_1^{\bar{q}}(x) > 0$, Soffer bound ✓ certain models

(iii) **polynomiality** Lorentz inv. + time-reversal, even N (if odd, highest power ξ^{N-1})

$$\int \mathrm{d}x\, x^{N-1} H^q(x,\xi,t) = h_0^{q(N)}(t) + h_2^{q(N)}(t)\,\xi^2 + \ldots + h_N^{q(N)}(t)\,\xi^N \quad ✓$$

$$\int \mathrm{d}x\, x^{N-1} E^q(x,\xi,t) = e_0^{q(N)}(t) + e_2^{q(N)}(t)\,\xi^2 + \ldots + e_N^{q(N)}(t)\,\xi^N \ ✓$$

$-\,e_N^{q(N)}(t) = h_N^{q(N)}(t)$ ✓ only ChQSM! (rigorous analytical proof)

(iv) ***D*-term** $\to$ even N highest powers ("Polyakov-Weiss terms") ✓ "discovered"

(v) **form factors of EMT**

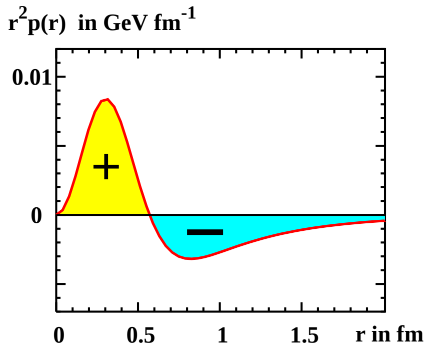
gravitational FFs, $N = 2$

$T_{00}(r) \to \int \mathrm{d}^3x\, T_{00}(r) = M_N$ ✓

$\varepsilon^{ijk} x_j T_{0k}(r) \to$ Ji sum rule $J_N = \frac{1}{2}$ ✓

$T_{ij}(r) \to \int_0^\infty \mathrm{d}r\, r^2 p(r) = 0$ ✓

$\hookrightarrow$ **forces**



side remark:
insight from parton densities:
how are the quarks distributed?
here dynamics: **why** so distributed?
mechanical response function
grain of salt: $\sim 3\%$ rel. corr. proton

PDFs

What can we expect in effective theory?

- $\boldsymbol{xN_c = \mathcal{O}(1)}$ applicable $\rightarrow$ "non-exceptional x" (no $x \rightarrow 0$, no $x \rightarrow 1$)
- small $x \leq (M\rho)^2/N_c \sim 0.1$ sensitive to **UV**-details of theory
- to leading order **model quark = QCD quark** $+ \underbrace{\mathcal{O}(M^2\rho^2)}$ at low scale $\mu \sim \rho^{-1}$

suppressed in instanton vacuum

- **gluons** not ignored, but (twist-2 gluons) suppressed by $\overbrace{\mathcal{O}(M^2\rho^2)} \sim 30\,\%$ at $\mu \sim \rho^{-1}$
- solve $\int \mathcal{D}U \; \ldots$ in large-N_c: $\mathbf{PDF}(\boldsymbol{x}) = \boldsymbol{N_c^2 a_{\mathrm{LO}}(xN_c) + N_c a_{\mathrm{NLO}}(xN_c) + \ldots}$
- compare to meson-cloud models which "expand" to 1st order in $g_{\pi NN} = g_A\, M_N/f_\pi \sim 12.7$
  in ChQSM **all orders** included in soliton field (non-perturbative method)
- **flavor structure:** $u \pm d$ leading vs $u \mp d$ subleading (general large N_c)

  f_1: $u + d \gg u - d$

  g_1: $u - d \gg u + d$

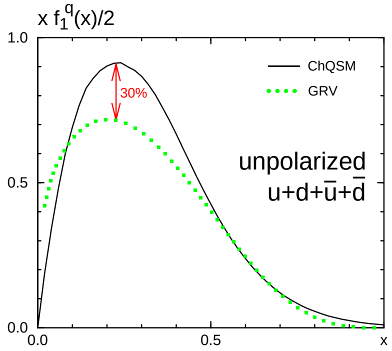
  h_1: $u - d \gg u + d$ analog for $\bar{q}$

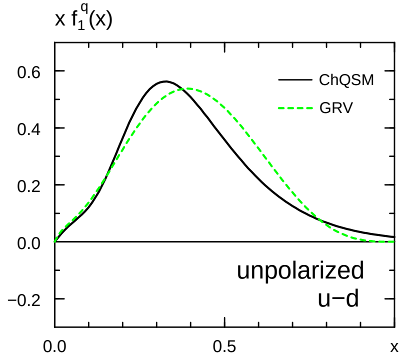
$\Rightarrow$ focus on "non-exceptional x"
expect "precision" of 30 % or so

results for quarks

historical plots (GRV, GRSV, ...)

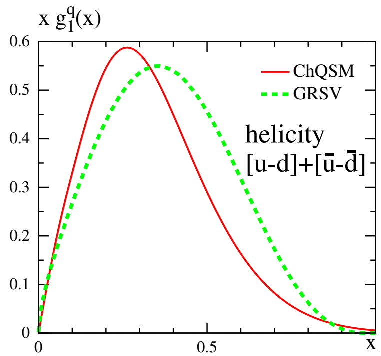
- unpolarized
  Diakonov et al, NPB 1996
  Pobylitsa et al, PRD 1998

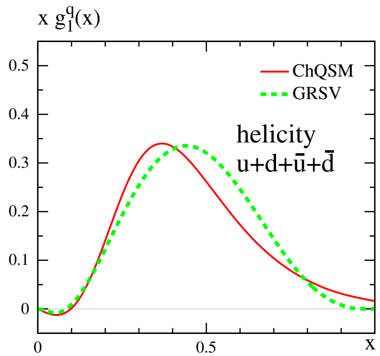




room for gluons in singlet
non-singlet fine, overall ✓

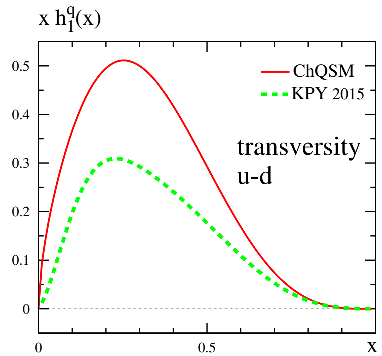
- helicity
  Diakonov et al, NPB 1996
  Goeke et al, 2001

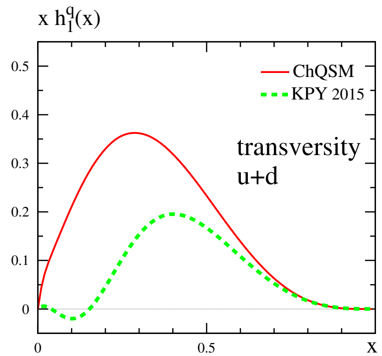




non-singlet, singlet within
what one can expect ✓

- transversity
  PS, Urbano et al, PRD 2001





early stage of extractions
within model accuracy ✓

sea quarks

- model results:

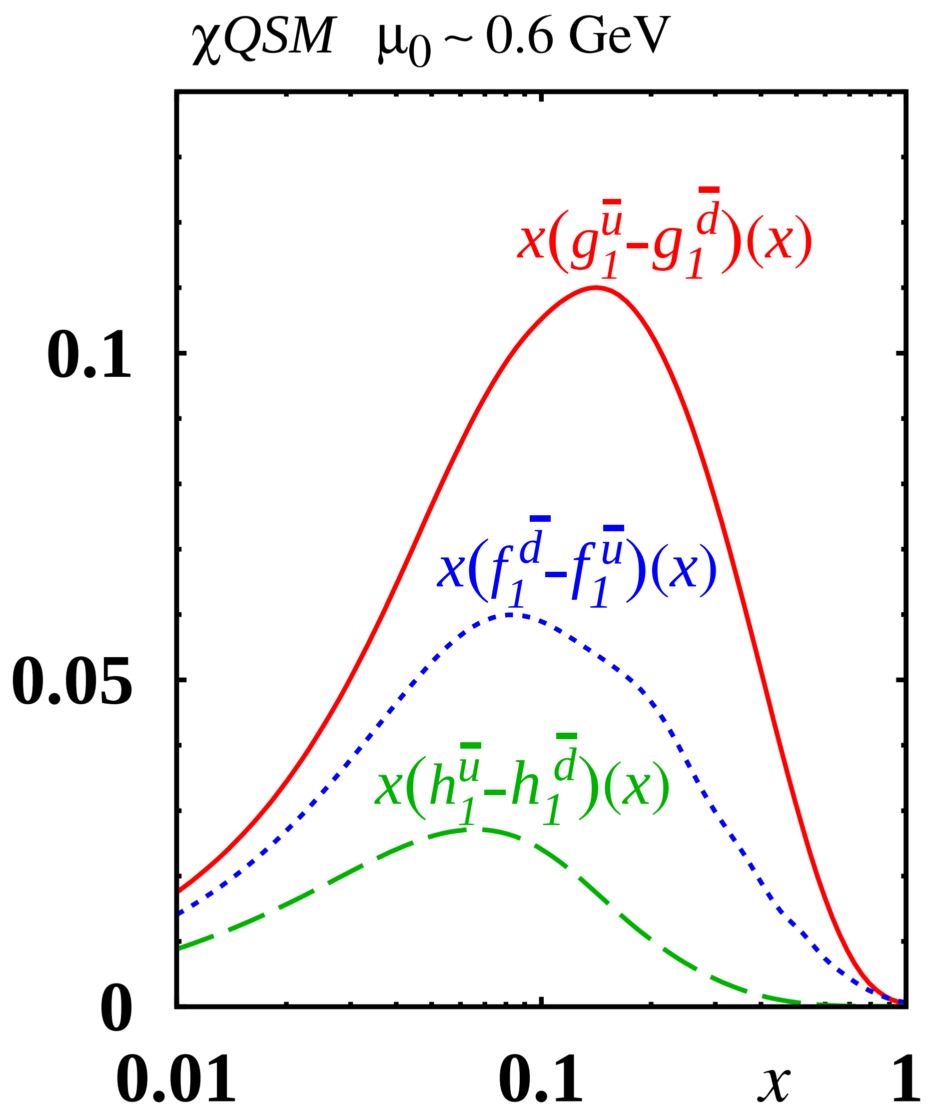
  flavor asymmetries in all twist-2 PDFs:

  helicity Diakonov et al, NPB 1996
  unpolarized Pobylitsa et al, PRD 1998
  transversity PS et al, PRD 2001

$$(g_1^{\bar u} - g_1^{\bar d})(x) \sim N_c^2$$

$$(f_1^{\bar d} - f_1^{\bar u})(x) \sim N_c$$

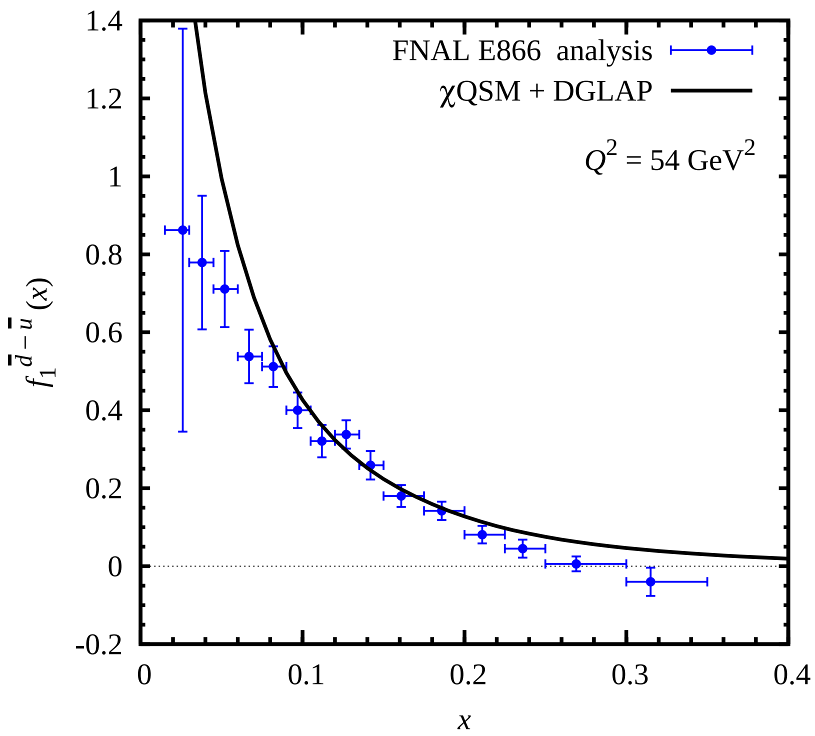
$$(h_1^{\bar u} - h_1^{\bar d})(x) \sim N_c^2$$



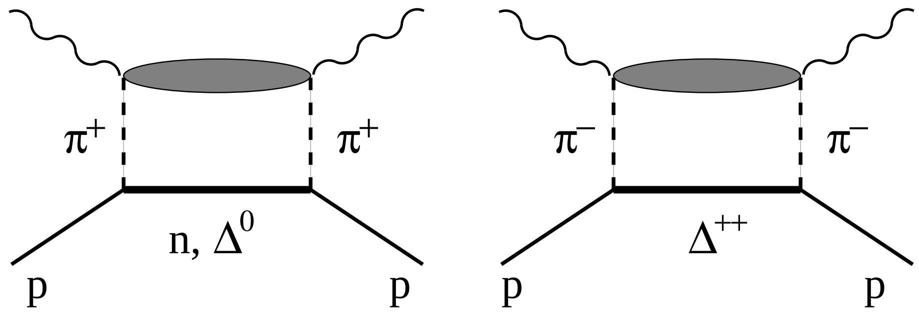
unpolarized sea: $\bar{d} - \bar{u}$

- model result
  Pobylitsa et al, PRD 1998
  LO non-singlet evolution vs
  J. C. Peng et al, PRD 58 (1998)

  Gottfried sum:
  $I_G = \frac{1}{3} + \frac{2}{3} \int \mathrm{d}x \, (f_1^{\bar{u}} - f_1^{\bar{d}})(x) = 0.219$



- **why?**
  expand model expression in ∂U
  ⇔ **Sullivan process** (→ Wally)
  (no small parameter to justify
  but gives a feeling about
  involved quantum numbers)



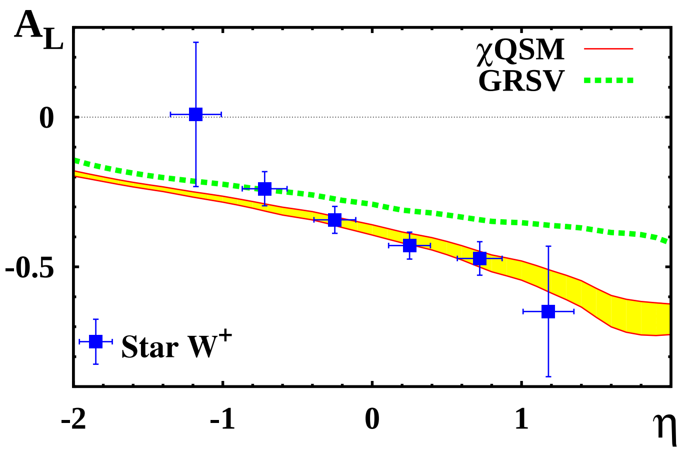
helicity sea: $\bar{u} - \bar{d}$

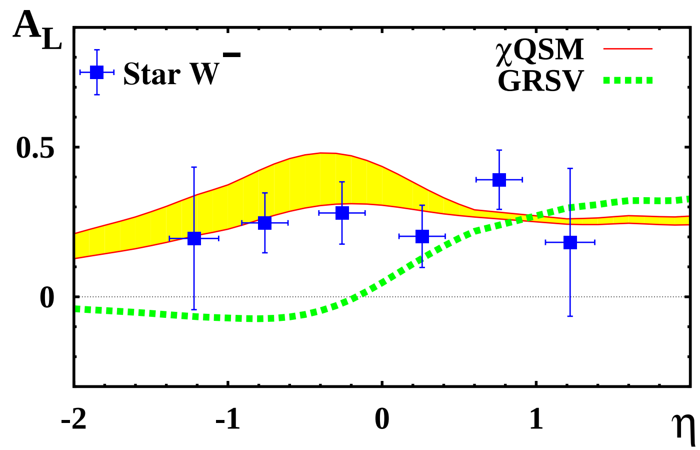
back in 2001: change of basis

$$u,\ d,\ \bar{u},\ \bar{d},\ \ldots \to \underbrace{(u+\bar{u})}_{\text{DIS}},\ \underbrace{(d+\bar{d})}_{\text{DIS}},\ \underbrace{(\bar{u}+\bar{d})}_{\text{DIS}},\ \underbrace{(\bar{u}-\bar{d})}_{\text{model}},\ \ldots$$

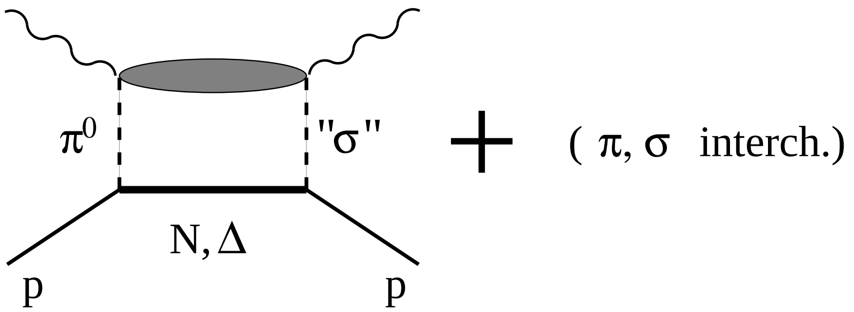
- model result
  Diakonov et al, NPB 1996
  predictions for $W^{\pm}$ in pp
  Dressler et al EPJC 2001
  (thanks to Werner)

  L. Adamczyk et al.
  (STAR Collaboration),
  PRL 113, (2014) 072301
  → talks by Bernd Surrow
  and Elke Aschenauer



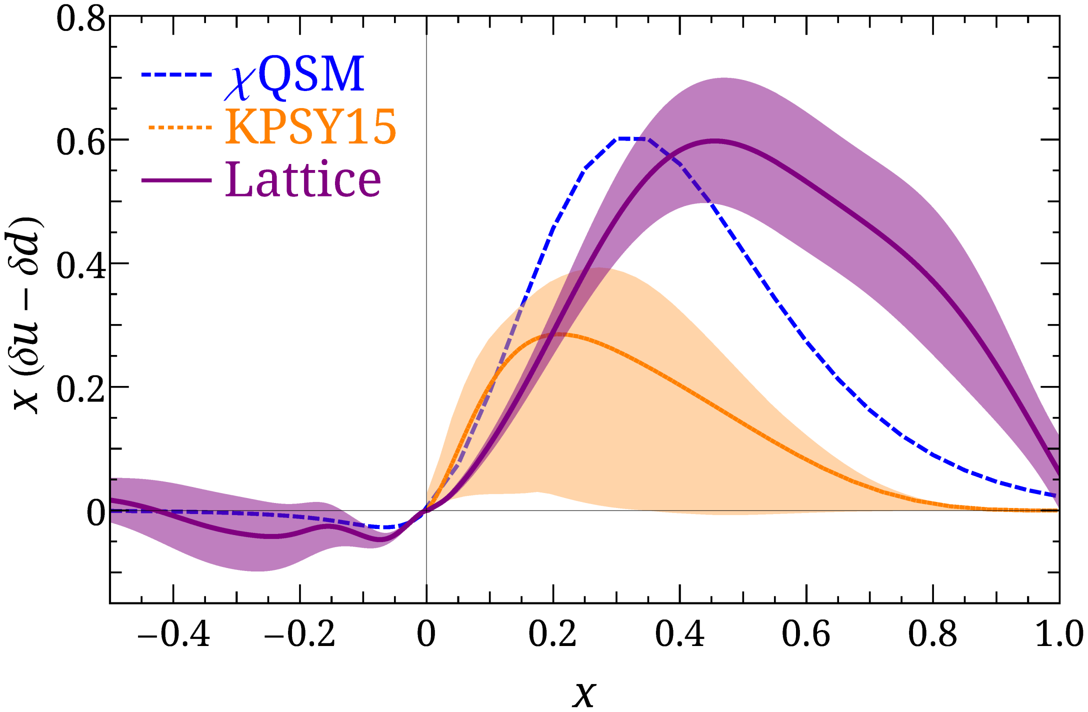


- **why?**
  expand model expression in ∂U
  ⇔ ***σ-π* interference**
  (no small parameter to justify
  but gives a feeling about
  involved quantum numbers)

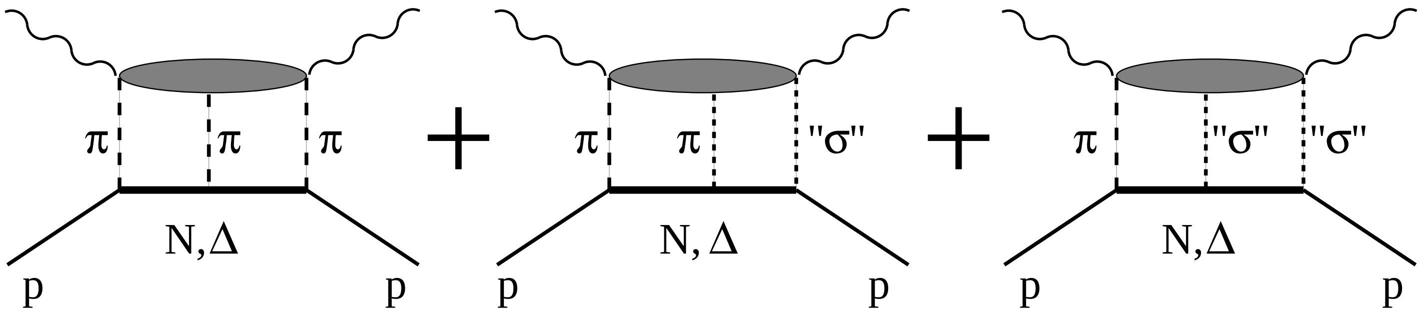


transversity sea: $\bar{u} - \bar{d}$

- model result
  PS et al, PRD 2001
  waiting for experimental test
  meanwhile compare to lattice
  Chen et al, NPB 911 (2016) 246
  (→ Huey-Wen Lin's talk)
  (+ Kang, Prokudin, Sun, Yuan PRD93)



- **why?**
  expand model expression in ∂U
  ⇔ **higher order chiral dynamics!**
  (no small parameter to justify)



emerging picture:

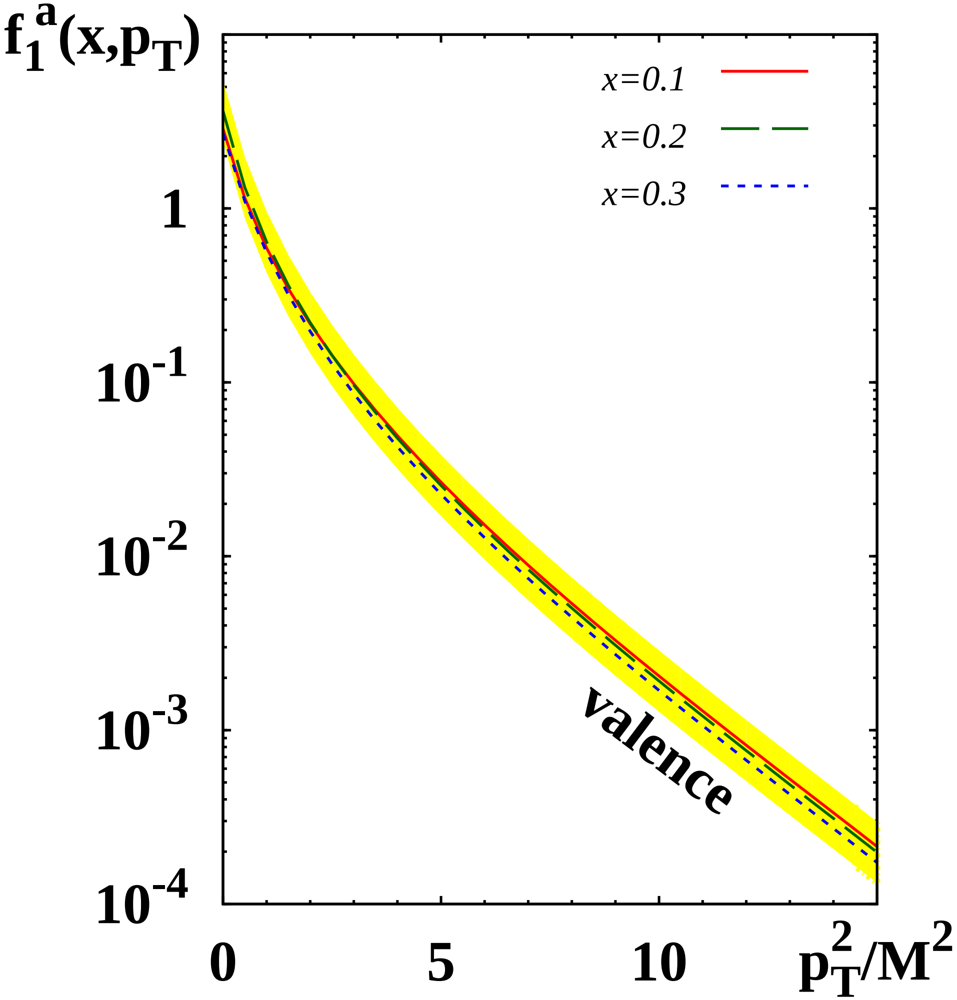
$\bar{q}$-asymmetry	experiment	χQSM
$(f_1^{\bar{d}} - f_1^{\bar{u}})(x) \sim N_c$	✓	✓
$(g_1^{\bar{u}} - g_1^{\bar{d}})(x) \sim N_c^2$	✓	promising
$(h_1^{\bar{u}} - h_1^{\bar{d}})(x) \sim N_c^2$	future	waiting

do we understand?

- $(g_1^{\bar{u}} - g_1^{\bar{d}})(x)$ sizable, perhaps larger than $(f_1^{\bar{d}} - f_1^{\bar{u}})(x)$. Why? Explanation: large-N_c
- but why should $(g_1^{\bar{u}} - g_1^{\bar{d}})(x)$ and $(f_1^{\bar{d}} - f_1^{\bar{u}})(x)$ be sizable in first place?
- and why should $(h_1^{\bar{u}} - h_1^{\bar{d}})(x)$ be less sizable?

$\hookrightarrow$ go beyond 1-D for new insights:
look at TMDs $f_1^{\bar{q}}(x, p_T)$, $g_1^{\bar{q}}(x, p_T)$, $h_1^{\bar{q}}(x, p_T)$

TMDs in ChQSM:

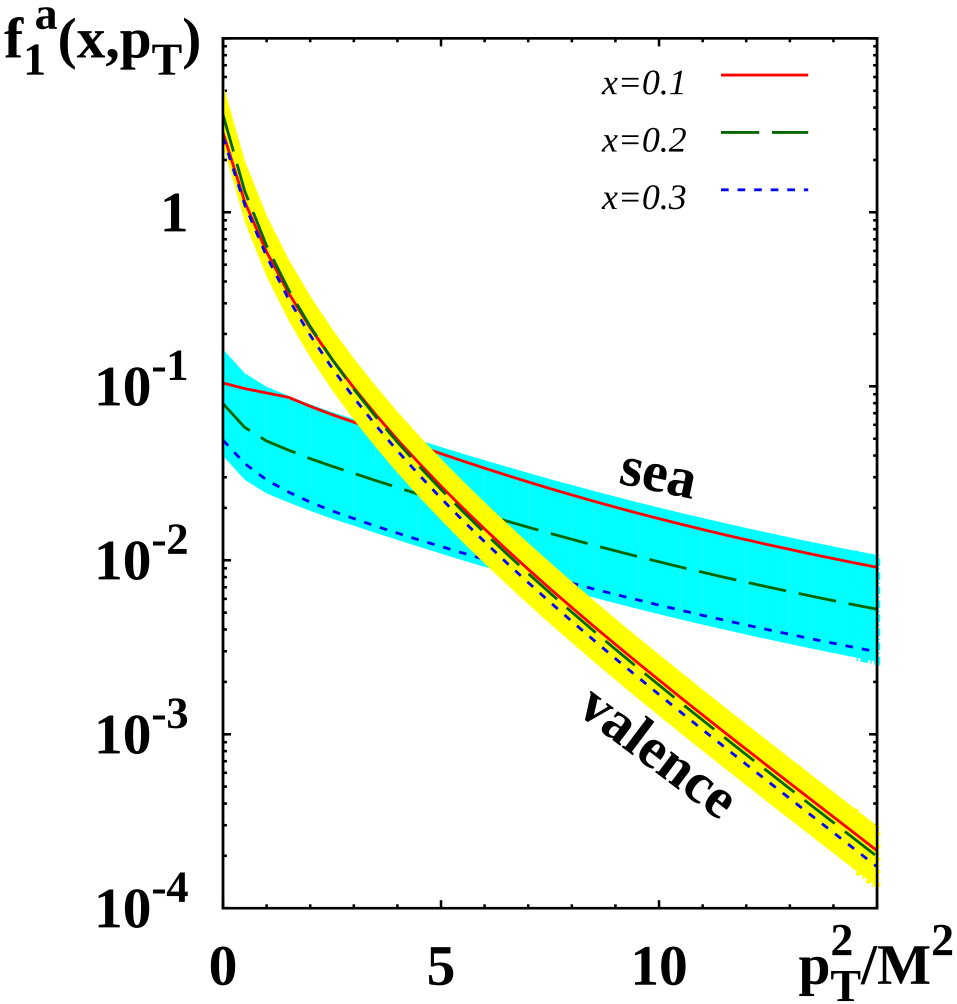


- **valence quarks** $\equiv (u+d)-(\bar{u}+\bar{d})$

  $\langle p_T^2\rangle_{\rm val} \sim 0.15\text{GeV}^2 \sim \mathcal{O}(M^2)$

  $\rightarrow$ bound state (similar: bag, spectator, LFCM)

TMDs in ChQSM:



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  $\langle p_T^2\rangle_{\rm val} \sim 0.15\,\text{GeV}^2 \sim \mathcal{O}(M^2)$

  $\rightarrow$ bound state (similar: bag, spectator, LFCM)

- **sea quarks** $\equiv \bar{q} \equiv (\bar{u}+\bar{d})$ **!**

  $p_T \sim 1/\rho$ power-like behavior

  quasi model-independent:

  $$f_1^{\bar{q}}(x,p_T) \approx f_1^{\bar{q}}(x)\,\frac{C_1\,M^2}{M^2+p_T^2}$$

  $$C_1 = \frac{2N_c}{(2\pi)^3 F_\pi^2} \quad \leftarrow \text{chiral dynamics!}$$

- **valence vs sea: qualitatively different!!**

  quantitatively different $\langle p_T^2\rangle_{\rm sea} \sim 3\,\langle p_T^2\rangle_{\rm val}$**!!**

- $g_1^{\rm val}(x,p_T)$ **vs.** $g_1^{\rm sea}(x,p_T)$ **similar behavior !!!**

  here: val $\equiv (u-d)-(\bar{u}-\bar{d})$, sea $\equiv (\bar{u}-\bar{d})$

  remarkable: $$g_1^{\bar{q}}(x,p_T) \approx g_1^{\bar{q}}(x)\,\frac{C_1\,M^2}{M^2+p_T^2}$$

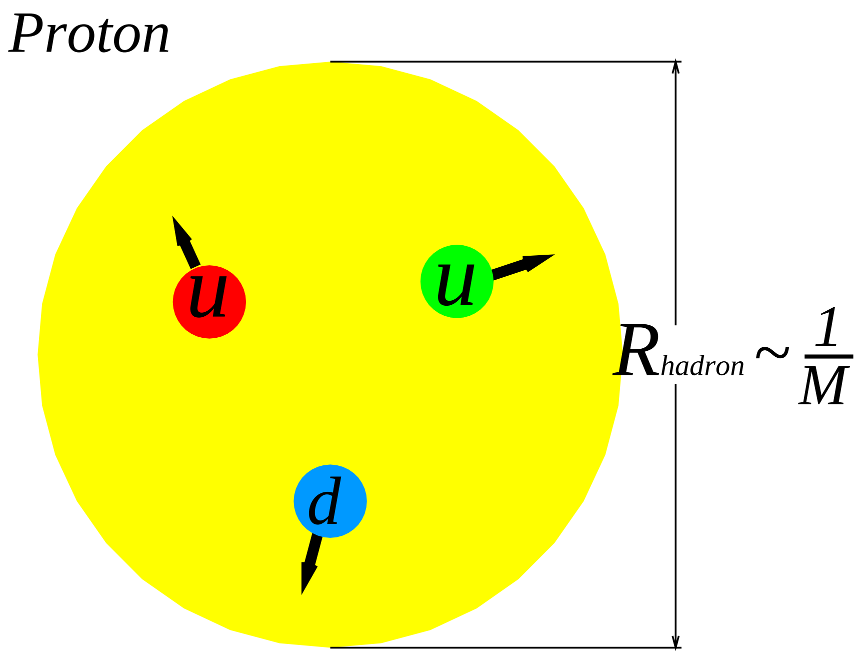
  same coefficient $C_1 \leftarrow$ **chiral dynamics!!**

Why is that ...?

valence quark picture

realized in quark models: whether ChQSM,
spectator (Jakob et al), LFCM (Pasquini et al),
bag (Avakian et al), NJL-jet (Matevosyan et al),
details differ, but **bound-state** is bound-state

$$\langle p_T^2 \rangle_{\text{val}} \sim M^2$$



but what binds these valence quarks?
it's the **soliton field** due to χSB,
strong coupling $f_{\pi q\bar{q}} = M/F_\pi \sim 4$
chiral field generates $\bar{q}q$ pairs
correlated at χSB scale ρ**!**

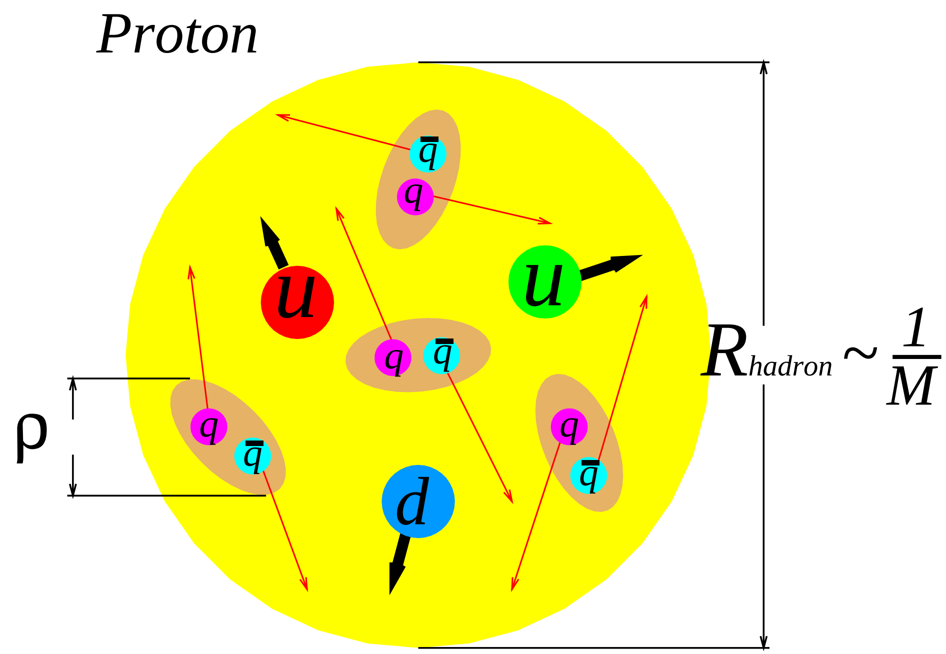
... signature of chiral symmetry breaking!

short-range correlations of $q, \bar{q}$ pairs !!!

QCD vacuum structure
(**"Dirac sea"** in model)
PS, Strikman, Weiss 2013

$$\langle p_T^2 \rangle_{\mathrm{val}} \sim M^2$$

$$\langle p_T^2 \rangle_{\mathrm{sea}} \sim \rho^{-2}$$



$$\langle p_T^2 \rangle_{\mathrm{val}} / \langle p_T^2 \rangle_{\mathrm{sea}} \sim M^2 \rho^2 \sim M^2/(\mathrm{cutoff})^2 \ll 1$$

('diluteness' of instanton medium) Diakonov, Petrov, Weiss 1996

transversity TMD (ongoing work)

- much different p_T-dependence:

$$h_1^q(x,p_T) \sim \frac{1}{(M^2+p_T^2)^2}$$

vs. $f_1^q(x,p_T) \sim \frac{1}{(M^2+p_T^2)}$ and $g_1^q(x,p_T) \sim \frac{1}{(M^2+p_T^2)}$ for $M^2 \ll p_T^2 \ll \rho^{-2}$

- consequences:

  p_T of transversity "of valence type" $\langle p_T^2\rangle_{h_1} \ll \langle p_T^2\rangle_{f_1}$ or $\langle p_T^2\rangle_{g_1}$

  clear: much different chiral mechanism

  $\boldsymbol{f_1^{\bar q} \propto \sigma^*\sigma + \pi^*\pi}$ $\leftrightarrow$ Vector current

  $\boldsymbol{g_1^{\bar q} \propto \sigma^*\pi + \pi^*\sigma}$ $\leftrightarrow$ Axial vector current

  $\boldsymbol{h_1^q}$ **and** $\boldsymbol{h_1^{\bar q} \propto (\sigma\,\sigma^*\pi \pm \sigma\,\pi^*\pi \pm \pi\,\pi^*\pi) \mp}$ **c.c.** $\leftrightarrow$ "tensor current"

remarks

- sizable $f_1^{\bar u+\bar d}(x,p_T) \to$ sizable $f_1^{\bar u+\bar d}(x)$ (enhanced by chiral short range correlations)
- $f_1^{\bar u-\bar d}(x,p_T)$ suppressed by $1/N_c$ but the same chiral enhancement! So still large!
- sizable $g_1^{\bar u-\bar d}(x,p_T) \to$ sizable $g_1^{\bar u-\bar d}(x)$ feels chiral correlations & leading in large-N_c
- $g_1^{\bar u+\bar d}(x,p_T)$ also feels chiral short range correlations but suppressed by $1/N_c$
- $h_1^{\bar q}(x,p_T)$: higher order chiral dynamics, hence smallest flavor asymmetry

application for phenomenology:

CSS in b_T-space: $\tilde{f}_1^a(x, b_T) = \int d^2p_T \, e^{i\vec{p}_T\vec{b}_T} f_1^a(x, p_T)$

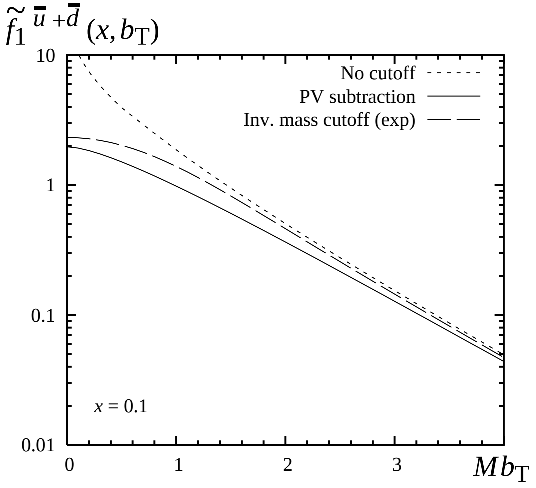
large-b_T: long-distance, non-perturbative physics, fit

usual assumption: universal Gaussian-b_T fall-off

Landry et al 2003; Konychev, Nadolsky 2006

model: valence vs sea, exponential fall-off

→ Collins, Rogers 2014



large b_T-region

independent of UV-details (regularization)

quasi model-independent ⟶ chiral-dynamics

experimental tests: ($q =$ val + sea, $\bar{q} =$ sea)

SIDIS (HERMES, COMPASS, JLab; JLab12, EIC)

kinematic leverage, explore fragmentation (challenge)

e.g.: $K^+ = u\bar{s} \sim$ (val. + sea) vs $K^- = \bar{u}s \sim$ (sea)

$(\pi^+ + \pi^-)$ vs $(\pi^+ - \pi^-)$

correlations in current ↔ target fragmentation

when correlated $q\bar{q}$ pair "split up"!

$Q^2 \sim$ few GeV^2 not too large

(to avoid loss of correlation

due to gluon radiation)

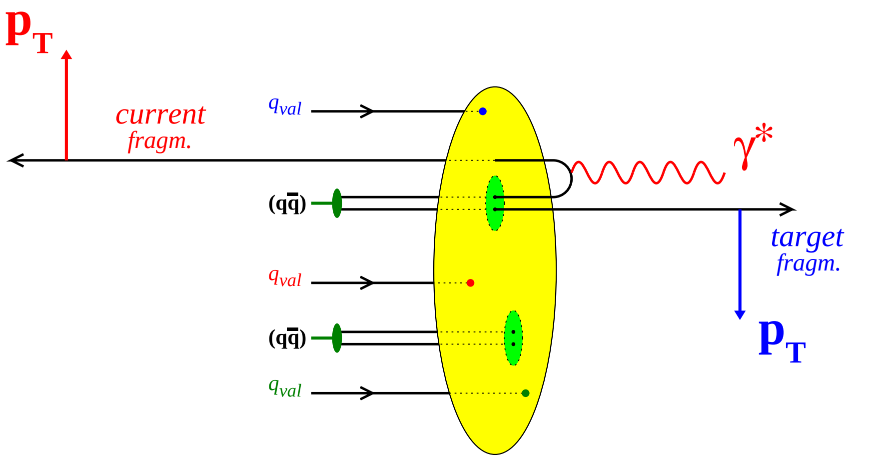
Kotzinian et al

hadron colliders

multi parton correlations (RHIC, Tevatron, LHC)

→ L. Frankfurt, M. Strikman, C. Weiss

Drell-Yan: pp vs $\bar{p}p$, RHIC, Fermilab, ...



short-range correlations $\sim \rho \ll R$

"opposite asymmetries" in fracture functions (?)

conclusions

- χ**SB key feature** of strong interactions, at $\boldsymbol{\rho \sim 0.3\,\mathrm{fm} \ll R_{\mathrm{hadron}}}$

- realized in **chiral quark soliton model** (chiral, consistent, can do GPDs)

- predictions and good description of **sea quark flavor asymmetries**

- $(f_1^{\bar{d}} - f_1^{\bar{u}})(x)$ ✓ $\quad (g_1^{\bar{u}} - g_1^{\bar{d}})(x)$ ✓ $\quad (h_1^{\bar{u}} - h_1^{\bar{d}})(x)$

- underlying mechanism: **chiral symmetry breaking** at scale $\rho \ll R_{\mathrm{hadron}}$

- more insight $\rightarrow$ **TMDs:** $\langle p_T^2 \rangle_{\mathrm{sea}} > \langle p_T^2 \rangle_{\mathrm{val}}$ interplay of ρ and R_{hadron}
  encouraging, more work and tests needed

- **chiral physics at** $\mu_0 \sim \rho^{-1}$ of importance for
  non-perturbative parton properties

conclusions

- χ**SB key feature** of strong interactions, at $\boldsymbol{\rho \sim 0.3\,\mathrm{fm} \ll R_{\mathrm{hadron}}}$
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Thank you!