EMC Theory:
The Polarized EMC effect

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Quantitative challenges in EMC and SRC Research and Data-Mining

Massachusetts Institute of Technology

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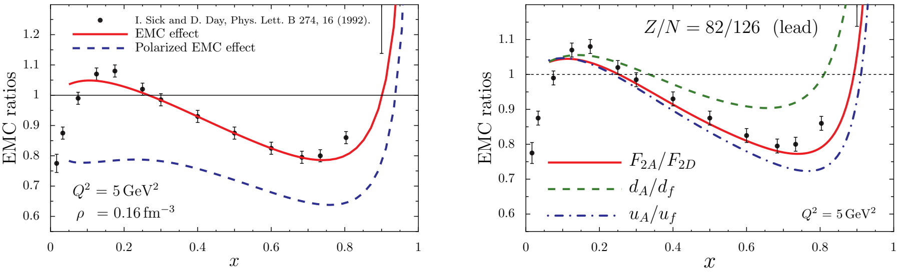
Understanding the EMC effect

- *The puzzle posed by the EMC effect will only be solved by conducting new experiments that expose novel aspects of the EMC effect*
- Measurements should help distinguish between explanations of EMC effect e.g. whether *all nucleons* are modified by the medium or only those in SRCs
- Important examples are:
  - *EMC effect in polarized structure functions*
  - *flavour dependence of EMC effect*
- JLab has an approved experiment to measure the spin structure of ^{7}Li



Theory approaches to EMC effect

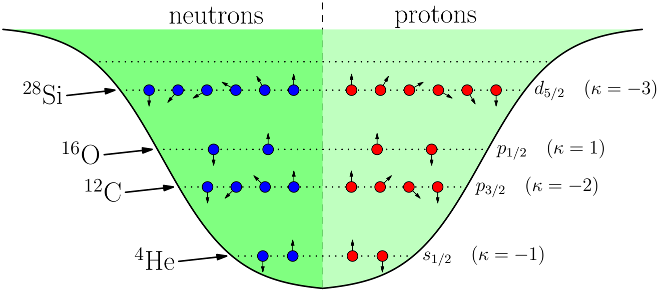
- To address the EMC effect must determine nuclear quark distributions:

$$q_A(x_A) = \frac{P^+}{A}\int \frac{d\xi^-}{2\pi} e^{iP^+\,x_A\,\xi^-/A}\langle A,P|\overline{\psi}_q(0)\,\gamma^+\,\psi_q(\xi^-)|A,P\rangle$$

- Common to approximate using convolution formalism

$$q_A(x_A) = \sum_{\alpha,\kappa}\int_0^A dy_A \int_0^1 dx\ \delta(x_A - y_A\,x)\ f_{\alpha,\kappa}(y_A)\ q_{\alpha,\kappa}(x)$$

  - $\alpha =$ (bound) protons, neutrons, pions, deltas. . . .



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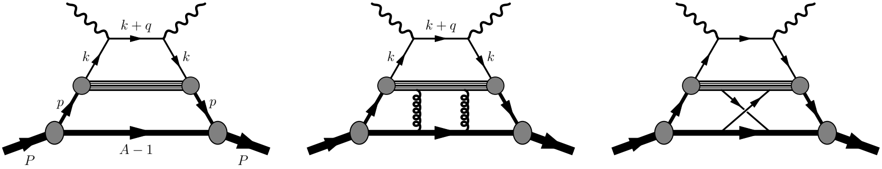
  - α = (bound) protons, neutrons, pions, deltas. . . .
  - $q_\alpha(x)$ light-cone distribution of quarks q in bound hadron α
  - $f_\alpha(y_A)$ light-cone distribution of hadrons α in nucleus



Sum Rules and Convolution Formalism

- Recall convolution model:

$$q_A(x_A) = \sum_\alpha \int_0^A dy_A \int_0^1 dx\ \delta(x_A - y_A\, x)\ f_\alpha(y_A)\ q_\alpha(x)$$

- All credible explanations of the EMC effect must satisfy baryon number and momentum sum rules:

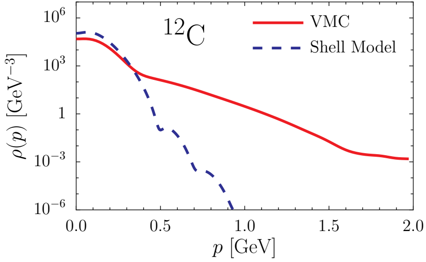
$$\int_0^A dx_A\, u_A^-(x_A) = 2\,Z + N, \qquad \int_0^A dx_A\, d_A^-(x_A) = Z + 2\,N,$$
$$\int_0^A dx_A\, x_A \left[u_A^+(x_A) + d_A^+(x_A) + \ldots + g_A(x_A)\right] = Z + N = A,$$

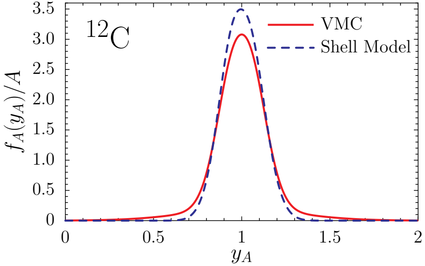
- In convolution formalism these sum rules imply

$$\sum_\alpha n_B^\alpha \int_0^A dy_A\, f_\alpha(y_A) = A \qquad \sum_\alpha \int_0^A dy_A\, y_A\, f_\alpha(y_A) = A$$

  - quark distributions $q_\alpha(x)$ should satisfy baryon number and momentum sum rules for hadron α

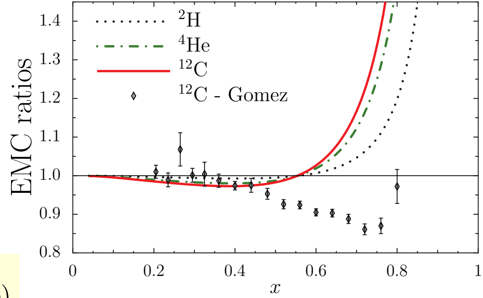
Nuclear Wave Functions





- Modern GFMC or VMC nucleon momentum distributions have significant high momentum tails
  - indicates momentum distributions contain SRCs: ~20% for ^{12}C
- Light cone momentum distribution of nucleons in nucleus is given by

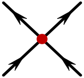
$$f(y_A) = \int \frac{d^3\vec{p}}{(2\pi)^3}\, \delta\left(y_A - \frac{p^+}{P^+}\right)\, \rho(p)$$



Quarks, Nuclei and the NJL model

Continuum QCD

"integrate out gluons" →

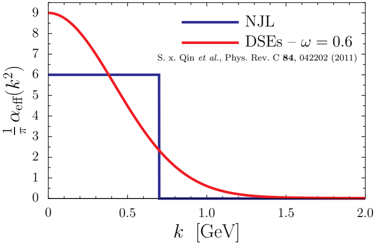


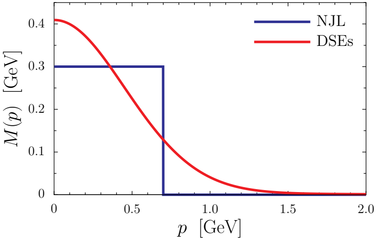
$\frac{1}{m_g^2}\ \Theta(\Lambda^2 - k^2)$

- this is just a modern interpretation of the Nambu–Jona-Lasinio (NJL) model
- model is a Lagrangian based covariant QFT, exhibits dynamical chiral symmetry breaking & quark confinement; elements can be QCD motivated via the DSEs

Quark confinement is implemented via proper-time regularization

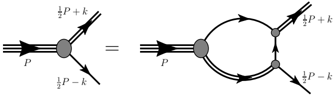
- quark propagator: $[\not{p} - m + i\varepsilon]^{-1} \quad \rightarrow \quad Z(p^2)[\not{p} - M + i\varepsilon]^{-1}$
- wave function renormalization vanishes at quark mass-shell: $Z(p^2 = M^2) = 0$
- *confinement is critical for our description of nuclei and nuclear matter*

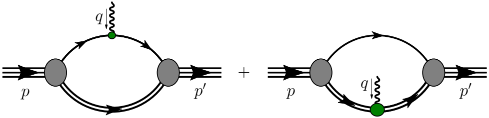




Nucleon Electromagnetic Form Factors

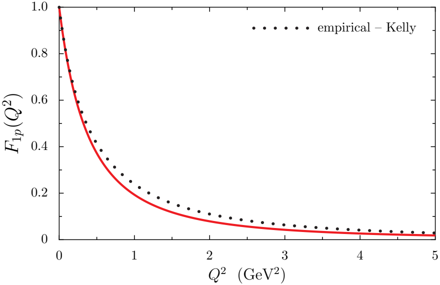
- Nucleon = quark+diquark
- Form factors given by Feynman diagrams:

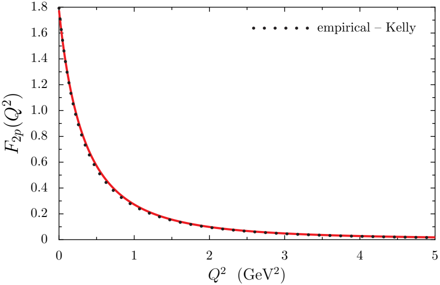




- Calculation satisfies electromagnetic gauge invariance; includes
  - dressed quark–photon vertex with ρ and ω contributions
  - contributions from a pion cloud

[ICC, W. Bentz and A. W. Thomas, Phys. Rev. C **90**, 045202 (2014)]





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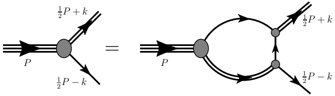

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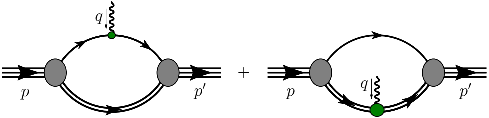

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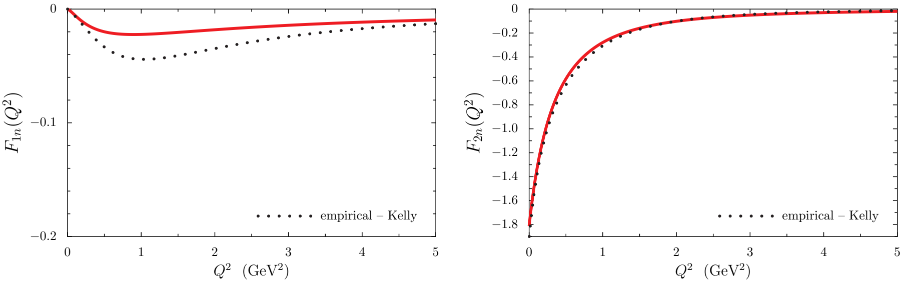
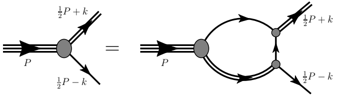
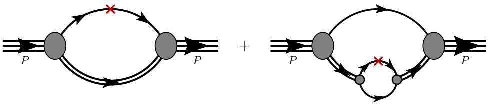


Nucleon quark distributions

- Nucleon = quark+diquark

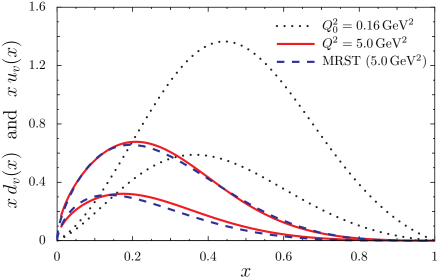


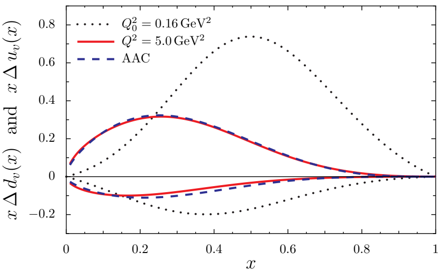
- PDFs given by Feynman diagrams: $\langle\gamma^+\rangle$



- Covariant, correct support; satisfies sum rules, Soffer bound & positivity

$$\langle q(x) - \bar{q}(x)\rangle = N_q, \quad \langle x\,u(x) + x\,d(x) + \ldots\rangle = 1, \quad |\Delta q(x)|\,,\ |\Delta_T q(x)| \leqslant q(x)$$





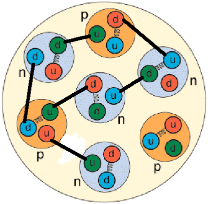
[ICC, W. Bentz and A. W. Thomas, Phys. Lett. B **621**, 246 (2005)]

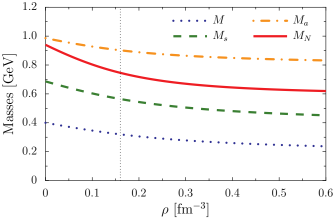
NJL at Finite Density

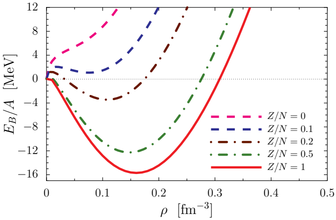
- Finite density (mean-field) Lagrangian: $\bar{q}q$ interaction in $\sigma,\ \omega,\ \rho$ channels

$$\mathcal{L} = \overline{\psi}_q \left(i\,\partial\!\!\!/ - M^{*} - V\!\!\!/_q\right)\psi_q + \mathcal{L}'_I$$

- *Fundamental physics – mean fields couple to the quarks in nucleons*







- Quark propagator: $S(k)^{-1} = k\!\!\!/ - M + i\varepsilon \;\rightarrow\; S_q(k)^{-1} = k\!\!\!/ - M^{*} - V\!\!\!/_q + i\varepsilon$

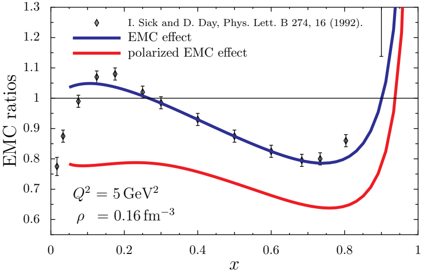
- Hadronization + mean–field $\Longrightarrow$ effective potential (solve self-consistently)

$$\mathcal{E} = \mathcal{E}_V + \mathcal{E}_p + \mathcal{E}_n - \frac{\omega_0^2}{4\,G_\omega} - \frac{\rho_0^2}{4\,G_\rho}$$

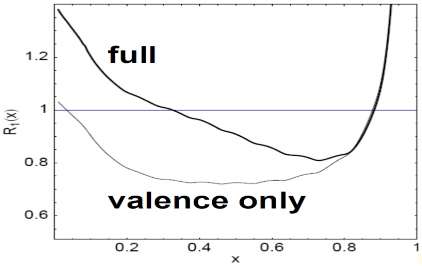
  - $\mathcal{E}_V$ = vacuum energy
  - $\mathcal{E}_{p(n)}$ = energy of nucleons moving in $\sigma,\ \omega,\ \rho$ mean-fields

EMC and Polarized EMC effects

[ICC, W. Bentz and A. W. Thomas, Phys. Rev. Lett. **95**, 052302 (2005)]



[J. R. Smith and G. A. Miller, Phys. Rev. C **72**, 022203(R) (2005)]



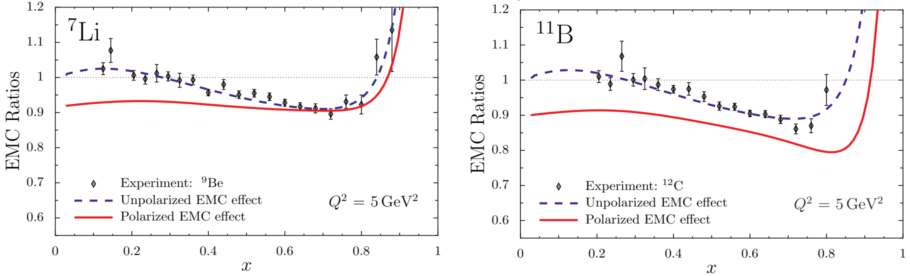
- Definition of polarized EMC effect:
  - ratio equals unity if no medium effects

$$\Delta R = \frac{g_{1A}}{g_{1A}^{\text{naive}}} = \frac{g_{1A}}{P_p\, g_{1p} + P_n\, g_{1n}}$$

- Large polarized EMC effect arises because in-medium quarks are more relativistic ($M^* < M$)
  - lower components of quark wave functions are enhanced and these usually have larger orbital angular momentum
  - *in-medium we find that quark spin is converted to orbital angular momentum*
- *A large polarized EMC effect would be difficult to accommodate within traditional nuclear physics and most other explanations of the EMC effect*

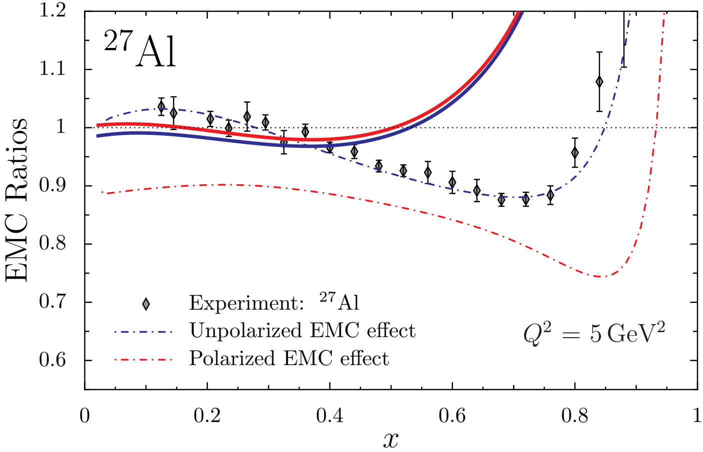
EMC effects in Finite Nuclei

[ICC, W. Bentz and A. W. Thomas, Phys. Lett. B **642**, 210 (2006)]



- Spin-dependent cross-section is suppressed by $1/A$
  - should choose light nucleus with spin carried by proton e.g. $\Longrightarrow$ ^{7}Li, ^{11}B, ...
- Effect in ^{7}Li is slightly suppressed because it is a light nucleus and proton does not carry all the spin (simple WF: $P_p = 13/15$ & $P_n = 2/15$)
- Experiment now approved at JLab [E12-14-001] to measure spin structure functions of ^{7}Li (GFMC: $P_p = 0.86$ & $P_n = 0.04$)
- *Everyone with their favourite explanation for the EMC effect should make a prediction for the polarized EMC effect in ^{7}Li*

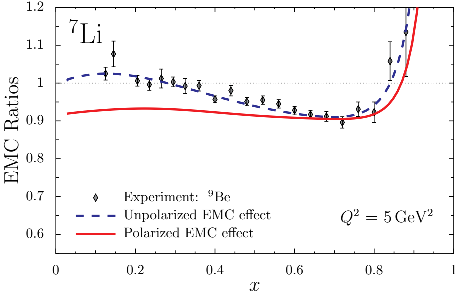
Turning off Medium Modification



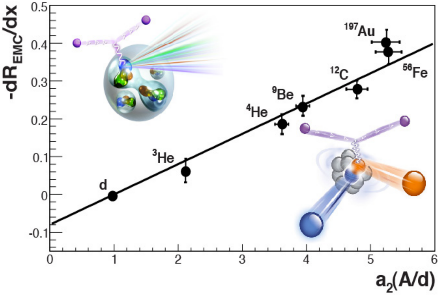
- Without medium modification both EMC & polarized EMC effects disappear
- Polarized EMC effect is smaller than the EMC effect – this is natural within standard nuclear theory and also from SRC perspective
- Large splitting very difficult without *mean-field* medium modification

Mean-field vs SRC induced Medium Modification

[ICC, W. Bentz and A. W. Thomas, Phys. Lett. B **642**, 210 (2006)]



[L. B. Weinstein *et al.*, Phys. Rev. Lett. **106** 052301 (2011)]



- Explanations of EMC effect using SRCs also invoke medium modification
  - since about 20% of nucleons are involved in SRCs, need medium modifications about 5 times larger than in mean-field models
- For polarized EMC effect only 2–3% of nucleons are involved in SRCs
  - it would therefore be natural for SRCs to produce a smaller polarized EMC effect
- Observation of a large polarized EMC effect would imply that SRCs are less likely to be the mechanism responsible for the EMC effect

Nuclear spin sum

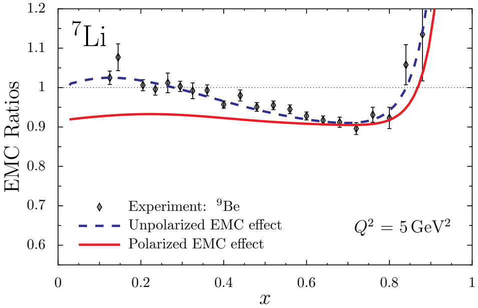
Proton spin states	Δu	Δd	Σ	g_A
p	0.97	-0.30	0.67	1.267
^{7}Li	0.91	-0.29	0.62	1.19
^{11}B	0.88	-0.28	0.60	1.16
^{15}N	0.87	-0.28	0.59	1.15
^{27}Al	0.87	-0.28	0.59	1.15
Nuclear Matter	0.79	-0.26	0.53	1.05

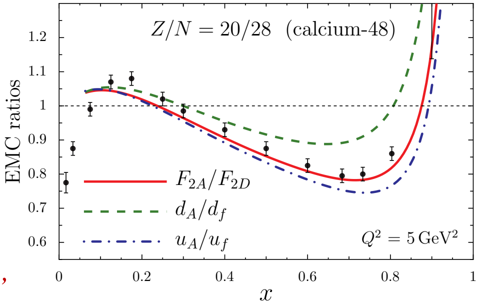
- Angular momentum of nucleon: $J = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$
  - in medium $M^* < M$ and therefore quarks are more relativistic
  - lower components of quark wavefunctions are enhanced
  - quark lower components usually have larger angular momentum
  - $\Delta q(x)$ very sensitive to lower components
- Therefore, in-medium quark spin → orbital angular momentum

Conclusion

- Understanding the EMC effect is a critical step towards a QCD based description of nuclei
  - need new experiments that provide clean access to novel aspects of the EMC effect
- Key example is the approved JLab experiment that will measure the polarized EMC effect in ^{7}Li
  - I hope our community can get behind this experiment
  - also PVDIS!!
- A next frontier is GPDs and TMDs of nuclei at JLab and an EIC

QCD town meeting: *"... must solve problem posed by the EMC effect ..."*

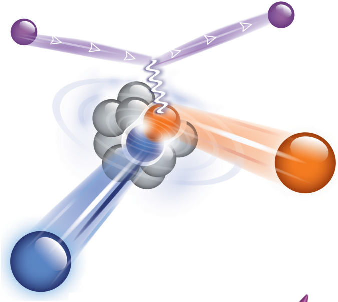


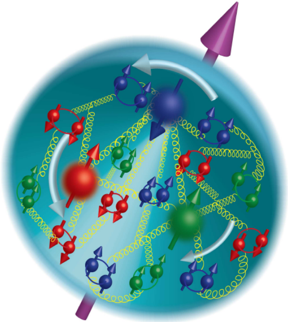


Backup Slides

Explanations of the EMC effect

- Traditional explanations include:
  - nuclear binding and Fermi motion
  - pion excess in nuclei
- QCD motivated explanations include:
  - dynamical rescaling
  - multi-quark clusters, e.g. 6, 9, . . . quark bags
  - nucleon swelling and suppression of point-like configurations
  - medium modification of bound nucleon wave functions
- Hybrid explanations include:
  - short-range nucleon-nucleon correlations (SRCs)
- After 30 years data has ruled out almost none of these explanations!





Confinement in NJL model

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- In general the NJL model is not confining; quark propagator is simply

$$S(k) = \frac{1}{\not{k} - M + i\varepsilon} = \frac{\not{k} + M}{k^2 - M^2 + i\varepsilon}$$

  - quark propagator has a pole $\Longrightarrow$ quarks are part of physical spectrum

- However the proper-time scheme is unique $\frac{1}{X^n} = \frac{1}{(n-1)!}\int_0^\infty d\tau\, \tau^{n-1}\, e^{-\tau X}$

$$S(k) = \int_0^\infty d\tau\, (\not{k} + M)\, e^{-\tau\left(k^2 - M^2\right)} \to \underbrace{\frac{\left[e^{-(k^2-M^2)/\Lambda_{UV}^2} - e^{-(k^2-M^2)/\Lambda_{IR}^2}\right]}{k^2 - M^2}}_{\equiv Z(k^2)} [\not{k} + M]$$

- quark propagator does not have a pole: $Z(k^2) \overset{k^2 \to M^2}{=} \frac{1}{\Lambda_{IR}^2} - \frac{1}{\Lambda_{UV}^2} \neq \infty$

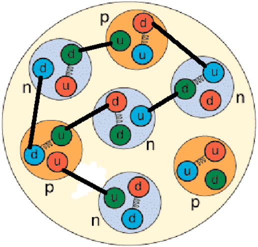
- Important consequences are:
  - saturation of nuclear matter
  - have a Δ bound state for $M < 400\,\mathrm{MeV}$, etc

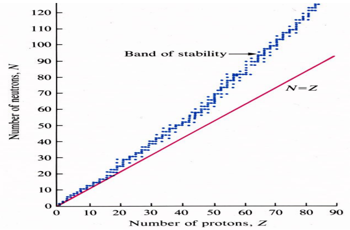
- Finite density Lagrangian: $\bar{q}q$ interaction in $\sigma,\ \omega,\ \rho$ channels

$$\mathcal{L} = \overline{\psi}_q \left(i\,\not{\partial} - M^* - \not{V}_q\right)\psi_q + \mathcal{L}'_I$$

[W. Bentz, A.W. Thomas, Nucl. Phys. A **696**, 138 (2001)]

Fundamental idea: mean-fields couple to quarks in bound nucleons





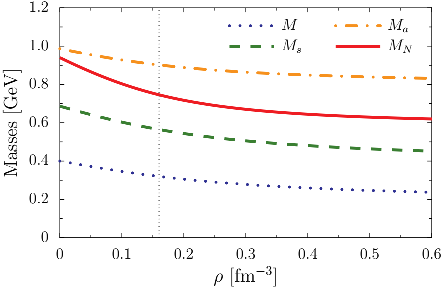
- Quark propagator: $S^{-1} = \not{k} - M + i\varepsilon \ \rightarrow\ S_q^{-1} = \not{k} - M^* - \not{V}_q + i\varepsilon$

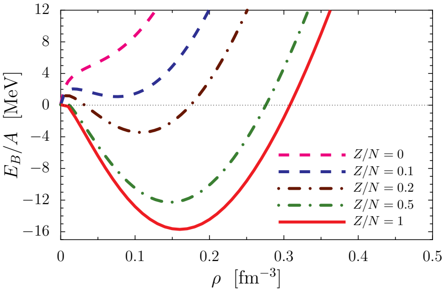
- Hadronization + mean–field $\Longrightarrow$ effective potential

$$V_{u(d)} = \omega_0 \pm \rho_0, \qquad \omega_0 = 6\,G_\omega\,(\rho_p + \rho_n)\,, \qquad \rho_0 = 2\,G_\rho\,(\rho_p - \rho_n)$$

  - $G_\omega \Longleftrightarrow Z = N$ saturation & $G_\rho \Longleftrightarrow$ symmetry energy

Nuclear Matter Results





- Constituent mass: $M^* = m - 2\,G_\pi \langle\overline{\psi}\psi\rangle^*$
  - small restoration of chiral symmetry: $|\langle\overline{\psi}\psi\rangle^*| < |\langle\overline{\psi}\psi\rangle|$
- Curvature [“scalar polarizability”] important for saturation
  - is a consequence of confinement and prevents nuclear matter collapse
- Hadronization → effective potential: $\mathcal{E} = \mathcal{E}_V - \frac{\omega_0^2}{4\,G_\omega} - \frac{\rho_0^2}{4\,G_\rho} + \mathcal{E}_p + \mathcal{E}_n$
  - $\mathcal{E}_V$: vacuum energy
  - $\mathcal{E}_{p(n)}$: energy of nucleons moving in σ, ω, ρ mean-fields