Spectral Function Approach in Describing Valence Quarks in the Nucleon and Nucleus

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Motivation: Valence quarks in the nucleon and nucleus

Valence quarks play a unique role in QCD dynamics of the nucleon

- They define baryonic number of the nucleon:

- They represent effective "three fermion" system with complex interaction among themselves and with nucleon environment

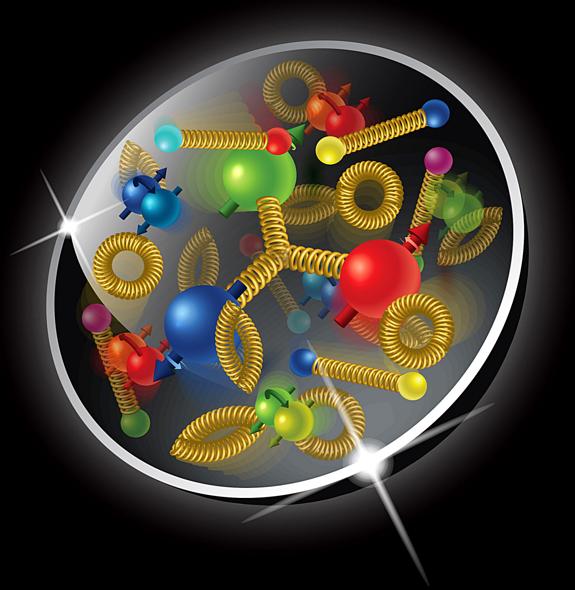
- Because of their conserved number the concept of mean-field interaction can be introduce to discuss their interaction with the nucleon environment

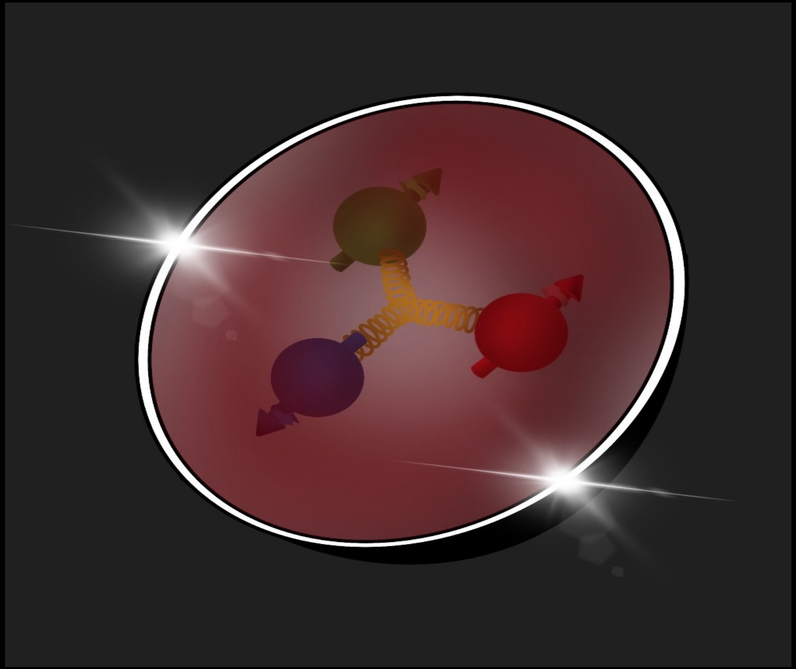
- Quantum mechanically, this becomes a problem of fermions in the strong external field – (see e g. Migdal Fermions in the Strong Field)

- Short range interaction among three valence quarks responsible to the generation of high x distribution of PDFs

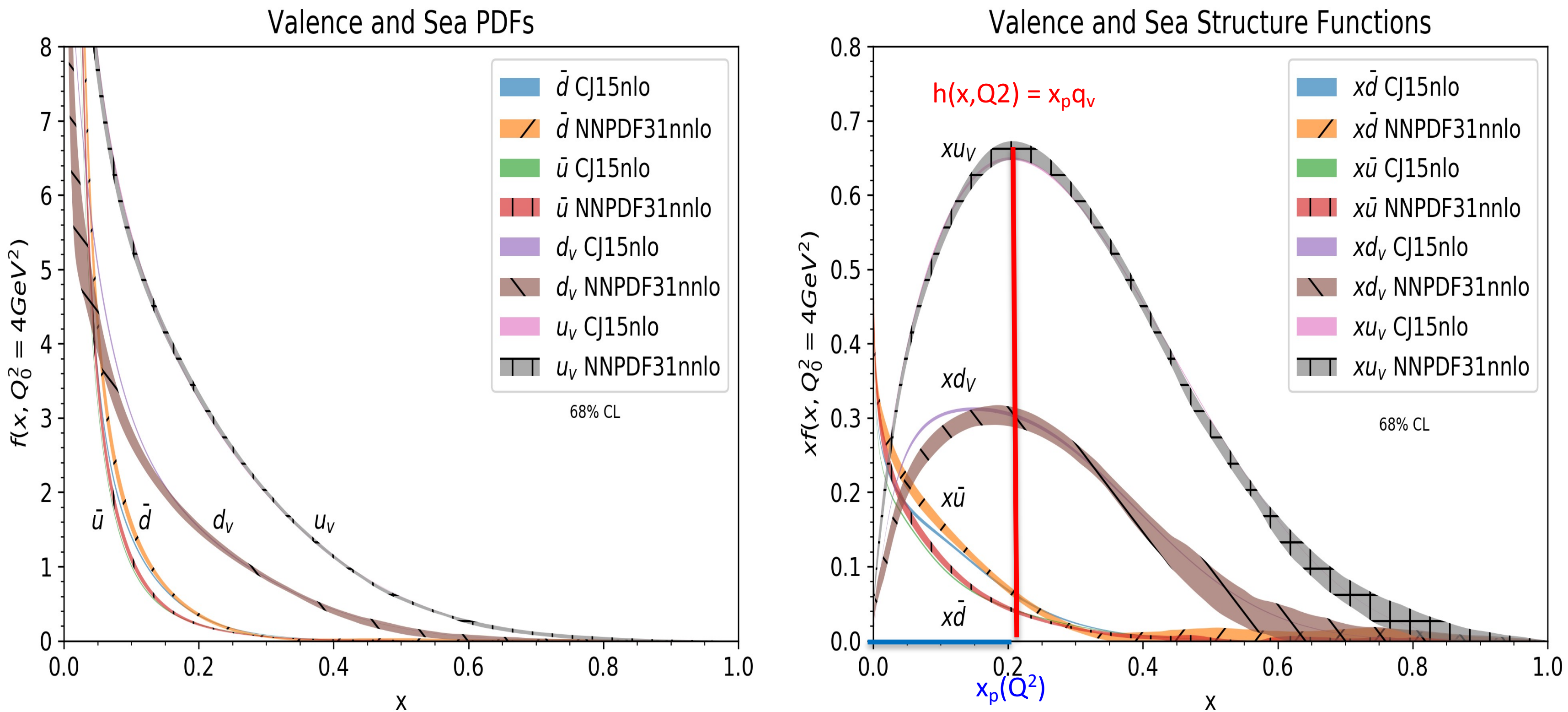
Valence quarks in the nucleon

at medium to high x: $0.1 < x < 1$

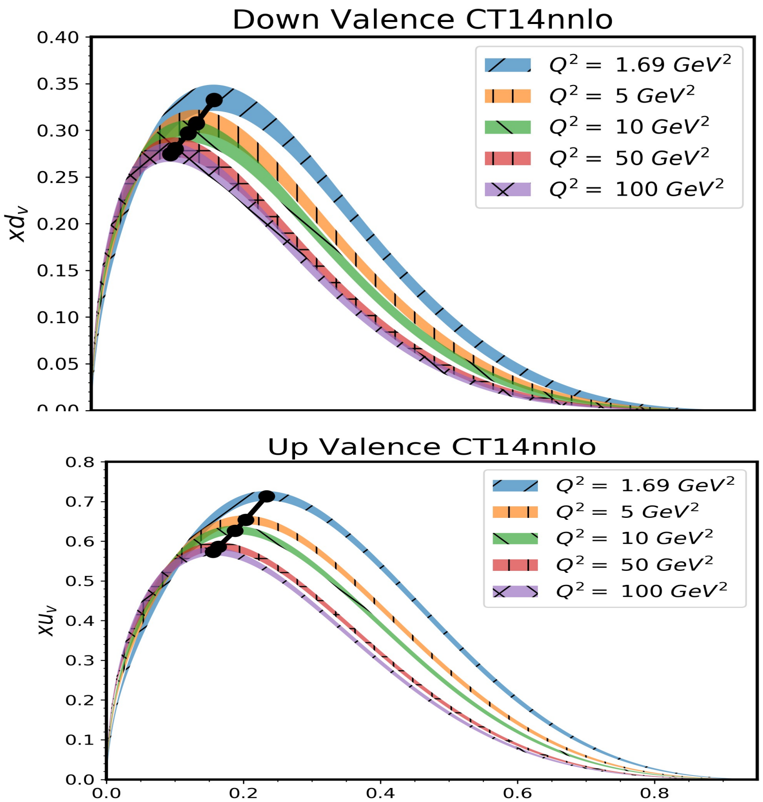




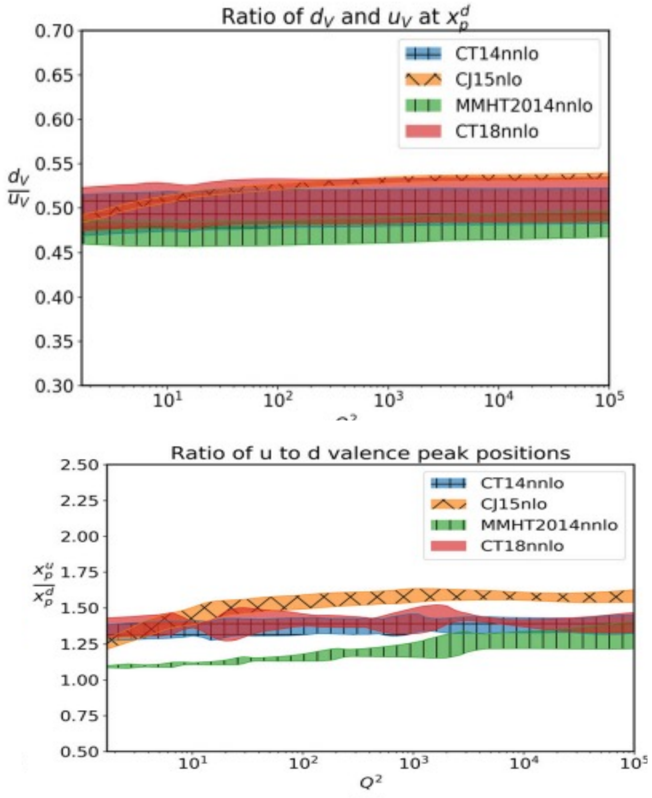
- Treating the height of the peak $h(x_p,Q^2)$ and position of the peak x_p as "physical observables":



- Treating the **height of the peak** $h(x_p,Q^2)$ and **position of the peak** x_p as **"physical observables"**:



(b)



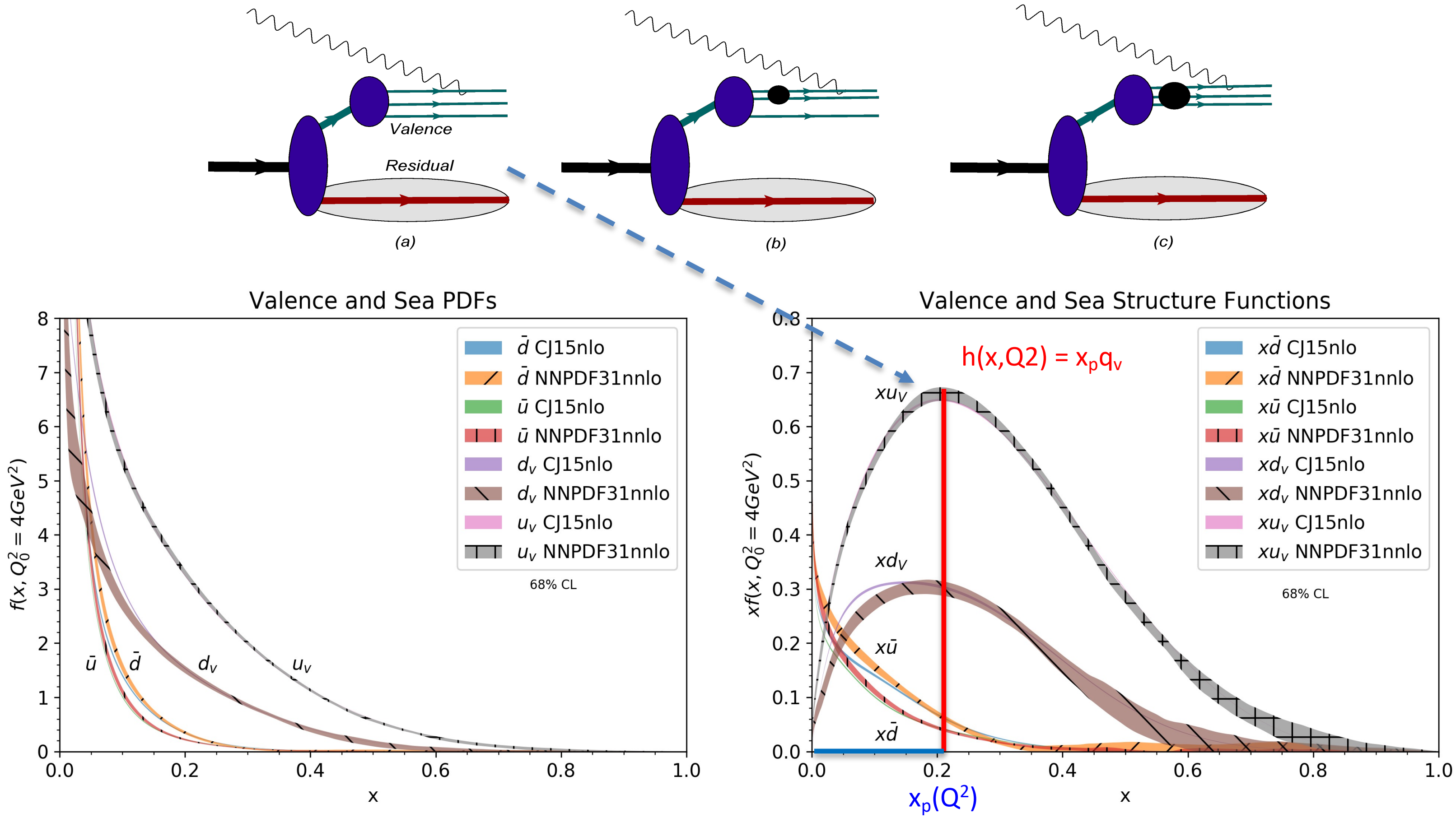
(b)

“New Approaches” in modeling valence quark dynamics

- In general the peaking property of bound Fermi-system is a hallmark for mean-field dynamics

- Our assumption is that the peaking feature of valence quark distributions is due to interaction of valence quarks in the strong mean field generated by “residual nucleon system”

- We introduce concept of “residual nucleon system” as as composite part of the light-front wave function of valence quarks


Valence
Residual
(a)
(b)
(c)
Valence and Sea PDFs
f(x, Q0^2 = 4GeV^2)
d̄ CJ15nlo
d̄ NNPDF31nnlo
ū CJ15nlo
ū NNPDF31nnlo
d_v CJ15nlo
d_v NNPDF31nnlo
u_v CJ15nlo
u_v NNPDF31nnlo
68% CL
ū
d̄
d_v
u_v
x
Valence and Sea Structure Functions
xf(x, Q0^2 = 4GeV^2)
h(x,Q2) = x_p q_v
xu_V
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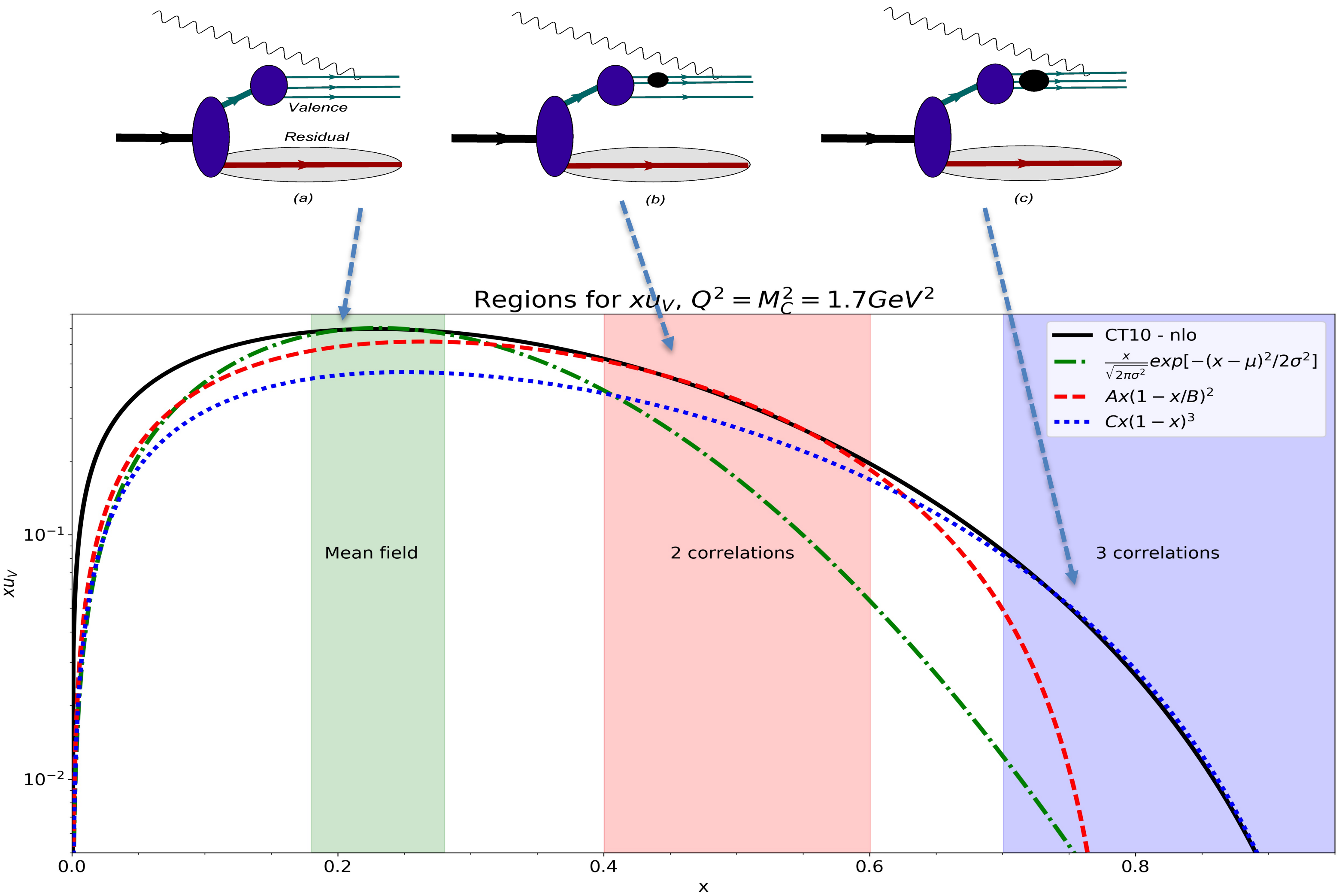
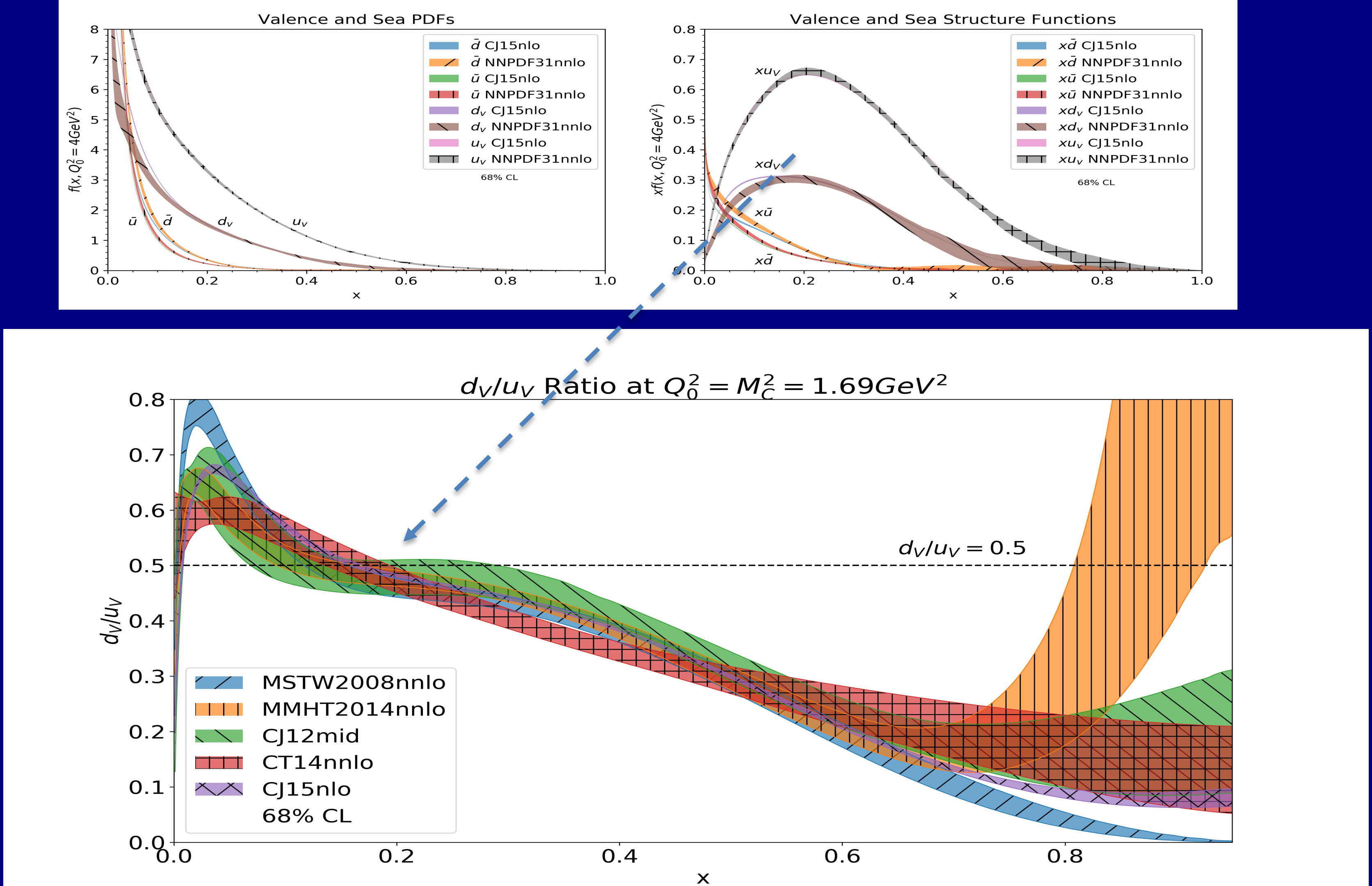
xū NNPDF31nnlo
xd_v CJ15nlo
xd_v NNPDF31nnlo
xu_v CJ15nlo
xu_v NNPDF31nnlo
68% CL
x_p(Q^2)
x



Valence
Residual
(a)
(b)
(c)
Regions for xu_V, $Q^2 = M_C^2 = 1.7GeV^2$
CT10 - nlo
$\frac{x}{\sqrt{2\pi\sigma^2}} exp[-(x-\mu)^2/2\sigma^2]$
$Ax(1-x/B)^2$
$Cx(1-x)^3$
Mean field
2 correlations
3 correlations
xu_V
10^{-1}
10^{-2}
0.0
0.2
0.4
0.6
0.8
x



Valence and Sea PDFs
$f(x, Q_0^2 = 4GeV^2)$
$\bar{d}$ CJ15nlo
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68% CL
$\bar{u}$
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x
Valence and Sea Structure Functions
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$x\bar{d}$ CJ15nlo
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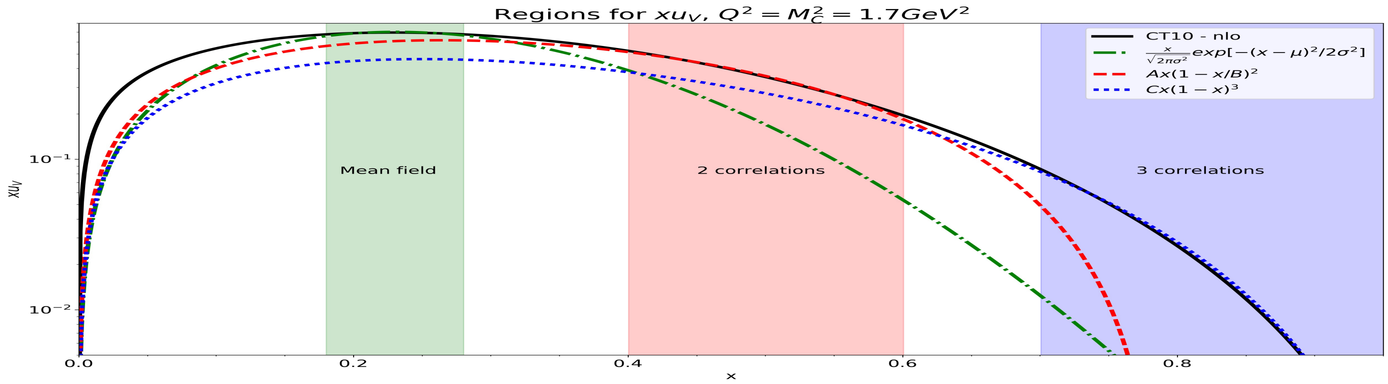
d_V/u_V Ratio at $Q_0^2 = M_C^2 = 1.69GeV^2$
d_V/u_V
$d_V/u_V = 0.5$
MSTW2008nnlo
MMHT2014nnlo
CJ12mid
CT14nnlo
CJ15nlo
68% CL
x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Mean field
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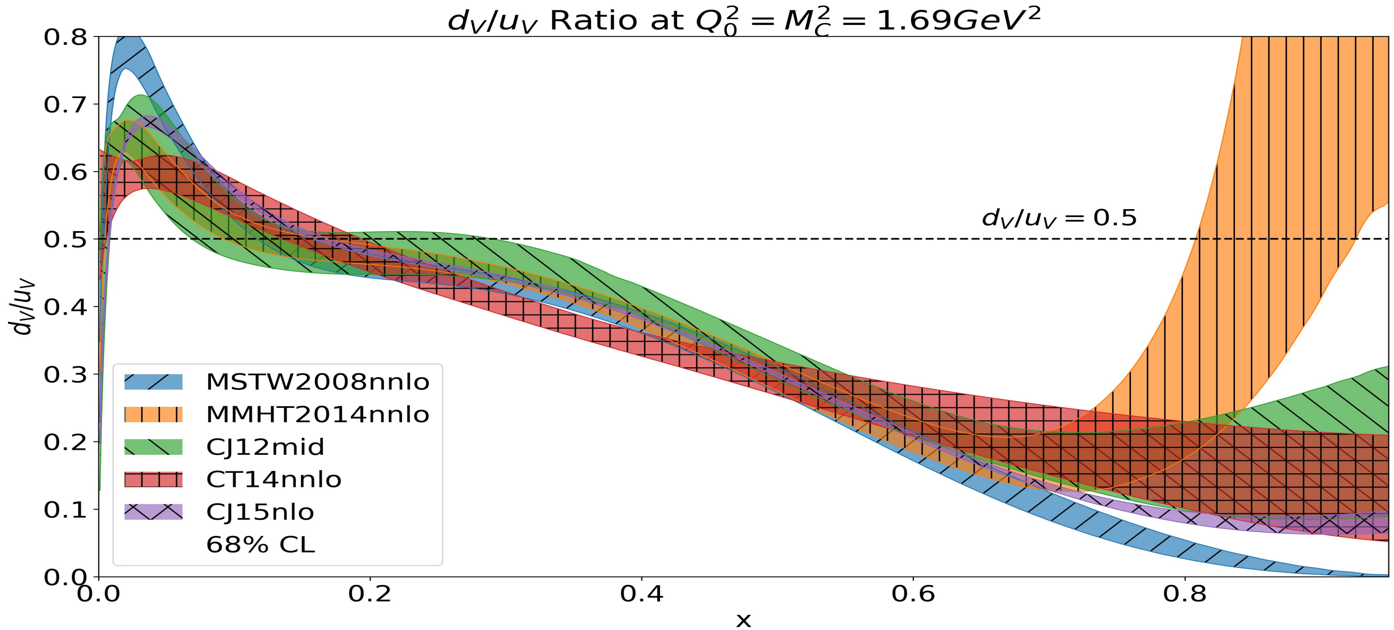
d_V/u_V Ratio at $Q_0^2 = M_C^2 = 1.69 GeV^2$
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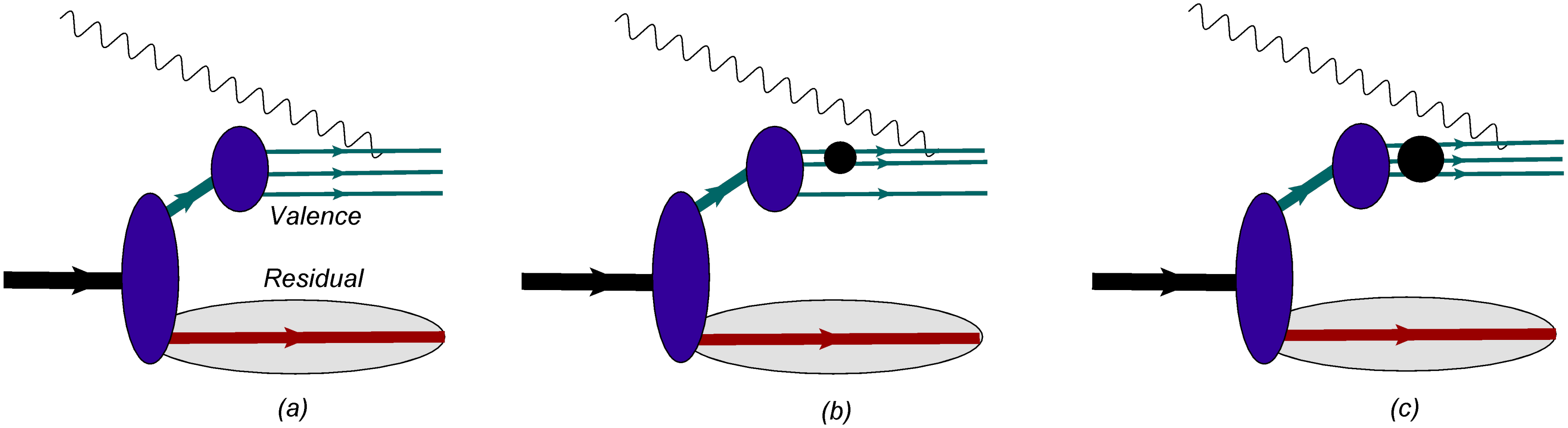
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.0
0.2
0.4
0.6
0.8
x

Main assumptions of the model

Dynamics: The main assumption is that the mean field, two- and three- quark short-range correlations define the dynamics of the valence quarks in the range of

$0.1 \leq x \leq 1$.



Valence Quarks in the Nucleon:

- The model assumes an existence of almost massless valence three-quark cluster V in the nucleon.
- The cluster is compact with the transverse separation between and qq, $b_{qq} \lesssim 0.3$ Fm.
- Valence quark system defines the baryonic number but not necessarily the total isospin of the nucleon. It can have total total isospin, $I_V = 1/2$ or $3/2$ each of them corresponding to the different excitations or masses of the residual nucleon system. *(For the lowest mass of the recoil system one expects the 3q system to have the same isospin and its projection that the considered nucleon has.)*

Residual Structure:

- Introducing residual structure of the nucleon with the spectrum of mass, m_R - spectral function formalism in the description of the nucleon structure.

- The model assumes a certain universality of the residual structure, R, entering in all three mechanisms of generation of valence quark distribution.

- This universality is reflected in the fact that one can fix its main properties within mean field and apply it in the calculation of 2q- and 3q- correlation contributions.

- The mass spectrum of the residual system is continuous and effectively depends on whether u- or d- valence quarks are probed.

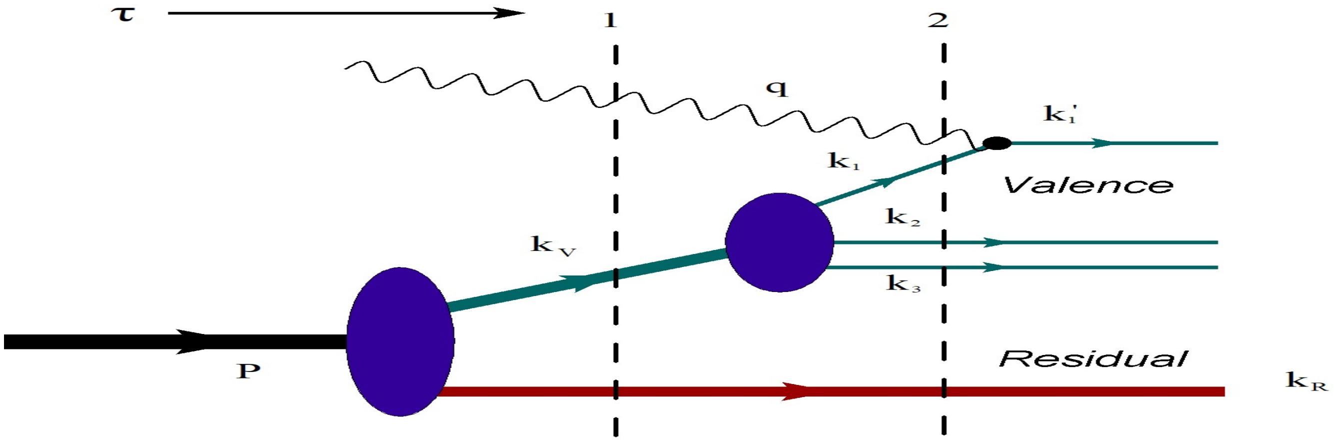
$$m_R(u/d) = \alpha_{u/d} \cdot m_R(I_V = \frac{1}{2}, I_V^3 = \frac{1}{2}) + \beta_{u/d} \cdot m_R(I_V = \frac{1}{2}, I_V^3 = -\frac{1}{2}) + \gamma(u/d) \sum_{I_V^3 = -\frac{3}{2}}^{\frac{3}{2}} m_R(I_V = \frac{3}{2}, I_V^3) + \cdots$$

For proton: $m_R(u) < m_R(d)$

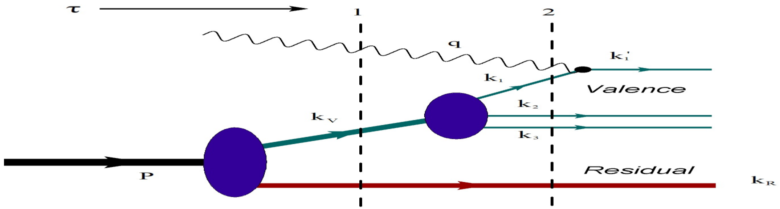
- QCD evolution will increase: $m_R(Q^2)$

Mean-Field Model of Valence Quark Distributions

- The valence 3q system occupies a region of ~ 0.6~Fm and is described by mutually couple
three-dimensional harmonic oscillators, thus satisfying confinement condition.
They don't define the total radius of the nucleon.
- Valence quarks are almost massless with the invariant energy of 3q system contributing to the nucleon mass.
The residual system generates the mean field and occupies a volume less or equal to the nucleon volume.



Light-Front Wave Functions



$|Hadron\rangle$ described as Fock expansion in Light Front Wave Functions:

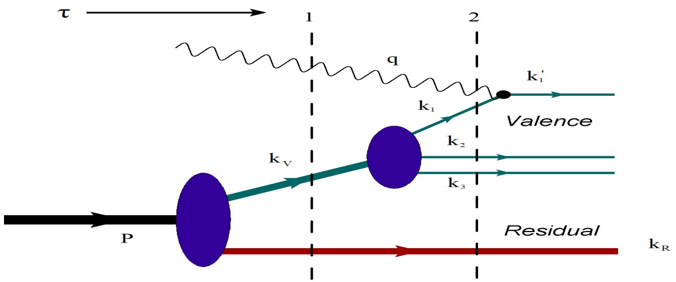
$$|Hadron\rangle = \sum_i \int [d\mu_i]\, \Psi_i \; |i\rangle$$

$$|N\rangle = \int [d\mu_{3q}]\, \psi_{3q} |qqq\rangle + \int [d\mu_{4q,\bar{q}}]\, \psi_{4q,\bar{q}} |qqq\,\bar{q}q\rangle + \int [d\mu_{3q,1g}]\, \psi_{3q,1g} |qqq\;\rangle + \cdots$$

Infinite set of coupled integral equations

$$\sum_{n'} \int [d\mu'_{n'}]\, \langle n : x_i, \vec{k}_{\perp i}, \lambda_i | H | n' : x'_i, \vec{k}'_{\perp i}, \lambda'_i \rangle\, \Psi_{n'/h}(x'_i, \vec{k}'_{\perp i}, \lambda'_i) = \frac{M^2 + \vec{P}_\perp^2}{2P^+} \Psi_{n/h}(x_i, \vec{k}_\perp, \lambda_i) \,,$$

Phenomenological Light-Front Wave Functions



$$\psi_{VR}(x_V, \mathbf{k}_{R,\perp}, x_R, \mathbf{k}_{V,\perp}) = \frac{\bar{\chi_V}\bar{\chi_R}\Gamma^{B\to VR}u(p_N, h_N)}{m_N^2 - \frac{k_{V,\perp}^2 + m_V^2}{x_V} - \frac{k_{R,\perp}^2 + m_R^2}{x_R}}$$

$$\psi_{3q}(\{\beta_i, \mathbf{k}_{i,\perp}, h_i\}_{i=1}^3) = \frac{\prod_{i=1}^3 \bar{u}(k_i, h_i)\Gamma^{V\to 3q}\chi_V}{m_V^2 - \sum_{i=1}^3 \frac{k_{i,\perp}^2 + m_i^2}{\beta_i}}$$

where $\{\beta_i, \mathbf{k}_{i,\perp}, h_i\}_{i=1}^3$ denotes the LC momenta and helicities of the three valence quarks in the wave function.

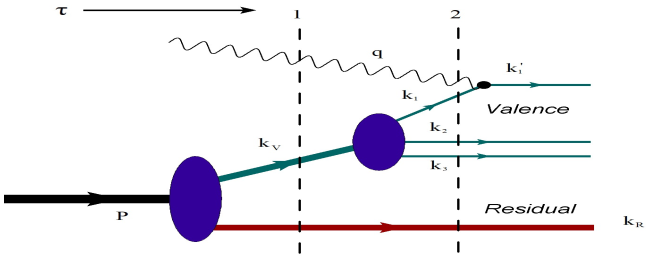
Reference Frame, Kinematics and Structure Function

$$p_N^\mu = (p_N^+, \frac{m_N^2}{p_N^+}, \mathbf{0}_\perp), \quad q^\mu = (0, \frac{2p\cdot q}{p_N^+}, \mathbf{q}_\perp), \quad Q^2 = -q^2 = |\mathbf{q}_\perp|^2,$$

$$p_N^+ \gg m_N, k_i^-, k_{i,\perp},$$

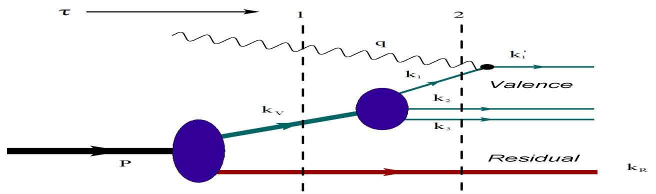
$$F_2(x,Q^2) \equiv \sum_i e_i^2 x f_i(x,Q^2), = \frac{MQ^2}{2x(p_N^+)^2} W_N^{++}$$

$$W_N^{\mu\nu} = \frac{1}{4\pi M}\int \sum_X \sum_{s_X} J^{\mu,\dagger}(p_X,s_X,,p_N,s_N) J^\nu(p_X,s_X,p_N,s_N)(2\pi)^4\delta^4(q+p_N-p_X)\delta(p_X^2-M_X^2)\frac{d^4p_X}{(2\pi)^3}\frac{1}{2(2\pi)}$$



$$A^\mu = \sum_{h_V,h_1} \frac{1}{k_V^+}\frac{1}{k_1^+}\frac{\bar{u}(k_1',h_1')(ie_1\gamma^\mu)u(k_1,h_1)}{\mathcal{D}_1}\frac{\prod_{i=1}^3 \bar{u}(k_i,h_i)\Gamma^{V\to 3q}\chi_V\bar{\chi_V}\bar{\chi}_R\Gamma^{B\to VR}u(p_N,h_N)}{\mathcal{D}_2}$$

Calculation of the scattering amplitude



$$A^\mu = \sum_{h_1,h_V} \frac{1}{x_V}\frac{1}{\beta_1} \frac{\bar{u}(k_1',h_1')(ie_1\gamma^\mu)u(k_1,h_1)}{m_V^2 - \sum_{i=1}^3 \frac{k_{i,\perp}^2+m_i^2}{\beta_i}} \frac{\prod_{i=1}^3 \bar{u}(k_i,h_i)\Gamma^{V\to 3q}\chi_V \bar{\chi_V}\bar{\chi}_R \Gamma^{B\to VR} u(p_N,h_N)}{M^2 - \frac{k_{V,\perp}^2+m_V^2}{x_V} - \frac{k_{R,\perp}^2+m_R^2}{x_R}}$$

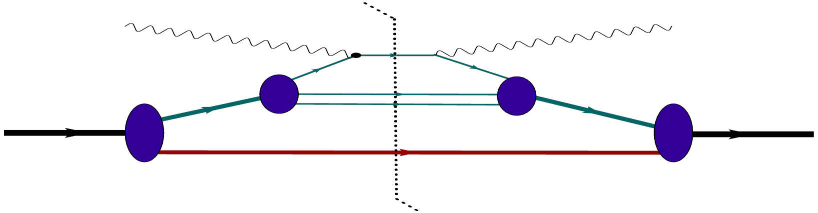
$$\psi_{VR}(x_V,\mathbf{k}_{R,\perp},x_R,\mathbf{k}_{V,\perp}) = \frac{\bar{\chi_V}\bar{\chi_R}\Gamma^{B\to VR}u(p_N,h_N)}{m_N^2 - \frac{k_{V,\perp}^2+m_V^2}{x_V} - \frac{k_{R,\perp}^2+m_R^2}{x_R}}$$

$$\psi_{3q}(\{\beta_i,\mathbf{k}_{i,\perp},h_i\}_{i=1}^3) = \frac{\prod_{i=1}^3 \bar{u}(k_i,h_i)\Gamma^{V\to 3q}\chi_V}{m_V^2 - \sum_{i=1}^3 \frac{k_{i,\perp}^2+m_i^2}{\beta_i}}$$

where $\{\beta_i,\mathbf{k}_{i,\perp},h_i\}_{i=1}^3$ denotes the LC momenta and helicities of the three valence quarks in the wave function.

$$A^\mu = \sum_{h_1,h_V} \bar{u}(k_1,h_1)(ie_1\gamma^\mu)u(k_1,h_1)\frac{\psi_{VR}(x_V,\mathbf{k}_{R,\perp},x_R,\mathbf{k}_{V,\perp})}{x_V}\frac{\psi_{3q}(\{\beta_i,\mathbf{k}_{i,\perp},h_i\}_{i=1}^3)}{\beta_1}$$

Calculation of the Structure Function



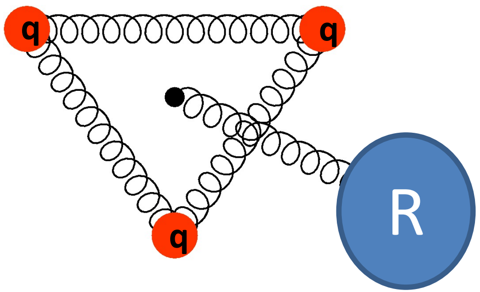
$$W_N^{\mu\nu}(x,Q^2) = \frac{1}{4\pi M_N}\sum_{\{h_i,\tau_i\}}\int \delta(1-\sum_{i=1}^{3} x_i - x_R)\frac{dx_R}{x_R}\prod_{i=1}^{3}\frac{dx_i}{x_i}16\pi^3\delta^{(2)}(\sum_{i=1}^{3}\mathbf{k}_{i,\perp}+\mathbf{k}_{R,\perp})\frac{d^2\mathbf{k}_{R,\perp}}{16\pi^3}\prod_{i=1}^{3}\frac{d^2\mathbf{k}_{i,\perp}}{16\pi^3}A^{\mu\dagger}A^{\nu}$$

$$F_2(x,Q^2) \equiv \sum_i e_i^2 x f_i(x,Q^2), = \frac{MQ^2}{2x(p_N^+)^2)}W_N^{++}$$

$$f_q(x_B) = \sum_{h_i}\int \delta(1-\sum_{i=1}^{3} x_i - x_R)\frac{dx_R}{x_R}\prod_{i=1}^{3}\frac{dx_i}{x_i}[d^2\mathbf{k}_\perp]16\pi^3\delta^{(2)}(\sum_{i=1}^{3}\mathbf{k}_{i,\perp}+\mathbf{k}_{R,\perp})\frac{d^2\mathbf{k}_{R,\perp}}{16\pi^3}\prod_{i=1}^{3}\frac{d^2\mathbf{k}_{i,\perp}}{16\pi^3}$$
$$\times\delta(x_1-x_B)|\psi_{3q}(\{\beta_i,\mathbf{k}_{i,\perp},h_i\}_{i=1}^{3})|^2|\psi_V(x_V,\mathbf{k}_{R,\perp},x_R,\mathbf{k}_{V,\perp})|^2.$$

Model – Light Front Wave Functions

- $\boldsymbol{\psi_{3q}}$ → relativistic mutually-coupled LF Harmonic Oscilator model

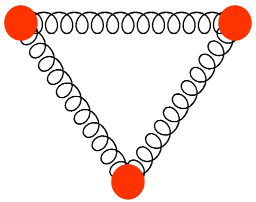


- $\boldsymbol{\psi_{VR}}$ → use Gaussian with non-relativistic kinematics

$$\boldsymbol{\psi_{3q}} \sim \exp\left[-\frac{B_R}{2}\sum_{i=1}^{3}\frac{\tilde{k}_{i,\perp}^2 + m^2}{x_i/x_V}\right]\sqrt{x_2 x_3}$$

$$\boldsymbol{\psi_{VR}} \sim \exp\left[-\frac{B_R}{2}\left(k_{R\perp}^2 + k_{R,z}^2\right)\right]\sqrt{x_R}$$

Modeling Wave Functions



Wave function of 3q valence system: Relativistic coupled Harmonic Oscillator

$$\psi_{3q}(\{x_i, \mathbf{k}_{i,\perp}\}_{i=1}^3) = 16\pi^3 m_N A_V \exp\Big[-\frac{B_V}{2}(k_{12,cm}^2 + k_{23,cm}^2 + k_{31,cm}^2)\Big]\sqrt{x_2 x_3}, \quad (1)$$

where A_V and B_V are parameters and $x_i, k_{i,\perp}$, $(i \neq j = 1,2,3)$ are LC momentum fractions and transverse momenta of each valence quark in the reference considered frame. The $k_{ij,cm}^2$s, $(i \neq j = 1,2,3)$ in the exponent of the wave function represent relative three momenta in the CM system of i, j pairs defined as follows:

$$k_{ij,cm}^2 = \frac{(s_{ij} - (m_i - m_j)^2)(s_{ij} - (m_i + m_j)^2)}{4 s_{ij}}, \quad (2)$$

where the invariant energy of the i, j pair is:

$$s_{ij} = (k_i + k_j)^+ (k_i + k_j)^- - (\mathbf{k}_{i,\perp} + \mathbf{k}_{j,\perp})^2 = (x_i + x_j)\left(\frac{k_{i,\perp}^2 + m_i^2}{x_i} + \frac{k_{j,\perp}^2 + m_j^2}{x_j}\right) - (\mathbf{k}_{i,\perp} + \mathbf{k}_{j,\perp})^2. \quad (3)$$

$$\tilde{k}_{i,\perp} = k_{i,\perp} - \frac{x_i}{x_V} k_{V,\perp}, \quad (i = 1,2,3)$$

$$\sum_{i=1}^{3} \tilde{k}_{i,\perp} = 0.$$

$$\psi_{3q}(\{x_i, \mathbf{k}_{i,\perp}\}_{i=1}^3) = 16\pi^3 m_N A_V \exp\left[-\frac{B_V}{8}\left(\sum_{i=1}^3 x_V \frac{\tilde{k}_{i,\perp}^2 + m^2}{x_i} - 9m^2\right)\right]$$

Modeling Wave Functions

Wave function of V-R system: Model in a Gaussian form

$$\psi_R(x_R, \mathbf{p}_{R,\perp}) = \sqrt{16\pi^3 m_N} A_R e^{-B_R p_R^2} \sqrt{x_R}$$

x_R – light-cone momentum fraction of the recoil system

p_R – relative momentum between CMs of V and R system

- Considering a non-relativistic approximation for recoil system $p_R < m_R$

$$p_{R,z} \approx (x_R m_N - m_R).$$

$$f_q(x_B) = \sum_{h_i} \int \delta(1 - \sum_{i=1}^{3} x_i - x_R) \frac{dx_R}{x_R} \prod_{i=1}^{3} \frac{dx_i}{x_i} [d^2\mathbf{k}_\perp] 16\pi^3 \delta^{(2)}(\sum_{i=1}^{3} \mathbf{k}_{i,\perp} + \mathbf{k}_{R,\perp}) \frac{d^2\mathbf{k}_{R,\perp}}{16\pi^3} \prod_{i=1}^{3} \frac{d^2\mathbf{k}_{i,\perp}}{16\pi^3}$$
$$\times \delta(x_1 - x_B) |\psi_{3q}(\{\beta_i, \mathbf{k}_{i,\perp}, h_i\}_{i=1}^{3})|^2 |\psi_V(x_V, \mathbf{k}_{R,\perp}, x_R, \mathbf{k}_{V,\perp})|^2.$$

$$f_q(x_B, Q^2) = \mathcal{N} \int_0^{1-x_B} dx_2 \int_0^{1-x_B-x_2} dx_3 \exp\left[-\frac{B_V x_V}{4} \sum_{i=1}^{3} \frac{m_i^2}{x_i} - B_R M_N^2 (x_V - (1 - \frac{M_R}{M_N}))^2 \right]$$
$$\times \frac{x_2 x_3}{x_V^3} \left(1 - e^{-a_{cm} Q_{cm}^{max2}}\right) \left(1 - e^{-a_{rel} Q_{rel}^{max2}}\right) \left(1 - e^{-B_R Q^2}\right)$$

where $a_{cm} = \frac{B_V x_V}{4} \frac{x_V}{x_3(x_1+x_2)}$ and $a_{rel} = \frac{B_V x_V}{4} \frac{x_1+x_2}{x_1 x_2}$.

considering large Q^2 and $m_q \to 0$ limit

$$f_q(x_B, Q^2) = \frac{\mathcal{N}}{6} \int_{x_B}^{1} dx_V \exp\left[-B_R m_N^2 \left(x_V - (1 - \frac{m_R}{m_N}) \right)^2 \right] \frac{(x_V - x_B)^3}{x_V^3}$$

where $\mathcal{N} = \frac{16\pi^3 A_V^2 A_R^2 m_N^3}{B_R B_V^2} e^{\frac{9}{4} B_V m_q^2}$

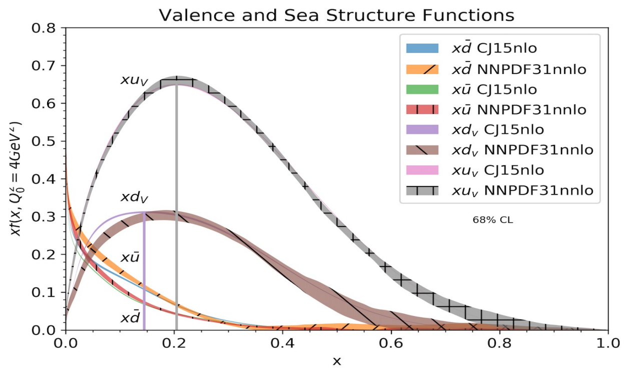
Qualitative Features of the Model

- Evaluating the integral at the maximum of exponent: $f_q(x_B, Q^2) \sim (1 - x_B - \frac{m_R}{m_N})^3$

In this case $$h(x_B, t) = x_B f_q(x_B, Q^2) \sim x_B \left(1 - x_B - \frac{m_R}{m_N}\right)^3$$

which peaks at $x_p \approx \frac{1}{4}(1 - \frac{m_R}{m_N})$.

At moderate Q^2 (M_c^2) characteristic $x_p \sim 0.2$ resulting in $m_R \sim m_\pi$.



In the model: $m_R(u) < m_R(d)$:

Explains $x_p^d < x_p^u$

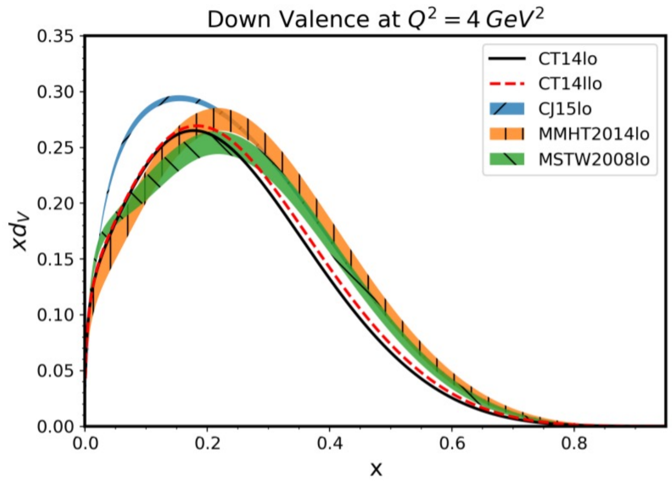
Nucleon - Peak

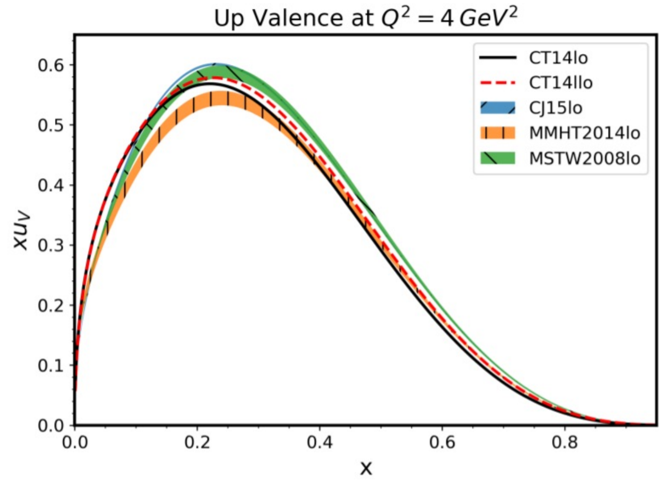
$$x_p \approx \frac{1}{4}\left(1 - \frac{m_R}{m_N}\right)$$

- For $m_R \approx m_\pi \ \rightarrow \ x_p \approx 0.2$
- Massless valence quarks
- Different from diquark (Close & Thomas (1988)):

$$x_p = 1 - \frac{m_{dq}}{m_N}$$

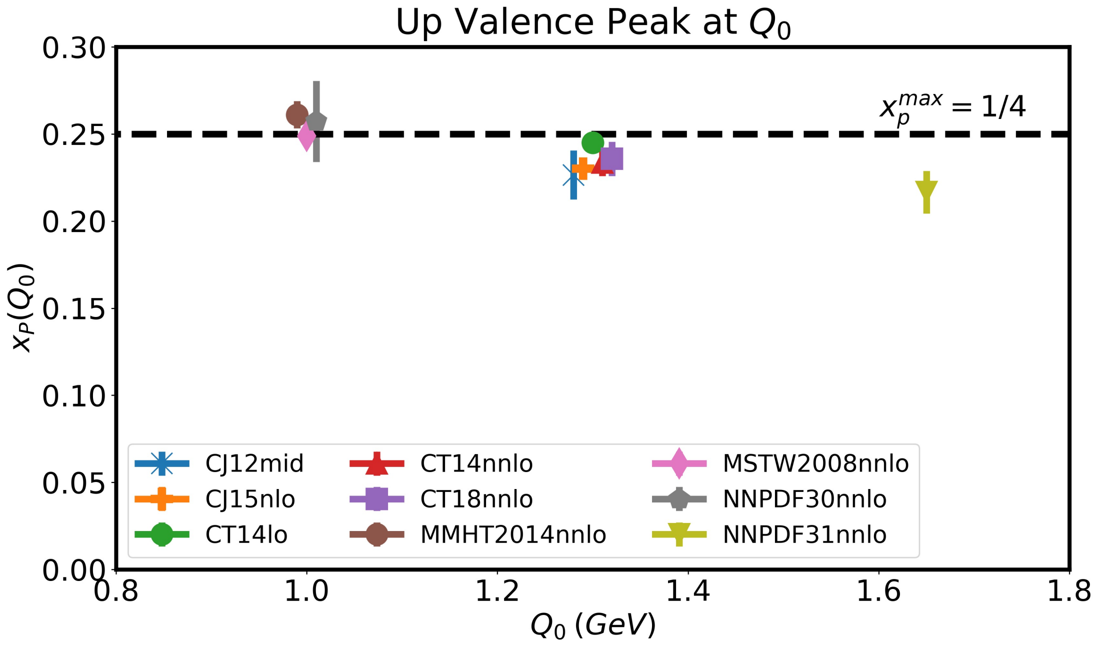
- $m_{dq} \approx 800\ MeV$, $x_p \leq 1$





Nucleon - PDF Sets

- Tested against PDF sets
- Test at lowest starting Q_0
- Universal $x_p = 1/4$ limit



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$$f_q(x_B,Q^2) = \frac{\mathcal{N}}{6}\int_{x_B}^{1} dx_V \exp\left[-B_R m_N^2\left(x_V-(1-\frac{m_R}{m_N})\right)^2\right]\frac{(x_V-x_B)^3}{x_V^3}$$

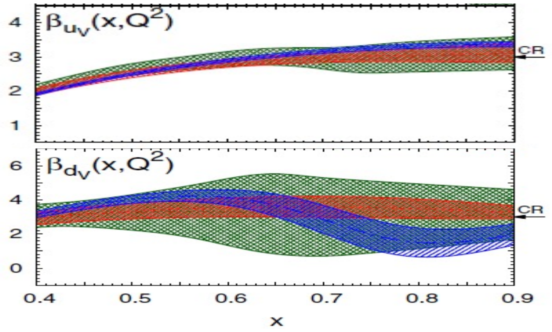
where $\mathcal{N} = \frac{16\pi^3 A_V^2 A_R^2 m_N^3}{B_R B_V^2} e^{\frac{9}{4}B_V m_q^2}$

Qualitative Features of the Model

- One can also evaluate the analytic behavior of $f_q(x_B,Q^2)$ at $x_B \rightarrow 1$:

For this we substitute $x_B = 1-\epsilon$ and in the $\epsilon \rightarrow 0$ limit evaluate the integral which results in

$$f_q(x_B,Q^2)\mid_{x_B\to 1} = \frac{\mathcal{N}}{24} e^{-B_R m_R^2} \cdot (1-x_B)^4.$$



this should be compared with $\sim(1-x)^3$ behavior following from pQCD

Ball et al. *Eur. Phys. J. C* 76, 7 (2016

Numerical Estimates: choosing the parameters of the model

the model has five parameters A_V, B_V, A_R, B_R and m_R.

- For valence quarks we assume that characteristic separations in the 3q system in the impact parameter space is $\langle b_{i,j}^2 \rangle \sim (0.3\mathrm{Fm})^2$. This allows us to evaluate $B_V = 4\langle b_{i,j}^2 \rangle \frac{x_i}{x_V} \approx \frac{4}{3}\langle b_{i,j}^2 \rangle$.
- We assume that this parameter does not change with the QCD evolution.

- For the recoil system, because of the use of we can relate $A_R = \left(\frac{B_R}{\pi}\right)^{\frac{3}{4}}$.
- We expect the parameter B_R, which characterizes the size of the residual system to depend on the residual mass and as a result to be Q^2 dependent.

- the parameter A_V is fixed through the normalization factor, $\mathcal{N}$ using: $\mathcal{N} = \frac{16\pi^3 A_V^2 A_R^2 m_N^3}{B_R B_V^2}$

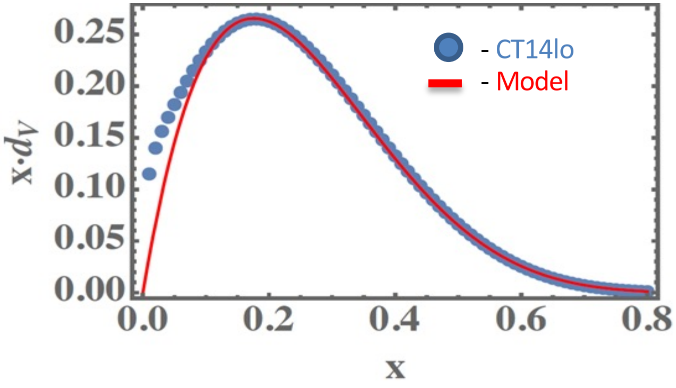
-the remaining parameters $\mathcal{N}$, m_R and B_R are evaluated by fitting to empirical PDFs

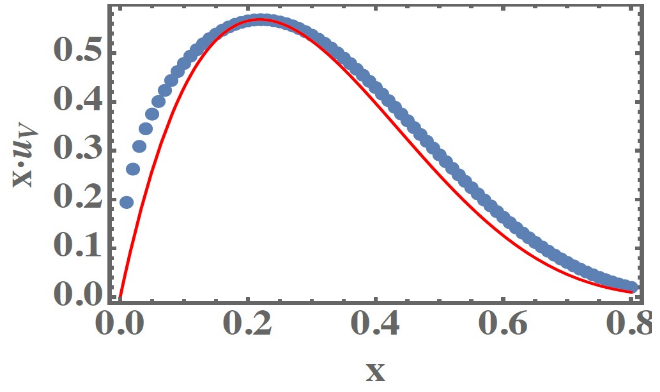
Nucleon - Fitting

- Fit at peak to CT14lo and minimizes χ^2 – Soft dominates

- d_V fits well at high x

- $u_V \rightarrow$ correlations important, less Soft





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Once parameters are fixed we can evaluate the strength of the missing high momentum component

- For the normalization one obtains for d-quark $N_d = 0.8$ and for u-quark $N_u = 1.54$. These results also indicates that one expects that Regge mechanism at $x < x_p$ and qq-correlations to contribute $\sim$ 20% and $\sim$23% of total normalizations for d- and u- quarks respectively.

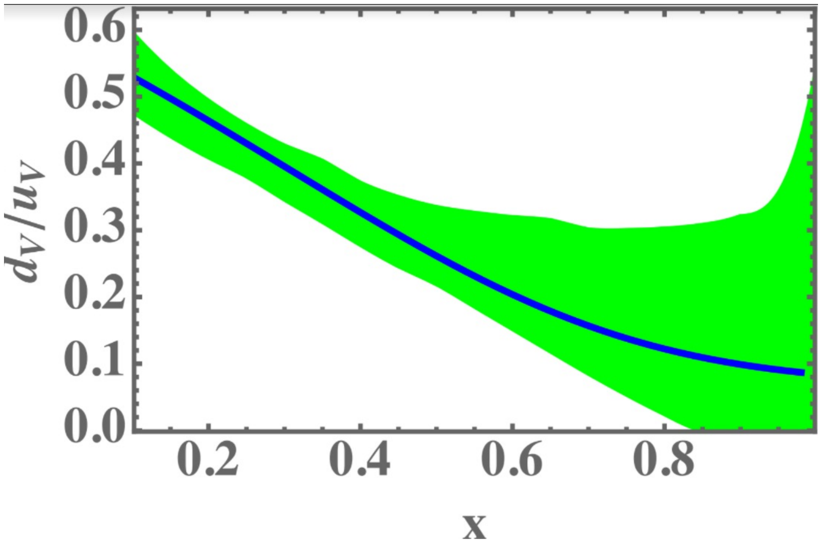
- The evaluation of the momentum sum rule $(P_q = \int xq_V(x)dx)$ yields $P_d = 0.1$ and $P_u = 0.246$ compared to $P_d = 0.108$ and $P_u = 0.264$ of CTNN distribution. Because of lesser contribution from the Regge mechanism in this case these estimates evaluate better the contribution from qq correlations. Here for qq-correlations one obtains for the d-quark, $\sim$ 8% and for the u-quark is $\sim$ 11%.

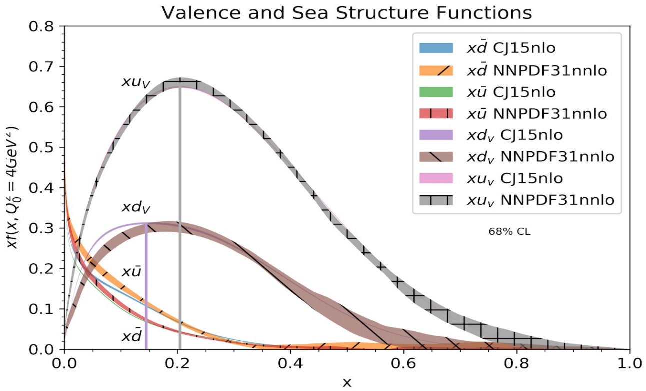
Predication of d/u ratio at xB→1

- Ratio as $x \to 1$

$$\frac{d_V}{u_V}\bigg|_{x\to 1} = 0.09$$

CJ15nlo : 0.09 ± 0.03
(w/ BONuS)
Scalar Diquark: 0
pQCD: 0.2

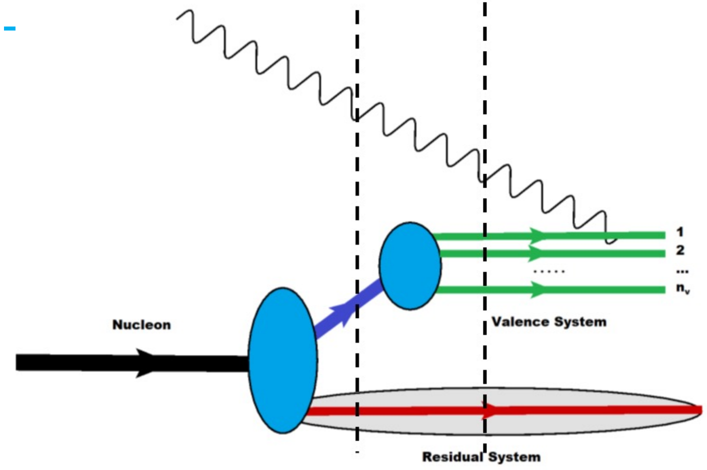


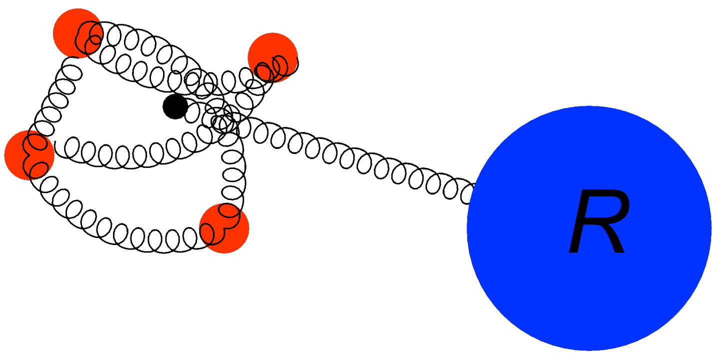


The reason of d/u fall-off is $m_R(u) < m_R(d)$

General $\boldsymbol{n_V}$ PDF Expression

$$xf(x) = \mathcal{N}'_{n_V}\, x \int_0^{1-x} dx_R \frac{(1 - x_R - x)^{2(n_V-1)-1}}{(1-x_R)^{n_V}} \exp\left[-\boldsymbol{B_R} m_H^2 \left(x\right.\right.$$





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General $\boldsymbol{n_V}$ PDF Expression

$$xf(x) = \mathcal{N}'_{n_V}\, x \int_0^{1-x} dx_R \frac{(1-x_R-x)^{2(n_V-1)-1}}{(1-x_R)^{n_V}} \exp\left[-\boldsymbol{B_R} m_H^2 \left(x - \frac{\boldsymbol{m_R}}{m_H}\right)^2\right]$$

- Asymptotic limit, $x \to 1$, for RMF model:

$$f(x) \sim_{x\to 1} (1-x)^{\beta_V}$$
$$\boldsymbol{\beta_V = 2(n_V - 1)}$$

- Compare **C**ounting **R**ule (CR, Brodsky-Farrar):

$$\beta_V = 2n - 3 + 2|\lambda_H - \lambda_q|$$

General $\boldsymbol{n_V}$ PDF Expression

$$xf(x) = \mathcal{N}'_{n_V}\, x \int_0^{1-x} dx_R \frac{(1 - x_R - x)^{2(n_V-1)-1}}{(1-x_R)^{n_V}} \exp\left[-\boldsymbol{B_R} m_H^2 \left(x - \frac{\boldsymbol{m_R}}{m_H}\right)^2\right]$$

- Peak for RFM model:

$$\boldsymbol{x_p \approx \frac{1}{2(n_V - 1)}\left(1 - \frac{m_R}{m_N}\right)}$$

$$\Rightarrow \boldsymbol{x_p \leq \frac{1}{2(n_V - 1)}}$$

Residual Structure:

- Introducing residual structure of the nucleon with the spectrum of mass, m_R represents an introduction of spectral function formalism in the description of the nucleon structure.
- The model assumes a certain universality of the residual structure, R, entering in all three mechanisms of generation of valence quark distribution.
- This universality is reflected in the fact that one can fix its main properties within one of the approaches (say within mean field model) and apply it in the calculation of 2q- and 3q- correlation contributions.
- The mass spectrum of the residual system is continuous and effectively depends on whether u- or d- valence quarks are probed.

For example the given valence quark can originate from 3-valence quark cluster having the total isospin and its projection same as the nucleon but it can also originate from the 3-quark cluster with isospin of 3/2 which will correspond to the higher mass of the residual nucleon. Thus in the case of the proton one can expand the residual nucleon mass in the form:

Outlook

- Check universal limit of peaking positions on lattice
- Add qq and qqq correlations
- Check Universality of residual state wave function
- With LFWF parameters fitted from PDFs, check validity by calculating predictions for other processes
- Can analyze SIDIS, DVCS through TMDs, GPDs w/ model for $x = 0.1 - 0.4$

SIDIS:

$$ep \to e'X\, h$$

DVCS:

$$ep \to e'p'\gamma$$