Magnetic Enhancement of Baryon Confinement Modeled via a Deformed Skyrmion

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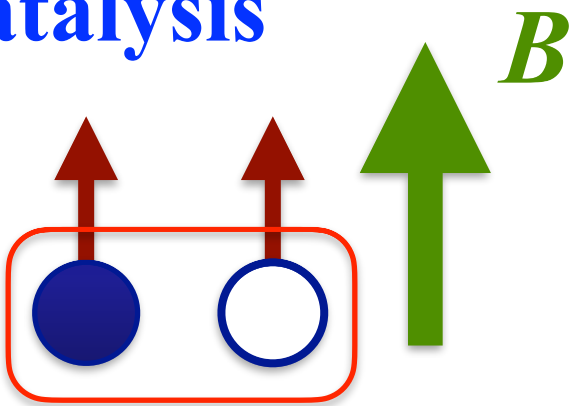
Hadrons under Strong B

Magnetic Catalysis



Chiral condensate
(scalar - isoscalar)

$L = 1$ and $S = 1$ making $J = 0$
more favored by strong B

Chiral Perturbation Theory **(Shushpanov-Smilga 1997)**

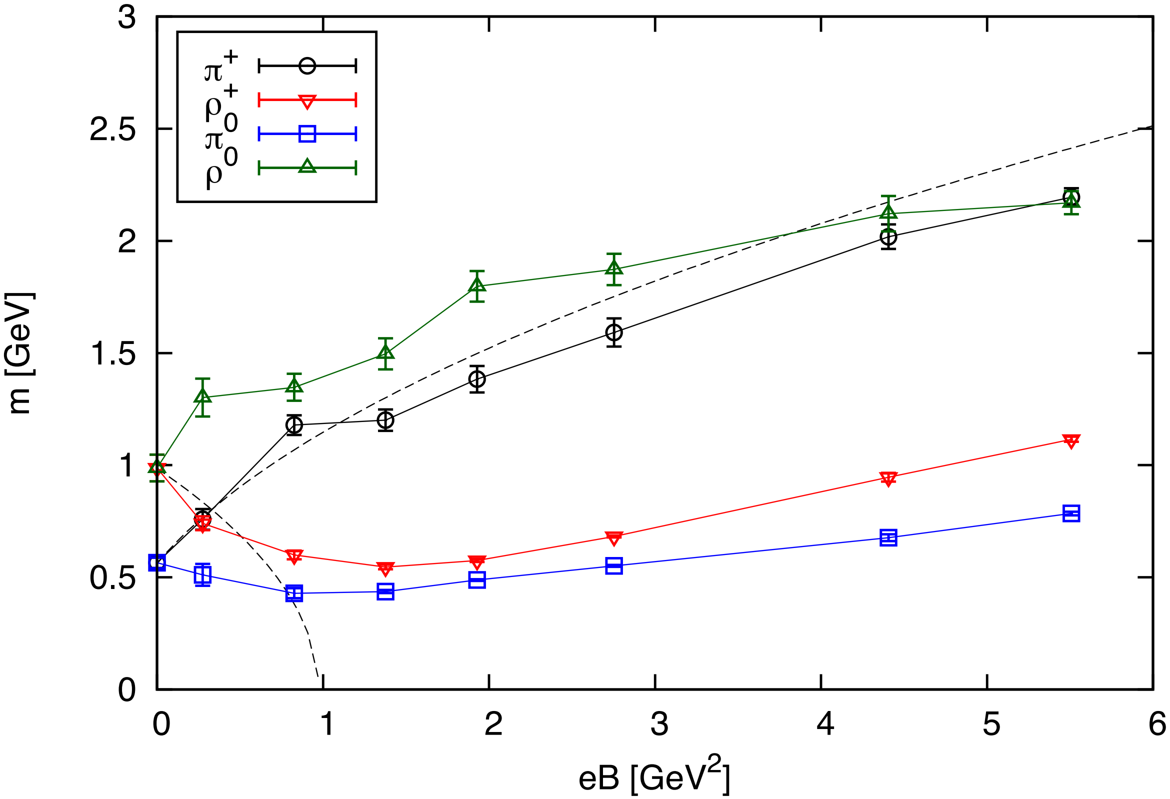
$$\Sigma(B) = \Sigma(0)\left(1 + \boxed{\frac{\ln 2}{16\pi^2 f_\pi^2}} eB + \cdots\right)$$

Positive coefficient

Hadrons under Strong B

Lattice-QCD

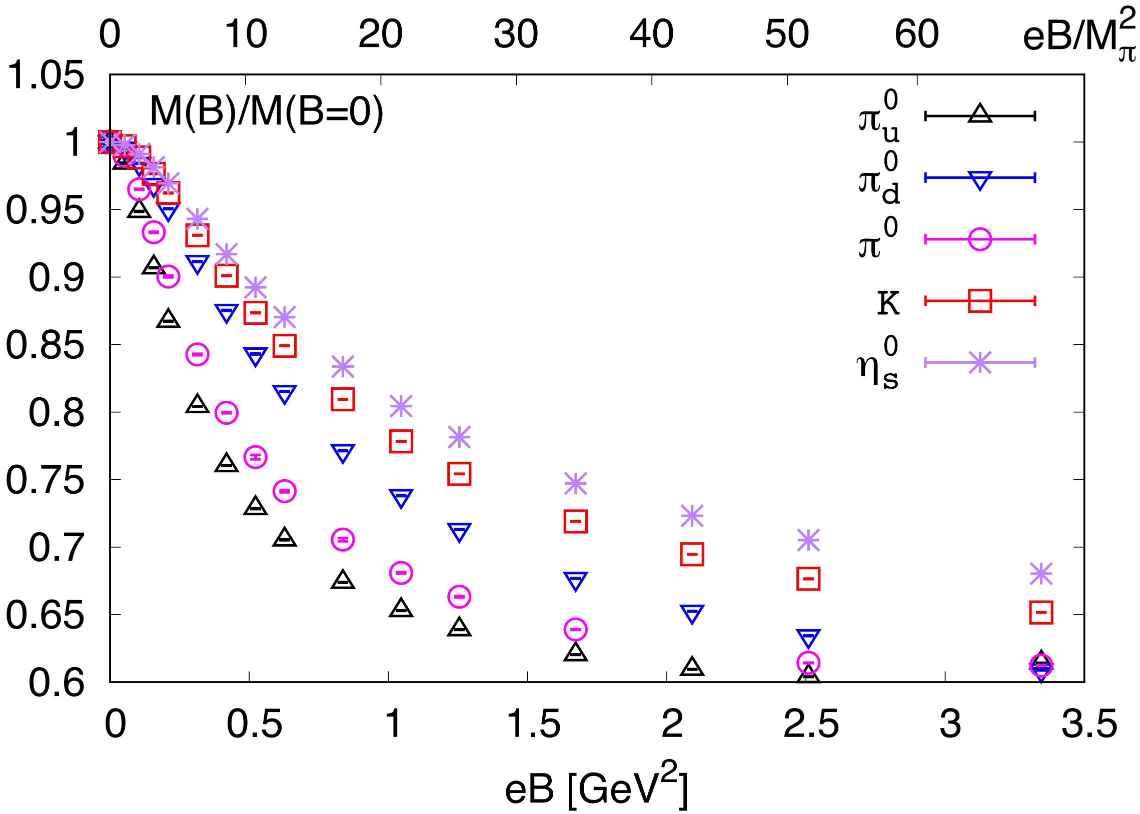
Hidaka-Yamamoto (2012)



Hadrons under Strong B

Lattice-QCD

Ding-Li-Tomiya-Wang-Zhang (2020)

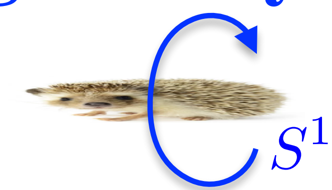


Larger binding energy with increasing *B* ?

Skyrmions under Strong B

Without *B* the baryon number is given by

$$\pi_3(\mathrm{SU}(2)) = \mathbb{Z}$$



Distinct homotopy connected?

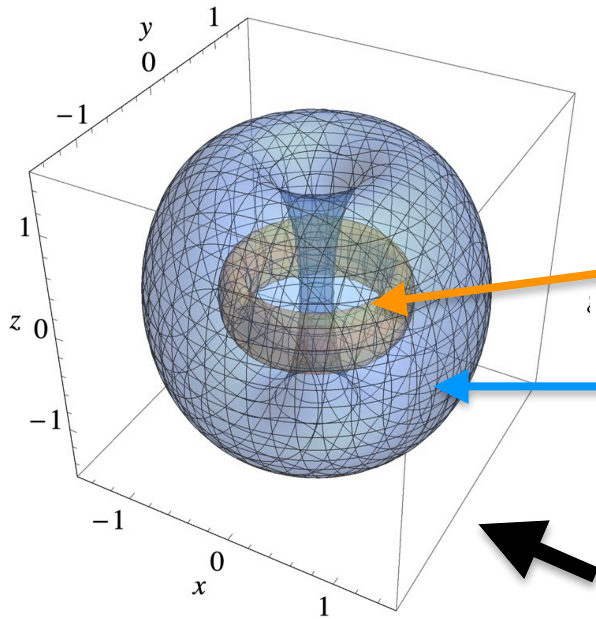
$$\pi_3(\mathrm{SU}(2)) = \mathbb{Z} \longrightarrow \pi_1(\mathrm{U}(1)) = \mathbb{Z}$$

$B = 0$ **?** $B \to \infty$

Phase transition, Crossover, ???

Skyrmions under Strong B

$$\Sigma = \mathrm{i}\boldsymbol{\tau}\cdot\boldsymbol{\Pi} + \Pi_4 \qquad \Pi_1^2 + \Pi_2^2 + \Pi_3^2 + \Pi_4^2 = 1$$



$\pi_3(\mathrm{SU}(2))$ winding is never unwound but it persist near the origin (where the ***B*** effect is small)

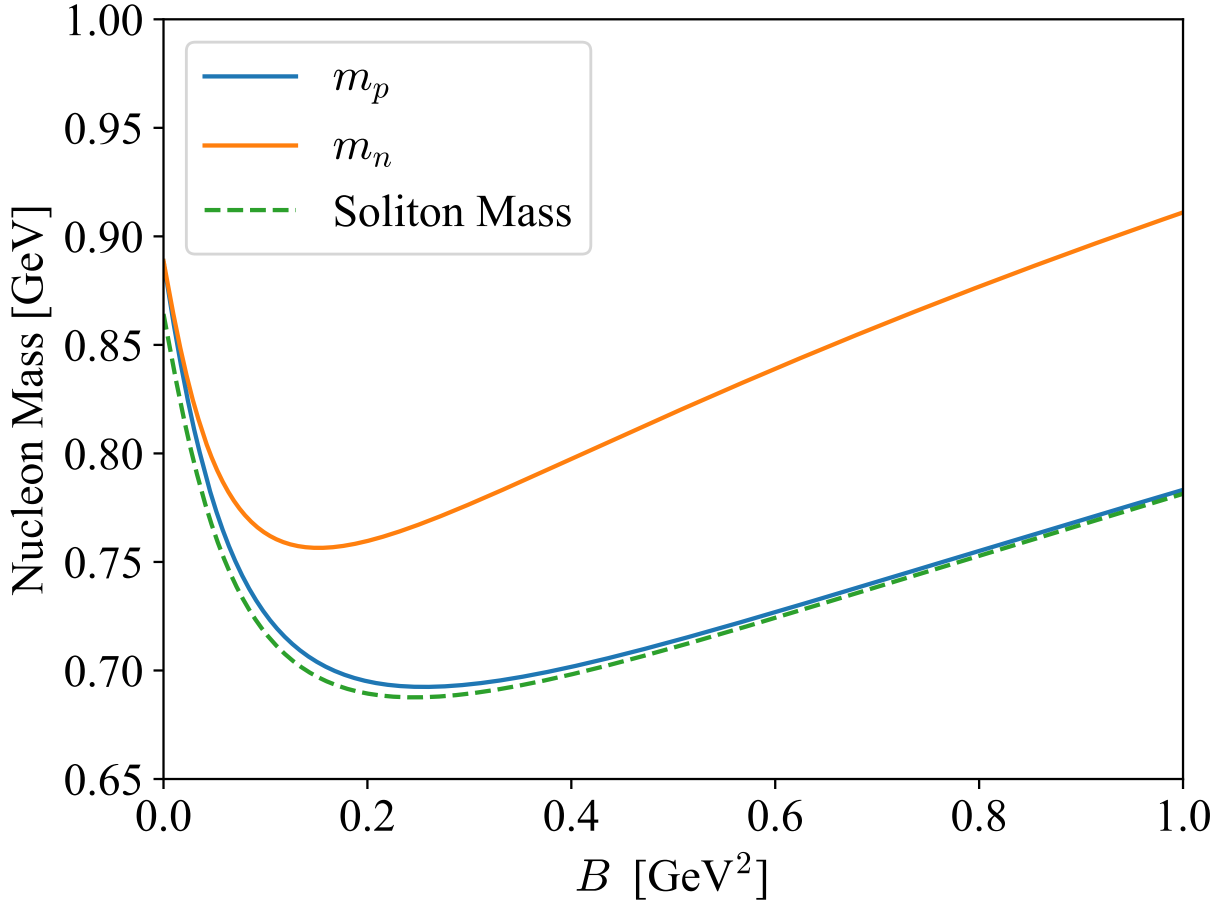
Dominated by charged pions

Dominated by neutral pions

Winding between constant $\Pi_1^2 + \Pi_2^2$ and $\Pi_3^2 + \Pi_4^2$ surfaces

Skyrmions under Strong B

Chen-Fukushima-Qiu (2021)

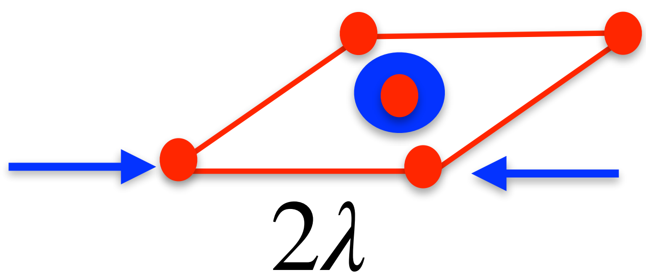


Skyrmions under Strong B

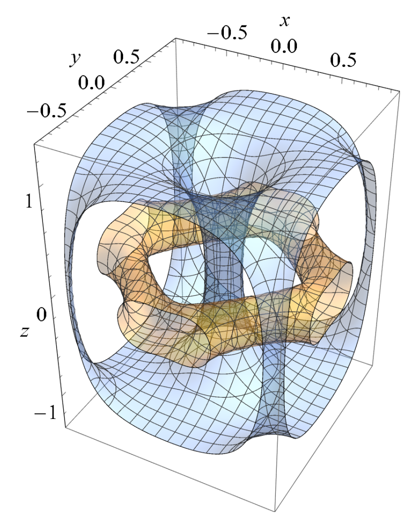
Chen-Fukushima-Qiu (2021)

"Matter" candidates: Normal Crystal & Domain Wall

Unit Cell (Area: $\Lambda = 4\lambda^2$)



$$\Pi_4(0,0,0) = -1$$
$$\Pi_4(\lambda,\lambda,0) = +1$$



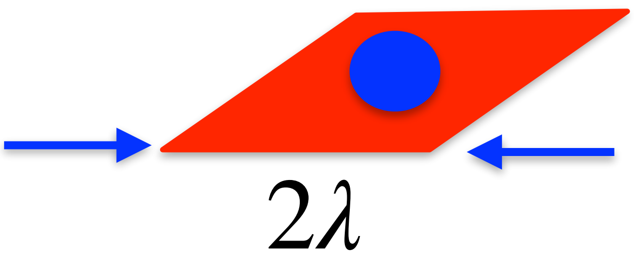
The baryon number from $\pi_3(\mathrm{SU}(2))$ is localized at the center and the edges.

Skyrmions under Strong B

Chen-Fukushima-Qiu (2021)

“Matter” candidates: Normal Crystal & Domain Wall

Unit Cell (Area: $\Lambda = 4\lambda^2$)



$$\Pi_4(0,0,0) = -1$$

$$\Pi_4(x,y,0) = -1$$

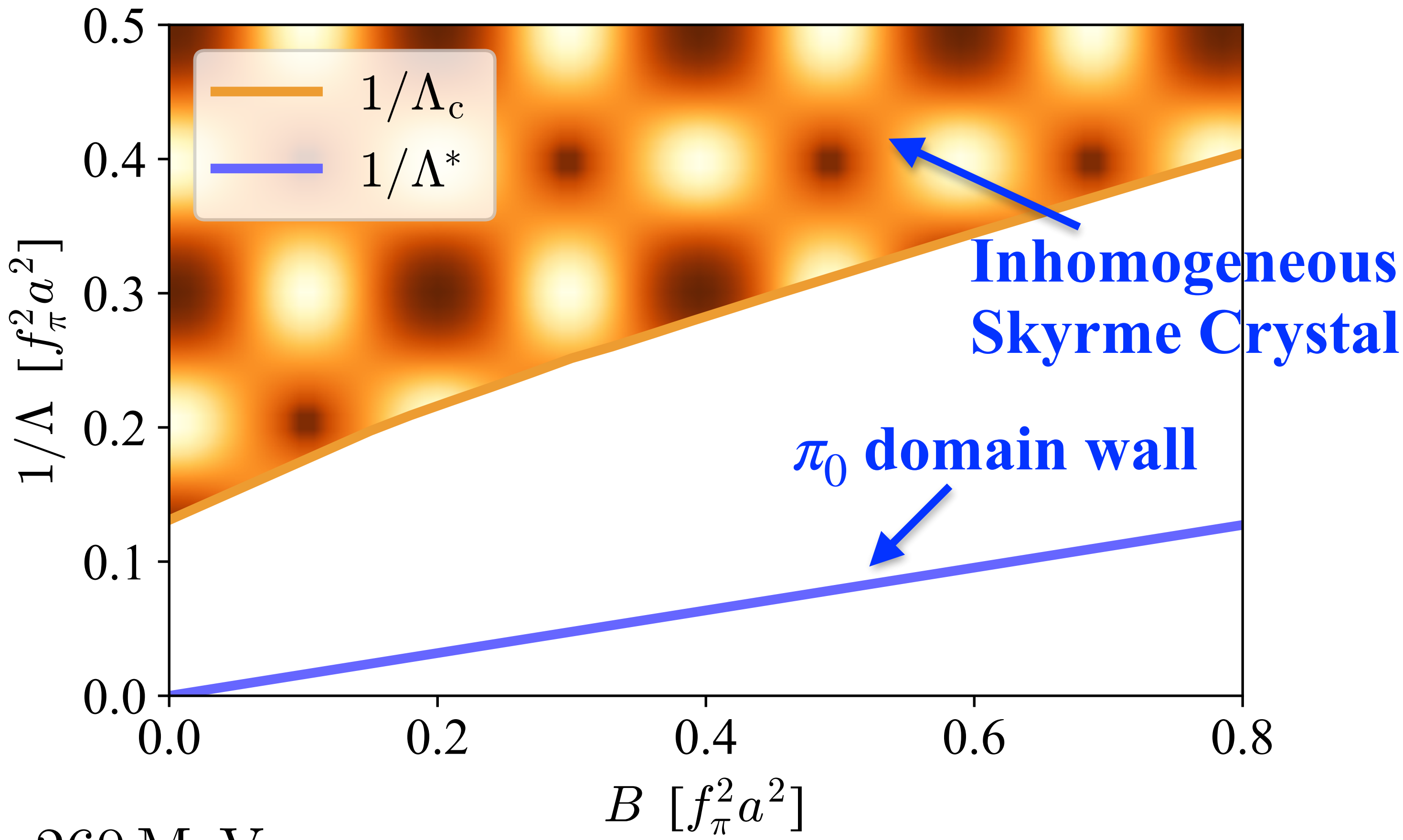
The baryon number from $\pi_1(\mathrm{U}(1))$ is homogeneously distributed on the π_0 domain walls.

The baryon density and the magnetic flux are quantized

$$B\Lambda^* = 2\pi$$ **Dirac quantization is strict!**

Skyrmions under Strong B

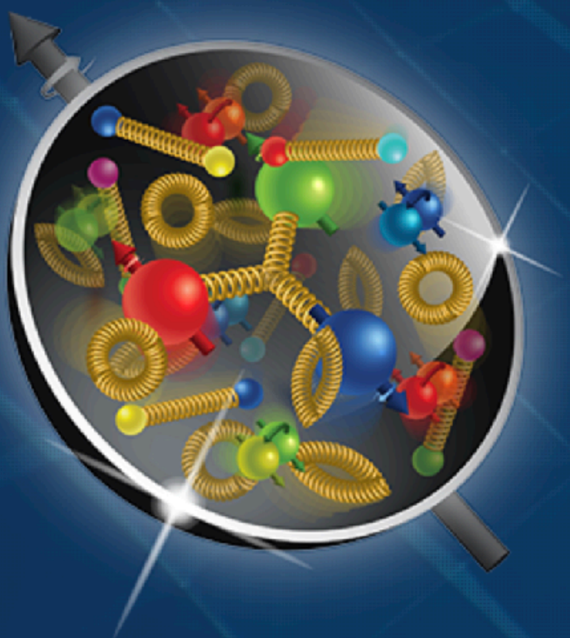
Chen-Fukushima-Qiu (2021)



$f_\pi a \sim 260\,\mathrm{MeV}$

Confinement of Baryons

Confinement of Baryons



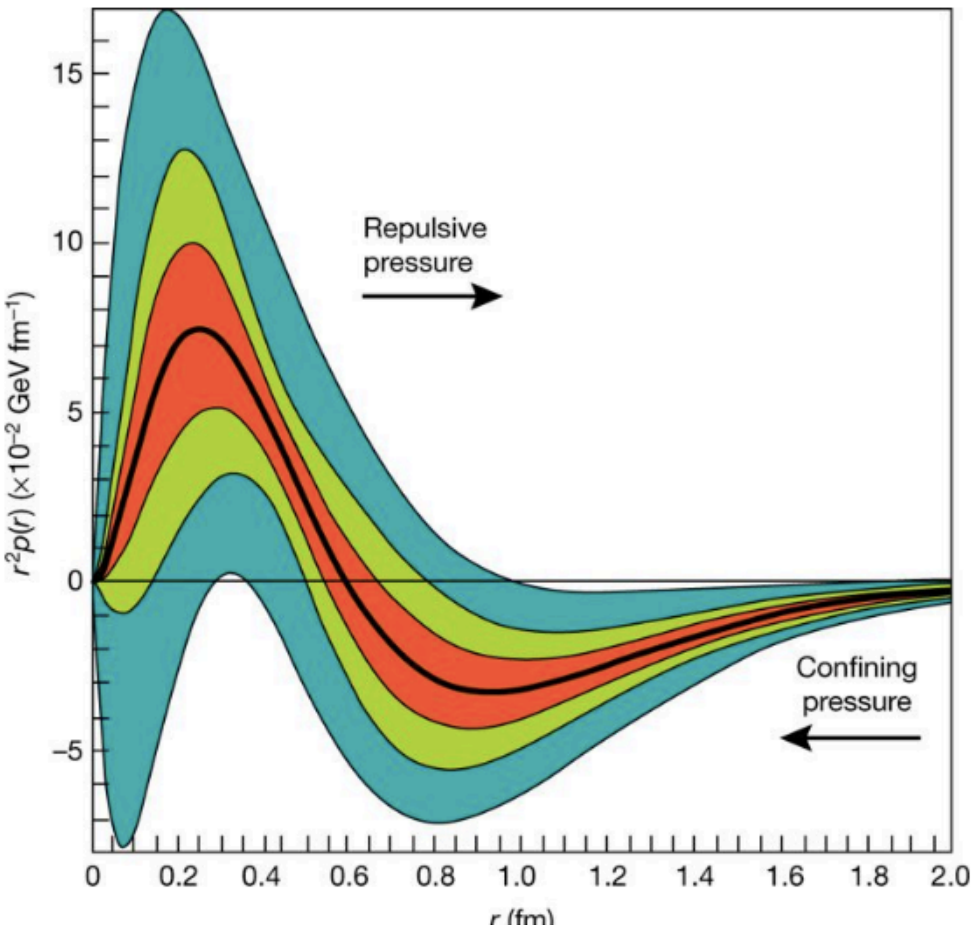
Quark and gluon confinement

Experiments at the EIC will offer novel insight into why quarks or gluons can never be observed in isolation, but must transform into and remain confined within protons and nuclei. The EIC—with its unique combinations of high beam energies and intensities—will cast fresh light into quark and gluon confinement, a key puzzle in the Standard Model of physics.

More

Confinement of Baryons

Burkert-Elouadrhiri-Girod (2018)



Deeply Virtual Compoton Scattering (DVCS)
→ D term

Force balance condition

$$\int d^3x\, p(\boldsymbol{x}) = 0$$

Confinement of Baryons

Chen-Fukushima-Qiu (2023)

Conservation law:

$$\partial^\mu T_{\mu\nu} = j_Q^\mu F_{\mu\nu}$$

Spatial integration with x_μ:

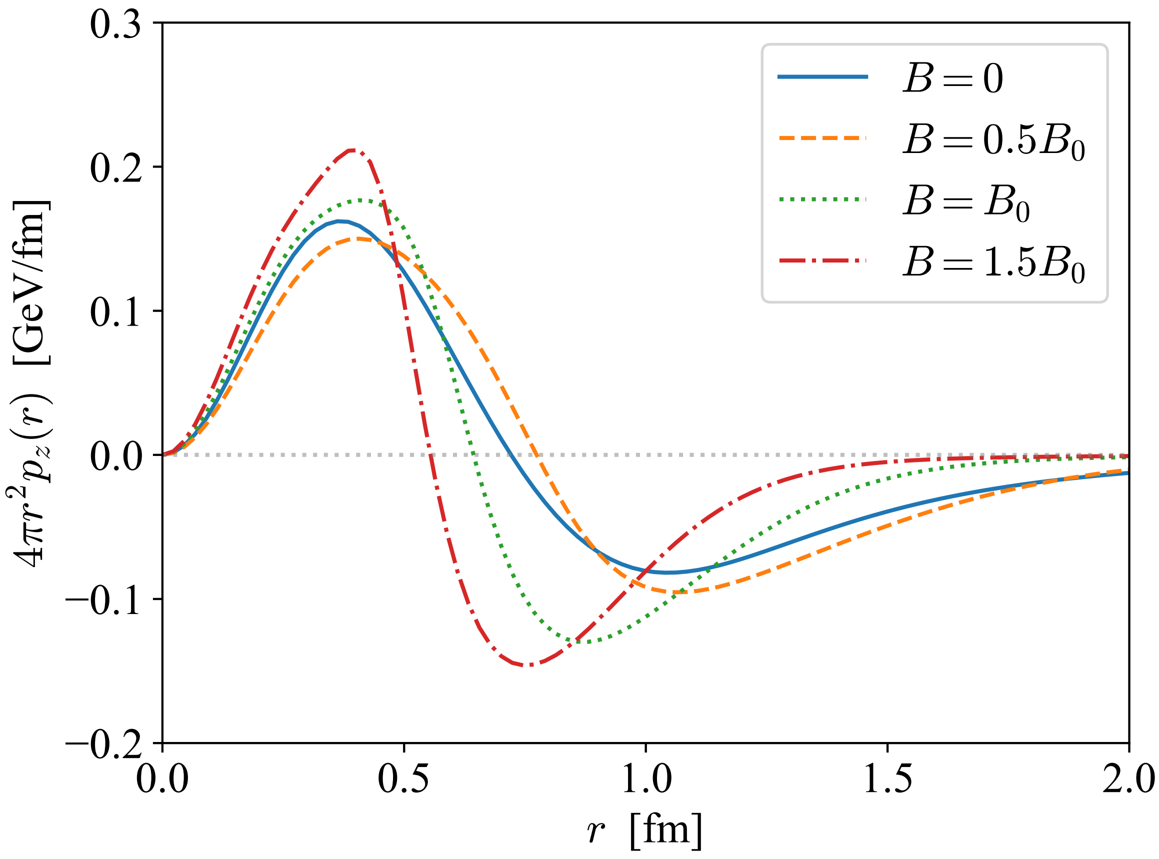
$$\int d^3x\, T_{\mu\nu} = -\int d^3x\, x_\mu j_Q^\lambda\, F_{\lambda\nu}$$

Pressure sum rule:

$$P_z = \int d^3x\, p_z = \int d^3x\, T_{zz} = 0$$

Confinement of Baryons

Chen-Fukushima-Qiu (2023)



Pressure sum rule holds along the magnetic direction.

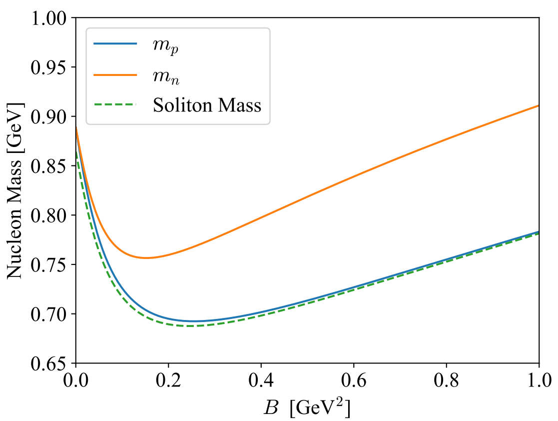
Oblate deformation is favored by *B*.

Confinement of Baryons

$$\int d^3x\, T_{\mu\nu} = -\int d^3x\, x_\mu j_Q^\lambda\, F_{\lambda\nu}$$

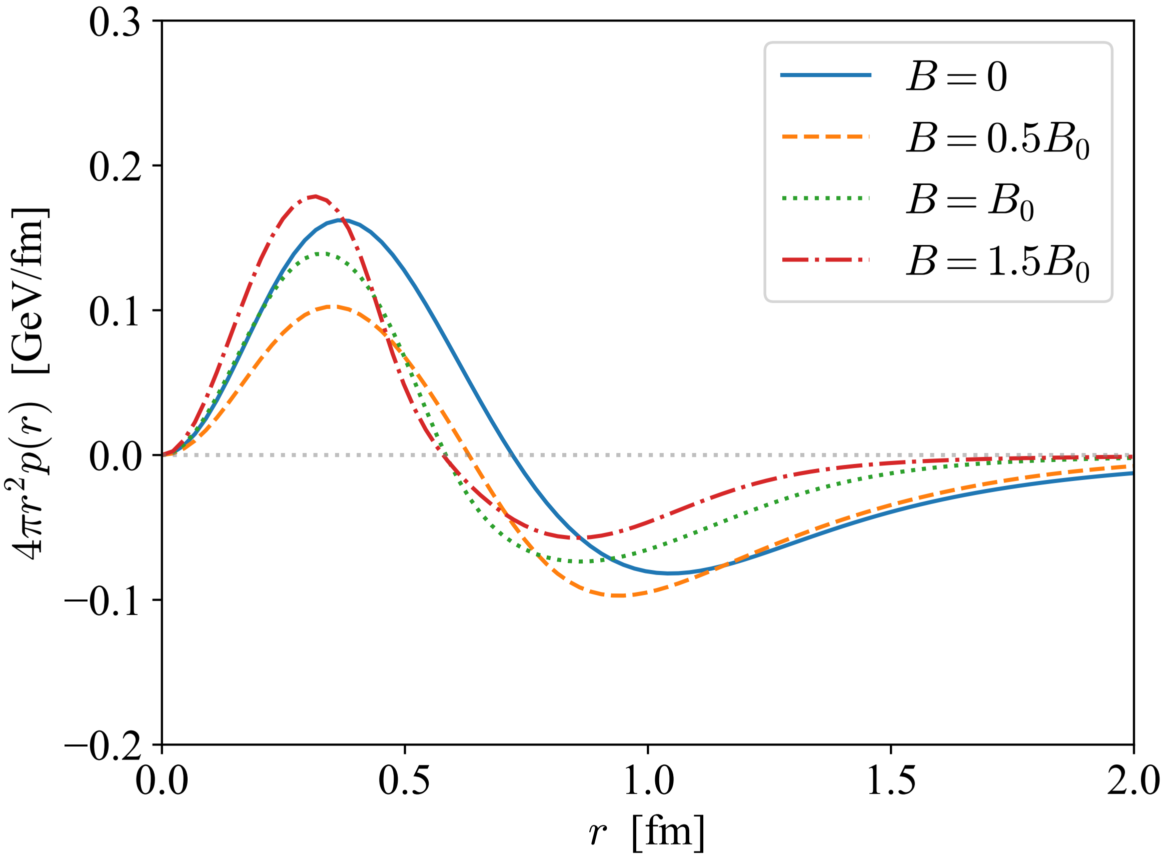
$$P = \int d^3x\, \frac{1}{3} \sum_{i=x,y,z} T_{ii} = -\frac{2}{3}\, \boldsymbol{\mu} \cdot \boldsymbol{B}$$

$$\boldsymbol{\mu} \equiv \int d^3x\, \frac{1}{2}\, \boldsymbol{r} \times \boldsymbol{j}_Q = -\frac{\partial M}{\partial \boldsymbol{B}}$$



Confinement of Baryons

Chen-Fukushima-Qiu (2023)



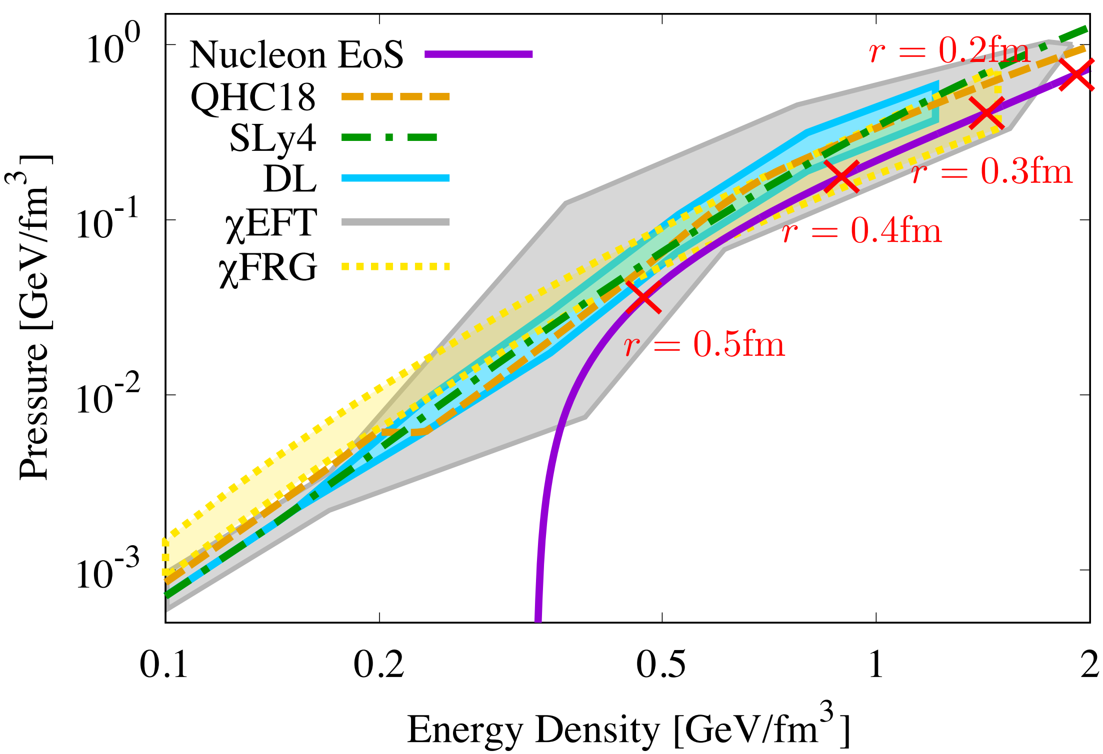
Less confining pressure is needed.

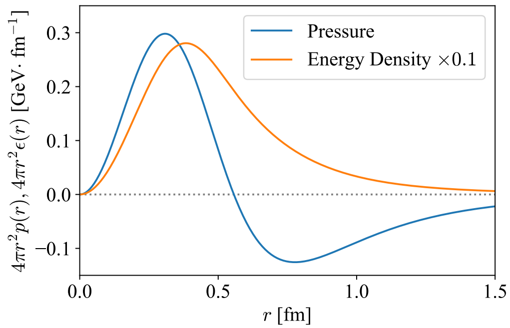
Confining force is provided by the magnetic pressure.

Depends on the sign of the magnetic moment?

Possible Application

Fukushima-Kojo-Weise (2020)





B-dependent EoS could be inferred.

Conclusions

- **Charged and neutron meson masses have been calculated in lattice-QCD.**

- **Pressure balance and confining pressure can be calculated / measured.**

- **Whether *B* favors confinement or deconfinement can be judged based on the pressure sum rule.**