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

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3rd Workshop on Quantitative Challenges in EMC and SRC Research

22-26 March, 2021

Valence quarks in the nucleon and nucleus

with Chris Leon and Joseph Maerovitz

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

- They define baryonic number of the nucleon:

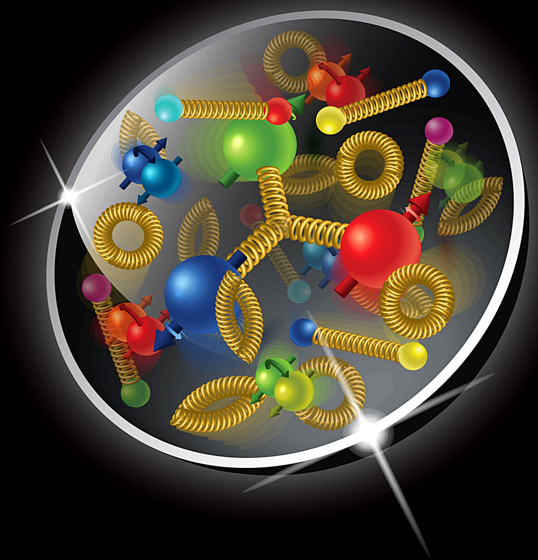
- They represent effective "three fermion" system with complex interaction among themselves and with nucleon environment

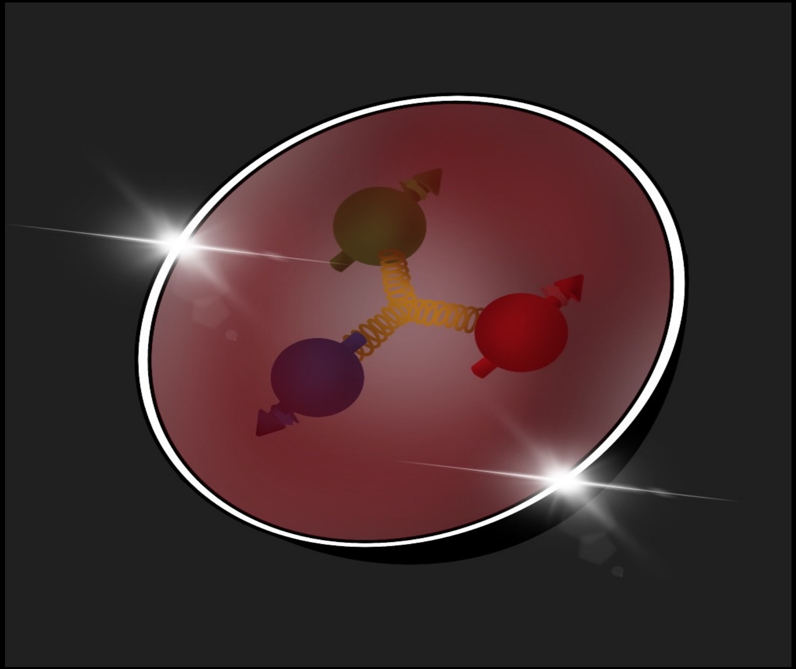
- Because of their conserved number the concept of mean-field interaction can be introduce to discuss their interaction with the nucleon environment

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

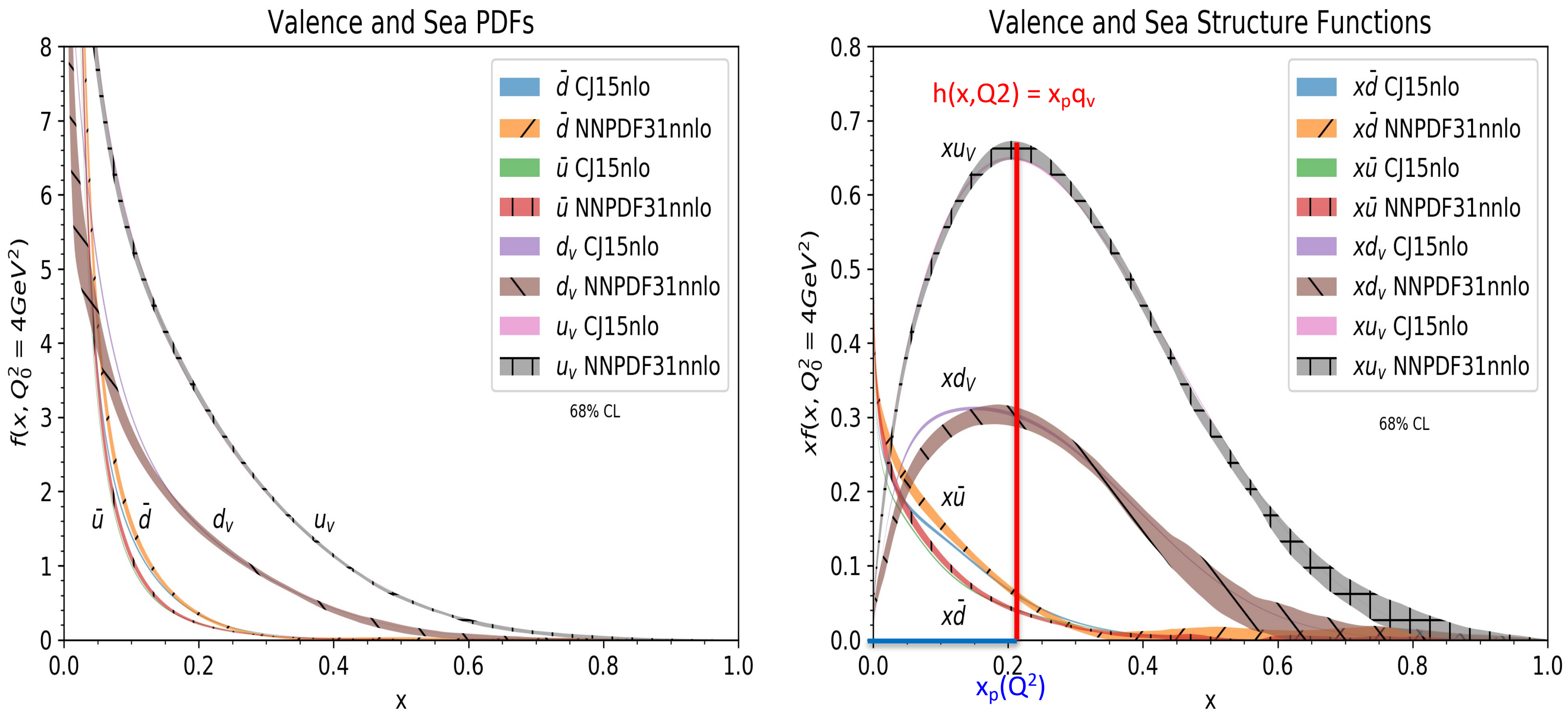
- Short range interaction among three valence quarks responsible to the generation of high x distribution of PDFs

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:**

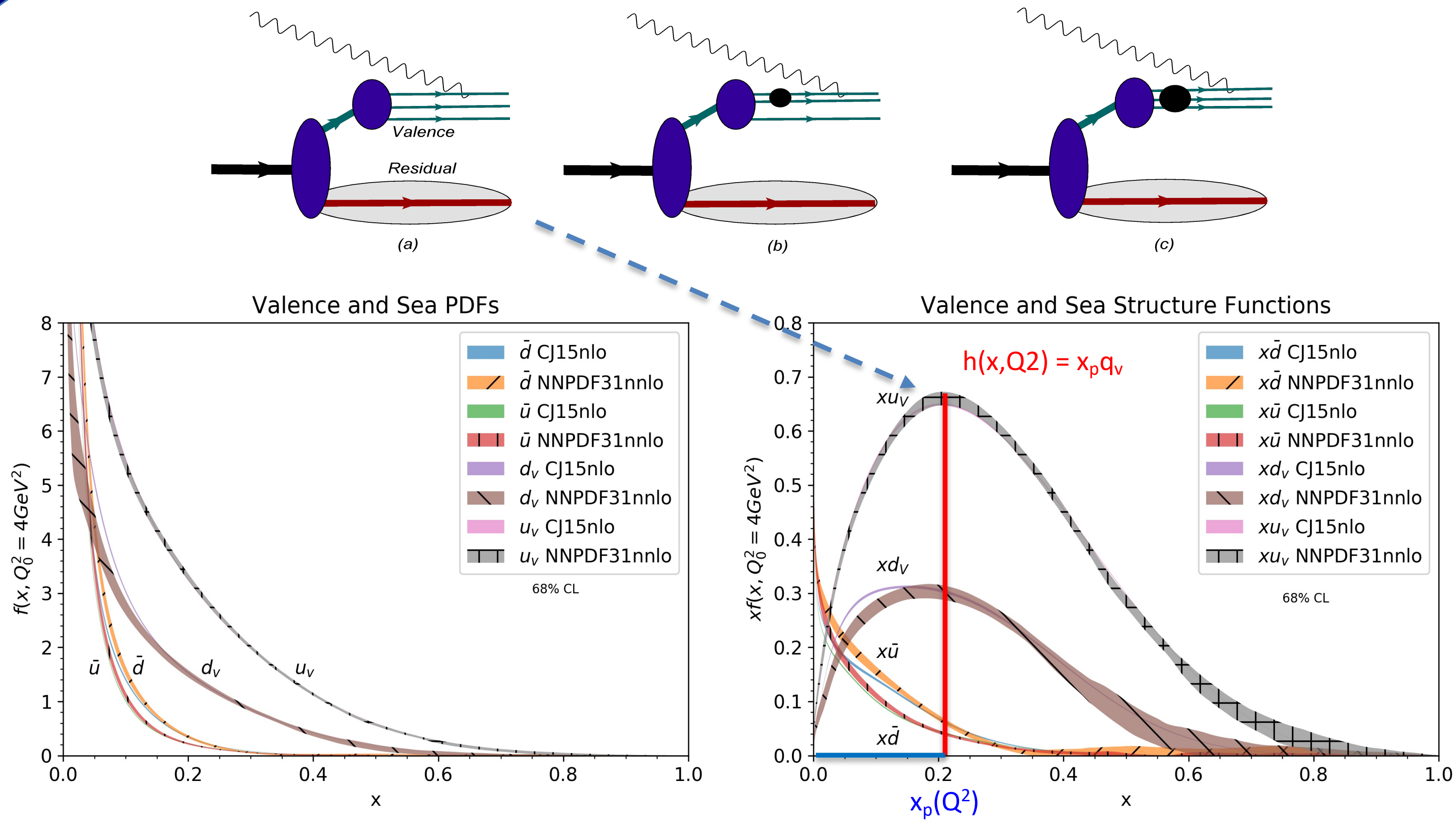


“New Approaches” in modeling valence quark dynamics

- 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
$f(x, Q_0^2 = 4GeV^2)$
$\bar{d}$ CJ15nlo
$\bar{d}$ NNPDF31nnlo
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d_v CJ15nlo
d_v NNPDF31nnlo
u_v CJ15nlo
u_v NNPDF31nnlo
68% CL
$\bar{u}$
$\bar{d}$
d_v
u_v
x
Valence and Sea Structure Functions
$xf(x, Q_0^2 = 4GeV^2)$
$h(x,Q2) = x_p q_v$
xu_V
xd_V
$x\bar{u}$
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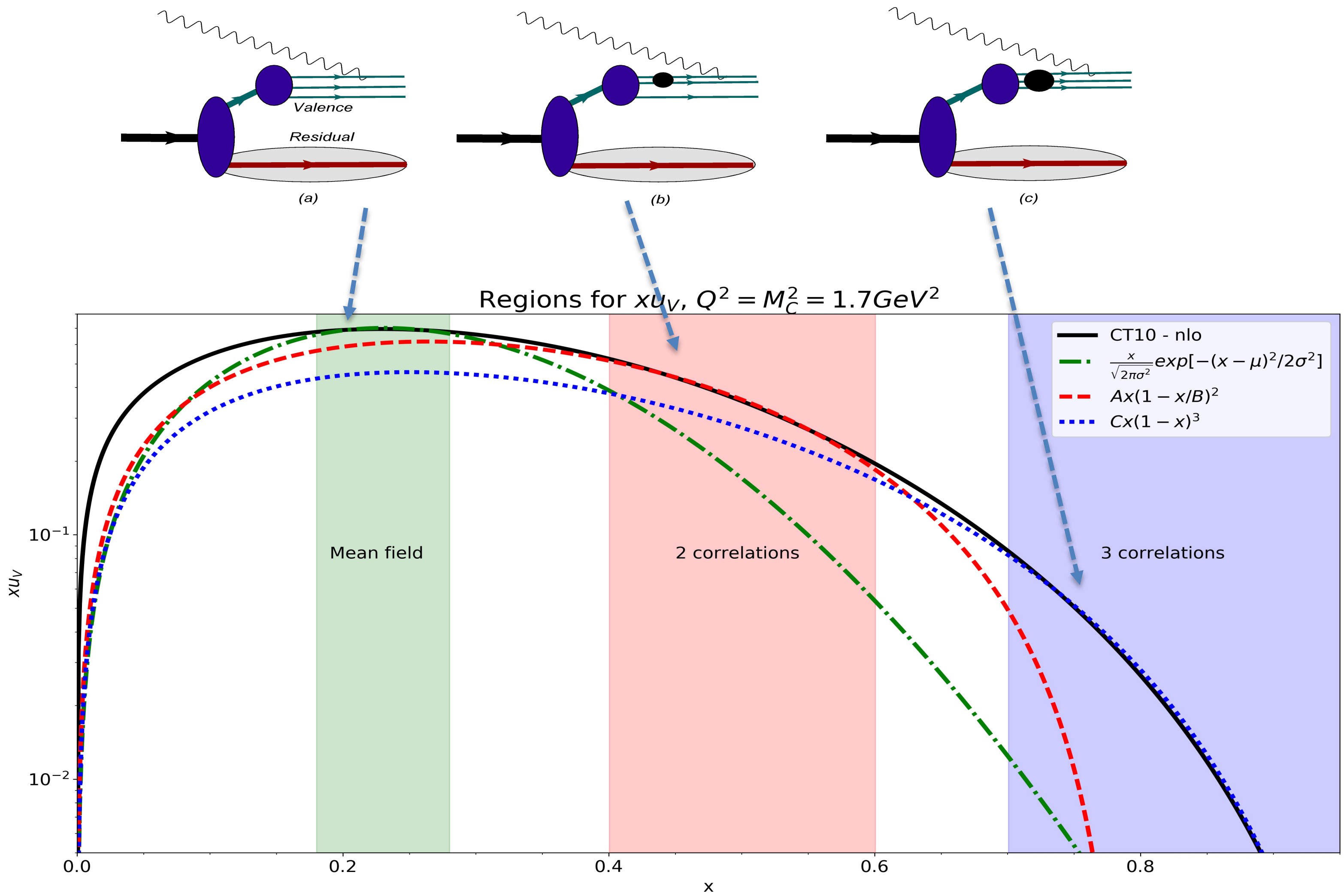
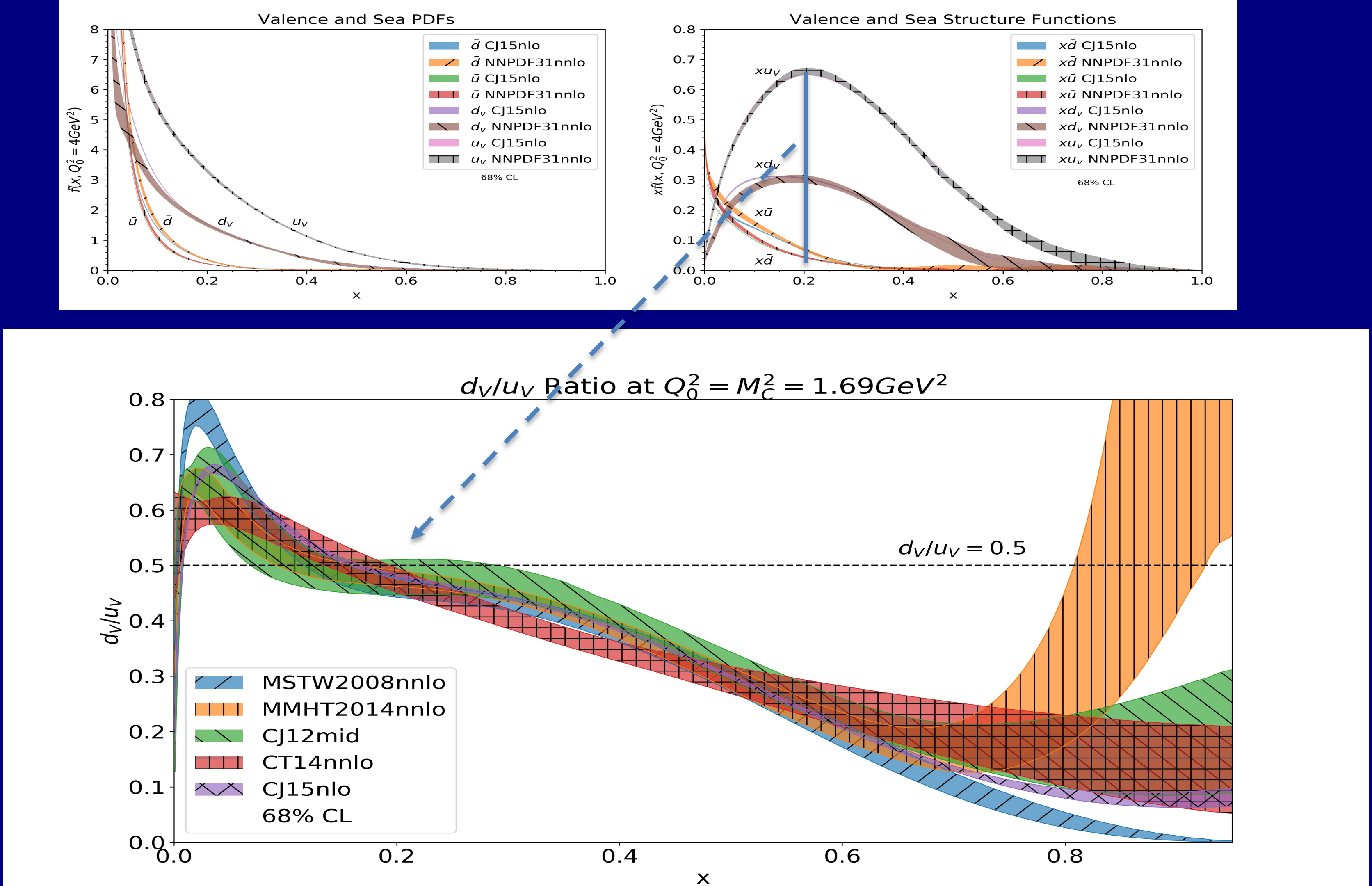
$x_p(Q^2)$
x


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
x
10^{-1}
10^{-2}
0.0
0.2
0.4
0.6
0.8



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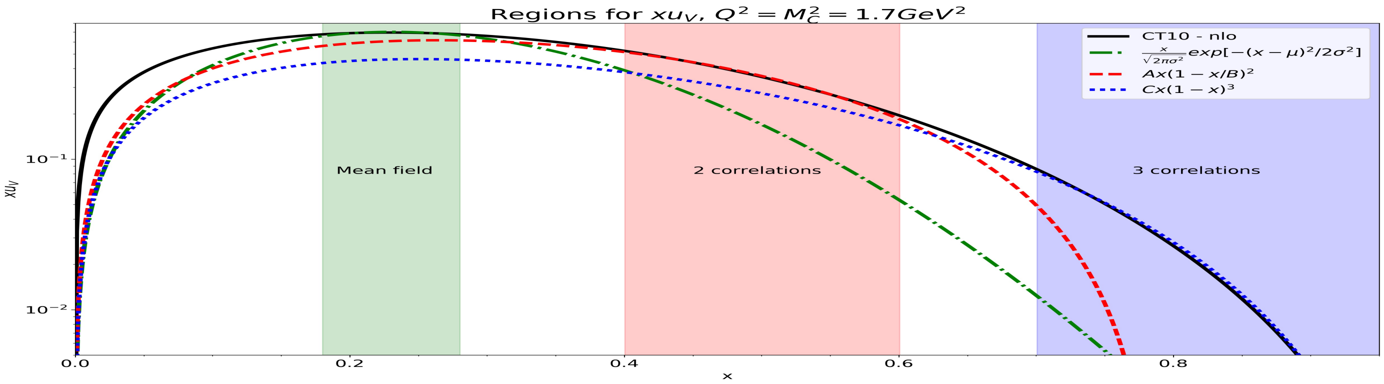
d_V/u_V Ratio at $Q_0^2 = M_C^2 = 1.69GeV^2$
d_V/u_V
$d_V/u_V = 0.5$
MSTW2008nnlo
MMHT2014nnlo
CJ12mid
CT14nnlo
CJ15nlo
68% CL
x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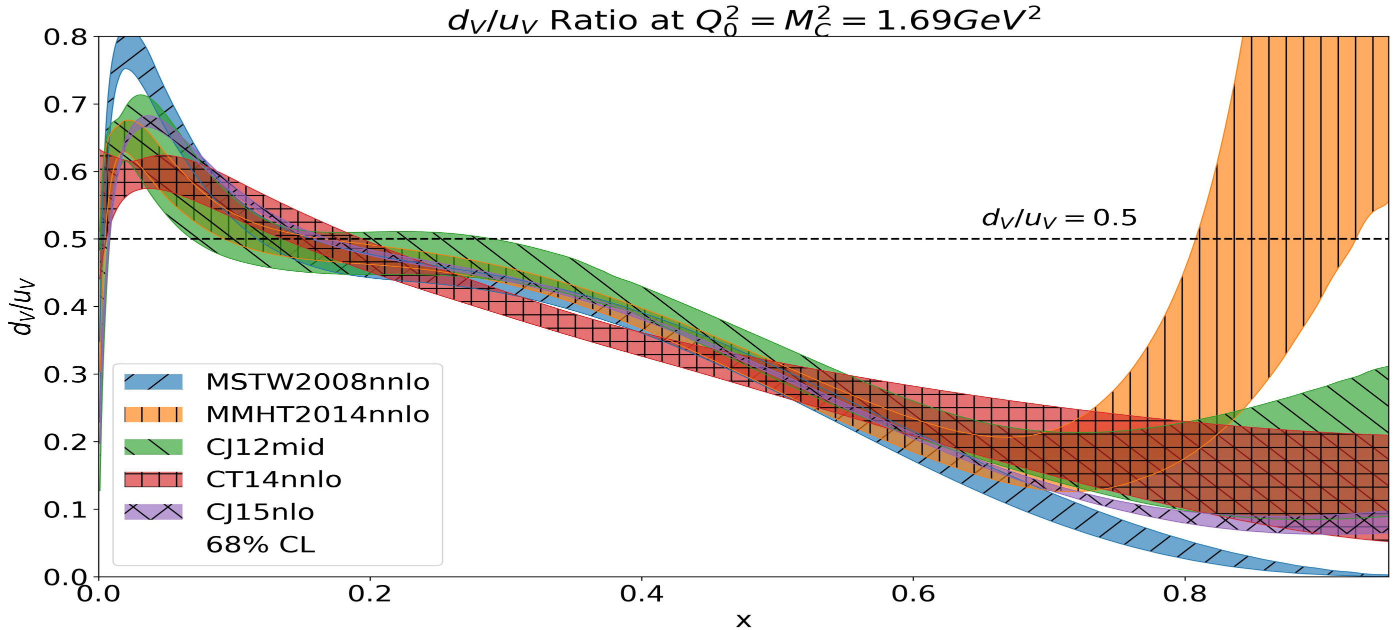
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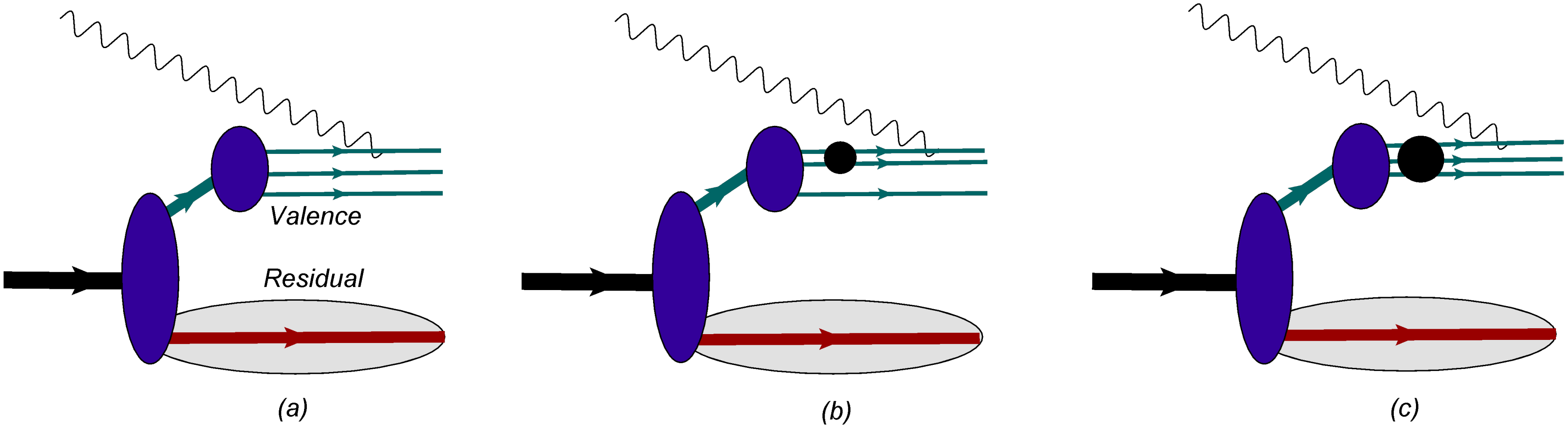
d_V/u_V
x

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 $0.1 \leq x \leq 1$.

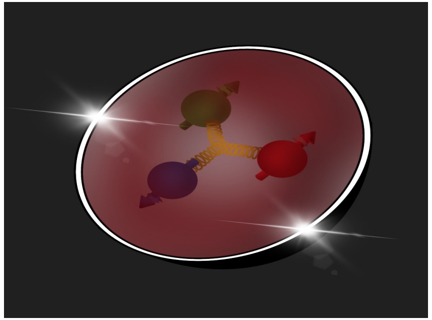


Valence Quarks in the Nucleon:

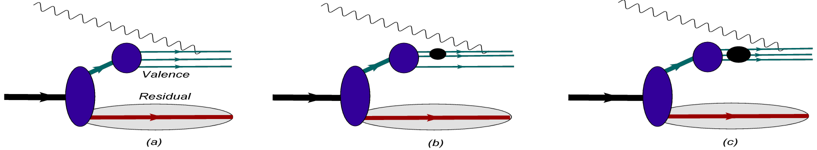
- The model assumes an existence of almost massless valence three-quark cluster V in the nucleon.

- The cluster is compact with the transverse separation between any 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 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.

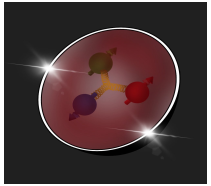
- This universality is reflected in the fact that one can fix its main properties within mean field and apply it in the calculation of 2q- and 3q- correlation contributions.

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

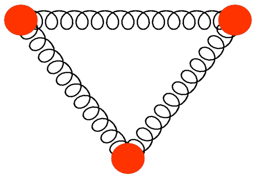
$$m_R(u/d) = \alpha_{u/d}\cdot m_R(I_V = \frac{1}{2}, I_V^3 = \frac{1}{2}) + \beta_{u/d}\cdot m_R(I_V = \frac{1}{2}, I_V^3 = -\frac{1}{2}) + \gamma(u/d) \sum_{I_V^3=-\frac{3}{2}}^{\frac{3}{2}} m_R(I_V = \frac{3}{2}, I_V^3) + \cdots$$

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

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



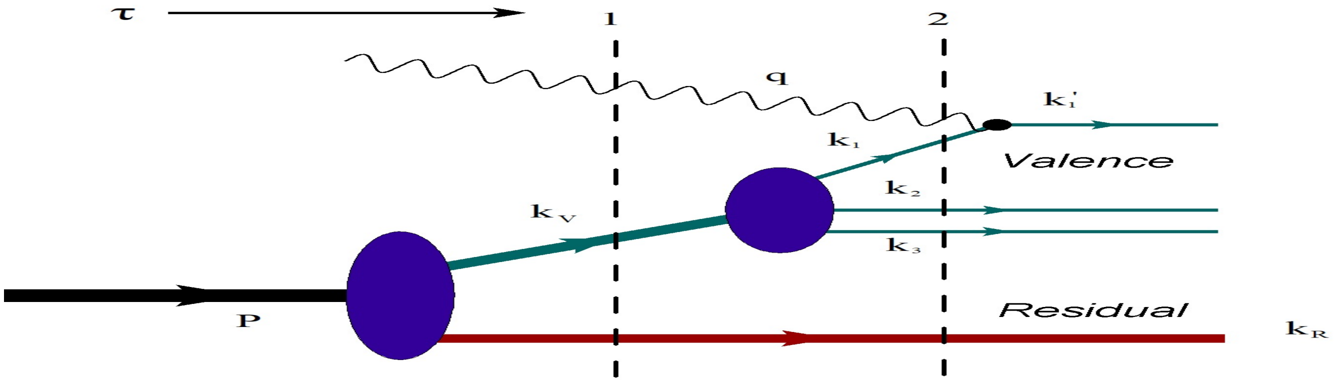
Mean-Field Model of Valence Quark Distributions



- The valence 3q system occupies a region of 0.6Fm and is described by mutually coupled three-dimensional harmonic oscillators, thus satisfying confinement condition.

- 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.



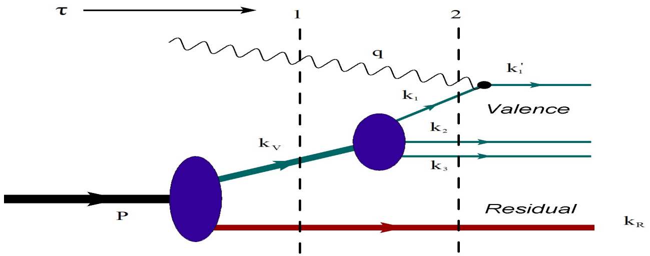
Reference Frame, Kinematics and Structure Function

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

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

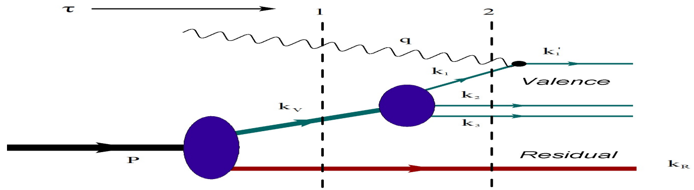
$$F_2(x,Q^2) \equiv \sum_i e_i^2 x f_i(x,Q^2), = \frac{MQ^2}{2x(p_N^+)^2)} W_N^{++}$$

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



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

Calculation of the scattering amplitude



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

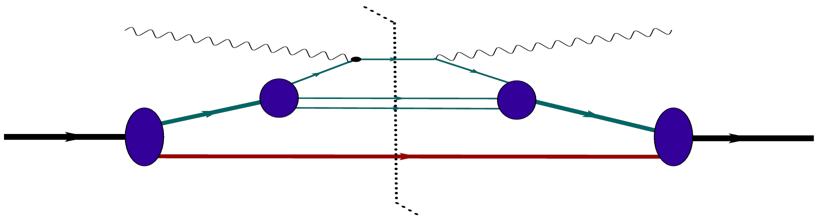
$$\psi_{VR}(x_V,\mathbf{k}_{R,\perp},x_R,\mathbf{k}_{V,\perp}) = \frac{\bar{\chi_V}\bar{\chi_R}\Gamma^{B\to VR}u(p_N,h_N)}{m_N^2 - \frac{k_{V,\perp}^2+m_V^2}{x_V} - \frac{k_{R,\perp}^2+m_R^2}{x_R}}$$

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

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 Structure Function

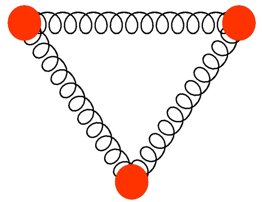


$$W_N^{\mu\nu}(x,Q^2) = \frac{1}{4\pi M_N}\sum_{\{h_i,\tau_i\}}\int \delta(1-\sum_{i=1}^{3} x_i - x_R)\frac{dx_R}{x_R}\prod_{i=1}^{3}\frac{dx_i}{x_i}16\pi^3\delta^{(2)}(\sum_{i=1}^{3}\mathbf{k}_{i,\perp}+\mathbf{k}_{R,\perp})\frac{d^2\mathbf{k}_{R,\perp}}{16\pi^3}\prod_{i=1}^{3}\frac{d^2\mathbf{k}_{i,\perp}}{16\pi^3}A^{\mu\dagger}A^{\nu}$$

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

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

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:

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

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

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

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

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: $f_q(x_B, Q^2) \sim (1 - x_B - \frac{m_R}{m_N})^3$

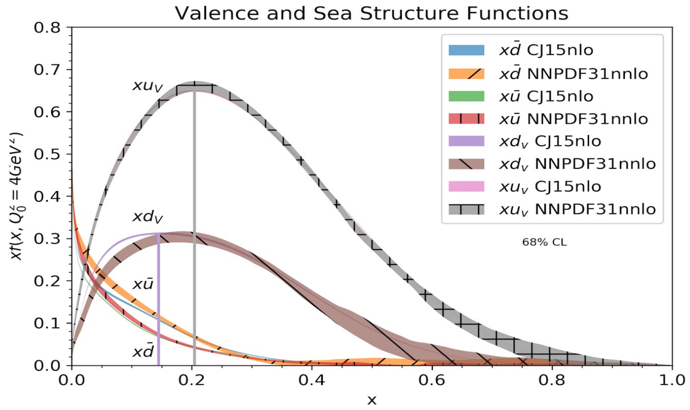
In this case $h(x_B, t) = x_B f_q(x_B, Q^2) \sim x_B \left(1 - x_B - \frac{m_R}{m_N}\right)^3$

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 $x_p^d < x_p^u$



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

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 $x_B \to 1$:

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

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

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

Numerical Estimates: choosing the parameters of the model

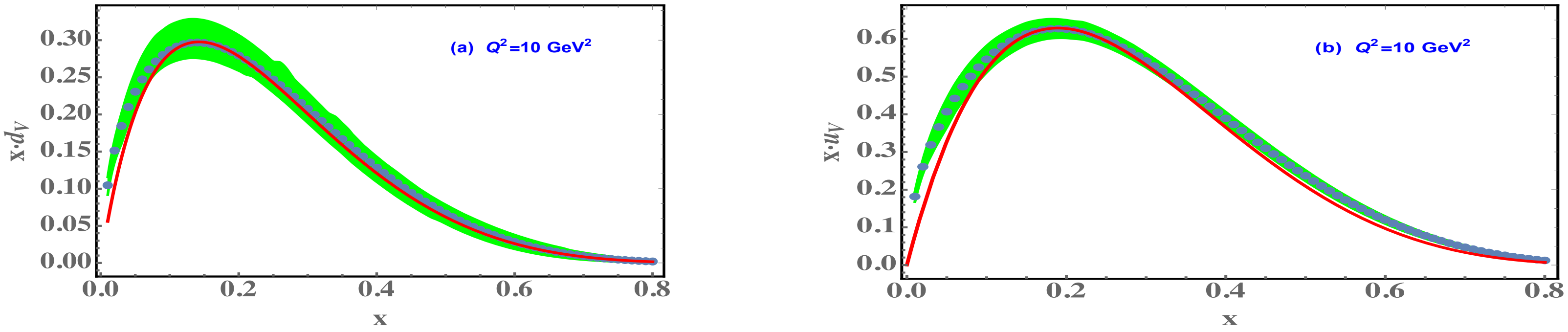
the model has five parameters A_V, B_V, A_R, B_R and m_R.

- For valence quarks we assume that characteristic separations in the 3q system in the impact parameter space is $\langle b^2_{i,j}\rangle \sim (0.3\mathrm{Fm})^2$. This allows us to evaluate $B_V = 4\langle b^2_{i,j}\rangle \frac{x_i}{x_V} \approx \frac{4}{3}\langle b^2_{i,j}\rangle$.
- 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: $\mathcal{N} = \frac{16\pi^3 A_V^2 A_R^2 m_N^3}{B_R B_V^2}$

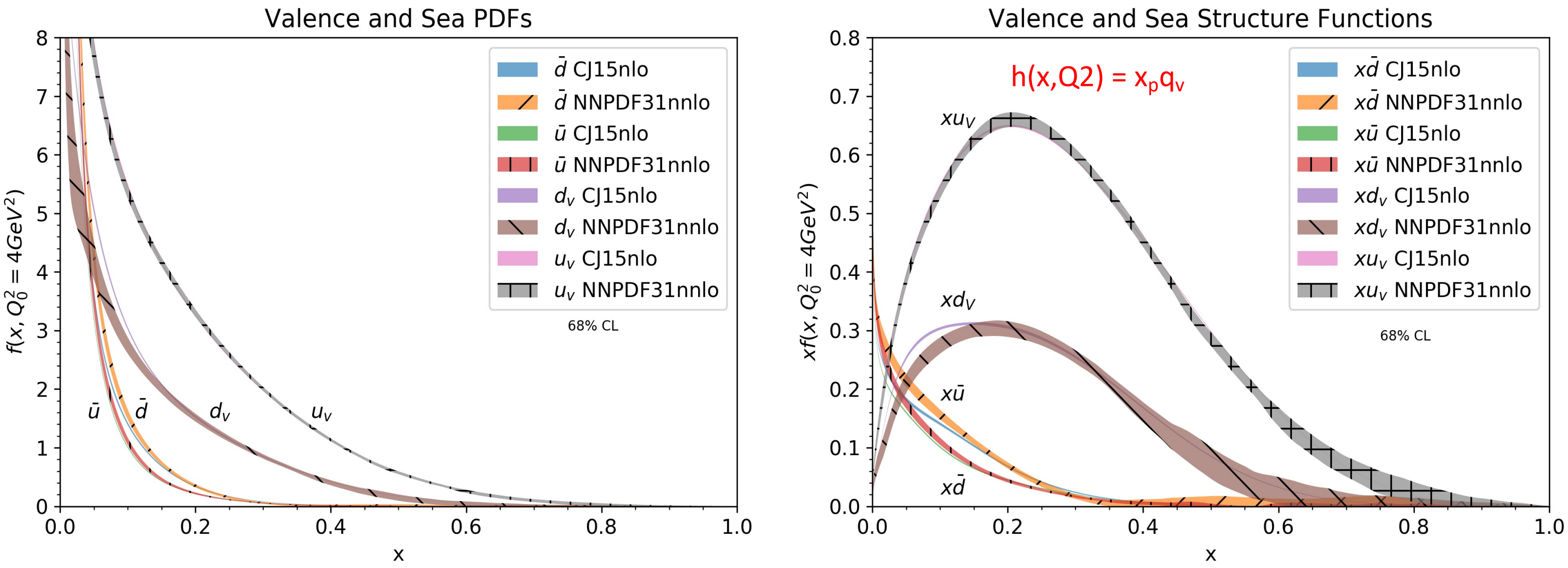
-the remaining parameters $\mathcal{N}$, m_R and B_R are evaluated by fitting to empirical PDFs



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

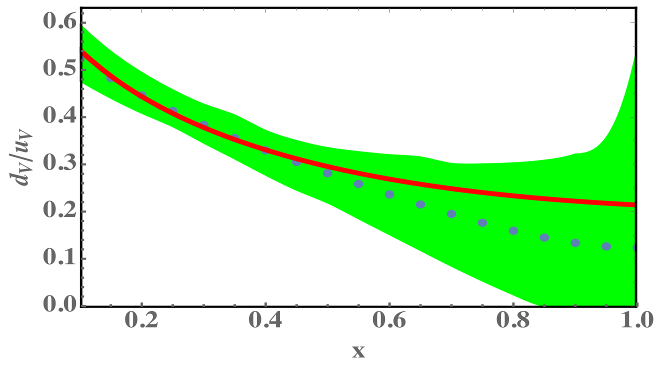
- For the normalization one obtains for d-quark $N_d = 0.8$ and for u-quark $N_u = 1.54$. These results also indicates that one expects that Regge mechanism at $x < x_p$ and qq-correlations to contribute $\sim$ 20% and $\sim$23% of total normalizations for d- and u- quarks respectively.

- 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%.



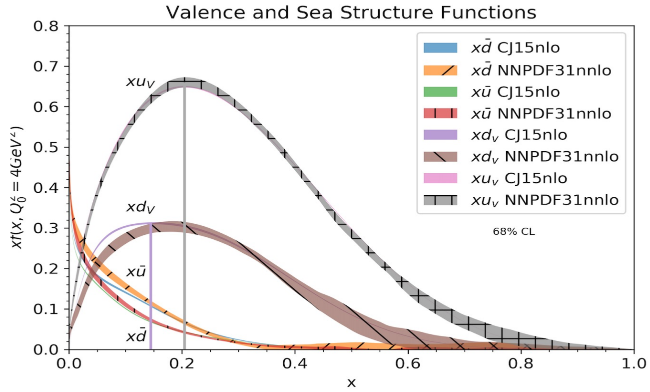
Valence and Sea PDFs
$f(x, Q_0^2 = 4GeV^2)$
x
$\bar{d}$ CJ15nlo
$\bar{d}$ NNPDF31nnlo
$\bar{u}$ CJ15nlo
$\bar{u}$ NNPDF31nnlo
d_v CJ15nlo
d_v NNPDF31nnlo
u_v CJ15nlo
u_v NNPDF31nnlo
68% CL
$\bar{u}$
$\bar{d}$
d_v
u_v
Valence and Sea Structure Functions
$xf(x, Q_0^2 = 4GeV^2)$
x
h(x,Q2) = $x_p q_v$
$x\bar{d}$ CJ15nlo
$x\bar{d}$ NNPDF31nnlo
$x\bar{u}$ CJ15nlo
$x\bar{u}$ NNPDF31nnlo
xd_v CJ15nlo
xd_v NNPDF31nnlo
xu_v CJ15nlo
xu_v NNPDF31nnlo
68% CL
xu_V
xd_V
$x\bar{u}$
$x\bar{d}$

Predication of d/u ratio at xB→1

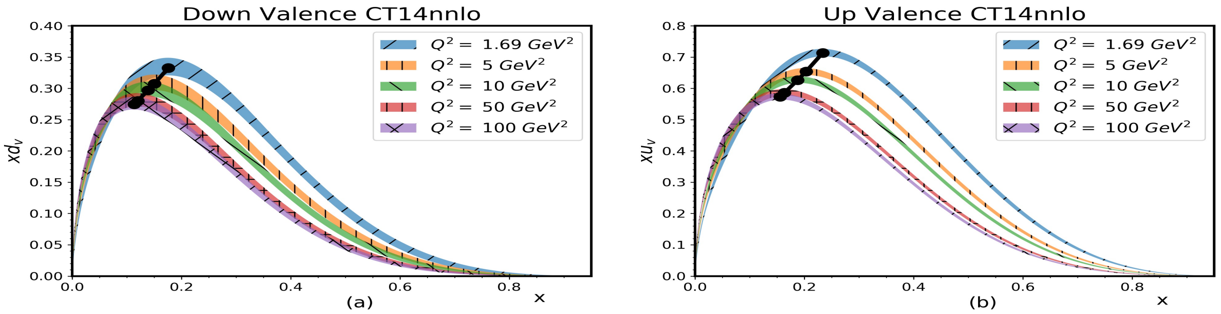


$$\frac{d_V}{u_V}\ |_{x\to 1} \approx 0.21.$$

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



Q2 dependence of parameters: N, BR and mR

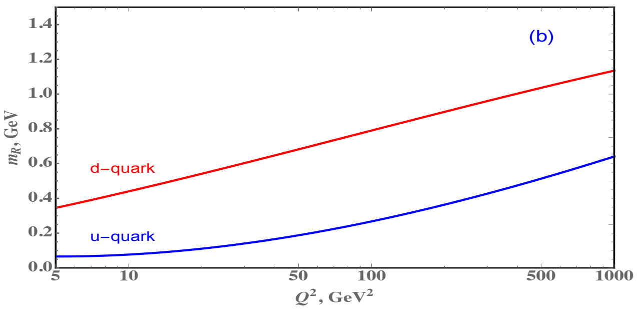


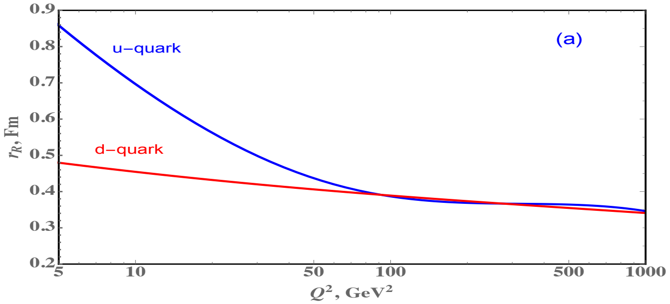
$$\begin{aligned}
\mathcal{N}(t) &= N_0 + N_1 t + N_2 t^2 + N_3 t^3, \\
B_R(t) &= B_{R0} + B_{R1} t + B_{R2} t^2 + B_{R3} t^3, \\
m_R(t) &= m_{R0} + m_{R1} t + m_{R2} t^2 + m_{R3} t^3
\end{aligned}$$

where $t = \log \frac{Q^2}{1GeV^2}$.

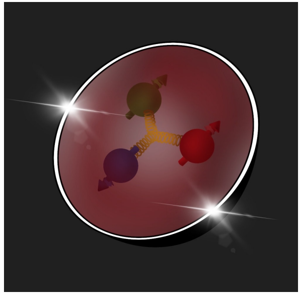
$$r_R(t) \approx \sqrt{\frac{3}{2} B_R(t)} \cdot 0.197327 \text{ Fm}.$$

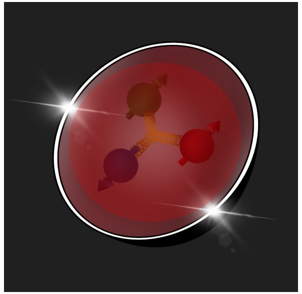
Q2 dependence of parameters: N, BR and mR

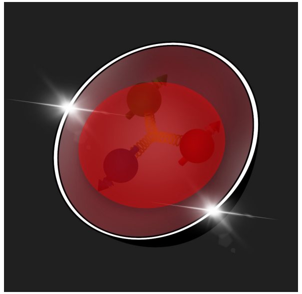


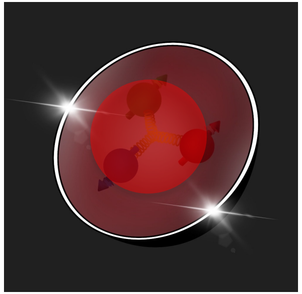


- Mass of the residual system increases as $\log Q^2$
- Gluon radiation of valence quarks confined in 3q system
- Mass gap is almost constant starting Q2>20 GeV2



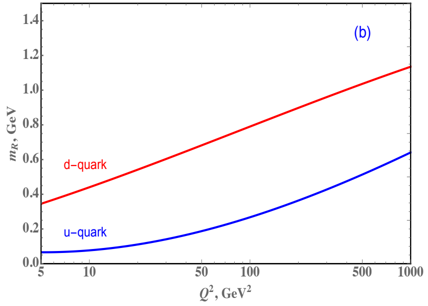






All these observations generate predictions that can be checked at EIC

- Mass of the residual system increases as $\log Q^2$

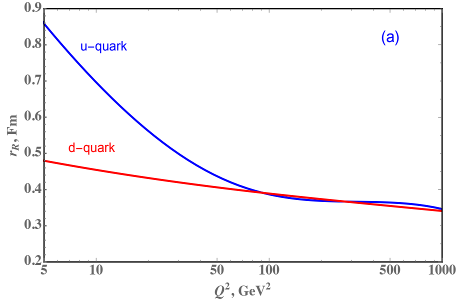


Invariant mass of gluonic jets in target fragmentation region in ep→ e'jets will increase wit logQ2 at x=0.2 and the increase rate can be calculated

- Mass gap is almost constant starting Q2>20 GeV2

Multiplicity of target fragmented pions depends whether valence u or d quarks was struck by virtual photon

- Gluon radiation of valence quarks confined in 3q system



Angular correlation of gluon radiation in target fragmentation region with with probed x.

Conclusion and some outlook

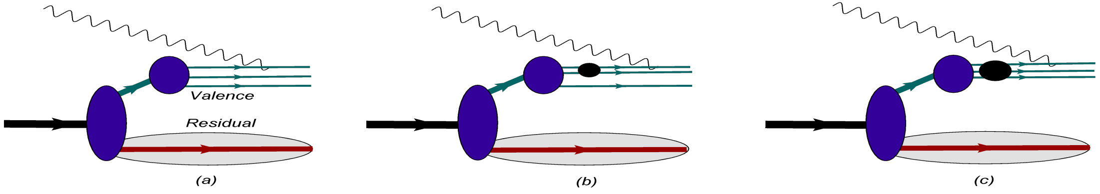
- We developed model of valence 3q+ recoil nucleon system in which explicitly included wave function of the recoil nucleon with mass spectrum

- Fitting to phenomenological valence quark PDFs allowed to fix parameters of both 3q mean field and residual nucleon system's wave function

- Estimated the overall possible contribution from qq and qqq correlations

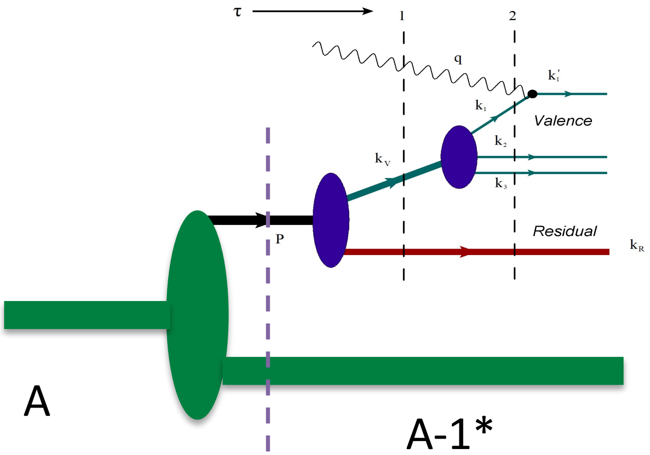
- These wave functions will allow us to calculate many other observables, such as form-factors, GPDs, TMDs …. sensitive to x=0.2 region of valence quarks

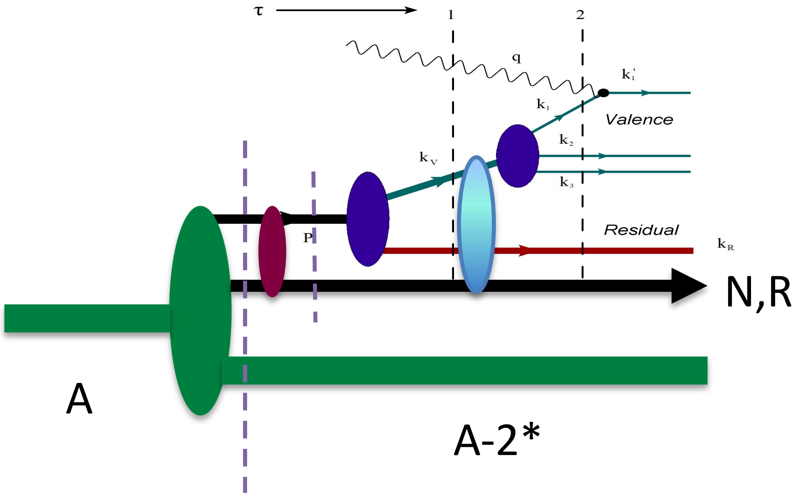
- The project currently underway is to include the qq to qqq correlations that can contribute in generation of high x tail od PDFs

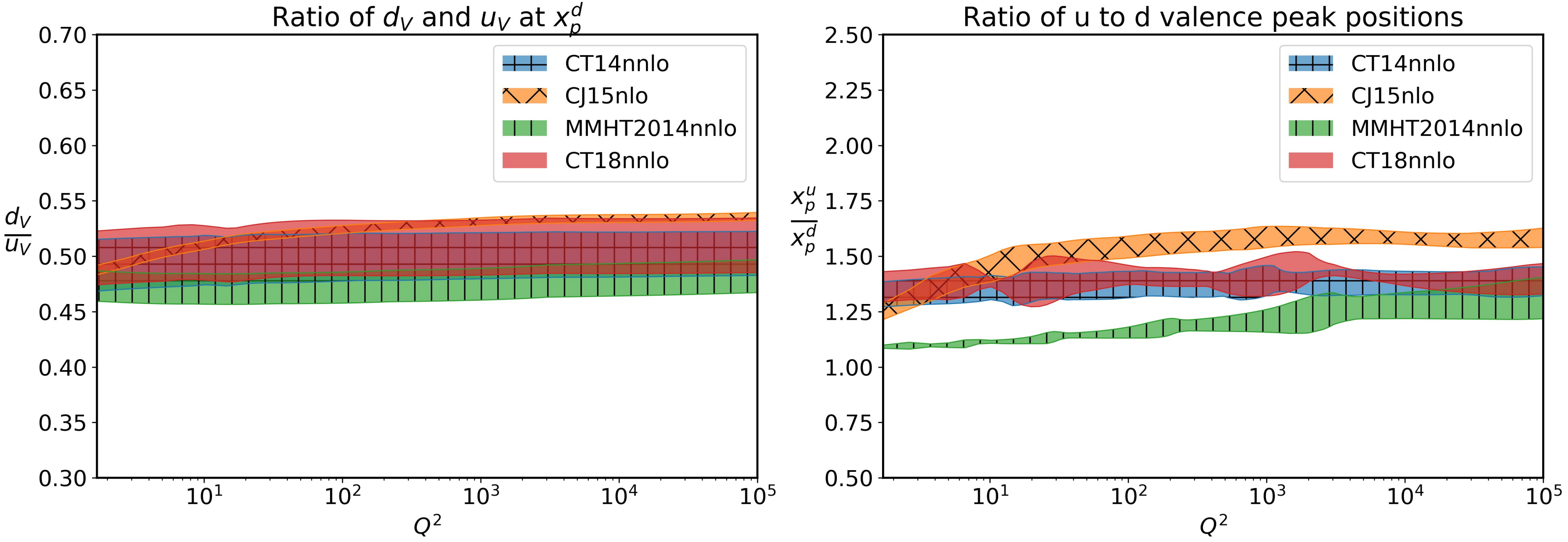


- Refinement and improvement of the model

Quarks in Nuclei







Ratio of d_V and u_V at x_p^d
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
$\frac{d_V}{u_V}$
CT14nnlo
CJ15nlo
MMHT2014nnlo
CT18nnlo
10^1
10^2
10^3
10^4
10^5
Q^2
Ratio of u to d valence peak positions
2.50
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50
$\frac{x_p^u}{x_p^d}$
CT14nnlo
CJ15nlo
MMHT2014nnlo
CT18nnlo
10^1
10^2
10^3
10^4
10^5
Q^2