Gluon parton distribution in hadron

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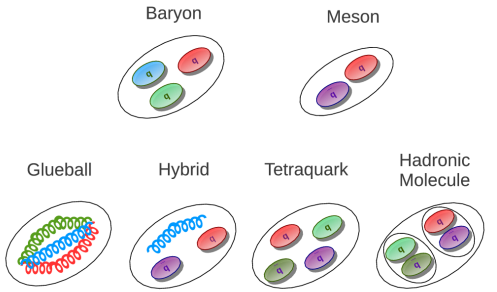
Internal structure of hadron

In general, before the internal structure of hadron is presented, here we explain classification of hadron based on their quantum numbers [1]:

- Hadrons can be classified into two families:
  1. Baryons, composed of an odd number of quarks (three quarks)
  2. Mesons, composed an even number of quarks (two quark– one quark and one antiquark)
- Exotic hadrons, composed more than three quarks $\rightarrow$ tetraquark state (exotic meson) i.e. Z(4430)$^-$ [Belle collaboration, 2007 and its resonance by LHCb in 2014), pentaquark state (exotic baryons) i.e.$P_c^+(4380)$ and $P_c^+(4450)$ [LHCb collaboration in 2015]



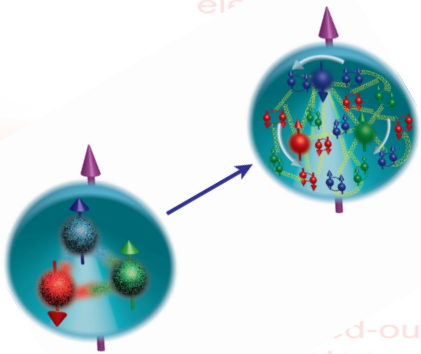
[1] M.Gell-Mann, PL8 (1964), 214-215

Internal structure of baryon based on gluons and quarks

Internal structure of baryon:

- 1980s we undertand that the proton structure made of [uud] quarks
- 1990s/2000s we understand that the proton structure [uud] with their spins + gluons + sea quarks
- Today, we know that proton consists of valence three quarks with their spins + gluons + sea quarks (quar-quark, quark-gluon and gluon-gluon collisions), which is more complex

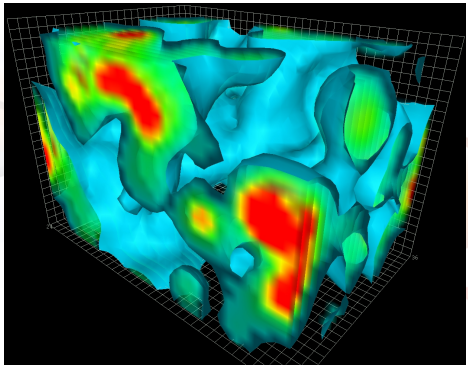
The important question is how the valence quark, gluon and sea quark distribute in the baryon and how they contribute to emergent hadron mass?



Structure of hadron based on gluons and valence quarks from lattice QCD

Visualizations of quantum chromodynamics (QCD) in the QCD vacuum [2]:

- Quantum fluctuations of the QCD vacuum (supercomputer simulation of QCD on $24^3 \times 36$ space-time lattice)
- Figure shows the interactions between gluons and quarks in free (vacuum) hadron
- QCD vacuum induces chromo-electric and chromo-magnetic field via space-time in the lowest energy state, which is contrast with the empty vacuum concept
- Gluon fluctuates in the short distance and large distance

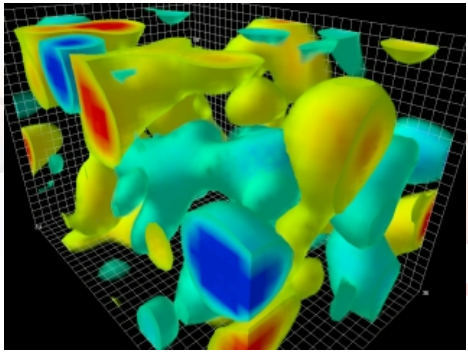


[2] Courtesy: Derek Leinweber, University of Adelaide

Structure of hadron based on gluons and valence quarks from lattice QCD

Visualizations of quantum chromodynamics (QCD) in the QCD vacuum [3]:

- Removing the noisy fluctuation in the short distance, the smooth long distance structure of gluons are shown
- The red color represents the energy of the gluon field is strong
- The winding of gluons are also revealed where gluons can wind in positive (red to yellow) or negative (blue to green)



This simulation shows the complications of the gluon dynamics in the vacuum?

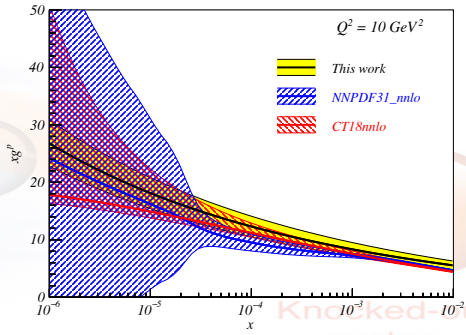
[3] Courtesy: Derek Leinweber, University of Adelaide

Gluon content of free proton

The gluon distribution in free proton from holography model and recent global analysis [4]:

- The gluon distribution in free proton as a function of x at $Q^2 = 10\ \mathrm{GeV}^2$
- Compared with the recent global analyses of NNPDF and CTEQ-TEA
- The error band of this result purely reflects the error bar of the HERA experimental data for the proton

Need more analyses for the gluon content of proton in particular at small -x and high -x



[4] Akira Watanabe, PLB**805**, 135470 (2020)

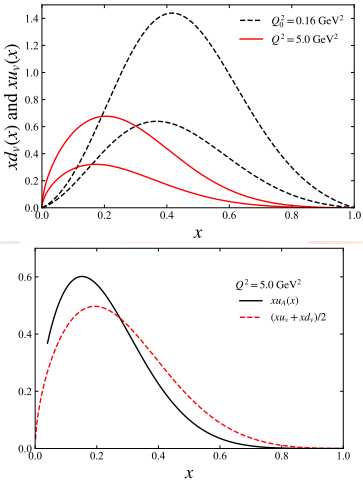
Gluon content of the proton and nuclear matter

The gluon structure of nuclei in the mean field model calculated by taking the structure of bound nucleon into account using the NJL model [5]:

- The spin-independent quark distribution in a free nucleon,

$$q(x) = -i \int \frac{d^4k}{(2\pi)^4} \delta\left(x - \frac{k^+}{p^+}\right) Tr[\gamma^+ M(p,k)]$$

- The spin-dependent distribution ($\Delta g(x)$) is defined by replacing $\gamma^+ \to \gamma^+\gamma_5$
- Spin-independent valence quark distribution of free nucleon (upper) and spin-independent valence quark PDF in symmetric nuclear matter (SNM) (bottom)



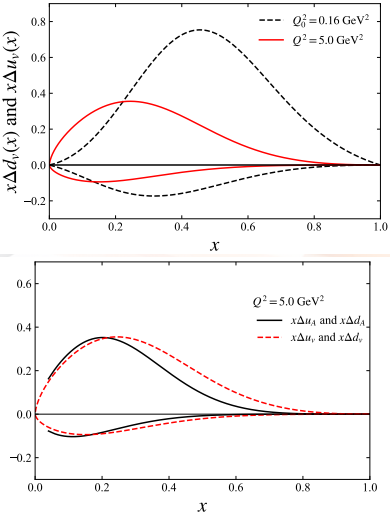
[5] Xuan-Gong Wang, *et. al.*, 2109.0359 (2021)

Gluon content of the proton in nuclear matter

The gluon structure of nuclei in the mean field model calculated by taking the structure of bound nucleon into account using the NJL model:

- Spin-dependent valence quark distribution in free nucleon (upper)
- Spin-dependent valence u and d quark PDF of single polarized proton in SNM

No data available for polarized EMC effect, therefore the gluonic of nucleon and nuclei can be accessed from the future experiment EIC and JLAB?



Gluon content of the proton in nuclear matter

The gluon structure of nuclei in the mean field model calculated by taking the structure of bound nucleon into account using the NJL model:

- The ratios of the unpolarized and polarized gluon distributions of nuclear matter to those free proton $g_A(x)/g_p(x)$ and $\Delta g_A(x)/\Delta g_p(x)$
- In this calculation the proton and neutron gluon PDFs are equal (charge symmetry breaking (violation) do not take into account).
- Gluon EMC effect are calculated using the formula $R_G \simeq g_A(x)/g_p(x)$ and $\Delta R_G \simeq \Delta g_A(x)/\Delta g_p(x)$

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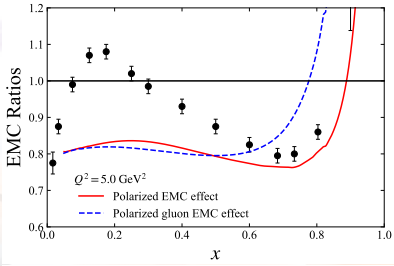
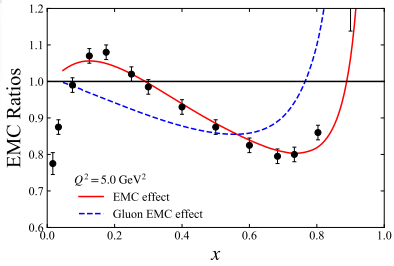
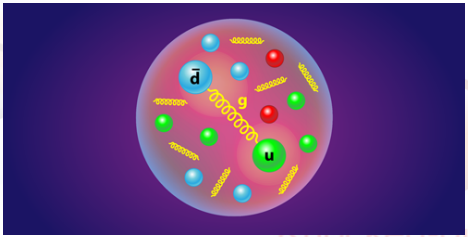




Structure of pion based on gluons and valence quarks

Internal structure of the pion, QCD Nambu Golstone Boson (chiral symmetry breaking)–EHM:

- Pion, the light meson, has very simple structure made up of a quark-antiquark pair
- Pion contains not only two valence quarks but also a virtual sea quarks that pop out and in of existence
- Pion has gluons carrying the string force that bind the quarks together
- Previous work found that the gluons contribute only 10 % of the pions momentum. However new data and global analysis found that gluon fraction contribute larger around 30 %,



We have limited data, therefore we need the results from the Electron-Ion Collider (EIC), COMPASS++/AMBER DY-CERN SPS and Electron-Ion Collider China (Eicc)

Gluons and valence quarks content of the pion

Internal structure of the pion from global analysis and models [6]:

- Pion valence-quark momentum distribution function xu_π (x): LQCD result (dot-dot-dashed (gray)), early continuum analysis (long-dashed (black)), modern continuum calculation (solid line (blue)), and experiment data from Conway (purple)
- Gluon distribution in the pion $xg_\pi(x)$ (dashed line (green), and sea-quark distribution xS_π (x) (dot-dashed (red))

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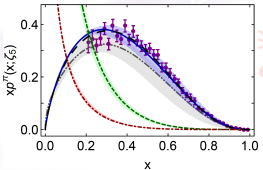
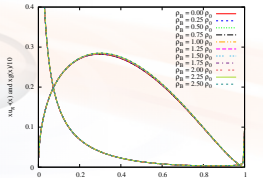
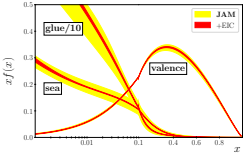
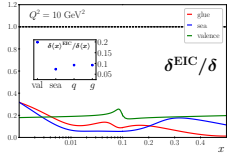






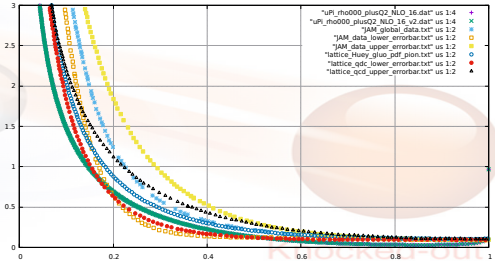


[6] Aguilar Arlene C, *et. al.*, EPJA**55**, 190 (2019)

Gluons and valence quarks content of the pion comparisons

Internal structure of the pion from global analysis, lattice QCD and NJL model:

- Gluon distribution in the pion calculated in the NJL model without momentum dependent (green), JAM global analysis without gluon resummation (blue), the lower error-bar of JAM analysis (orange), upper error-bar of JAM analysis (yellow), Lattice QCD calculation (light blue circle), lower error-bar of LQCD (red), upper error-bar of LQCD (black)
- The gluon distribution in the pion is in good agreement with the JAM analysis and LQCD



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Gluons and valence quarks content of free pion and bound pion in nuclear matter

Following the EMC effect in the nucleon, we observe the internal structure of the pion in free pion and nuclear matter in the NJL model:

- Valence quark distribution of free pion and nuclear matter (upper). These valence quark distributions are evolved using QCD evolution at $Q^2 = 16\ \mathrm{GeV}^2$.
- Gluon distribution of free pion and nuclear matter (bottom). Similar as the valence quark, the gluon distributions are evolved using QCD evolution at $Q^2 = 16\ \mathrm{GeV}^2$

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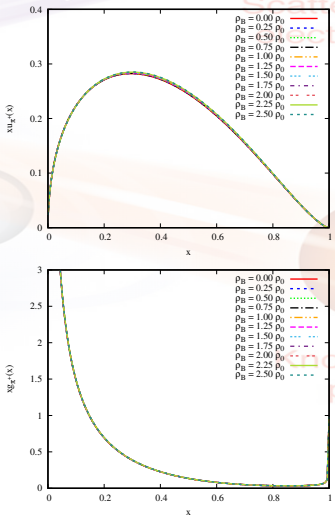

Ratios of valence quarks and gluons "EMC effect-like" of free pion and bound pion in nuclear matter

Internal structure of free pion and nuclear matter:

- Ratios for the valence quark distribution of free pion and bound pion in nuclear matter after evolving at $Q^2 = 16\ \mathrm{GeV}^2$ (upper)
- Ratios for the gluon distribution of free pion and bound pion in nuclear matter after evolving at $Q^2 = 16\ \mathrm{GeV}^2$ (bottom)

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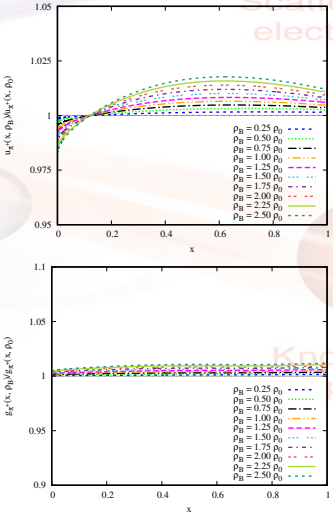
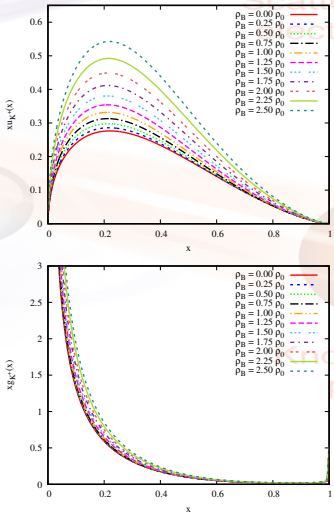


Gluons and valence quarks content of free kaon and bound kaon in nuclear matter

Gluon and valence quark structure of free kaon and nuclear matter in the NJL model:

- Valence quark distribution of free kaon and bound kaon in nuclear matter (upper). As in pion, the valence quark distributions are evolved using QCD evolution at $Q^2 = 16\ \mathrm{GeV}^2$.
- Gluon distribution of free kaon and bound kaon in nuclear matter (bottom). Similar as the valence quark, the gluon distributions are evolved using QCD evolution at $Q^2 = 16\ \mathrm{GeV}^2$ for various nuclear density

We have limited data, therefore we need the results from the Electron-Ion Collider (EIC), COMPASS-CERN SPS and Electron-Ion Collider China (Eicc)

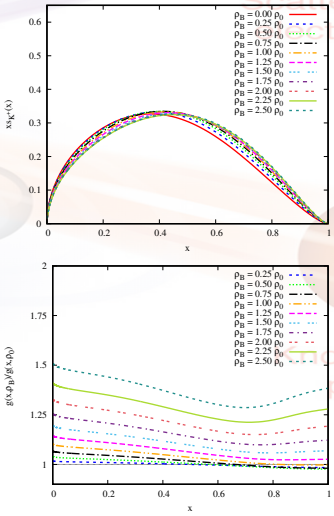


Gluons and valence quarks content of free kaon and bound kaon in nuclear matter

Strange valence quark structure of free kaon and bound kaon in nuclear matter in the NJL model:

- Strange valence quark distribution of free kaon and bound kaon in nuclear matter (upper). As up quark in the kaon, the strange valence quark distributions are evolved using QCD evolution at $Q^2 = 16\ \mathrm{GeV}^2$
- Ratios for the gluon distribution of free kaon and bound kaon in nuclear matter after evolving at $Q^2 = 16\ \mathrm{GeV}^2$ (bottom)

We have limited data, therefore we need the results from the Electron-Ion Collider (EIC), COMPASS-CERN SPS and Electron-Ion Collider China (Eicc)

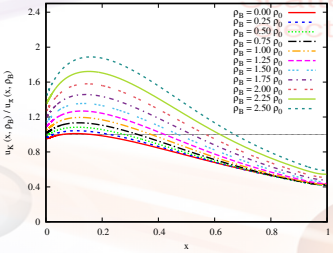


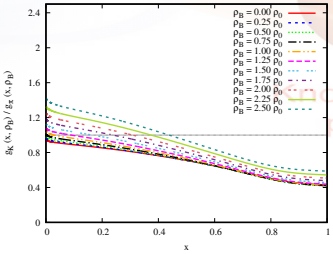
Ratios of valence quarks and gluon distributions of free pion and kaon and bound pion and kaon in NM

Valence quark and gluon structure of free pion and kaon and bound pion and kaon in nuclear matter using the NJL model–to understand the signal of EHM:

- Ratio of valence quark distribution of free pion and kaon and bound pion and kaon in NM evolved at $Q^2 = 16\ \mathrm{GeV}^2$ (upper)
- Ratio of gluon distribution of free pion and kaon and bound pion and kaon in NM evolved at $Q^2 = 16\ \mathrm{GeV}^2$ (bottom)

We have limited data, therefore we need the results from the Electron-Ion Collider (EIC), COMPASS-CERN SPS and Electron-Ion Collider China (Eicc)



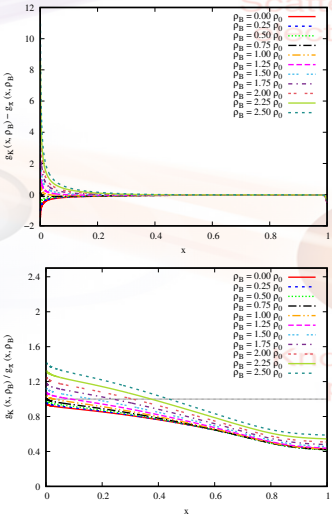


Gluons difference of free pion and kaon and bound pion and kaon in NM

Gluon content difference of free pion and kaon and bound pion and kaon in nuclear matter:

- The gluon content difference of free pion and kaon after evolved at $Q^2 = 16\ \text{GeV}^2$
- The gluon content difference of bound pion and kaon in nuclear matter after evolved at $Q^2 = 16\ \text{GeV}^2$

We have limited data, therefore we need the results from the Electron-Ion Collider (EIC), COMPASS-CERN SPS and Electron-Ion Collider China (Eicc)



Summary and outlook

- We have studied the gluon content of free pion, kaon and proton as well as bound pion, kaon and proton in nuclear matter
- Our prediction on gluon distribution in free pion and kaon as well as bound pion and kaon are very interesting and promising
- We will extend our calculation to momentum- and temperature-dependents parton distribution function and fragmentation function of the vector- and axial-vector mesons and their bound in NM– work in progress–stay tune!
- Also, it would be very challenging to extend our calculation to nuclear parton distributions (PDFs), fragmentation function or generalized parton distributions (GPDs) of nuclei, which is relevant to the heavy ion collisions (HIC)

THANK YOU VERY MUCH FOR ATTENTION !!

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