Nonperturbative strange sea in proton using wave functions inspired by light front holography

Alfredo Vega

In collaboration with
I. Schmidt, T. Gutsche and V. Lyubovitskij

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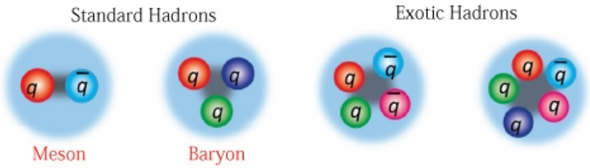
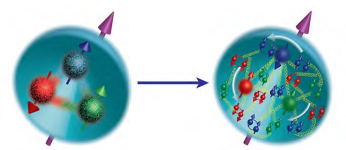
Introduction

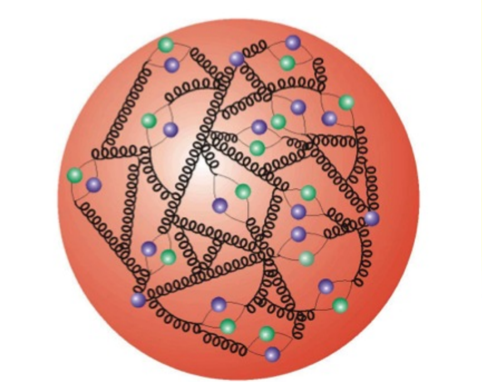


In many cases it is necessary to consider contribution of sea quarks and gluons in order to understand hadron properties

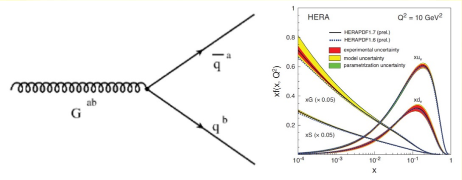


Sea quarks in nucleon arise through 2 different mechanism:

- Nonperturbative (Intrinsic).
- Perturbative (Extrinsic).



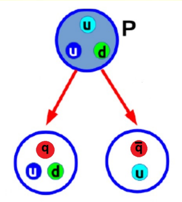
⋆ Extrinsic sources of sea quarks. [1]



- Arises from gluon radiation to $q\bar{q}$ pairs.
- Include QCD evolution.
- Strongly peaked at low x.
- Extrinsic sea quarks require $q = \bar{q}$. Asymmetries (very small, low x) arise at NNLO order.

[1] S. Catani, D. de Florian, G. Rodrigo and W. Vogelsang, Phys. Rev. Lett. **93**, 152003 (2004).

⋆ Intrinsic sources of sea quarks [2]



- Arises from $4q + \bar{q}$ fluctuations of N Fock state.
- At starting scale, peaked at intermediate x; more "valence-like" than extrinsic.
- In general, $q \neq \bar{q}$ for intrinsic sea.
- Intrinsic parton distriutions move to lower x under QCD evolution.

[2] e.g see F. G. Cao and A. I. Signal, Phys. Rev. D **60**, 074021 (1999).

Brodsky - Ma Model [3]

[3] S. J. Brodsky and B. Q. Ma, Phys. Lett. B **381**, 317 (1996).

In the light-front formalism the proton state can be expanded in a series of components as

$$|P\rangle = |uud\rangle\psi_{uud/p} + |uudg\rangle\psi_{uudg/p} + \sum_{q\bar{q}} |uudq\bar{q}\rangle\psi_{uudq\bar{q}/p} + \ldots$$

- It is possible to consider a different light front approach, in which the nucleon has components arising from meson-baryon fluctuations, while these hadronic components are composite systems of quarks.
- In this case the nonperturbative contributions to the $s(x)$ and $\bar{s}(x)$ distributions in the proton can be expressed as convolutions

$$s(x) = \int_x^1 \frac{dy}{y} f_{\Lambda/K\Lambda}(y) q_{s/\Lambda}\left(\frac{x}{y}\right) \quad \text{and} \quad \bar{s}(x) = \int_x^1 \frac{dy}{y} f_{K/K\Lambda}(y) q_{\bar{s}/K}\left(\frac{x}{y}\right)$$

Brodsky - Ma Model

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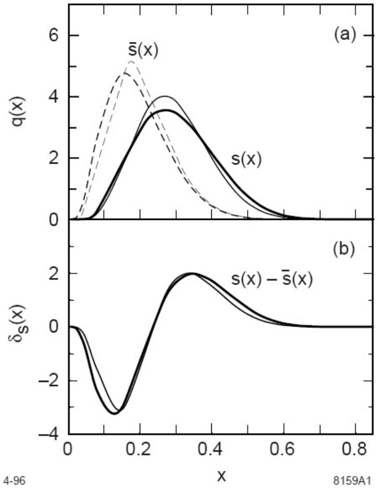
- $q_{s/\Lambda}$ and $q_{\bar{s}/K}$ are distributions of s quarks and $\bar{s}$ antiquarks in the Λ^0 and K^+, respectively.
- The functions $f_{\Lambda/K\Lambda}(y)$ and $f_{K/K\Lambda}(y)$ describe the probability to find a Λ or a K with light-front momentum fraction y in the $K\Lambda$ state.
- To do calculations we need wave functions.

$$f_{B/BM}(y) = \int \frac{d^2k}{16\pi^3} |\psi_{BM}(y,k)|^2$$

$$q_{s/\Lambda}(x) = \int \frac{d^2k}{16\pi^3} |\psi_{\Lambda}(x,k)|^2 \quad and \quad q_{\bar{s}/K}(x) = \int \frac{d^2k}{16\pi^3} |\psi_{K}(x,k)|^2$$

Brodsky - Ma Model



Holographic Light Front Wave Functions

◇ **Basic Idea.** [4]

Comparison of Form Factors in light front and in AdS side, offer us a possibility to relate AdS modes that describe hadrons with LFWF.

- In Light Front (for hadrons with two partons),

$$F(q^2) = 2\pi \int_0^1 dx \frac{(1-x)}{x} \int d\zeta \; \zeta J_0\left(\zeta q \sqrt{\frac{1-x}{x}}\right) \frac{|\widetilde{\psi}(x,\zeta)|^2}{(1-x)^2}.$$

- In AdS

$$F(q^2) = \int_0^\infty dz \; \Phi(z) J(q^2, z) \Phi(z),$$

where $\Phi(z)$ correspond to AdS modes that represent hadrons, $J(q^2, z)$ it is dual to electromagnetic current.

[4] S. J. Brodsky and G. F. de Teramond, Phys. Rev. Lett. **96**, 201601 (2006); Phys. Rev. D **77**, 056007 (2008).

Considering a soft wall model with a cuadratic dilaton, Brodsky and de Teramond found [5]

$$\psi(x, \mathbf{b}_\perp) = A\sqrt{x(1-x)}\; e^{-\frac{1}{2}\kappa^2 x(1-x)\mathbf{b}_\perp^2},$$

and in momentum space

$$\psi(x, \mathbf{k}_\perp) = \frac{4\pi A}{\kappa\sqrt{x(1-x)}} \exp\left(-\frac{\mathbf{k}_\perp^2}{2\kappa_1^2 x(1-x)}\right).$$

[5] S. J. Brodsky and G. F. de Teramond, Phys. Rev. Lett. **96**, 201601 (2006); Phys. Rev. D **77**, 056007 (2008).

Holographic Light Front Wave Functions

A generalizations of LFWF discused in previous section looks like

$$\psi(x, \mathbf{k}_\perp) = N \frac{4\pi}{\kappa\sqrt{x(1-x)}} g_1(x) \exp\left(- \frac{\mathbf{k}_\perp^2}{2\kappa_1^2 x(1-x)} g_2(x) \right).$$

You can found some examples in

- S. J. Brodsky and G. F. de Teramond, arXiv:0802.0514 [hep-ph].
- A. V, I. Schmidt, T. Branz, T. Gutsche and V. E. Lyubovitskij, PRD 80, 055014 (2009).
- S. J. Brodsky, F. G. Cao and G. F. de Teramond, PRD 84, 075012 (2011).
- J. Forshaw and R. Sandapen, PRL 109, 081601 (2012).
- S. Chabysheva and J. Hiller, Annals of Physics 337 (2013) 143 - 152.
- T. Gutsche, V. Lyubovitskij, I. Schmidt and A. V, PRD 87, 056001 (2013).

◇ Background for a generalization to arbitrary twist

- In AdS side, form factors in general looks like

$$F(q^2) = \int_0^\infty dz\ \Phi_\tau(z)\mathcal{V}(q^2, z)\Phi_\tau(z),$$

  Example: Fock expansion in AdS side for Protons [6], Deuteron form factors [7].

- We consider a shape that fulfill the following constraints:
  - At large scales $\mu \to \infty$ and for $x \to 1$, the wave function must reproduce scaling of PDFs as $(1-x)^\tau$.
  - At large Q^2, the form factors scales as $1/(Q^2)^{\tau-1}$.

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[6] Thomas Gutsche, Valery E. Lyubovitskij, Ivan Schmidt y A. V, Phys. Rev. D86 (2012) 036007; Phys. Rev. D87 (2013) 016017.

[7] Thomas Gutsche, Valery E. Lyubovitskij, Ivan Schmidt y A. V, Phys. Rev. D91 (2015) 114001.

◇ LFWF with Arbitrary Twist [8]

Recently we have suggested a LFWF at the initial scale μ_0 for hadrons with arbitrary number of constituents that looks like

$$\psi_\tau(x, \mathbf{k}_\perp) = N_\tau \frac{4\pi}{\kappa} \sqrt{log(1/x)}(1-x)^{(\tau-4)/2} Exp\left[-\frac{\mathbf{k}_\perp^2}{2\kappa^2} \frac{log(1/x)}{(1-x)^2}\right]$$

- The PDFs $q_\tau(x)$ and GPDs $H_\tau(x, Q^2)$ in terms of the LFWFs at the initial scale can be calculated.
- We can extend our LFWF to reproduce PFDs and GPDs evolved to an arbitrary scale.

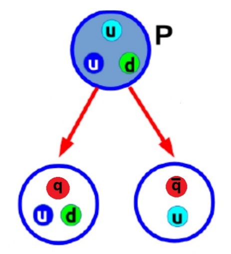
Note: In this wave function we can add massive quarks (grouped in clusters).

[8] Thomas Gutsche, Valery E. Lyubovitskij, Ivan Schmidt y A. V, Phys. Rev. D89 (2014) 054033.

$(s - \bar{s})$ Asymmetry with Holographic LFWFs [9]

[9] A. Vega, I. Schmidt, T. Gutsche and V. E. Lyubovitskij, arXiv:1511.06476 [hep-ph].

⋆ Summary.



$$s(x) = \int_x^1 \frac{dy}{y} f_{\Lambda/K\Lambda}(y) q_{s/\Lambda}\left(\frac{x}{y}\right) \quad \textit{and} \quad \bar{s}(x) = \int_x^1 \frac{dy}{y} f_{K/K\Lambda}(y) q_{\bar{s}/K}\left(\frac{x}{y}\right)$$

$$f_{B/BM}(y) = \int \frac{d^2k}{16\pi^3} |\psi_{BM}(y,k)|^2$$

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⋆ **LFWF used.**

◇ Gaussian.

$$\psi(x,k) = A\exp\left[-\frac{1}{8\kappa^2}\left(\frac{k^2}{x(1-x)}+\mu_{12}^2\right)\right]$$

◇ Holographic (Variant I).

$$\psi(x,k) = \frac{A}{\sqrt{x(1-x)}}\exp\left[-\frac{1}{2\kappa^2}\left(\frac{k^2}{x(1-x)}+\mu_{12}^2\right)\right]$$

◇ Holographic (Variant II).

$$\psi_\tau(x,k) = A_\tau f_\tau(x)\exp\left[-\frac{x\log(1/x)}{2\kappa^2(1-x)}\left(\frac{k^2}{x(1-x)}+\mu_{12}^2\right)\right]$$

where

$$\mu_{12}^2 = \frac{m_1^2}{x}+\frac{m_2^2}{1-x} \quad \textit{and} \quad f_\tau(x) = \frac{4\pi}{\kappa}\sqrt{\log(1/x)}(1-x)^{\frac{\tau-4}{2}}$$

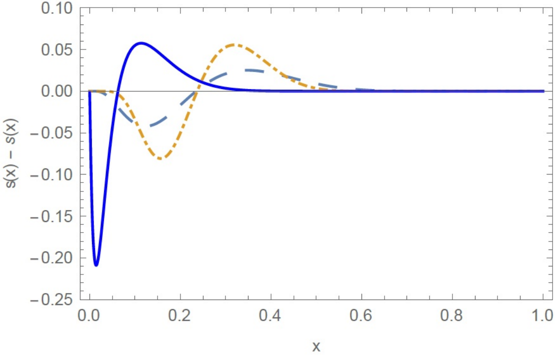

Figure: $s(x) - \bar{s}(x)$ plots for three different types of LFWFs: Gaussian LFWF (large dashed line – $\kappa = 330$ MeV), holographic LFWF (variant I), (dot dashed line – $\kappa = 350$ MeV) and holographic LFWF (variant II)(continuous line – $\kappa = 350$ MeV).

$(s-\bar{s})$ Asymmetry with a Holographic LFWF

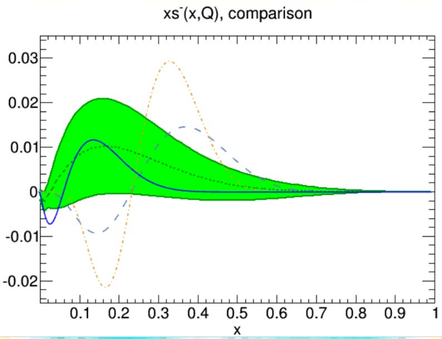

Figure: $xS^{-}=x(s(x)-\bar{s}(x))$. Green region and small dashed line correspond to MMHT (L.A. Harland-Lane, A.D. Martin, P. Motylinski and R.S.Thorne, Eur. Phys. J. C **75**, 204 (2015).)) that it was generated with APFEL (S. Carrazza, A. Ferrara, D. Palazzo and J. Rojo, J. Phys. G **42**, 057001 (2015).). Other lines correspond to same cases in Fig. 1.

$(s - \bar{s})$ Asymmetry with a Holographic LFWF

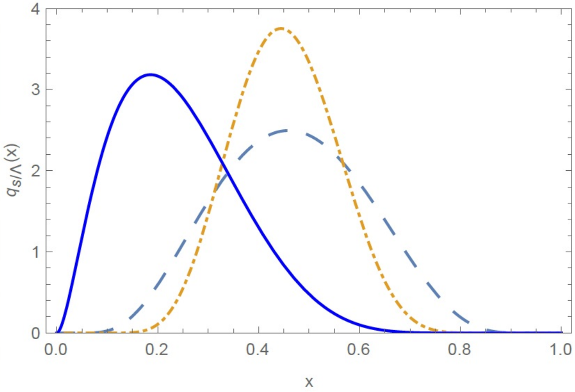

Figure: Strange quark density $q_{s/\Lambda}$. All notations as in Fig. 1.

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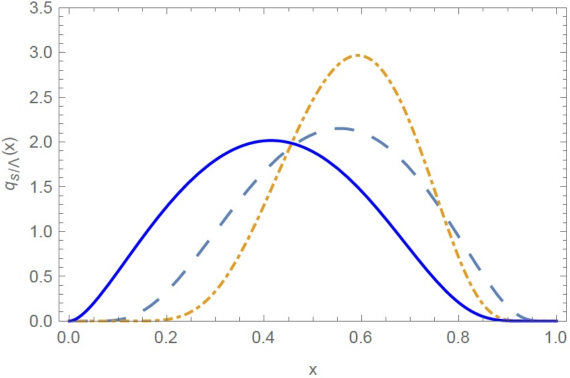

Figure: Strange quark density $q_{\bar{s}/K^+}$. All notations as in Fig. 1.

Final Comments and Conclusions

- We used a hadronic wave function inspired by Light Front Holography, that consider arbitrary number of constituent in hadron.
- We calculated the $s(x) - \bar{s}(x)$ asymmetry in a light-front model considering three types of LFWFs that produce different results.
- In all of these cases we observe that $s(x) < \bar{s}(x)$ for small values of x and $s(x) > \bar{s}(x)$ in the region of large x.
- Among LFWFs considered, the holographic that consider arbitrary number of constituent is closer to recent MMHT parametrization [10].
- Wave functions used could be useful in calculations of other hadron properties.

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That's all Folks!