Transverse Charge and Spin Structures of the Nucleon

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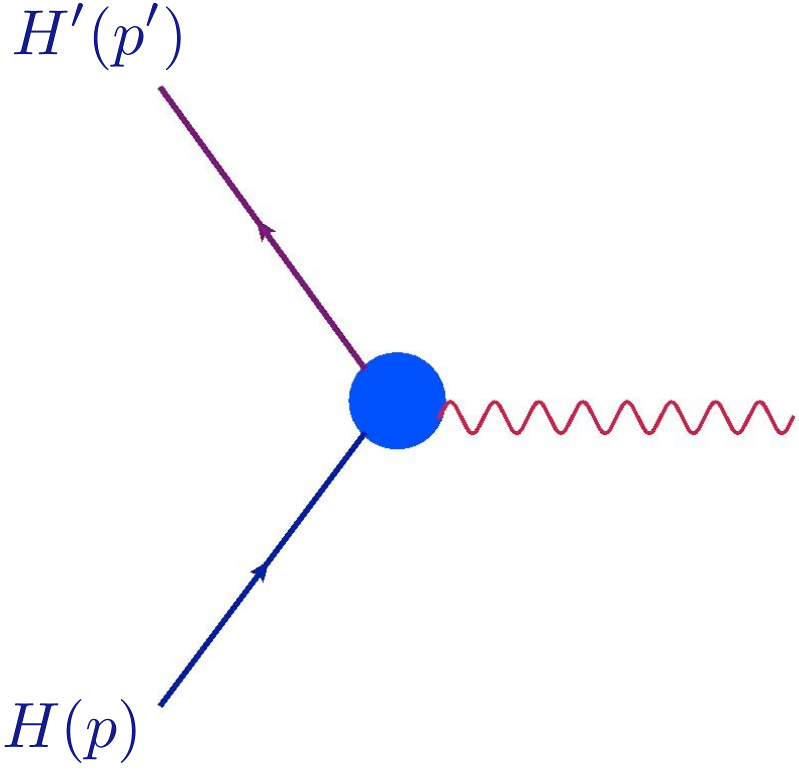
Structure of hadrons

Traditional way of studying structures of hadrons



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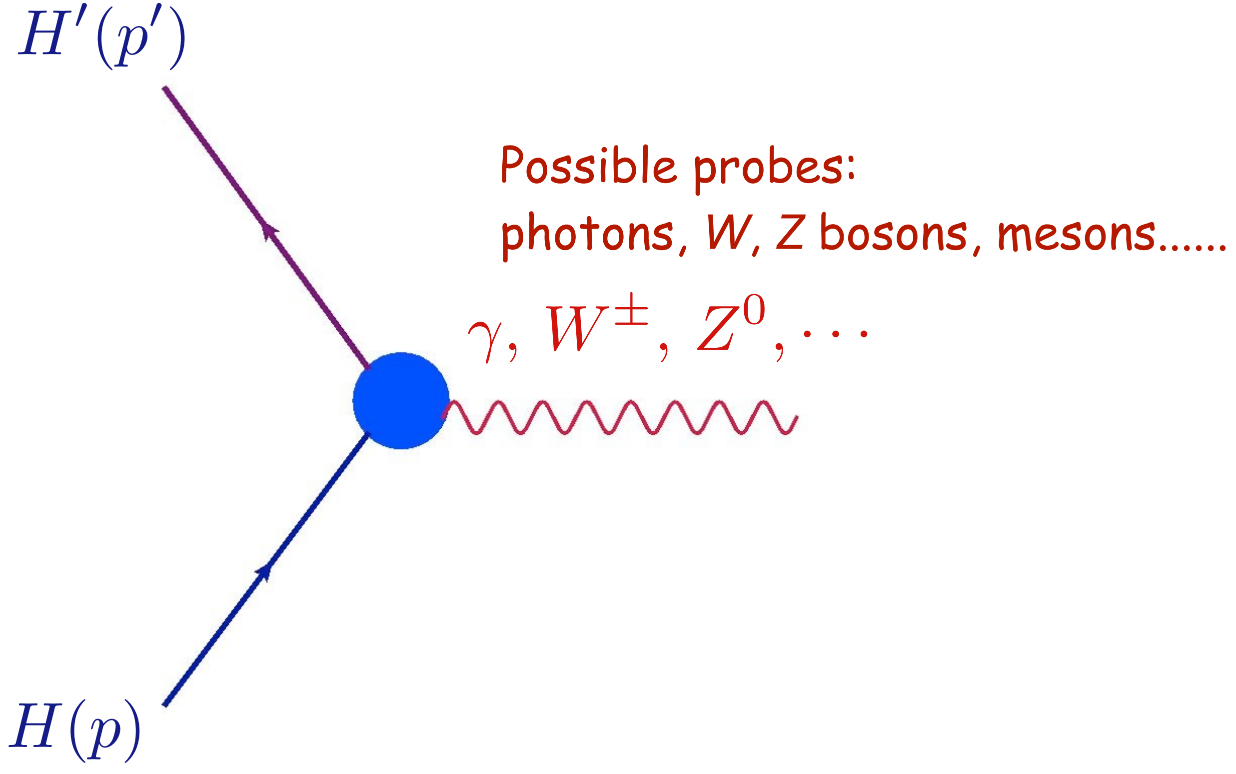
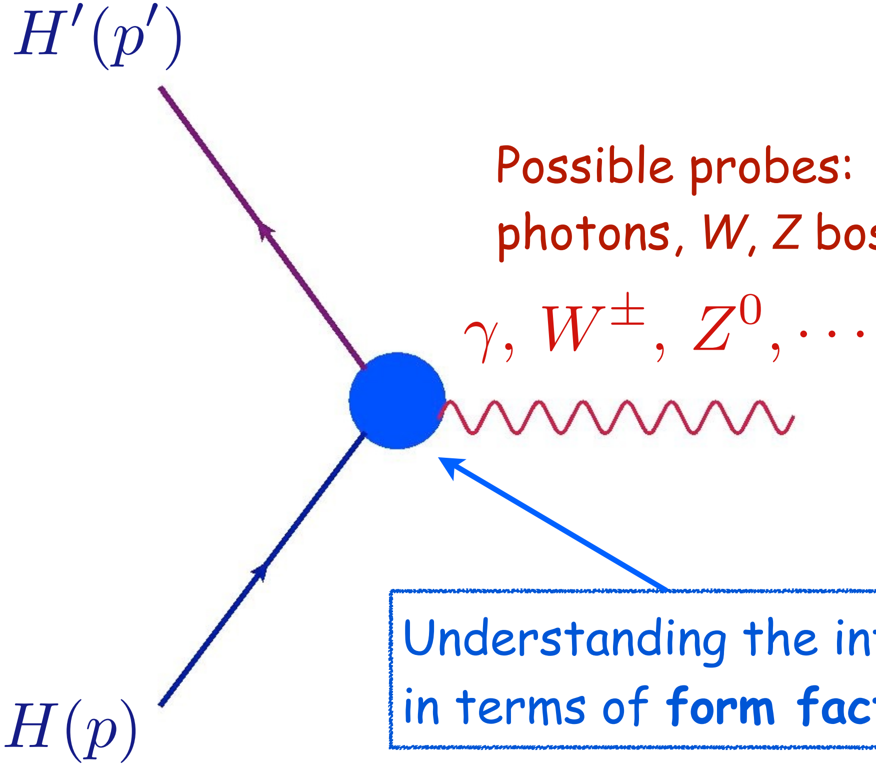


Structure of hadrons

Traditional way of studying structures of hadrons

Possible probes:
photons, *W*, *Z* bosons, mesons……



Understanding the internal structures of hadrons *H* in terms of **form factors**

Structure of hadrons

1. **Scalar form factors**: Sigma pion-nucleon term
   Quark contribution to the nucleon mass

$$\langle h(p')|\bar{\psi}(0)\psi(0)|h(p)\rangle \sim \Sigma_{\pi N}(t)$$

2. **Vector form factors**: Electromagnetic & weak properties
   Charge, EM radii, EM quark distributions in the nucleon

$$\langle N(p')|\bar{\psi}(0)\gamma_\mu\lambda^a\psi(0)|N(p)\rangle \sim G_E(t),\ G_M(t),\ G_E^s(t),\ G_M^s(t)$$

3. **Axial-vector form factors**: Weak properties, spin content of the nucleon, pion-N couplings (PCAC)......

$$\langle N(p')|\bar{\psi}(0)\gamma_\mu\gamma_5\lambda^a\psi(0)|N(p)\rangle \sim g_A(t),\ g_A^0(t),\ G_A^s(t),\ g_{\pi NN}\cdots$$

Structure of hadrons

4. **Energy-momentum tensor (gravitational) form factors**:
   Mass of the nucleon, orbital angular momentum,
   D1 term (pressure, shear force)

$$\langle N(p')|T_{\mu\nu}|N(p)\rangle \sim M_2(t),\ J(t),\ d_1(t)$$

5. **Tensor form factors**: Transverse spin structure of the nucleon

$$\langle N(p')|\bar{\psi}(0)\sigma_{\mu\nu}\lambda^a\psi(0)|N(p)\rangle \sim H_T(t),\ E_T(t),\ \tilde{H}_T(t)$$

→ As equally important as vector & axial-vector form factors
but No probes into these EMT and tensor form factors!

Structure of hadrons

Modern approach: Generalized parton distributions make it possible to get access to these EMT & tensor form factors.

Form factors as Mellin moments of the GPDs

In the present talk, I would like to concentrate on the EM & tensor form factors of the nucleon and their transverse charge & spin structures.

Chiral quark–soliton model

Merits of the chiral quark-soliton model

- Fully relativistic field theoretic model.
- Related to QCD via the Instanton vacuum.
- Renormalization scale is naturally given.
  $1/\rho \approx 600\,\mathrm{MeV}$
- All relevant parameters were fixed already.

$$\mathcal{Z}_{\chi\mathrm{QSM}} = \int \mathcal{D}U \exp(-S_{\mathrm{eff}})$$

$$S_{\mathrm{eff}} = -N_c \mathrm{Tr} \ln D(U)$$

HChK et al. Prog. Part. Nucl. Phys. Vol.37, 91 (1996)

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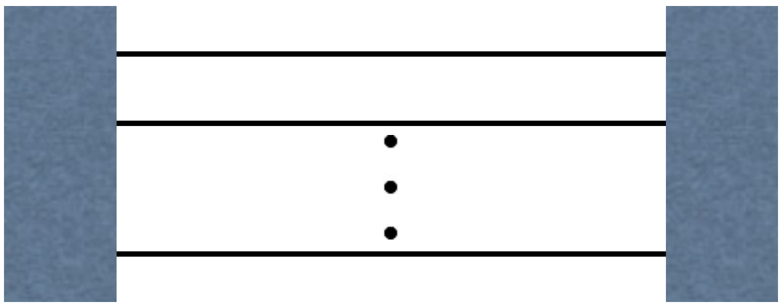
$$\hat{m} = \mathrm{diag}(m_u,\, m_d,\, m_s)\gamma_4$$

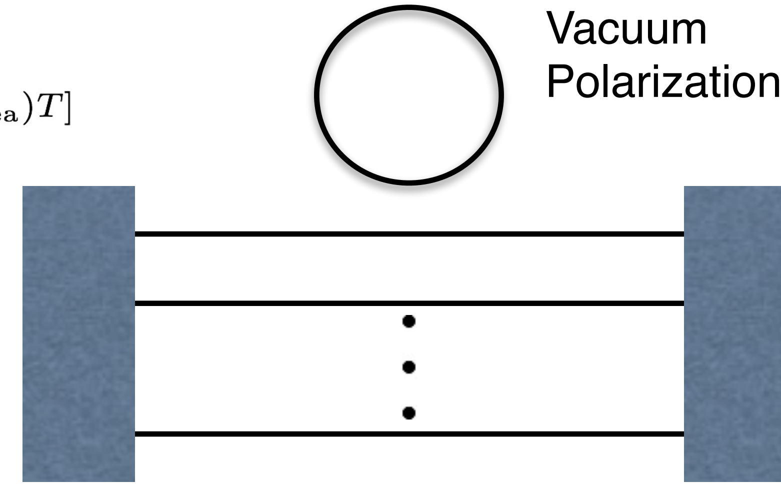
HChK et al. Prog. Part. Nucl. Phys. Vol.37, 91 (1996)

Chiral quark-soliton model

Classical solitons

$$\langle J_N(\vec{x},T)J_N^\dagger(\vec{y},-T)\rangle_0 \sim \Pi_N(T) \sim e^{-[(N_c E_{\rm val}+E_{\rm sea})T]}$$

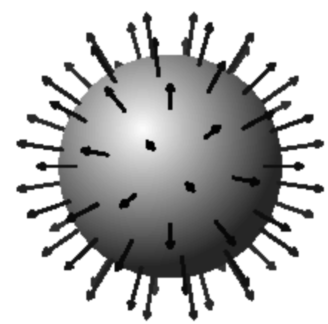




$$\frac{\delta}{\delta U}(N_c E_{\rm val} + E_{\rm sea}) = 0 \;\rightarrow\; M_{\rm cl} = N_c E_{\rm val}(U_c) + E_{\rm sea}(U_c)$$

Hedgehog Ansatz:

$$U_{\rm SU(2)} \;=\; \exp\left[i\gamma_5 \mathbf{n}\cdot\boldsymbol{\tau} P(r)\right]$$



hedgehog

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Chiral quark-soliton model

Collective (Zero-mode) quantization

$$U_0 = \begin{bmatrix} e^{i\vec{n}\cdot\vec{\tau}P(r)} & 0 \\ 0 & 1 \end{bmatrix}$$

$$U(\boldsymbol{x},t) \;=\; R(t)U_c(\boldsymbol{x}-\boldsymbol{Z}(t))R^\dagger(t)$$

$$\int DU[\cdots] \quad\rightarrow\quad \int DAD\boldsymbol{Z}[\cdots]$$

$$\mathcal{L} = -M_{sol} + \frac{I_1}{2}\sum_{i=1}^{3}{\Omega_i}^2 + \frac{I_2}{2}\sum_{i=4}^{7}{\Omega_i}^2 + \frac{N_c}{2\sqrt{3}}\Omega_8$$

HChK et al. Prog. Part. Nucl. Phys. Vol.95, (1995)

Chiral quark-soliton picture

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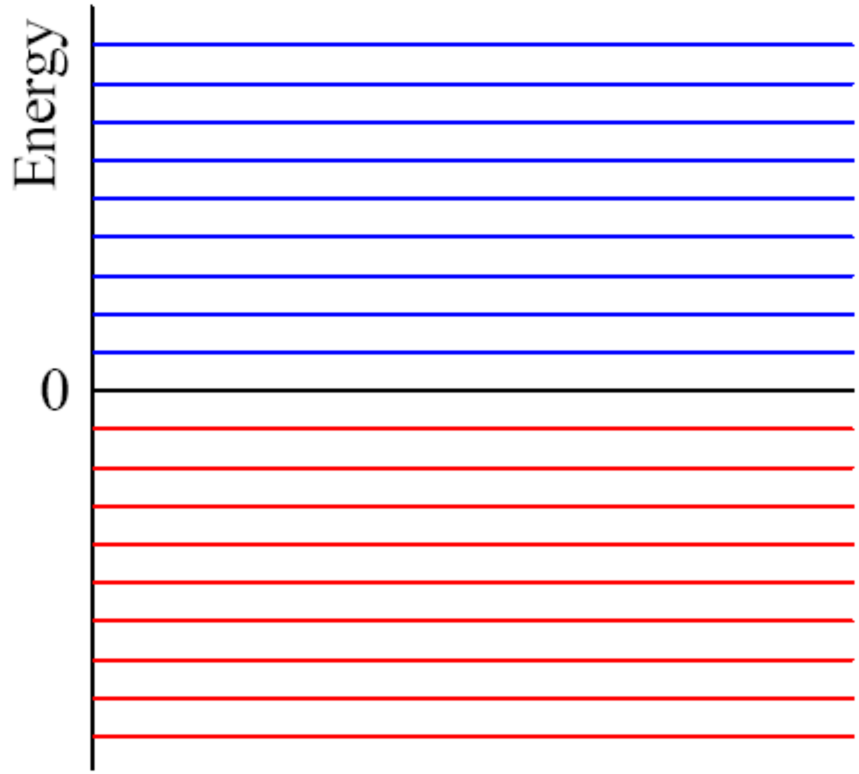

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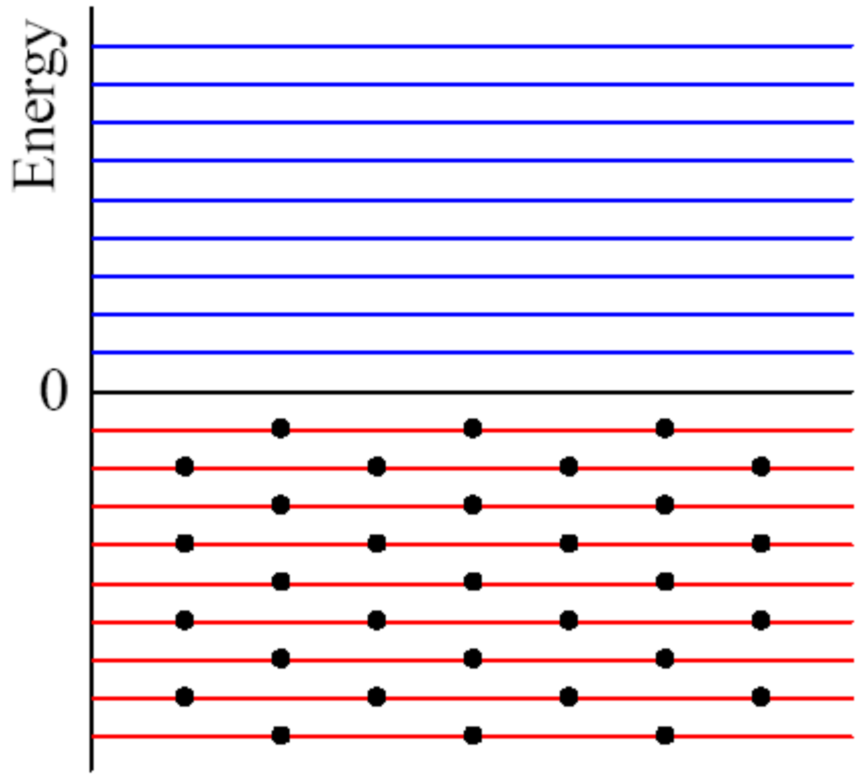

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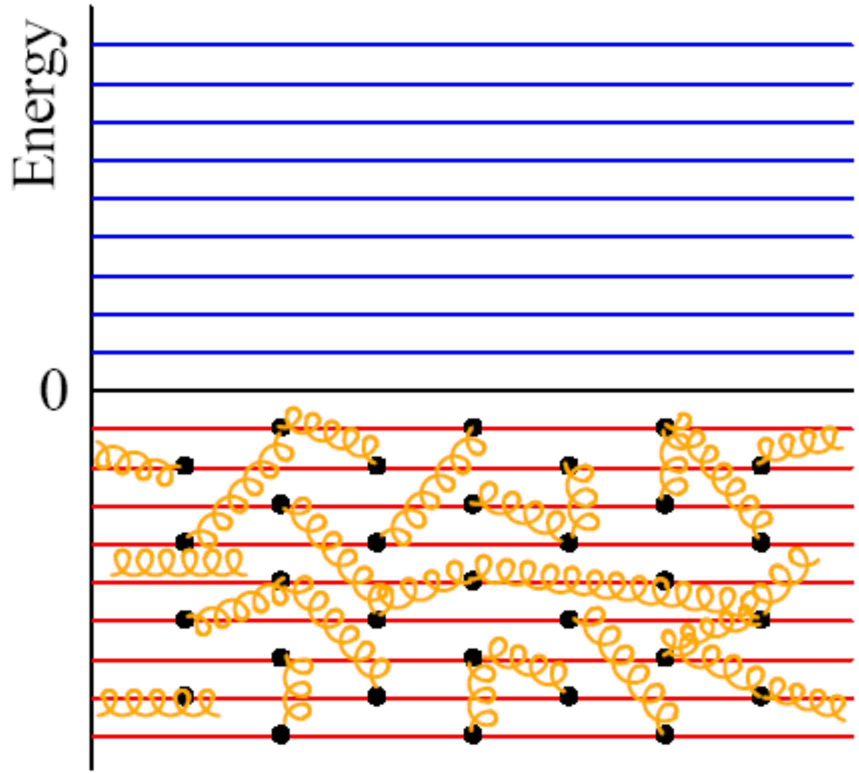

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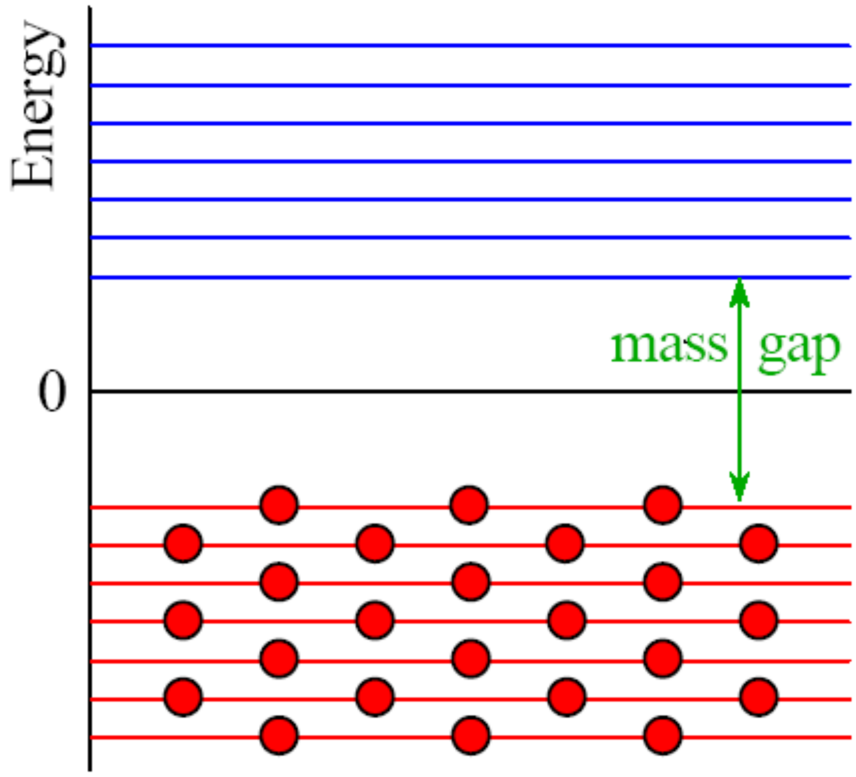

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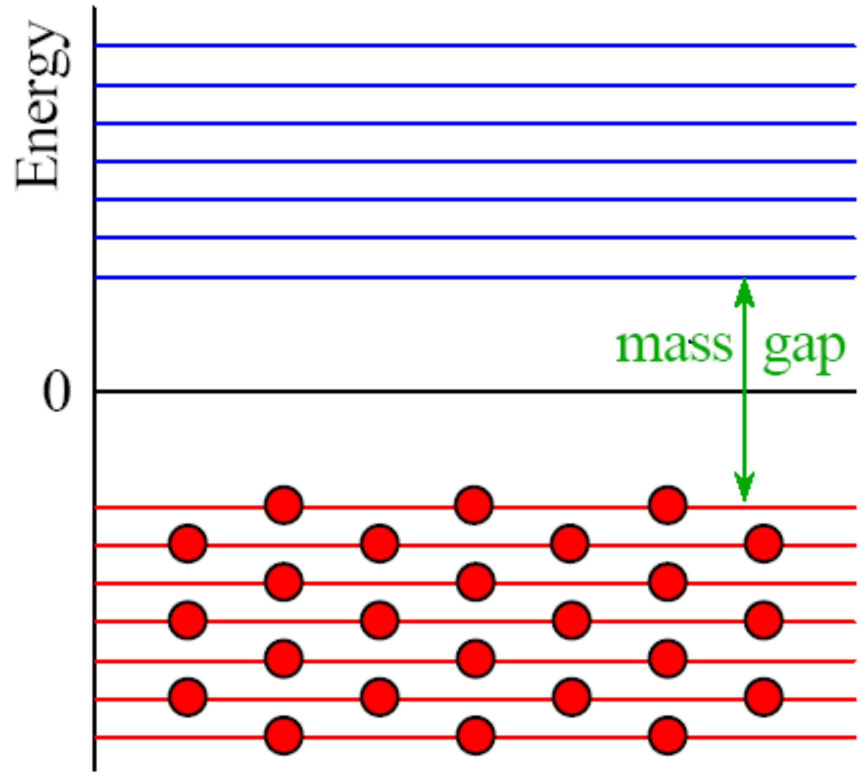

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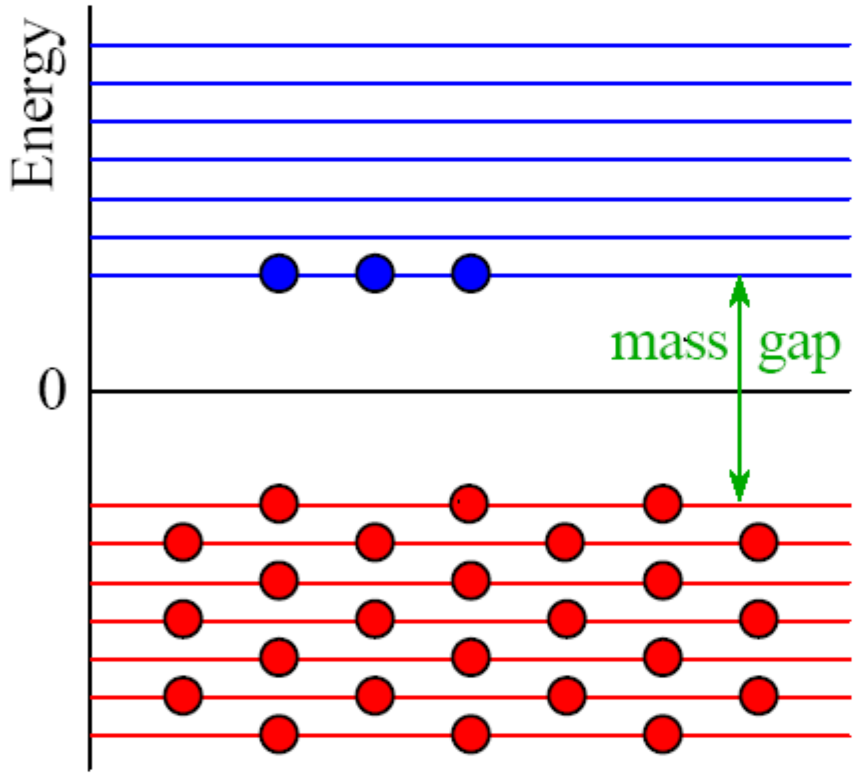

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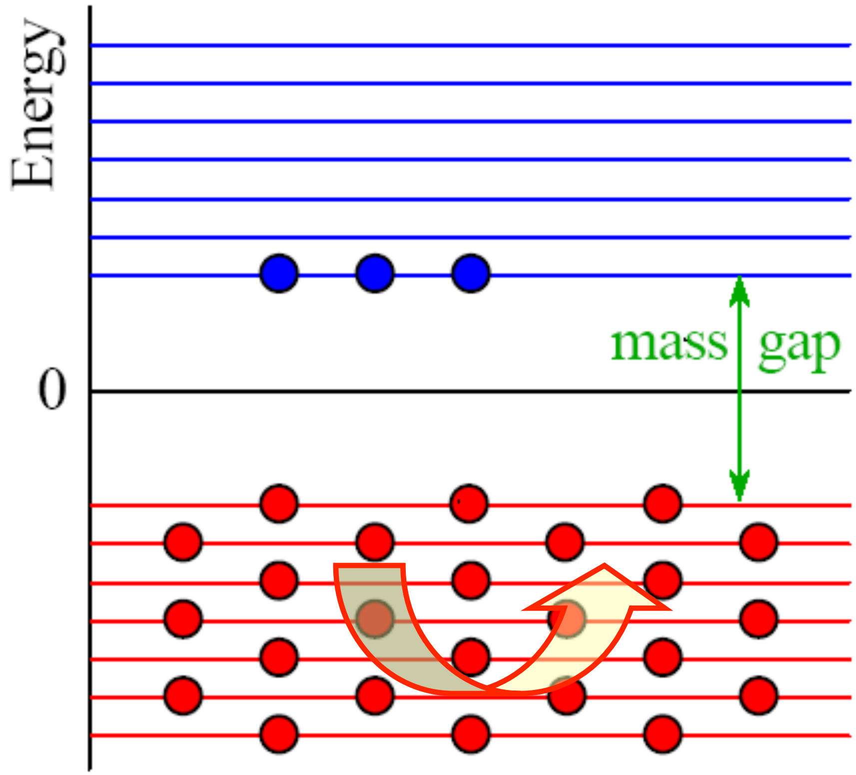

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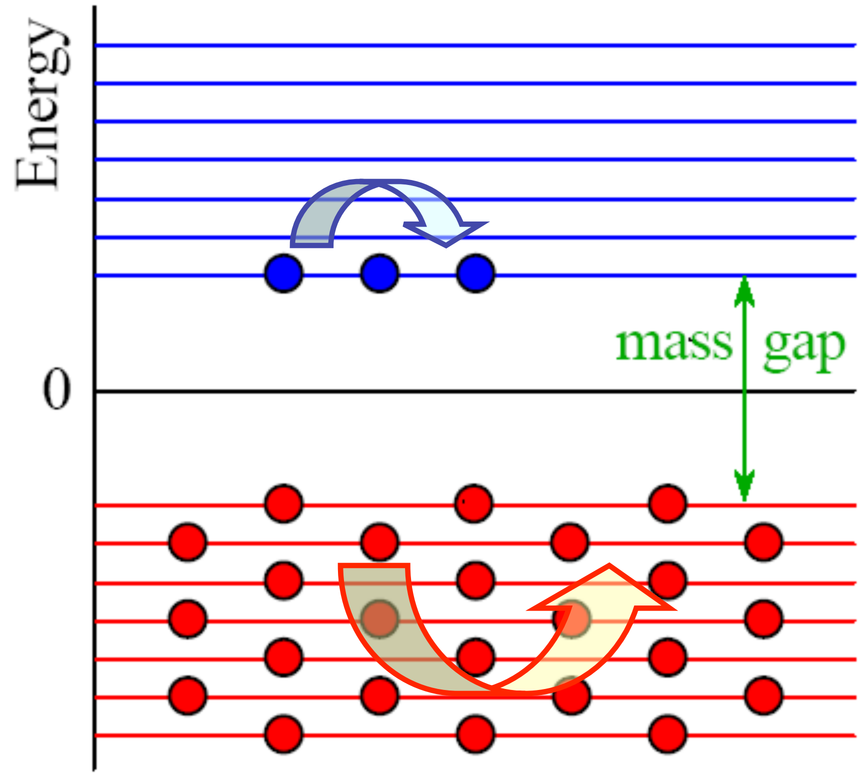

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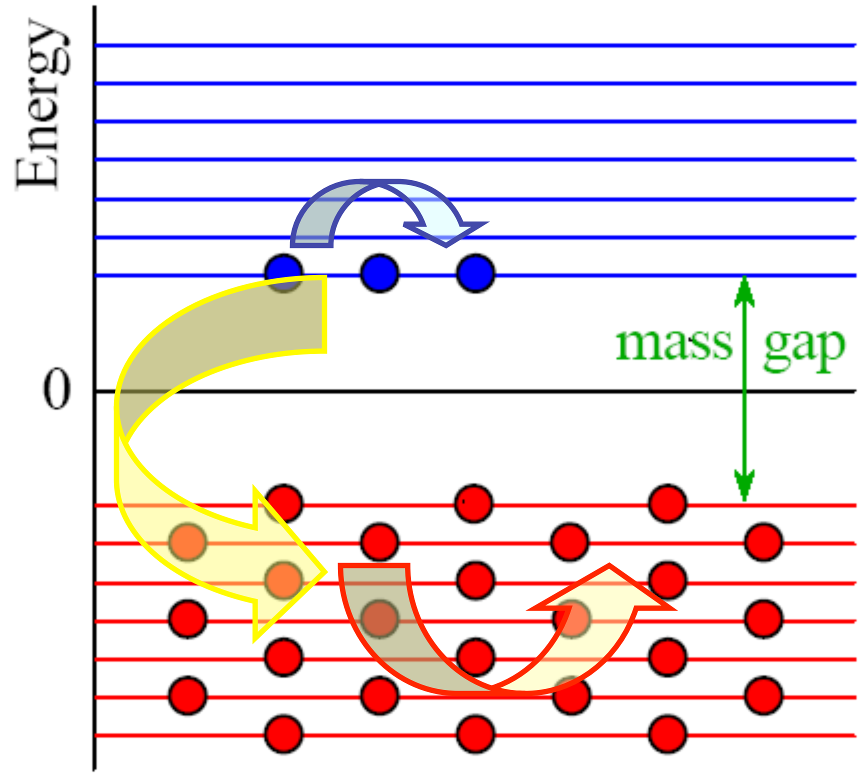

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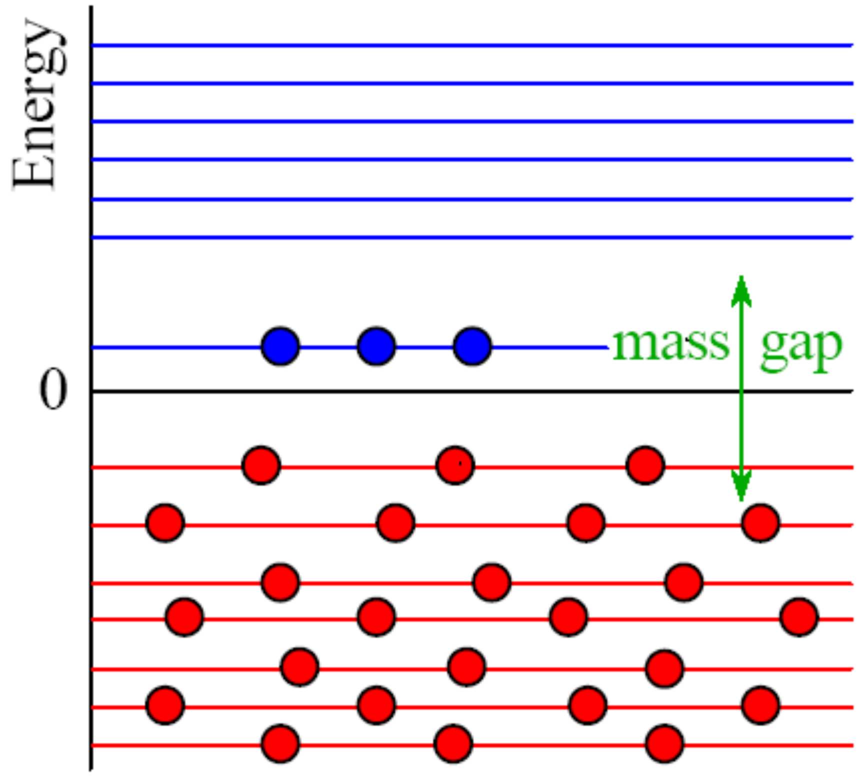

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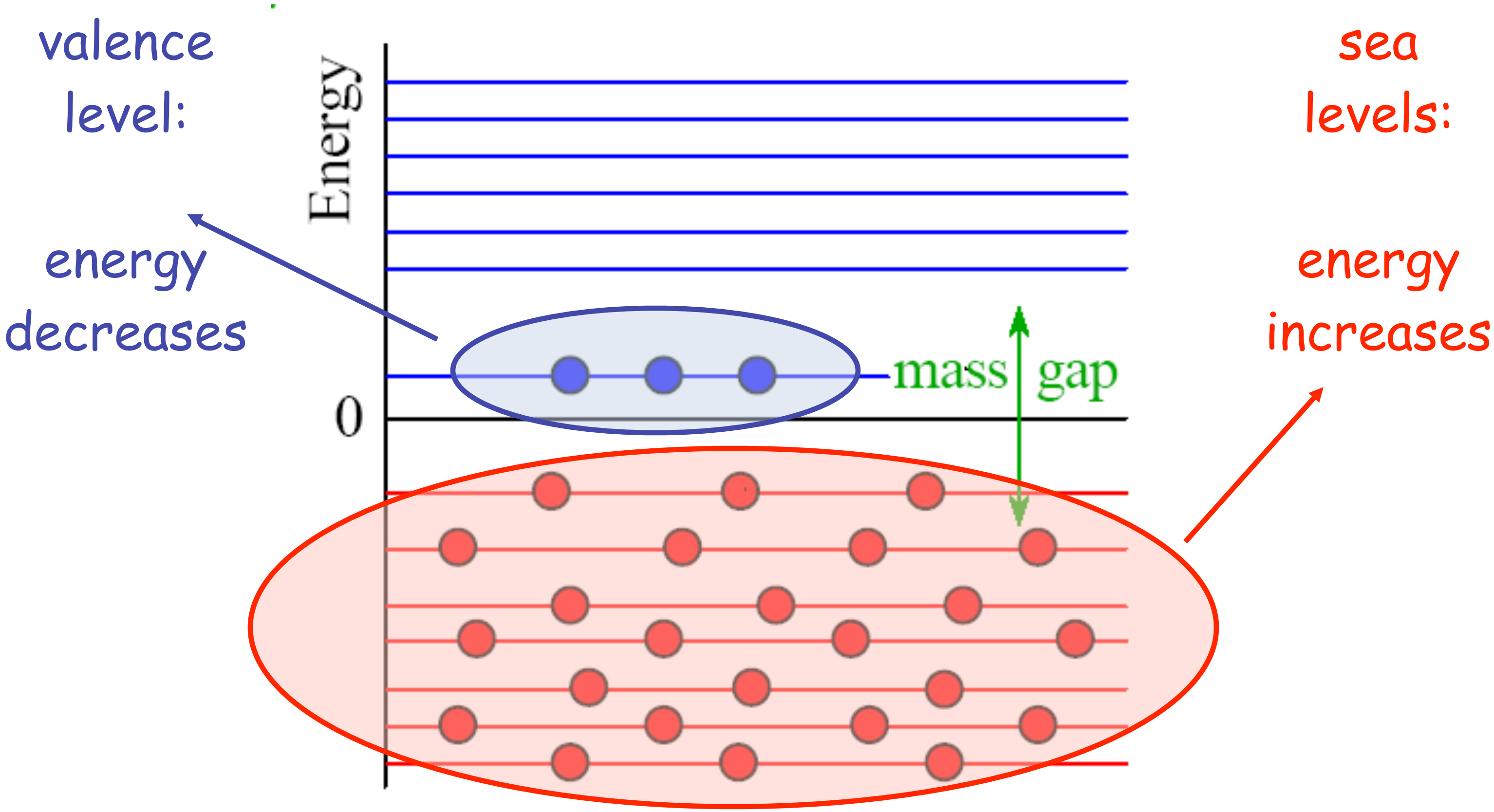
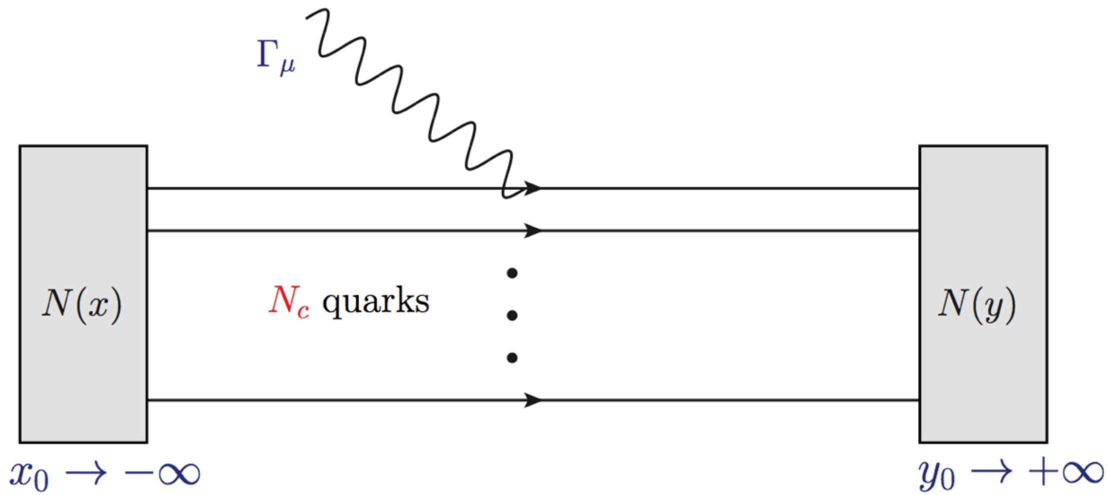


system stabilzes

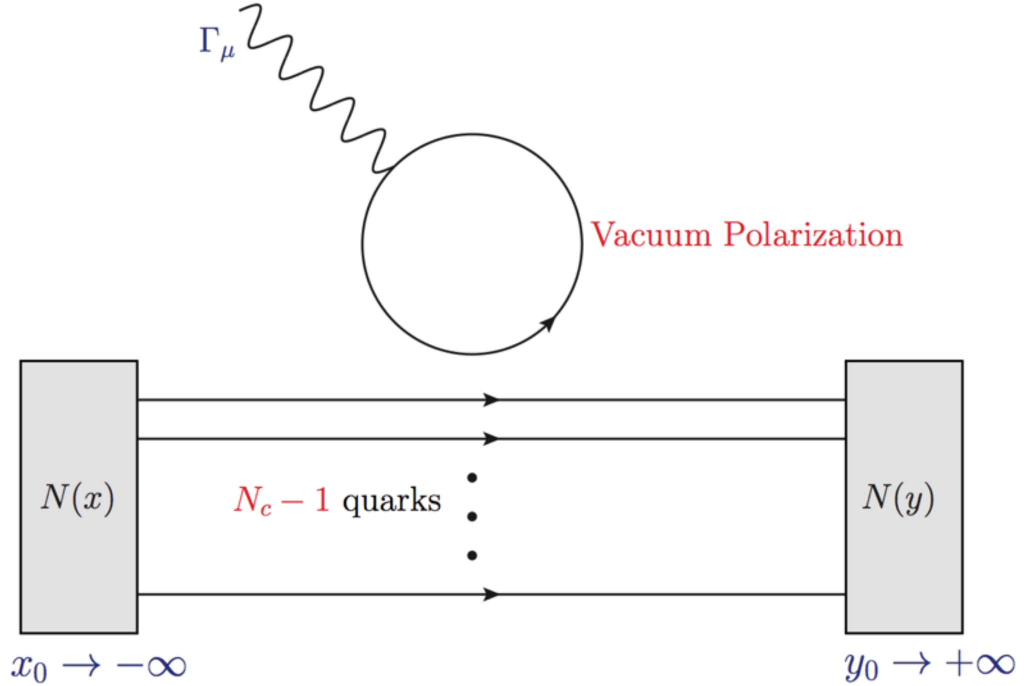
HChK et al. Prog. Part. Nucl. Phys. Vol.95, (1995)

Observables

Valence part

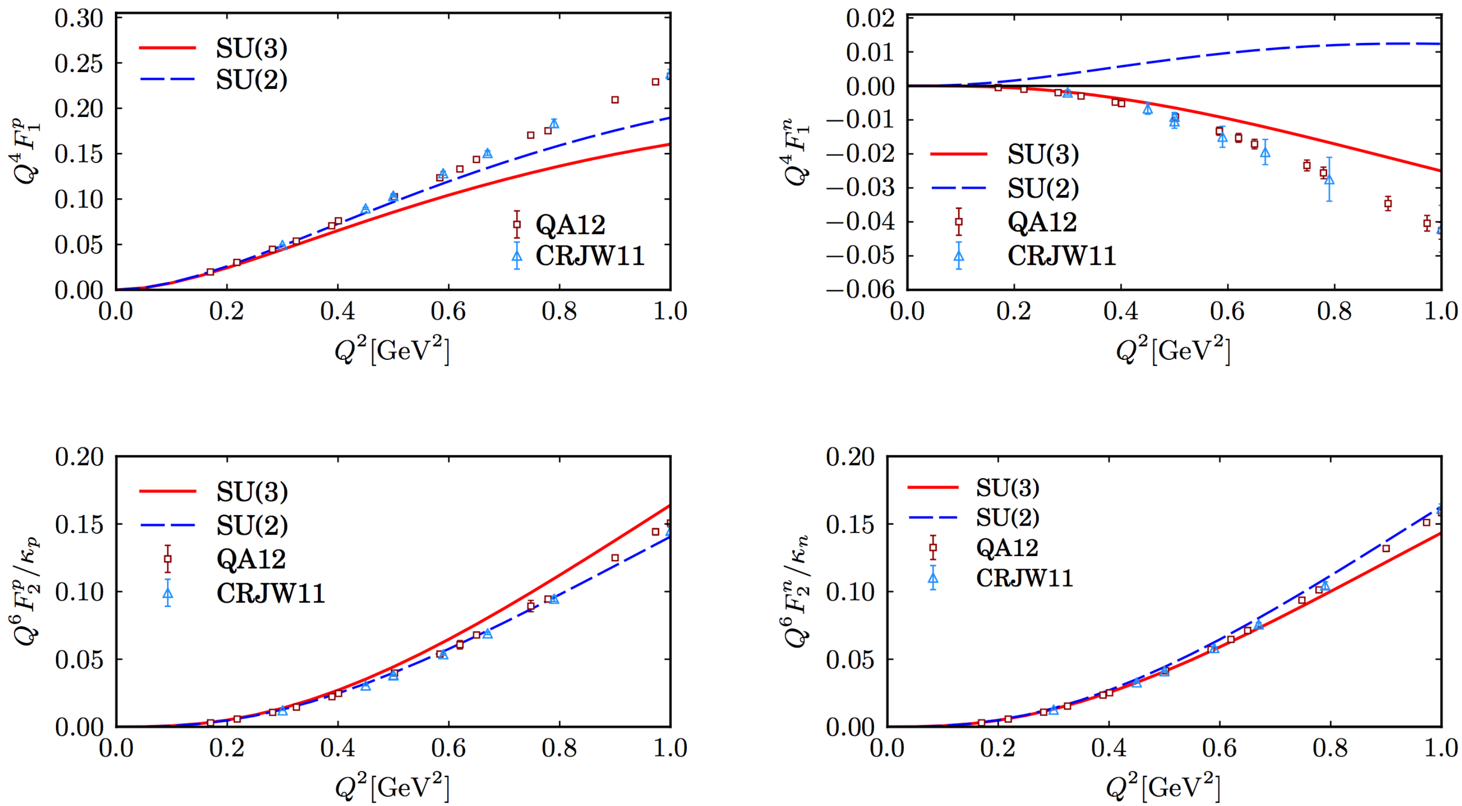


Sea part

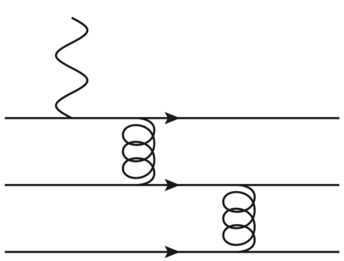


Dirac & Pauli Form factors

Proton Neutron



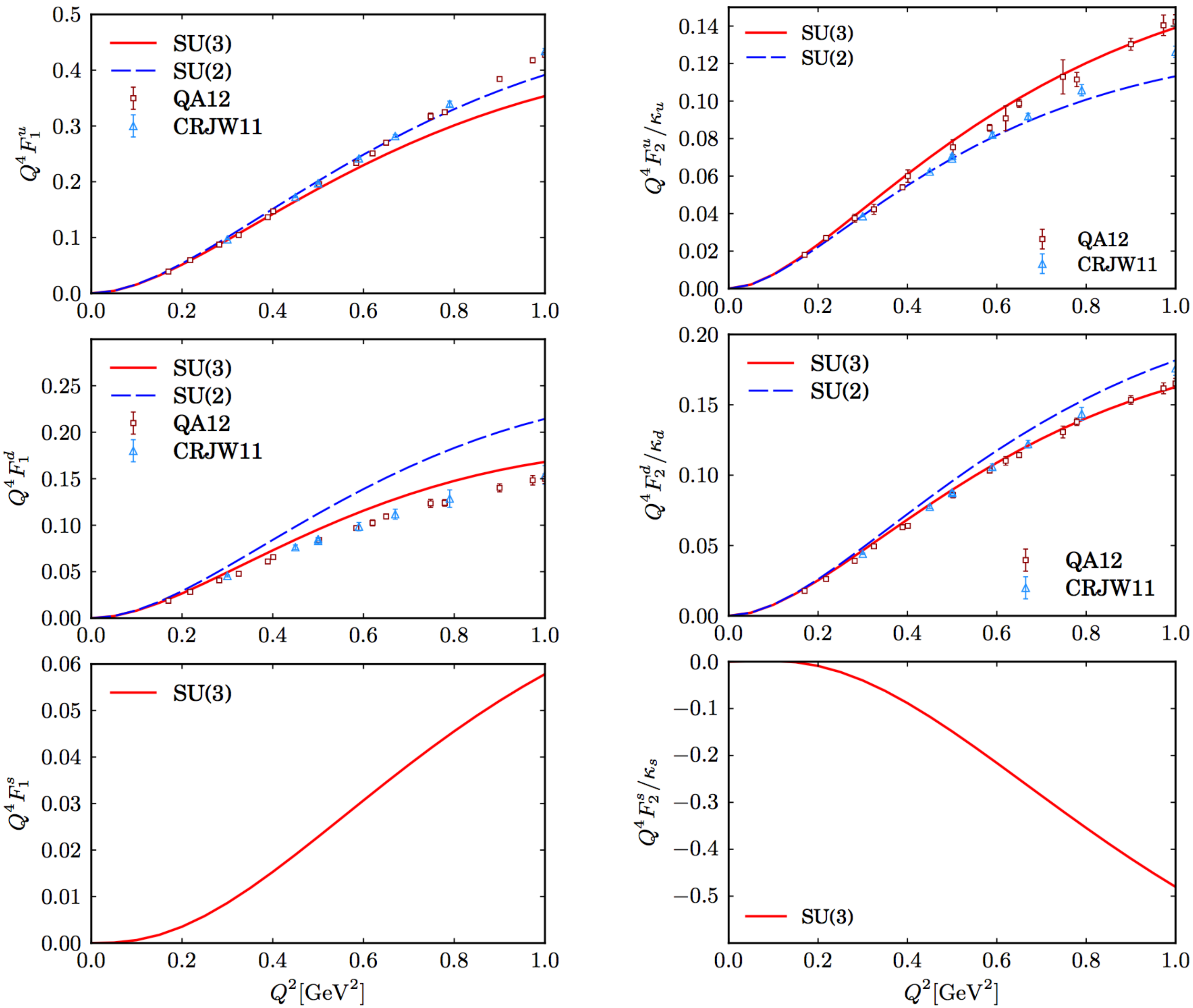
$$F_1(Q^2) \sim \frac{1}{Q^4},\ Q^2 \to \infty \qquad F_2(Q^2) \sim \frac{1}{Q^6},\ \ Q^2 \to \infty$$



S. J. Brodsky and G. R. Farrar, PRD 11, 1309 (1975).

Silva, Urbano, HChK, hep-ph/1305.6373

Dirac & Pauli Form factors



Up quark FFs

Down quark FFs

Strange quark FFs

Silva, Urbano, HChK, hep-ph/1305.6373

Transverse charge densities

Why transverse charge densities?

For the pion, Son's Talk on Tuesday.

$$\langle P', S'|\bar{\psi}(\mathbf{0})\gamma_\mu \hat{Q}\psi(\mathbf{0})|P, S\rangle$$
$$= \bar{u}(p', s')\left(\gamma_\mu F_1(t) + i\frac{\sigma^{\mu\nu}\Delta_n u}{2M_N}F_2(t)\right)u(p, s)$$

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GPDs

$$\int \frac{dx^-}{4\pi}\langle P', S'|\bar{q}(-\frac{x^-}{2}, \mathbf{0}_\perp)\gamma^+ q(\frac{x^-}{2}, \mathbf{0}_\perp)|P, S\rangle$$
$$= \frac{1}{2\bar{p}^+}\bar{u}(p', s')\left(\gamma^+ H_q(x, \xi, t) + i\frac{\sigma^{+\nu}\Delta_\nu}{2M_N}E_q(x, \xi, t)\right)u(p, s)$$

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GPDs

$$\int \frac{dx^-}{4\pi} \langle P', S' | \bar{q}(-\frac{x^-}{2}, \mathbf{0}_\perp) \gamma^+ q(\frac{x^-}{2}, \mathbf{0}_\perp) | P, S \rangle$$

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$$F_1(t) = \sum_q e_q \int dx H_q(x, 0, t),$$

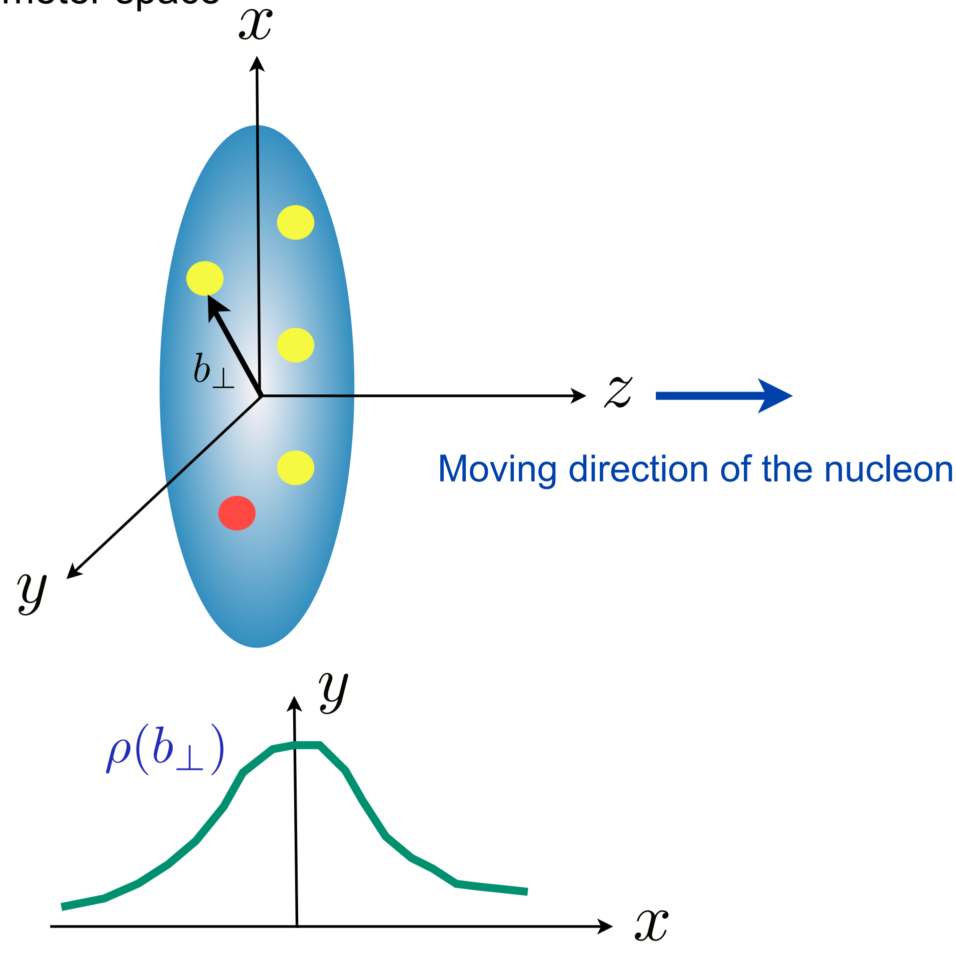
$$F_2(t) = \sum_q e_q \int dx E_q(x, 0, t)$$

Transverse charge densities

Why transverse charge densities?

2-D Fourier transform of the GPDs in impact-parameter space

$$q(x,\,\mathbf{b}) = \int \frac{d^2q}{(2\pi)^2} e^{i\mathbf{q}\cdot\mathbf{b}} H_q(x, -\mathbf{q}^2)$$



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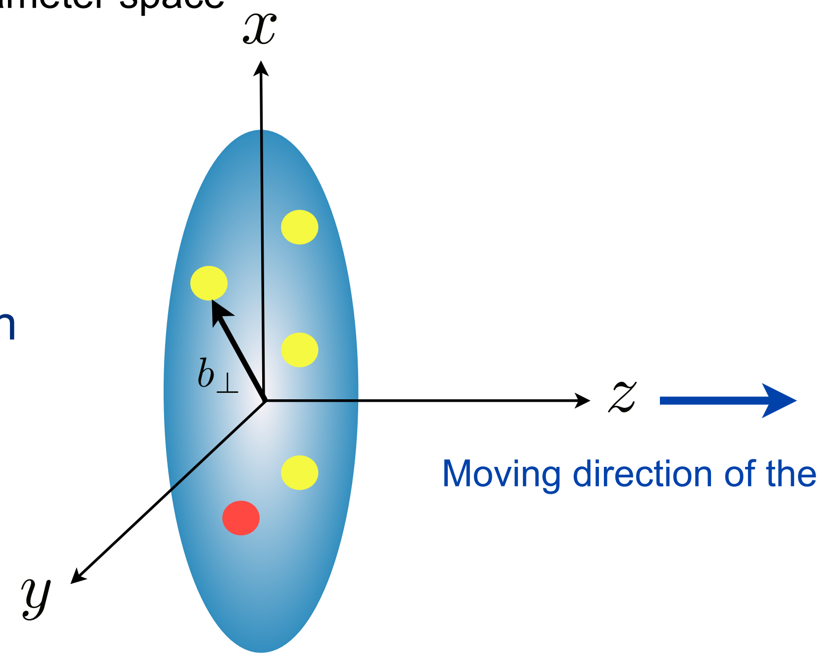
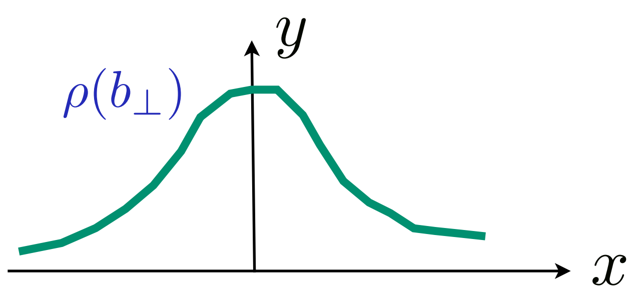
⇨ It can be interpreted as the probability distribution of a quark in the transverse plane.

M. Burkardt, PRD **62**, 071503 (2000); Int. J. Mod. Phys. A **18**, 173 (2003).



Moving direction of the nucleon

$$\rho(\mathbf{b}) := \sum_q e_q \int dx\, q(x,\,\mathbf{b}) = \int \frac{d^2q}{(2\pi)^2} F_1(Q^2) e^{i\mathbf{q}\cdot\mathbf{b}}$$



Transverse charge densities

Inside an unpolarized nucleon

M. Burkardt, PRD **62**, 071503 (2000); Int. J. Mod. Phys. A **18**, 173 (2003).

G.A. Miller, PRL **99,** 112001 (2007)

$$\rho_{\mathrm{ch}}^{\chi}(b) = \int_0^\infty \frac{dQ}{2\pi} Q J_0(Qb) F_1^{\chi}(Q^2)$$

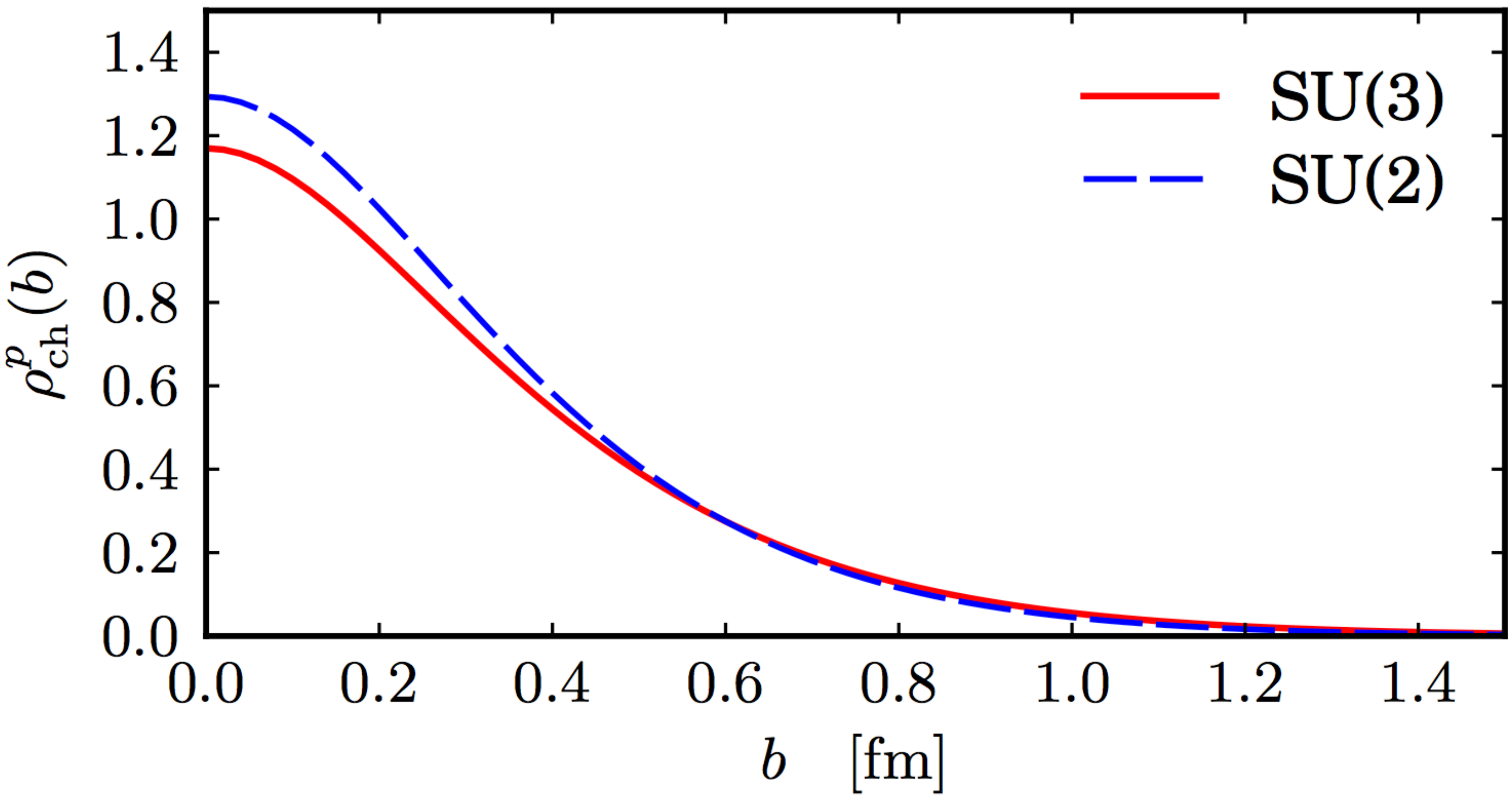
Inside a polarized nucleon

Carlson and Vanderhaeghen, PRL **100**, 032004

$$\rho_T^{\chi}(b) = \rho_{\mathrm{ch}}^{\chi}(b) - \sin(\phi_b - \phi_S)\frac{1}{2M_N}\int_0^\infty \frac{dQ}{2\pi} Q^2 J_1(Qb) F_2^{\chi}(Q^2)$$

Results

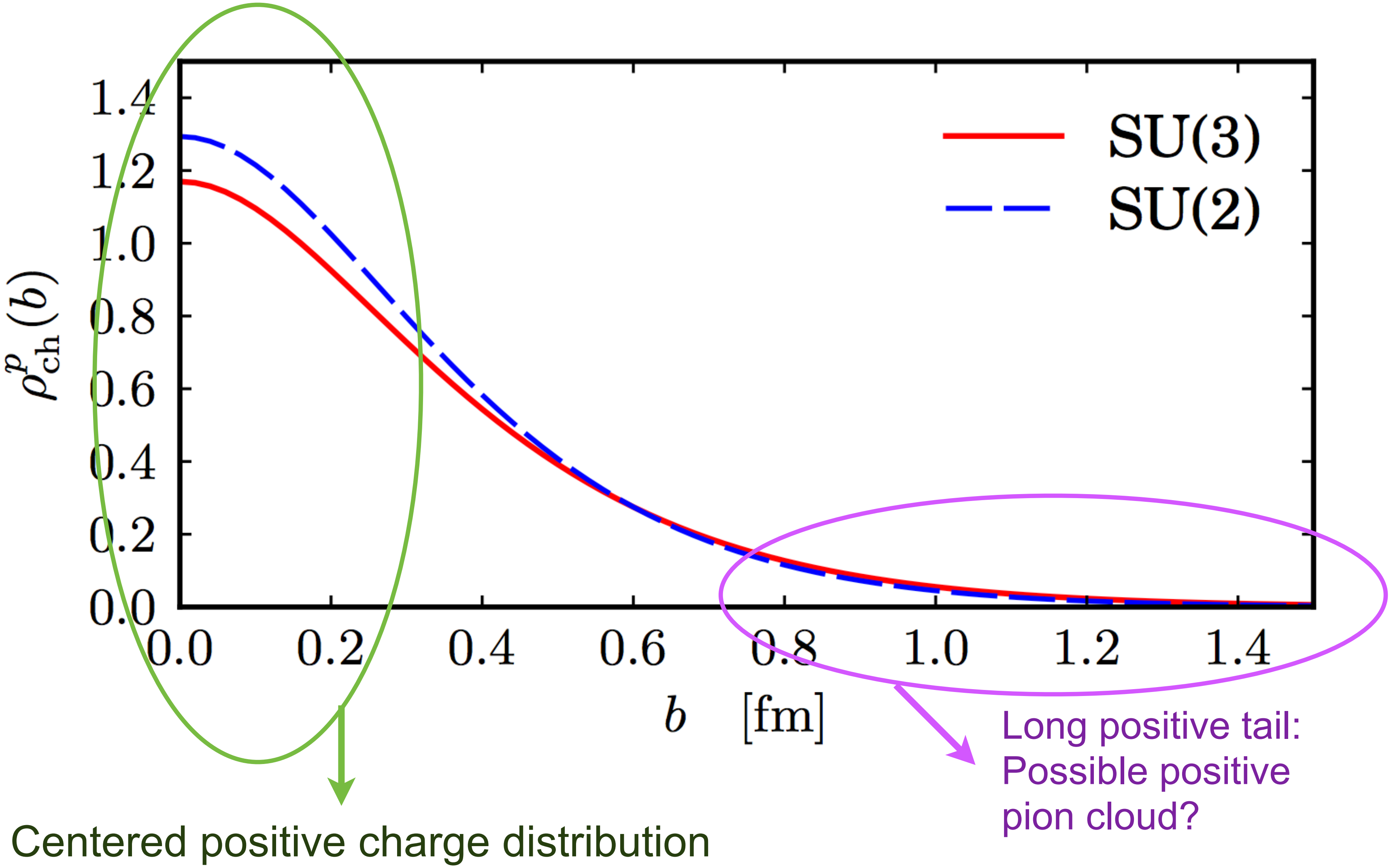
Transverse charge densities inside an **unpolarized** proton



Silva, Urbano, HChK, hep-ph/1305.6373

Results

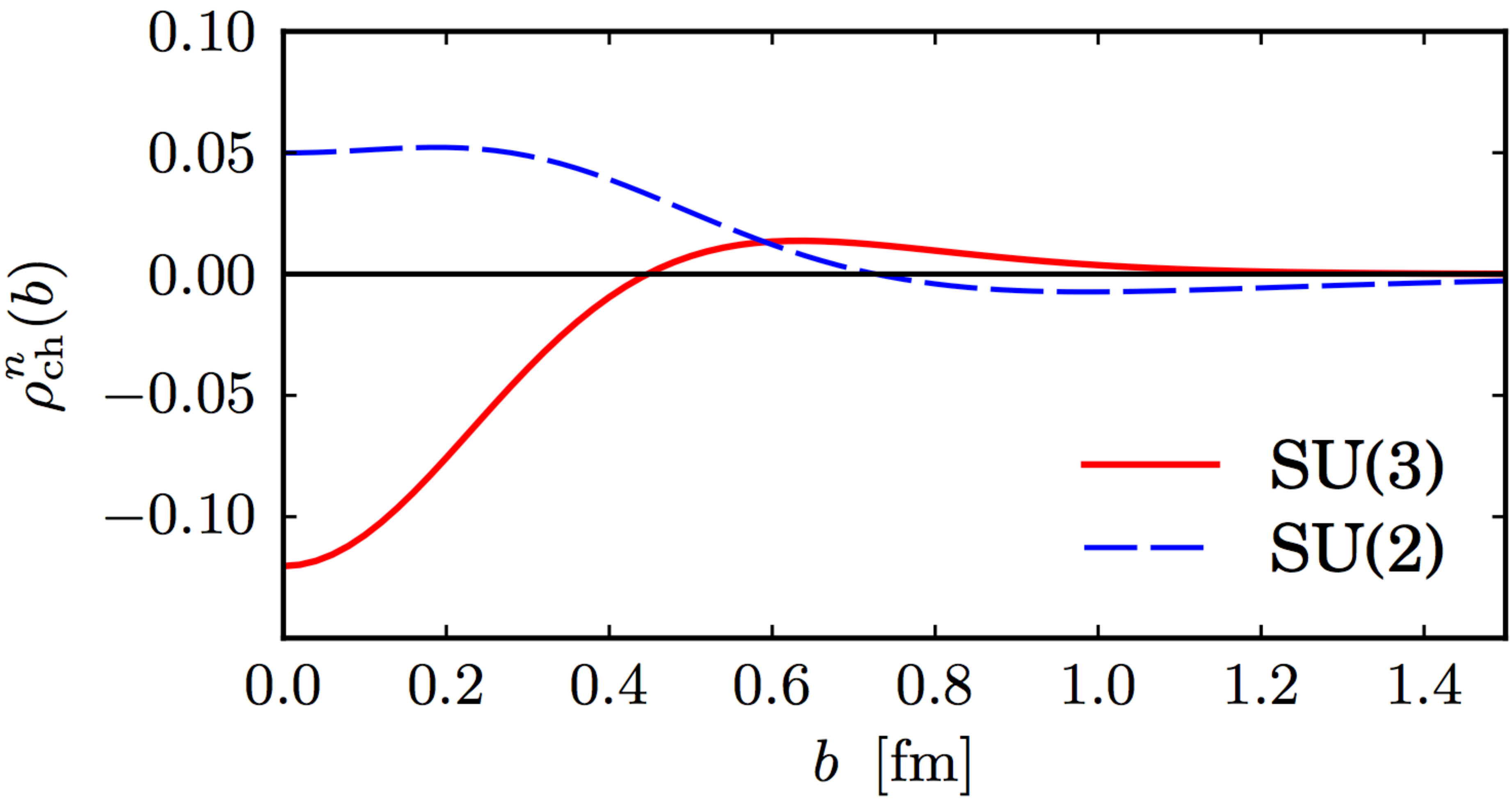
Transverse charge densities inside an **unpolarized** proton



Silva, Urbano, HChK, hep-ph/1305.6373

Results

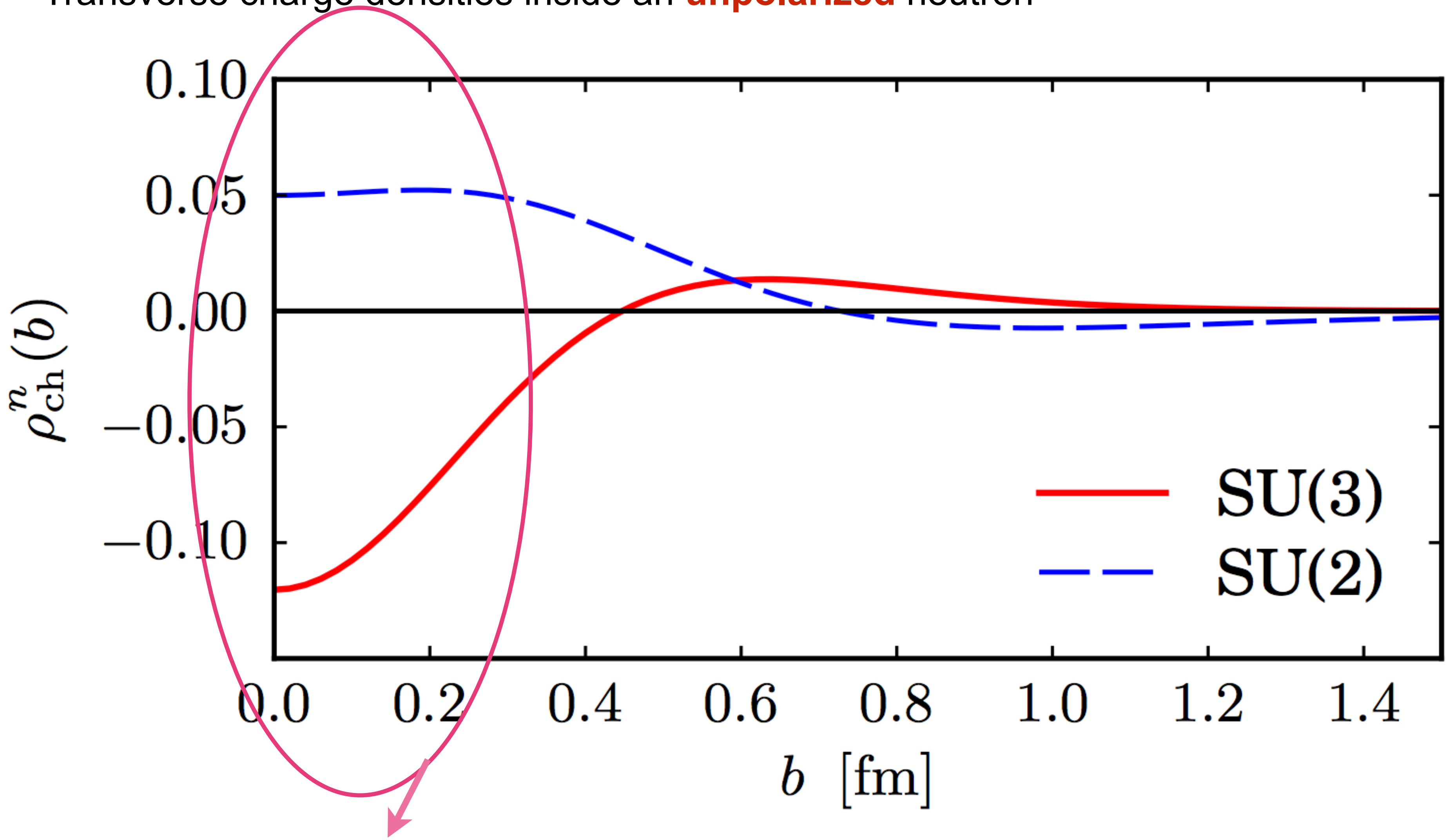
Transverse charge densities inside an **unpolarized** neutron



Silva, Urbano, HChK, hep-ph/1305.6373

Results

Transverse charge densities inside an **unpolarized** neutron



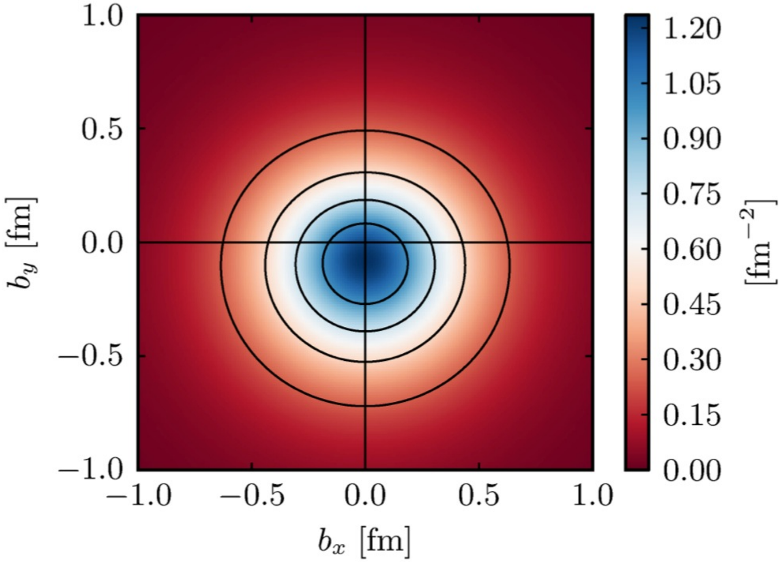
Surprisingly, negative charge distribution in the center of the neutron!

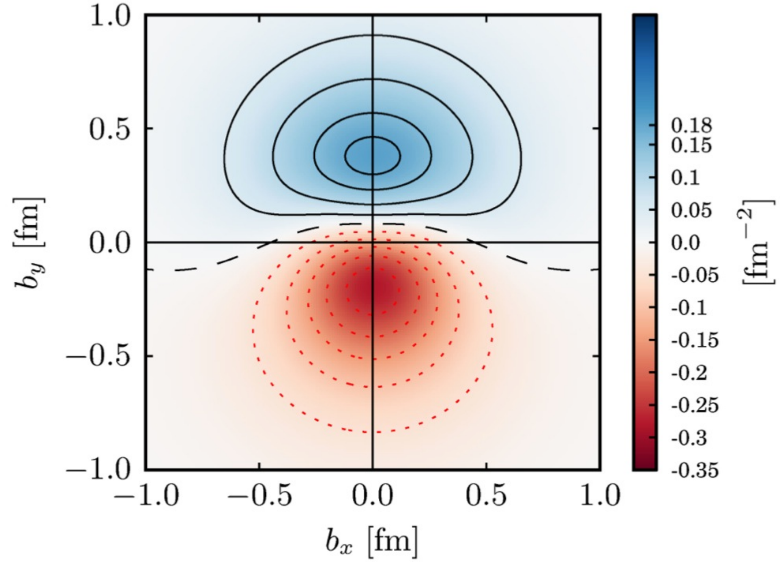
G.A. Miller, PRL **99,** 112001 (2007)

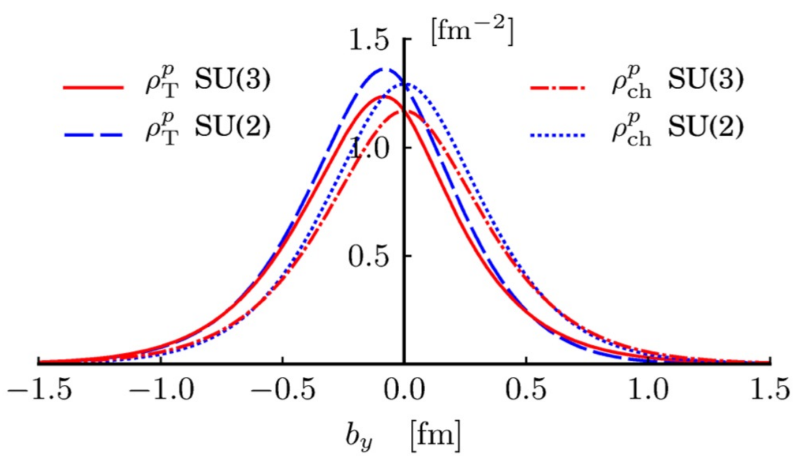
Silva, Urbano, HChK, hep-ph/1305.6373

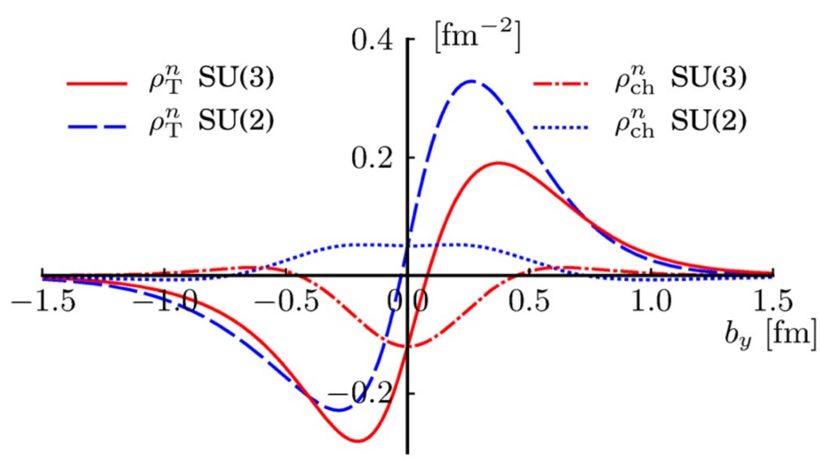
Results

Transverse charge densities inside an **polarized** nucleon





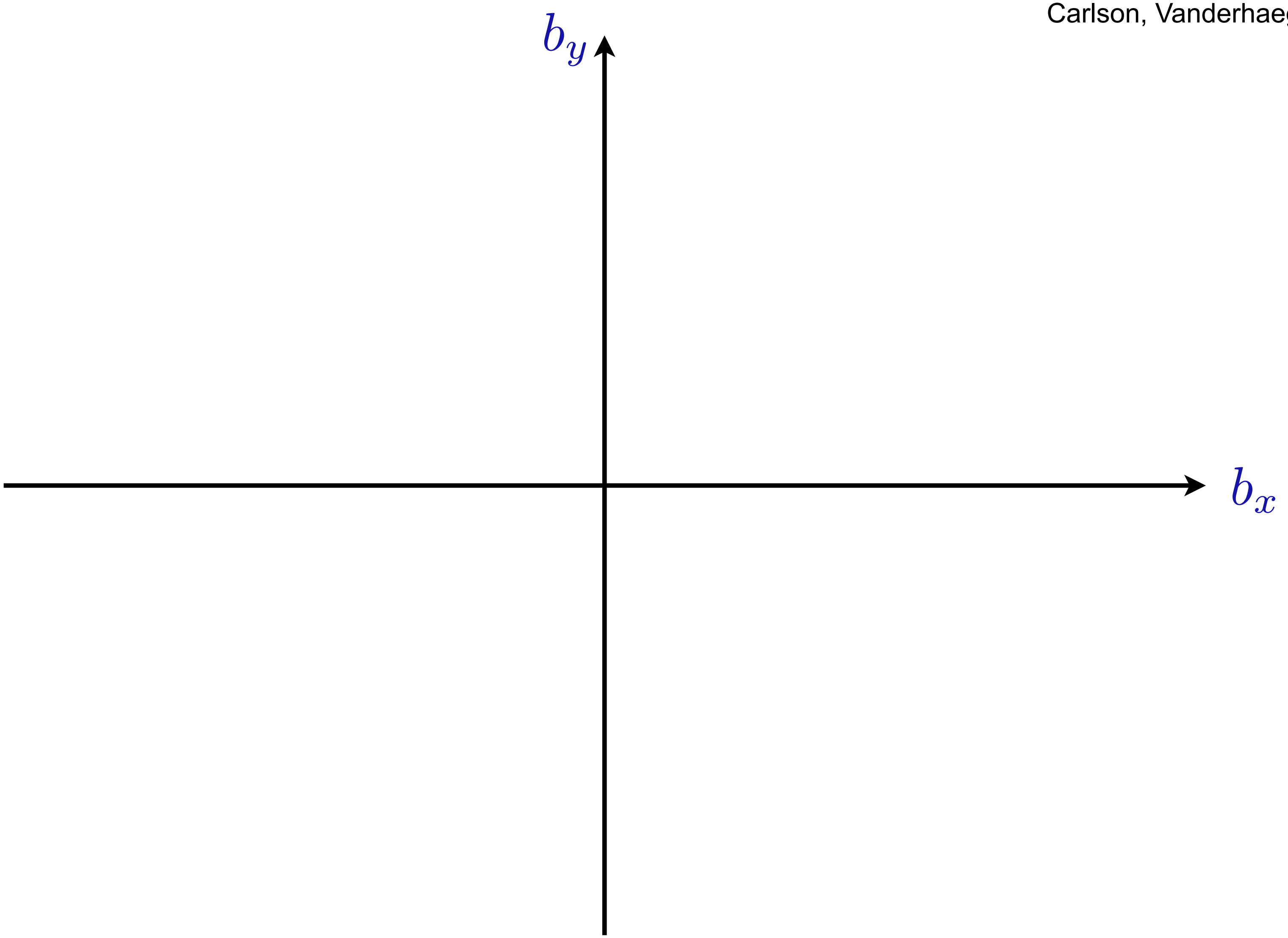




Silva, Urbano, HChK, hep-ph/1305.6373

Discussion

Carlson, Vanderhaeghen, PRL **100**, 032004



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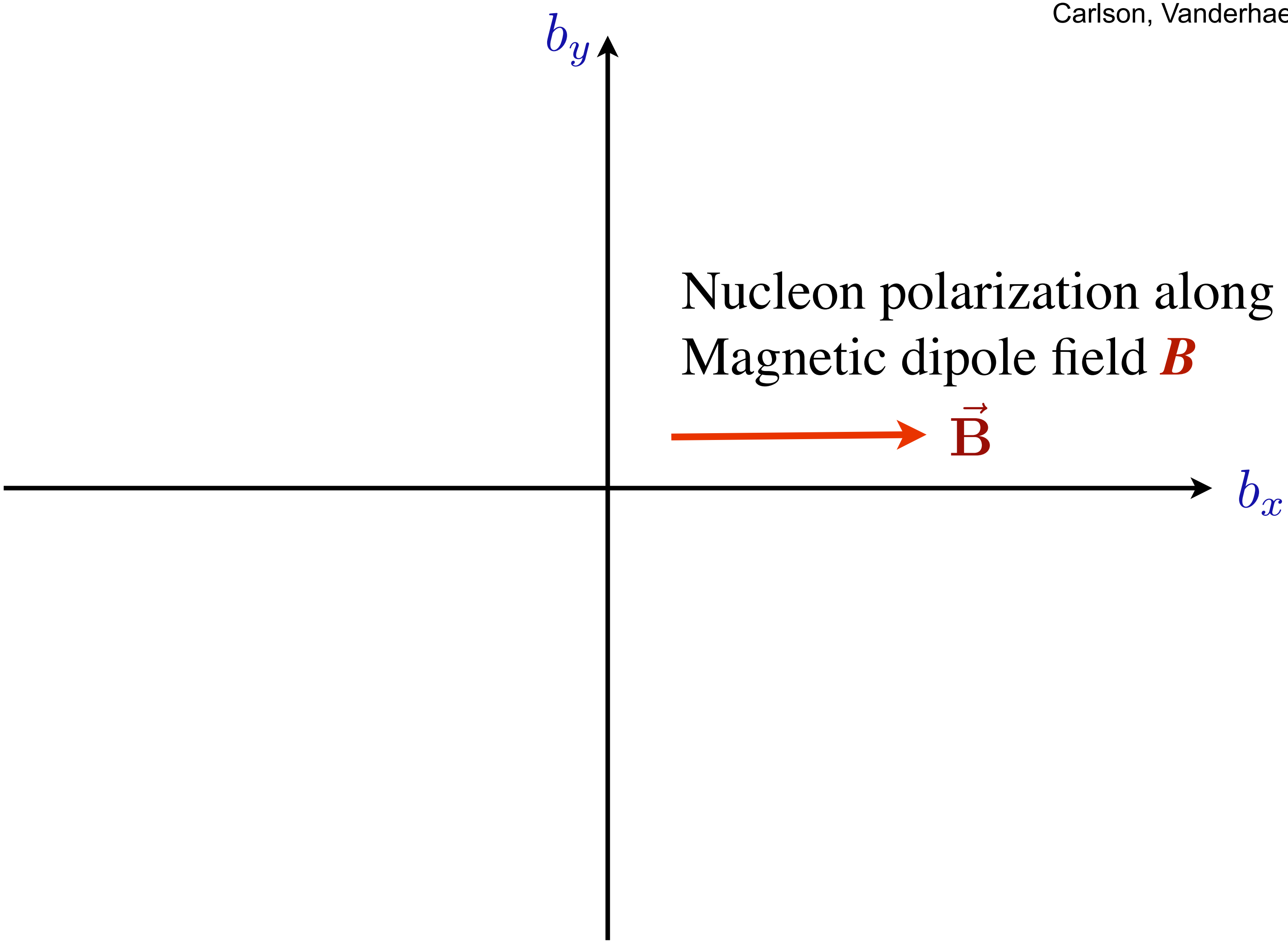
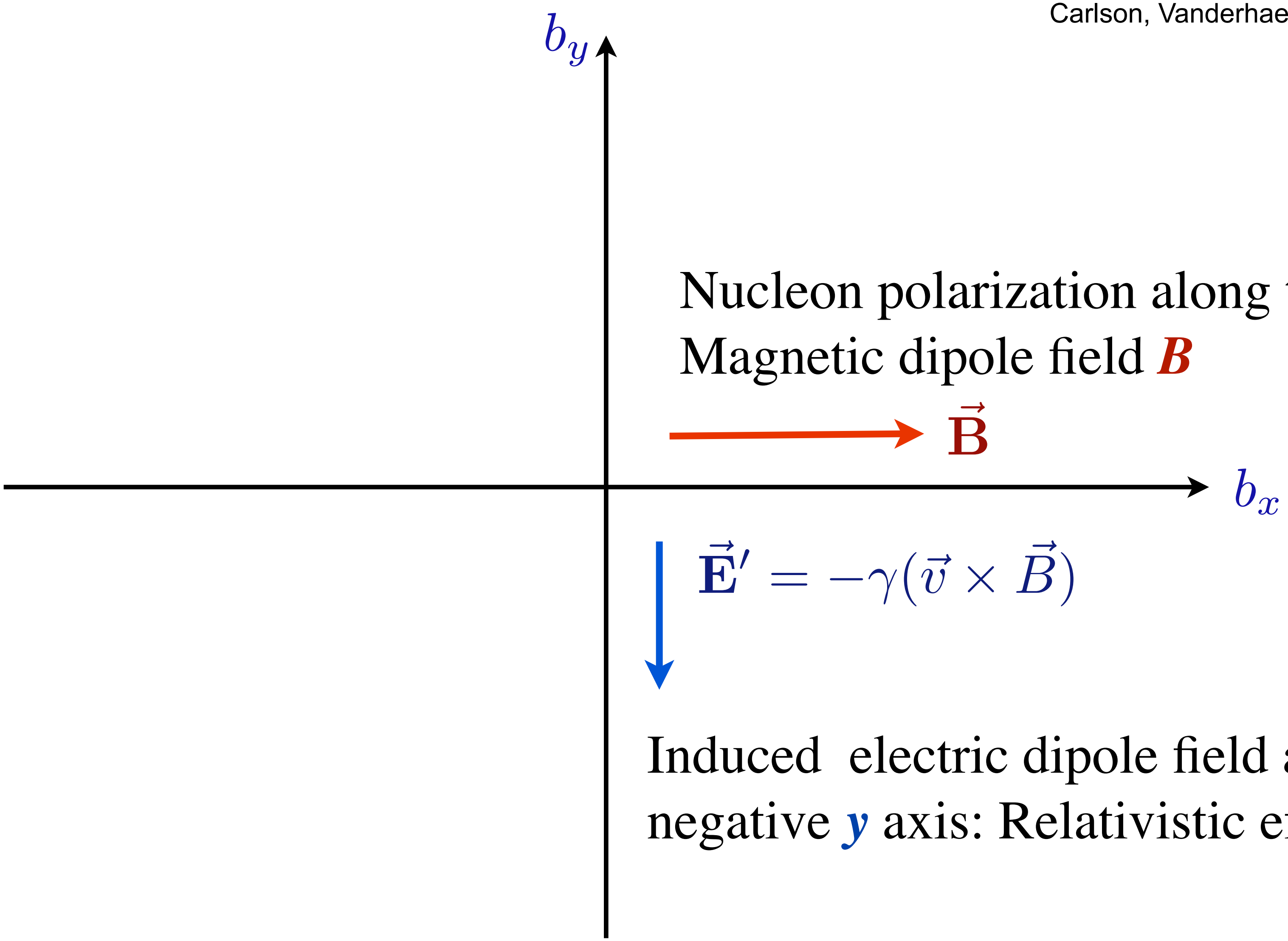


Nucleon polarization along the ***x*** axis:
Magnetic dipole field ***B***

Silva, Urbano, HChK, hep-ph/1305.6373

Discussion

Carlson, Vanderhaeghen, PRL **100**, 032004



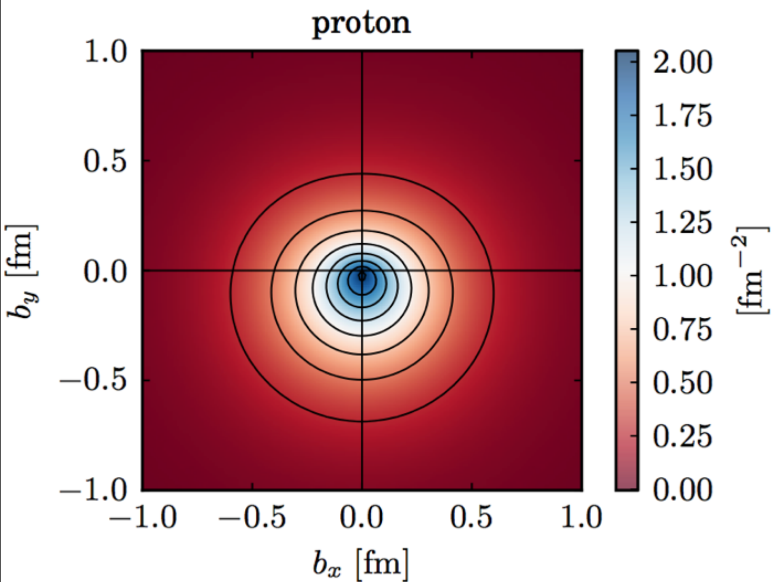
Nucleon polarization along the ***x*** axis:
Magnetic dipole field ***B***

$$\vec{\mathbf{E}}' = -\gamma(\vec{v} \times \vec{B})$$

Induced electric dipole field along the negative ***y*** axis: Relativistic effects

Silva, Urbano, HChK, hep-ph/1305.6373

Discussion



Carlson, Vanderhaeghen, PRL **100**, 032004

Nucleon polarization along the ***x*** axis:
Magnetic dipole field ***B***

$\vec{\mathrm{B}}$

b_x

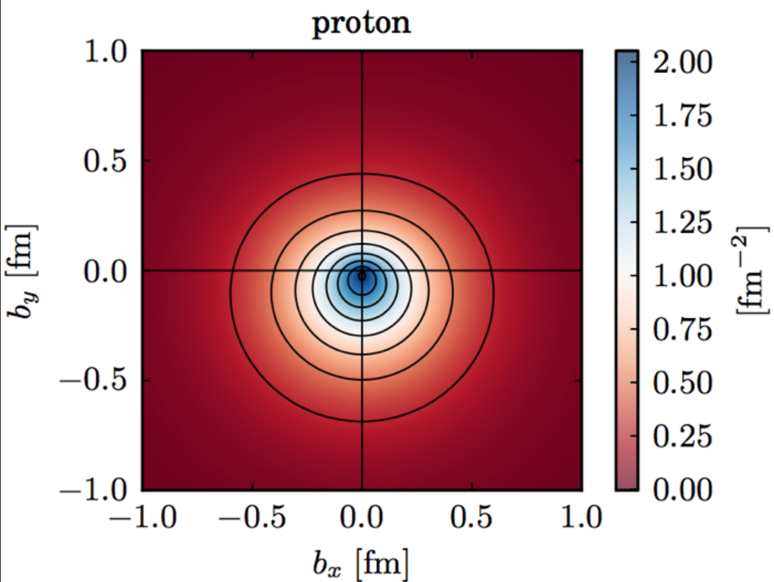
$$\vec{\mathbf{E}}' = -\gamma(\vec{v} \times \vec{B})$$

Induced electric dipole field along the negative ***y*** axis: Relativistic effects

Silva, Urbano, HChK, hep-ph/1305.6373

Discussion

Carlson, Vanderhaeghen, PRL **100**, 032004



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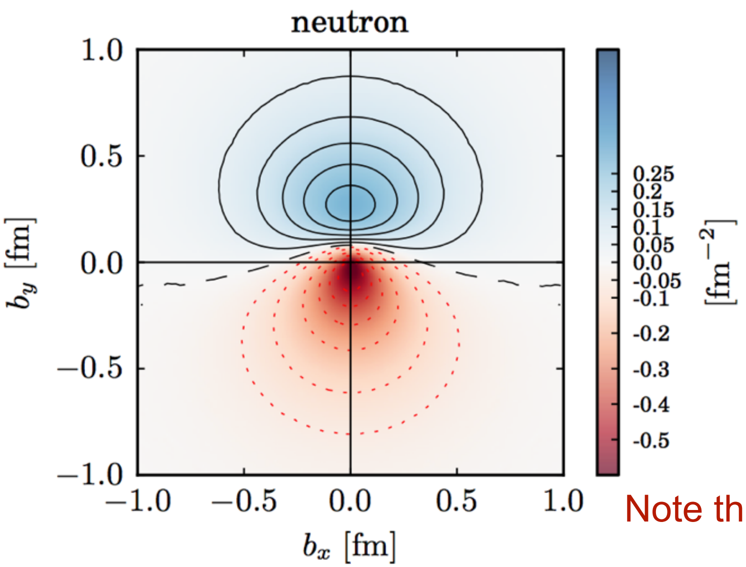


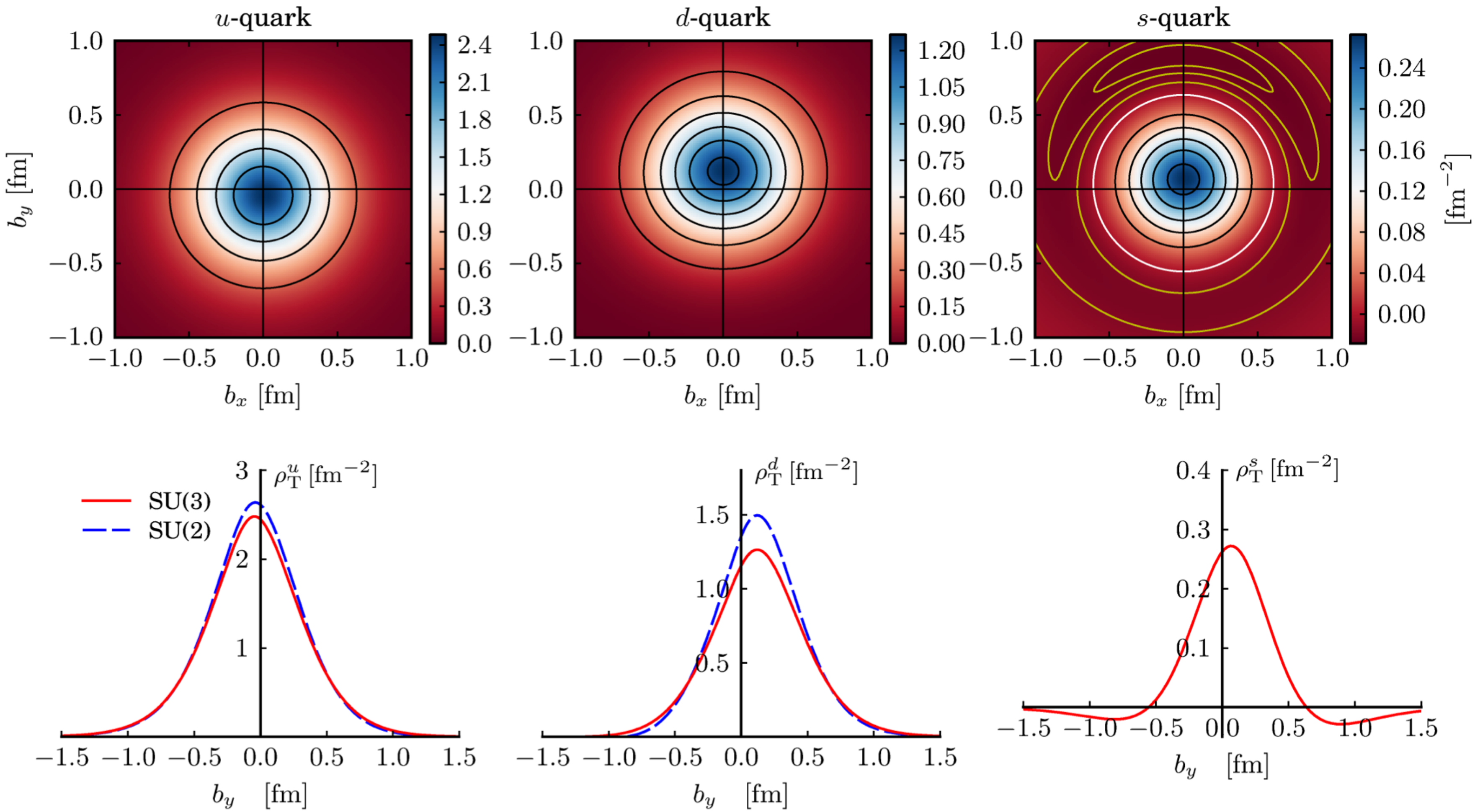
Induced electric dipole field along the negative ***y*** axis: Relativistic effects

Note that the neutron anomalous magnetic moment is negative!

Silva, Urbano, HChK, hep-ph/1305.6373

Results

Flavor-decomposed Transverse charge densities inside a polarized nucleon

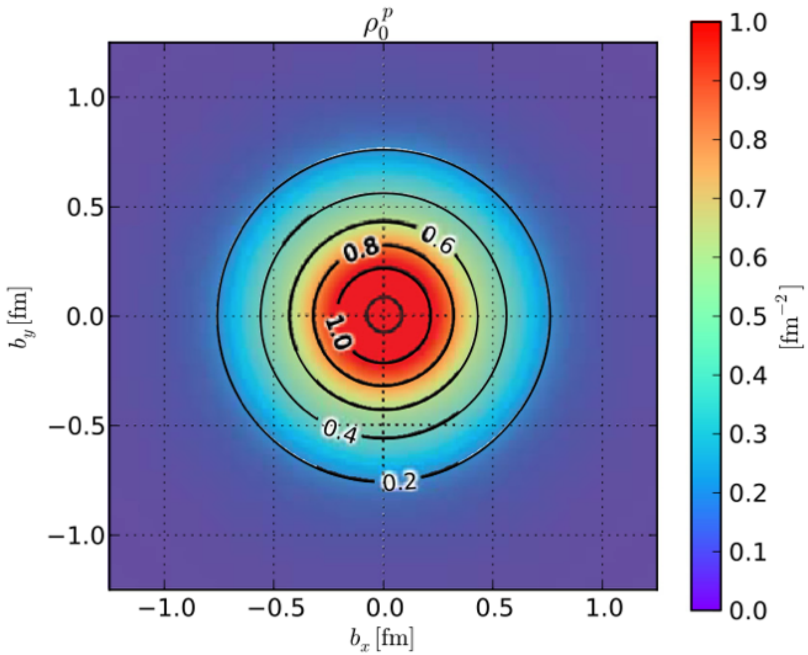


Silva, Urbano, HChK, hep-ph/1305.6373

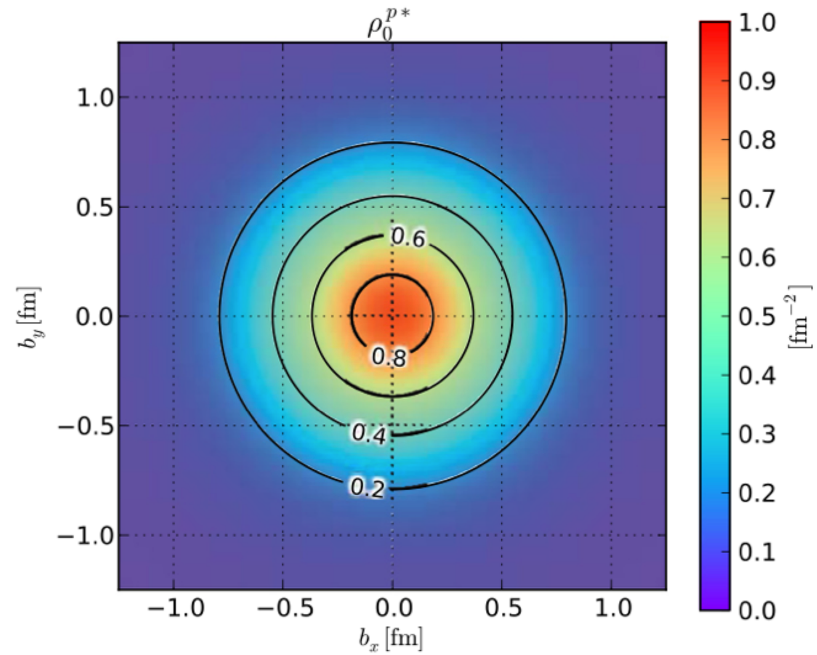
Results

Transverse charge densities inside an **unpolarized proton in nuclear matter**

Free-space Skyrme Model



Medium-Modified Skyrme Model



The proton bulges out in nuclear matter!

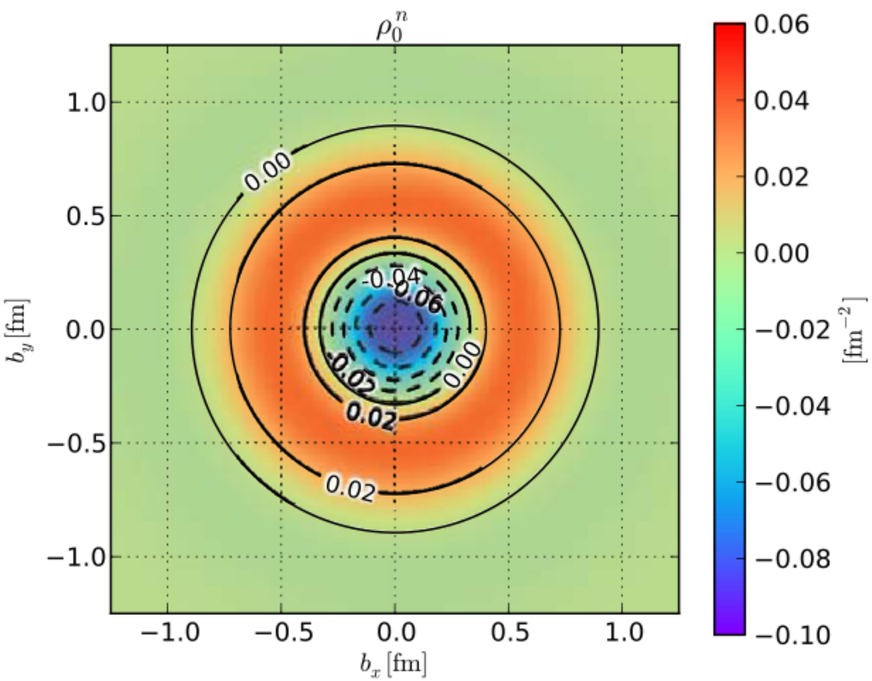
Yakhshiev's Talk on Tuesday for details.

U. Yakhshiev and HChK, PLB, (2013)

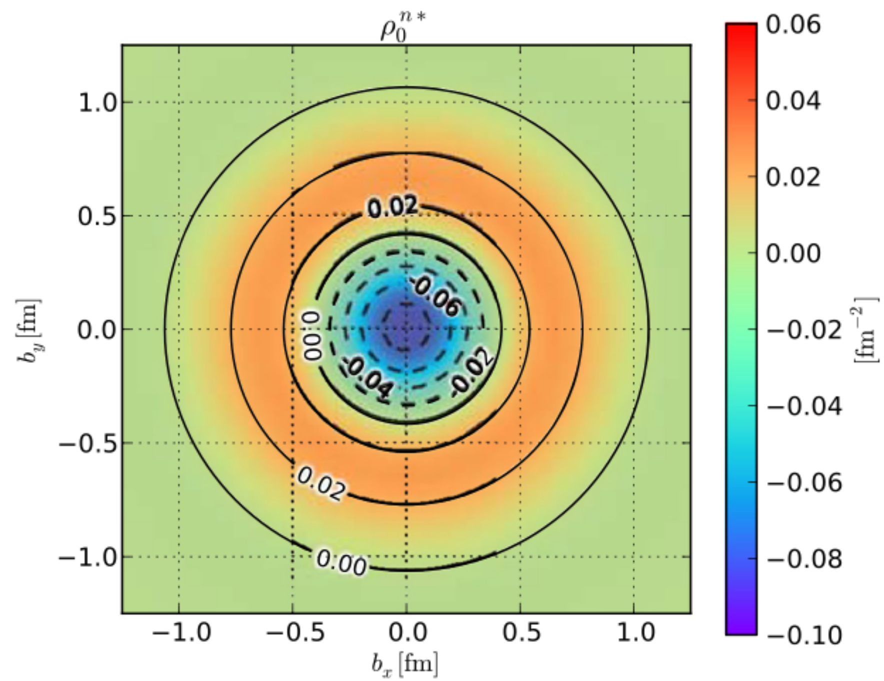
Results

Transverse charge densities inside an **unpolarized neutron in nuclear matter**

Free-space Skyrme Model



Medium-Modified Skyrme Model



The neutron also bulges out in nuclear matter!

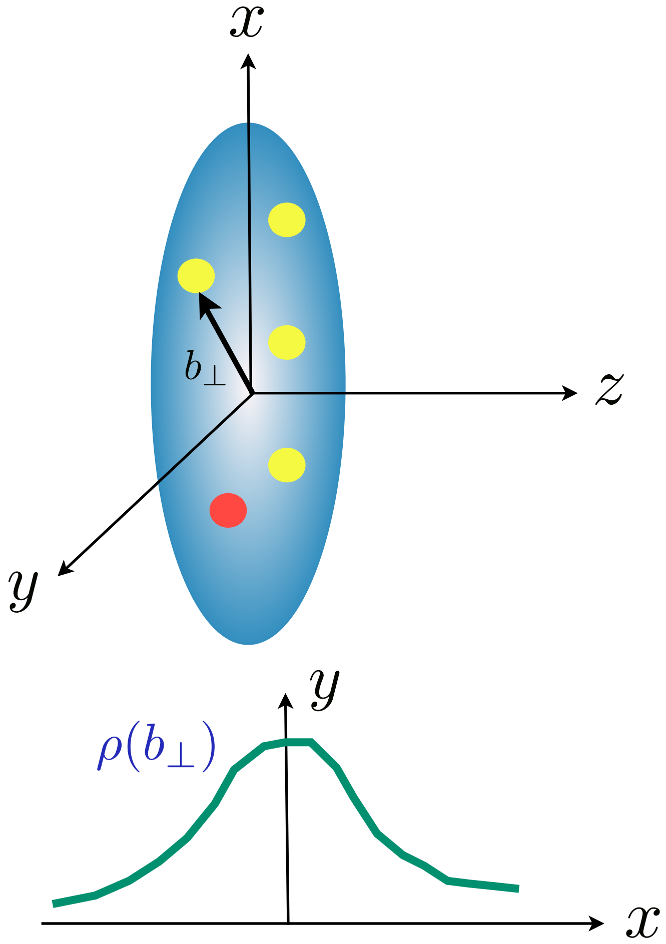
Yakhshiev's Talk on Tuesday for details.

U. Yakhshiev and HChK, PLB, (2013)

The spin structure of the Nucleon

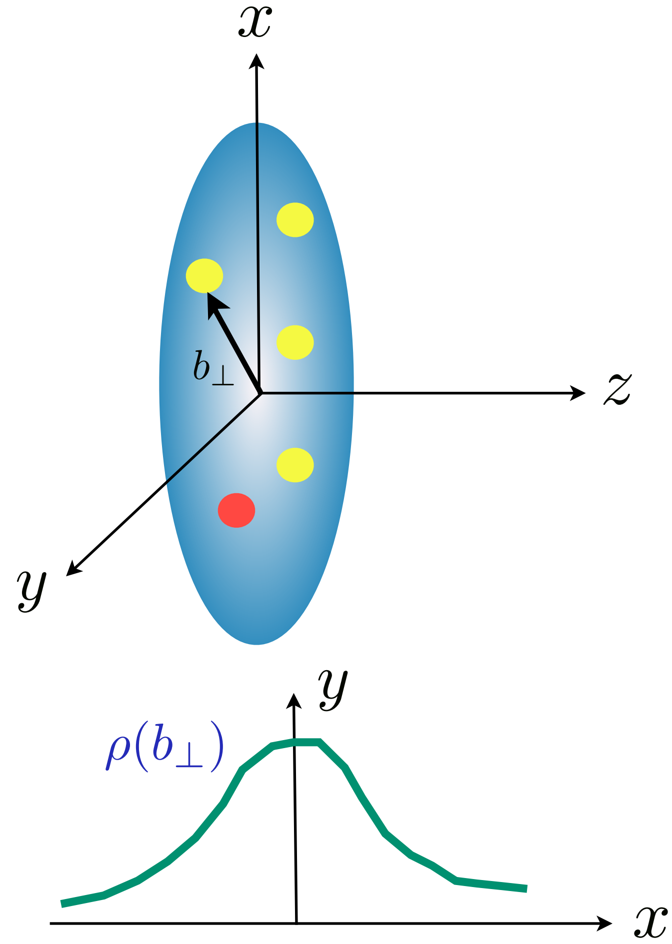
The spin structure of the Nucleon

Axial & Tensor Form factors, Axial-vector charges, Tensor charges

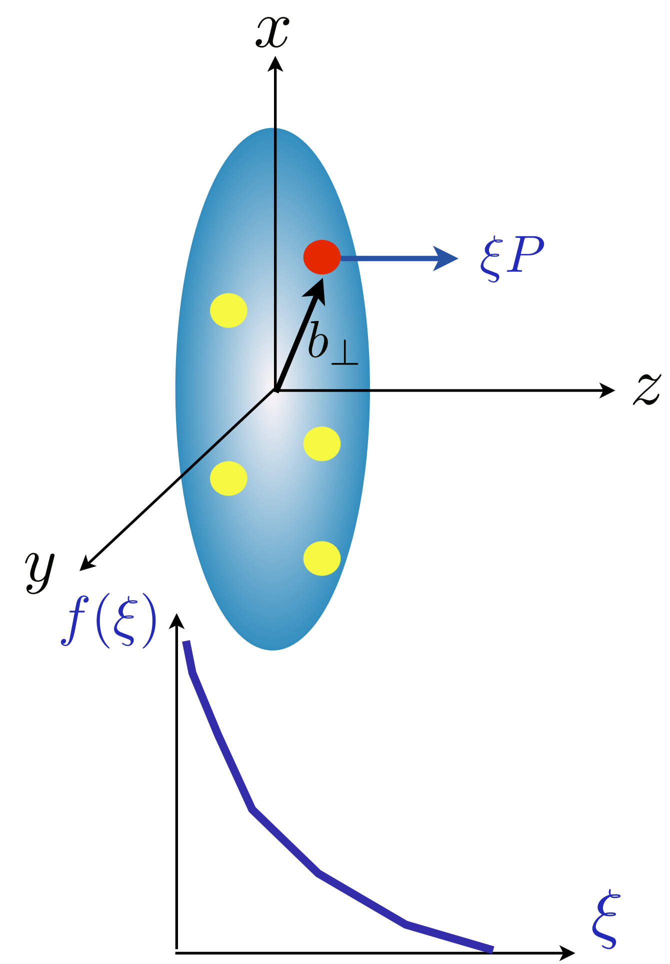


The spin structure of the Nucleon

Axial & Tensor Form factors, Axial-vector charges, Tensor charges



Structure functions



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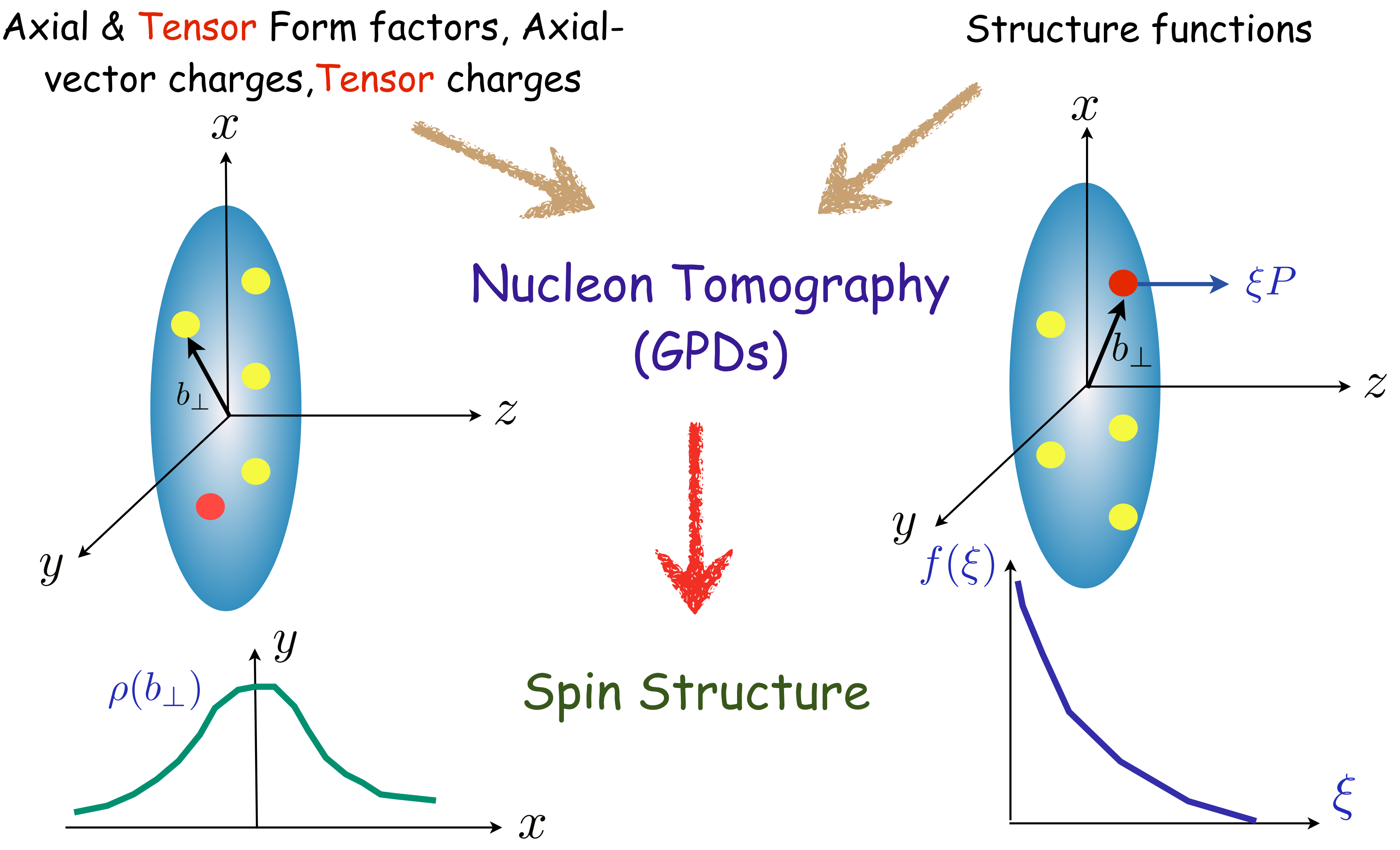

Tensor form factors

$$\langle N_{s'}(p')|\overline{\psi}(0) i\sigma^{\mu\nu}\lambda^{\chi}\psi(0)|N_s(p)\rangle = \overline{u}_{s'}(p')\left[H_T^{\chi}(Q^2) i\sigma^{\mu\nu} + E_T^{\chi}(Q^2)\frac{\gamma^{\mu}q^{\nu} - q^{\mu}\gamma^{\nu}}{2M} + \tilde{H}_T^{\chi}(Q^2)\frac{(n^{\mu}q^{\nu} - q^{\mu}n^{\nu})}{2M^2}\right]u_s(p)$$

$$\int_{-1}^{1} dx\, H_T^{\chi}(x,\xi,t) = H_T^{\chi}(q^2),$$

$$\int_{-1}^{1} dx\, E_T^{\chi}(x,\xi,t) = E_T^{\chi}(q^2),$$

$$\int_{-1}^{1} dx\, \tilde{H}_T^{\chi}(x,\xi,t) = \tilde{H}_T^{\chi}(q^2),$$

$$H_T^0(0) = g_T^0 = \delta u + \delta d + \delta s$$

$$H_T^3(0) = g_T^3 = \delta u - \delta d$$

$$H_T^8(0) = g_T^8 = \frac{1}{\sqrt{3}}(\delta u + \delta d - 2\delta s)$$

Tensor form factors

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$$H_T^{*\chi}(Q^2) = \frac{2M}{\mathbf{q}^2}\int\frac{d\Omega}{4\pi}\langle N_{\frac{1}{2}}(p')|\psi^\dagger\gamma^k q^k\lambda^\chi\psi|N_{\frac{1}{2}}(p)\rangle$$

$$\kappa_T^\chi = -H_T^\chi(0) - H_T^{*\chi}(0)$$

Together with the anomalous magnetic moment, this will allow us to describe the **transverse spin quark densities** inside the nucleon.

Tensor form factors

Tensor charges and anomalous tensor magnetic moments are scale-dependent.

$$\delta q(\mu^2) = \left(\frac{\alpha_S(\mu^2)}{\alpha_S(\mu_i^2)}\right)^{4/27}\left[1 - \frac{337}{486\pi}\left(\alpha_S(\mu_i^2) - \alpha_S(\mu^2)\right)\right]\delta q(\mu_i^2)\,,$$

$$\alpha_S^{NLO}(\mu^2) = \frac{4\pi}{9\ln(\mu^2/\Lambda_{\mathrm{QCD}}^2)}\left[1 - \frac{64}{81}\frac{\ln\ln(\mu^2/\Lambda_{\mathrm{QCD}}^2)}{\ln(\mu^2/\Lambda_{\mathrm{QCD}}^2)}\right]$$

$$\Lambda_{\mathrm{QCD}} = 0.248\,\mathrm{GeV}$$

M. Gluck, E. Reya, and A. Vogt, Z.Phys. C 67, 433(1995).

Results

	g_T^0	g_T^3	g_T^8	g_A^0	g_A^3	g_A^8	Δu	δu	Δd	δd	Δs	δs
χQSM SU(3)	0.76	1.40	0.45	0.45	1.18	0.35	0.84	1.08	-0.34	-0.32	-0.05	-0.01
χQSM SU(2)	0.75	1.44	$--$	0.45	1.21	$--$	0.82	1.08	-0.37	-0.32	$--$	$--$
NRQM	1	5/3	$--$	1	5/3	$--$	$\frac{4}{3}$	$\frac{4}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	$--$	$--$

HChK, M. Polyakov, K. Goeke, PRD 53, 4715R (1996)

Results

	g_T^0	g_T^3	g_T^8	g_A^0	g_A^3	g_A^8	Δu	δu	Δd	δd	Δs	δs
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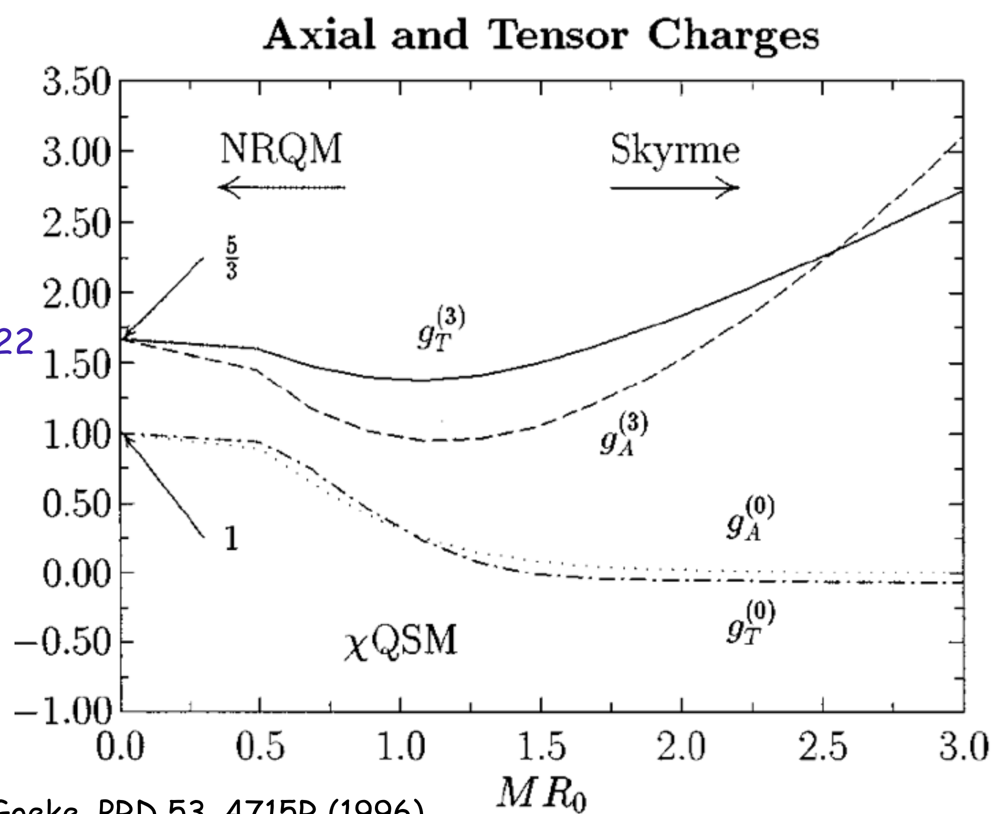
NRQM	1	5/3	−−	1	5/3	−−	$\frac{4}{3}$	$\frac{4}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	−−	−−

$$g_A^3 \sim (MR_0)^2 \qquad g_T^3 \sim MR_0$$

$$g_A^0 \sim \frac{1}{(MR_0)^4} \qquad g_T^0 \sim \frac{1}{MR_0}$$

T. Ledwig, A. Silva, HChK, Phys. Rev. D **82** (2010) 034022



HChK, M. Polyakov, K. Goeke, PRD 53, 4715R (1996)

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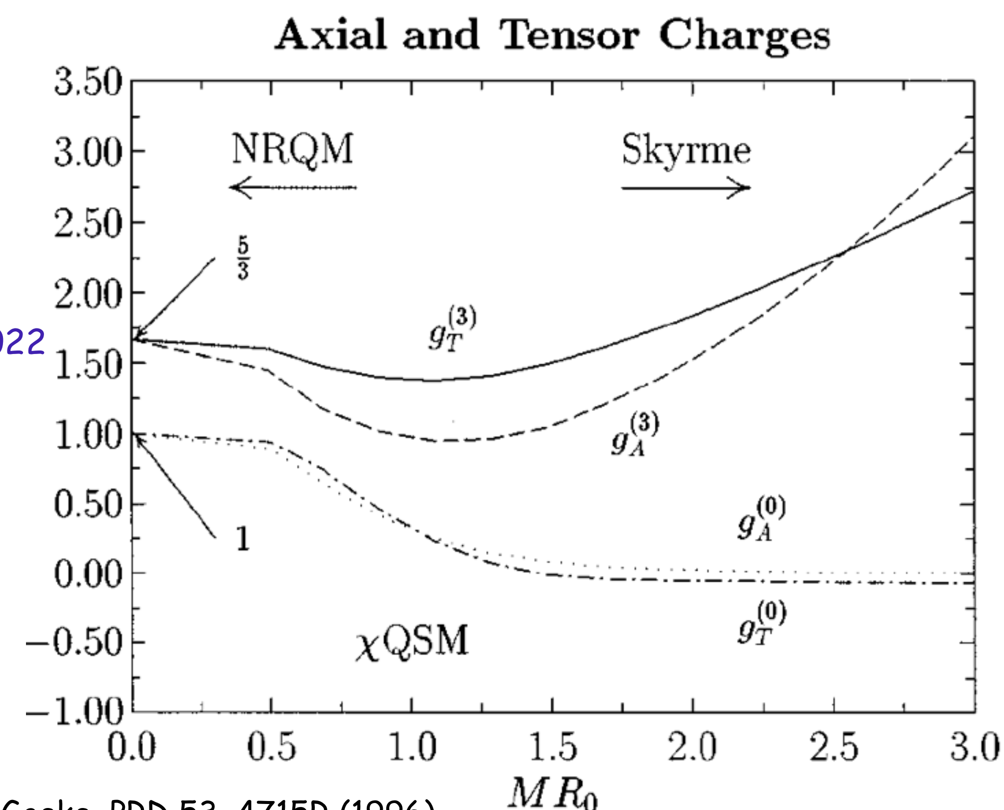
T. Ledwig, A. Silva, HChK, Phys. Rev. D **82** (2010) 034022

$$g_T^\chi > g_A^\chi$$



HChK, M. Polyakov, K. Goeke, PRD 53, 4715R (1996)

Results

Proton	This work	SU(2)	Lattice	SIDIS	NR
$\|\delta d/\delta u\|$	0.30	0.36	0.25	$0.42^{+0.0003}_{-0.20}$	0.25

T. Ledwig, A. Silva, HChK, Phys. Rev. D **82** (2010) 034022

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$$
\begin{aligned}
&\text{SIDIS [16] } (0.80\,\text{GeV}^2): && \delta u = 0.54^{+0.09}_{-0.22}\,, && \delta d = -0.231^{+0.09}_{-0.16},\\
&\text{SIDIS [16] } (0.36\,\text{GeV}^2): && \delta u = 0.60^{+0.10}_{-0.24}\,, && \delta d = -0.26^{+0.1}_{-0.18},\\
&\text{Lattice [21] } (4.00\,\text{GeV}^2): && \delta u = 0.86 \pm 0.13\,, && \delta d = -0.21 \pm 0.005\,,\\
&\text{Lattice [21] } (0.36\,\text{GeV}^2): && \delta u = 1.05 \pm 0.16\,, && \delta d = -0.26 \pm 0.01\,,\\
&\chi\text{QSM } (0.36\,\text{GeV}^2): && \delta u = 1.08\,, && \delta d = -0.32\,,
\end{aligned}
$$

[16] M. Anselmino et al. Nucl. Phys. B, Proc. Suppl. 191, 98 (2009)

[21] M. Goeckeler et al., PLB 627, 113 (2005)

T. Ledwig, A. Silva, HChK, Phys. Rev. D **82** (2010) 034022

Results

$\mu^2 = 0.36\,\mathrm{GeV}^2$

	Present work SU(3)	Present work SU(2)	Lattice
κ_T^u	3.56	3.72	3.00 (3.70)
κ_T^d	1.83	1.83	1.90 (2.35)
κ_T^s	$0.2 \sim -0.2$		
κ_T^u/κ_T^d	1.95	2.02	1.58

. Ledwig, A. Silva, HChK, Phys. Rev. D **82** (2010) 054014

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The present results are comparable with the lattice data!

M. Goeckeler et al. [QCDSF Coll. and UKQCD Coll.]
PRL 98, 222001 (2007)

. Ledwig, A. Silva, HChK, Phys. Rev. D **82** (2010) 054014

Transverse spin density

$$\rho(\mathbf{b},\,\mathbf{S},\,\mathbf{s}) = \frac{1}{2}\Bigg[\,H(b^2) - S^i\epsilon^{ij}b^j\,\frac{1}{M_N}\,\frac{\partial E(b^2)}{\partial b^2} - s^i\epsilon^{ij}b^j\,\frac{1}{M_N}\,\frac{\partial \kappa_T(b^2)}{\partial b^2}$$
$$+ s^i S^i \left\{H_T(b^2) - \frac{1}{4M_N^2}\nabla^2\tilde{H}_T(b^2)\right\}$$
$$+ s^i\left(2b^i b^j - b^2\delta^{ij}\right)S^j\,\frac{1}{M_N^2}\left(\frac{\partial}{\partial b^2}\right)^2\tilde{H}_T(b^2)\Bigg]\,,$$

M. Diehl & Ph. Haegler, Euro.Phys. J., C 44 (2005) 87.

Transverse spin density

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$$[\mathbf{S}, \mathbf{s}] = [(1,0),(0,0)],\ \ [\mathbf{S}, \mathbf{s}] = [(0,0),(1,0)]$$

M. Diehl & Ph. Haegler, Euro.Phys. J., C 44 (2005) 87.

Transverse spin density

$$\rho(\mathbf{b}, \mathbf{S}, \mathbf{s}) = \frac{1}{2}\left[H(b^2) - S^i \epsilon^{ij} b^j \frac{1}{M_N} \frac{\partial E(b^2)}{\partial b^2} - s^i \epsilon^{ij} b^j \frac{1}{M_N} \frac{\partial \kappa_T(b^2)}{\partial b^2} \right]$$

$$[\mathbf{S}, \mathbf{s}] = [(1,0),(0,0)], \; [\mathbf{S}, \mathbf{s}] = [(0,0),(1,0)]$$

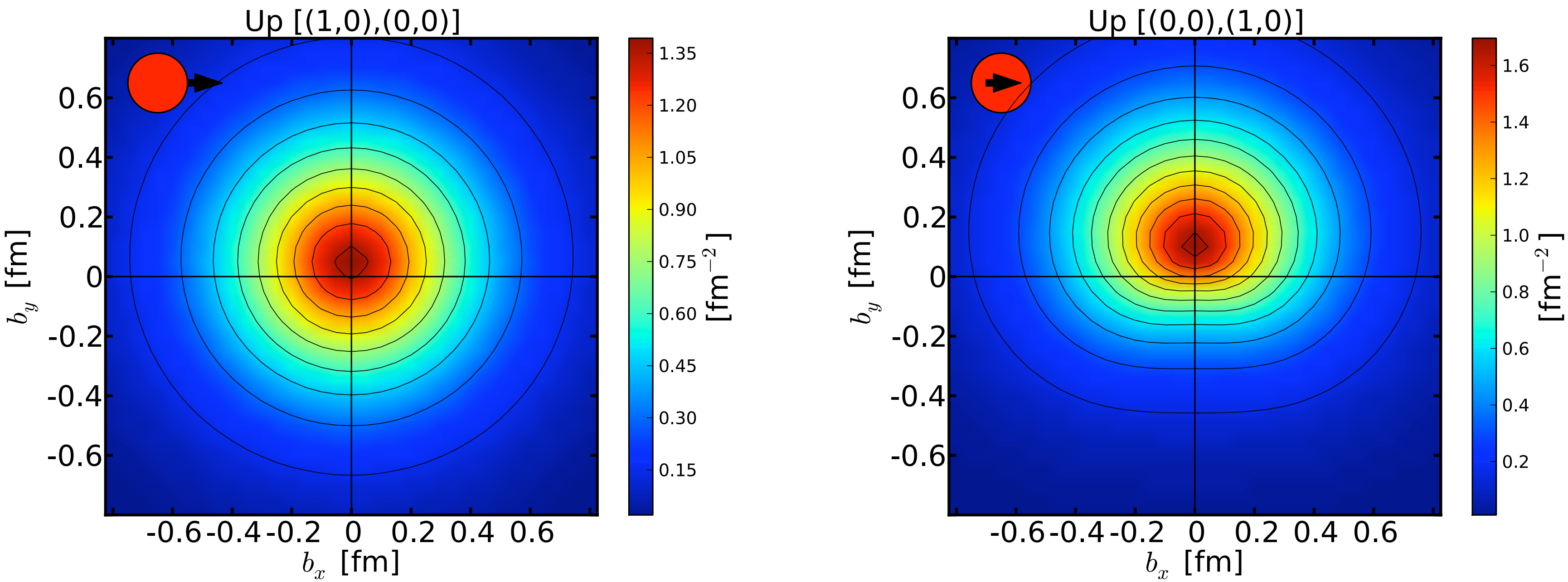
$$\mathcal{F}^\chi(b^2) = \int_0^\infty \frac{dQ}{2\pi} Q J_0(bQ) F^\chi(Q^2)$$

$$H(b^2) = F_1(b^2), \quad E(b^2) = F_2(b^2)$$

M. Diehl & Ph. Haegler, Euro.Phys. J., C 44 (2005) 87.

Results

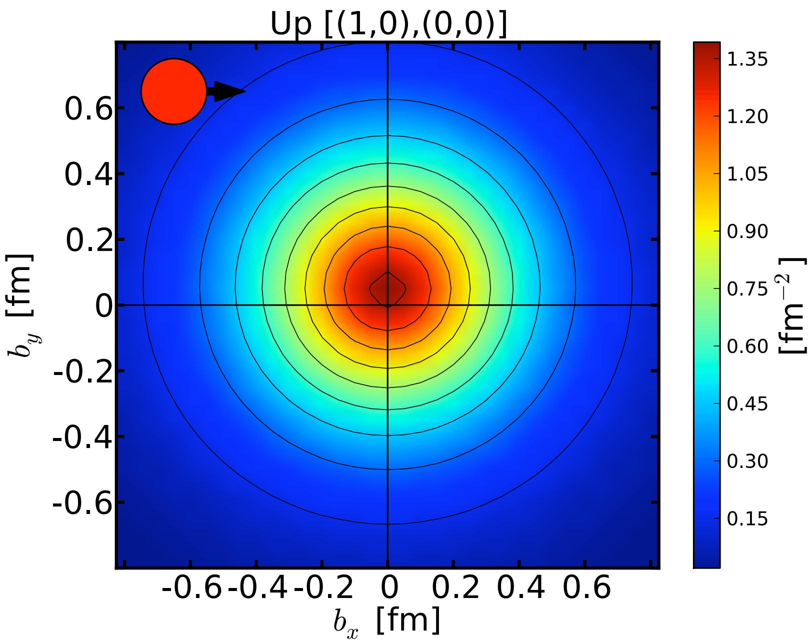
Up quark transverse spin density inside a nucleon

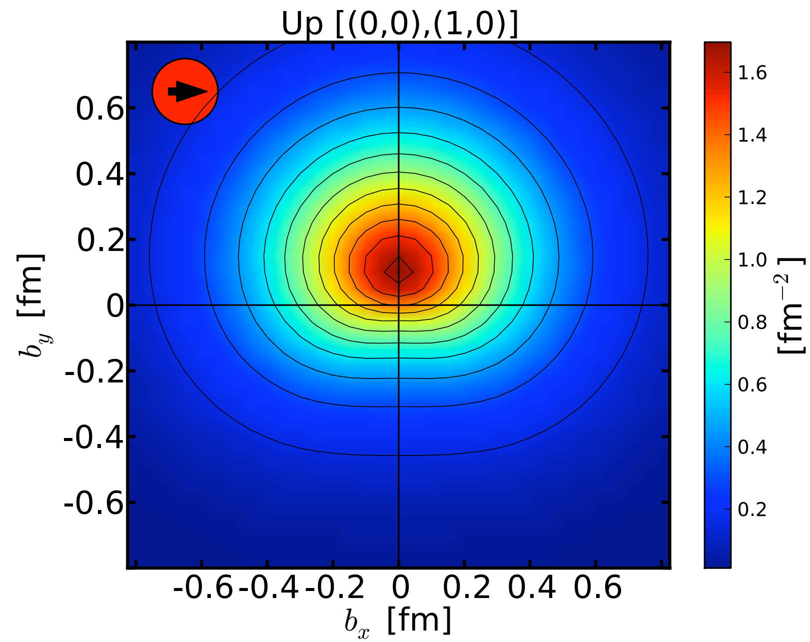


T. Ledwig & H-Ch.K, PRD 85, 034041 (2012)

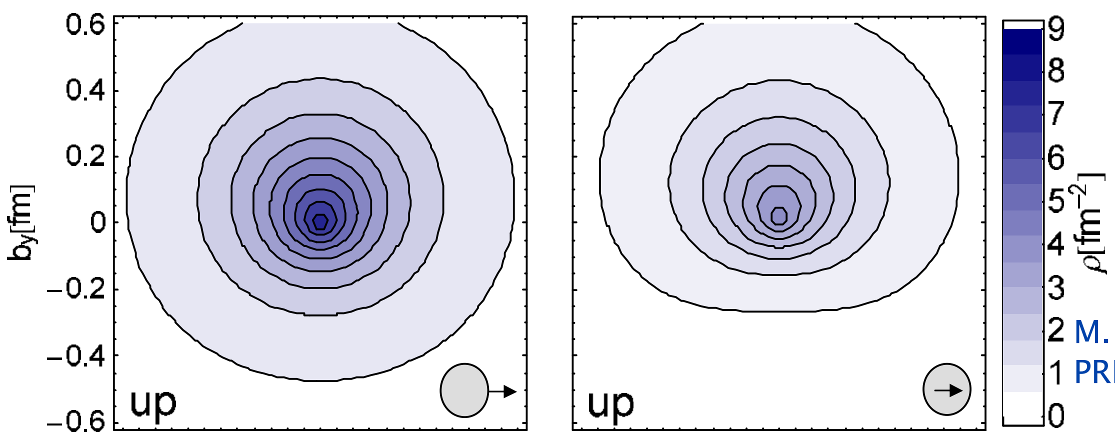
Results

Up quark transverse spin density inside a nucleon





T. Ledwig & H-Ch.K, PRD 85, 034041 (2012)



Lattice results

M. Goeckeler et al. [QCDSF Coll. and UKQCD Coll.]
PRL 98, 222001 (2007)

Results

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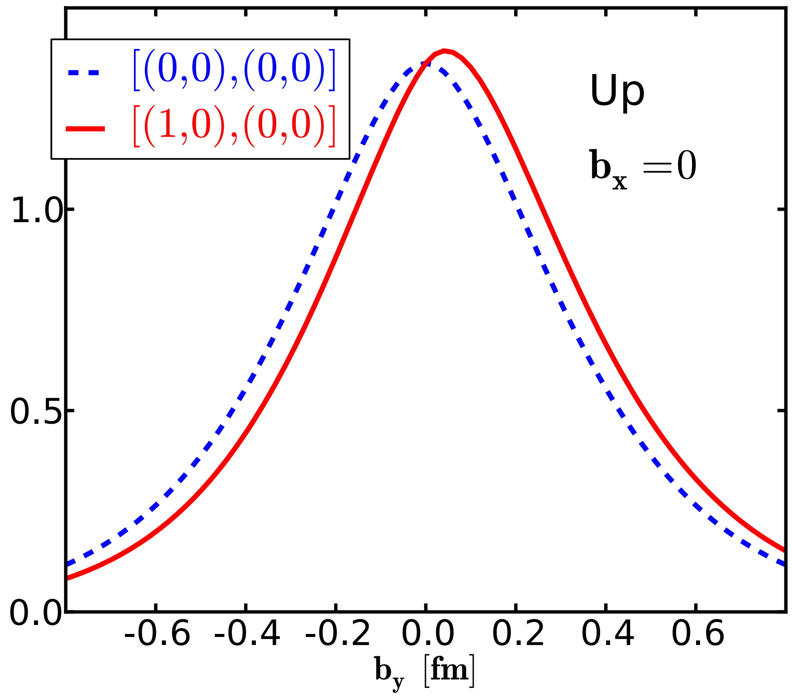
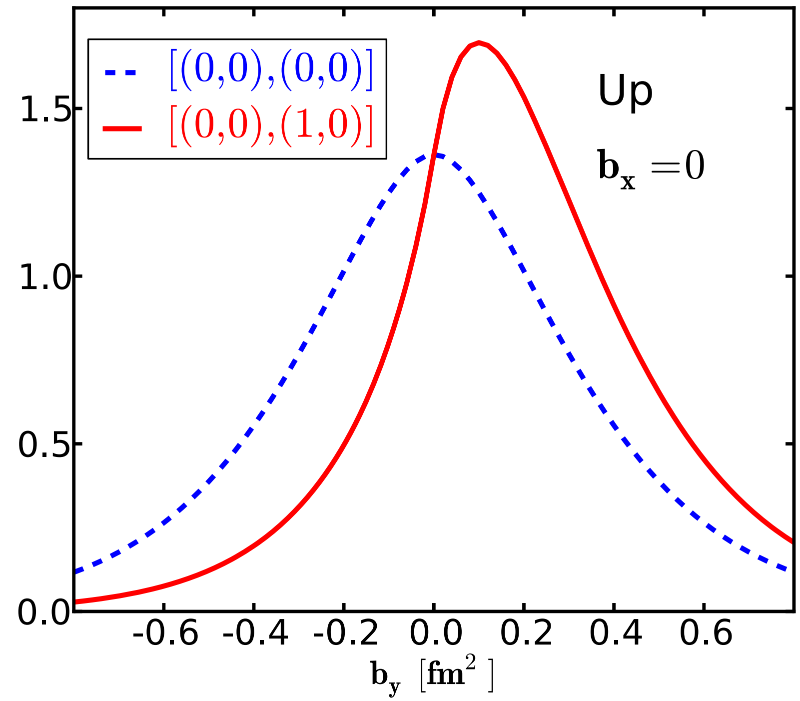
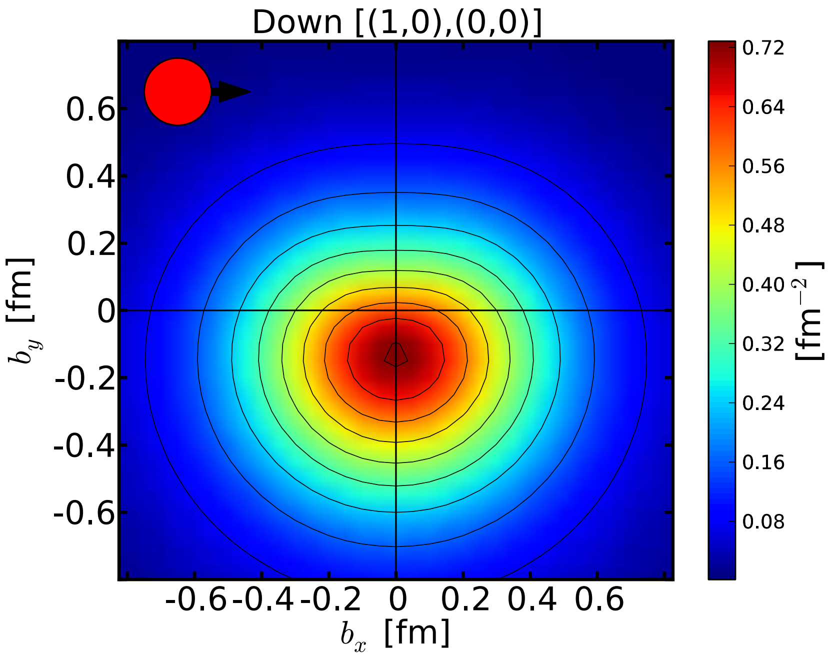
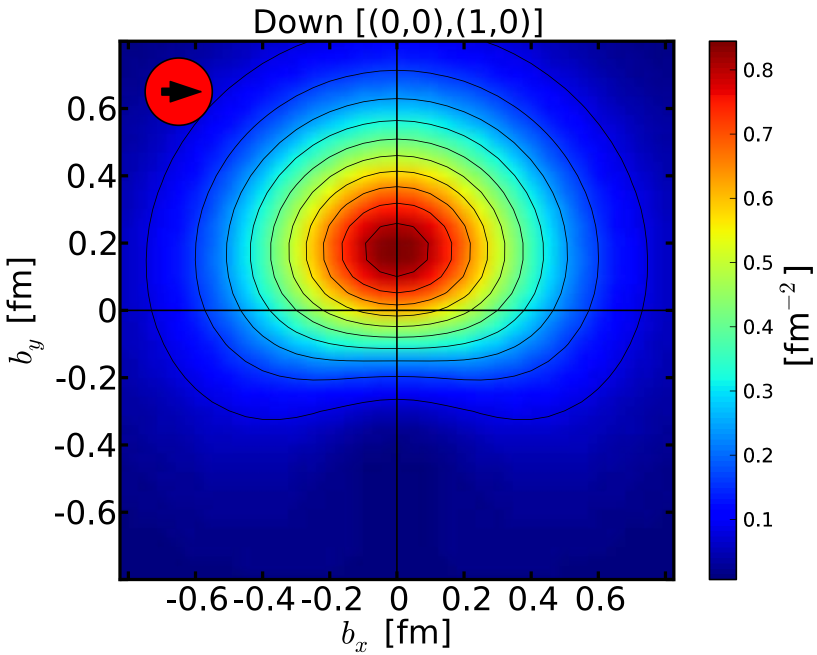




Results

Down quark transverse spin density inside a nucleon

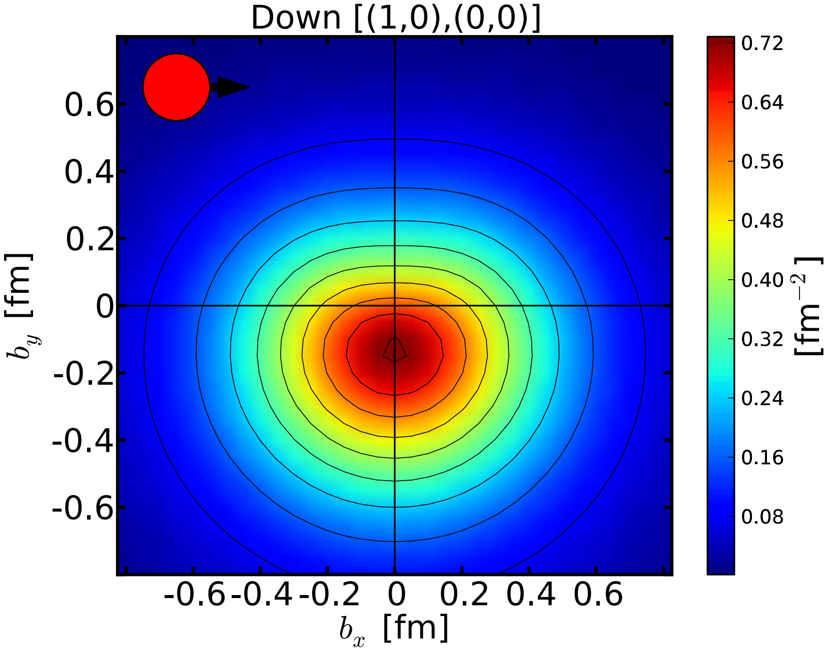


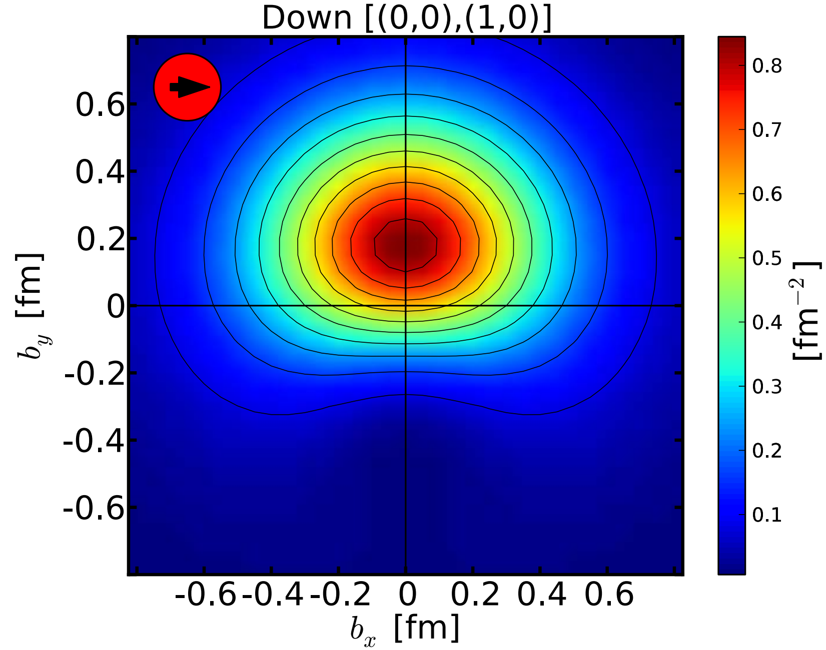


T. Ledwig & H-Ch.K, PRD 85, 034041 (2012)

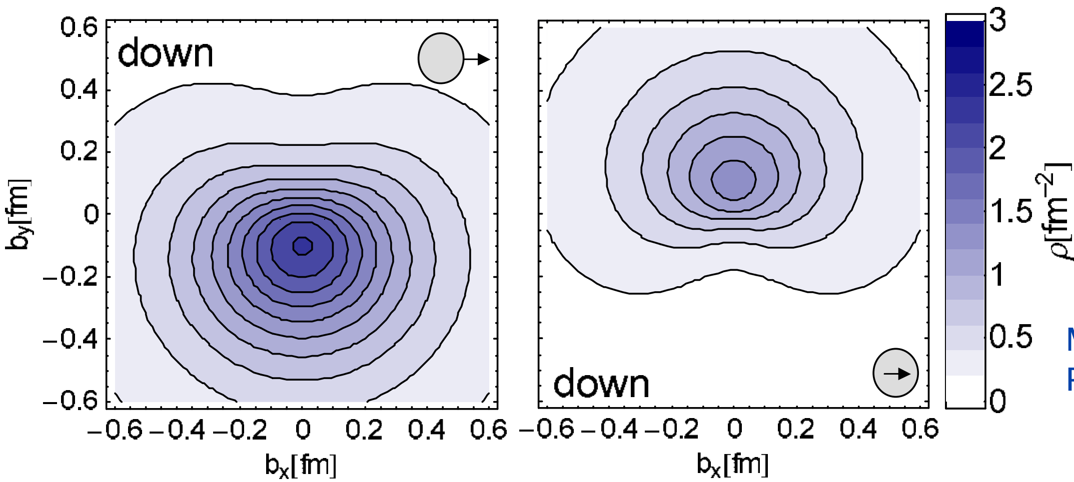
Results

Down quark transverse spin density inside a nucleon





T. Ledwig & H-Ch.K, PRD 85, 034041 (2012)



Lattice results

M. Goeckeler et al. [QCDSF Coll. and UKQCD Coll.]
PRL 98, 222001 (2007)

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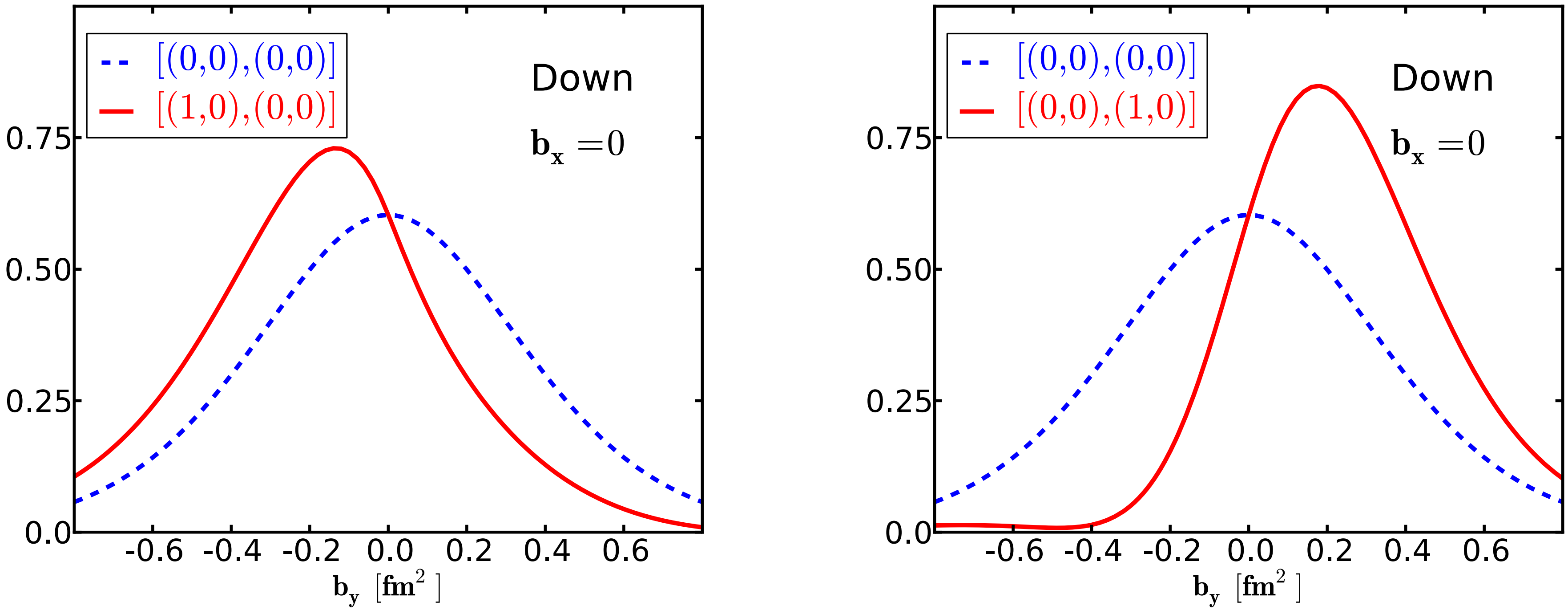
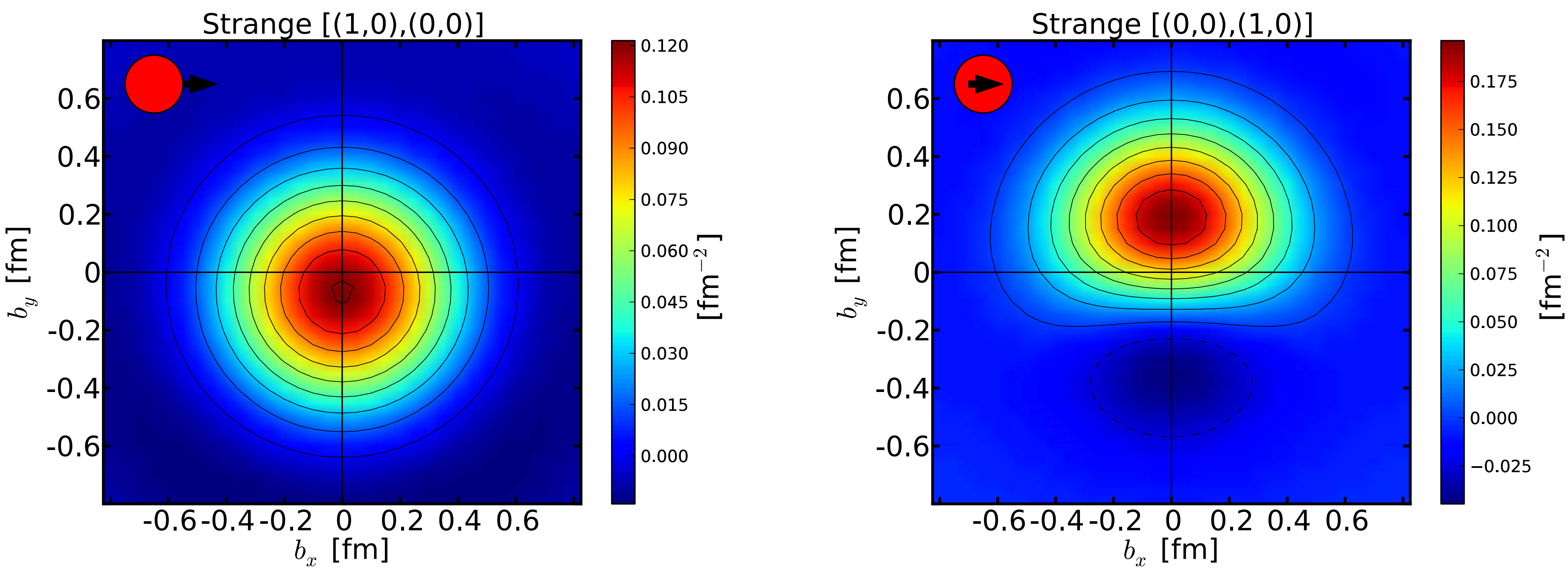


Results

Strange quark transverse spin density inside a nucleon

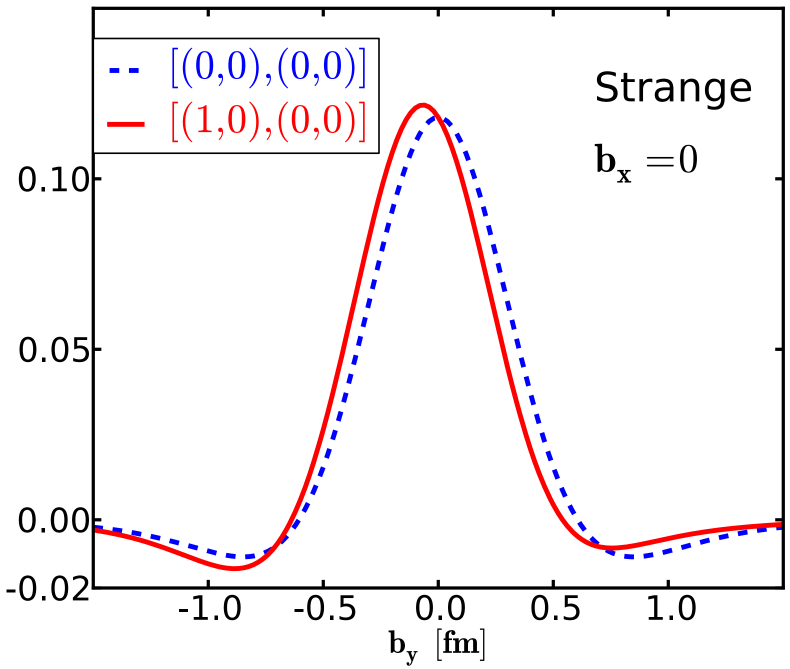


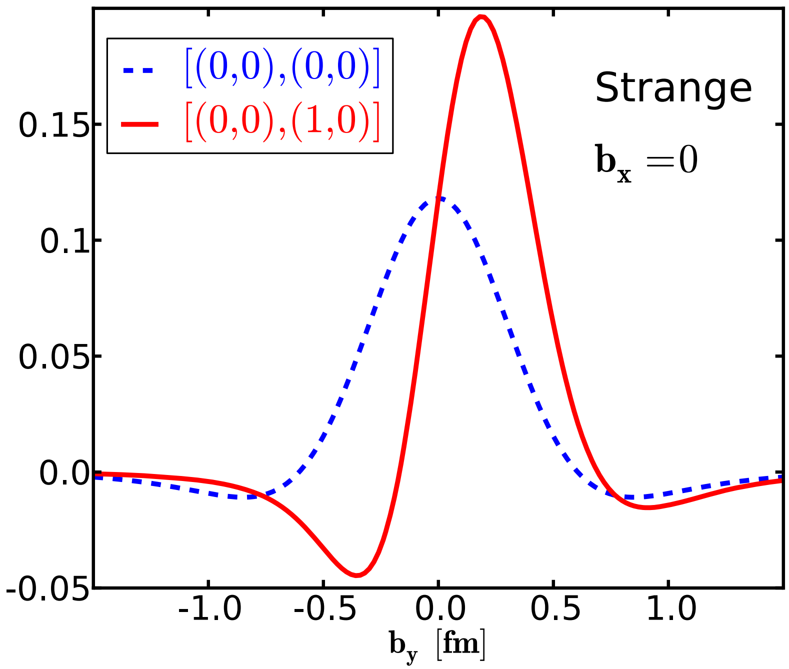
T. Ledwig & H-Ch.K, PRD 85, 034041 (2012)

This is the **first** result of the strange quark transverse spin density inside a nucleon

Results

Strange quark transverse spin density inside a nucleon





Results

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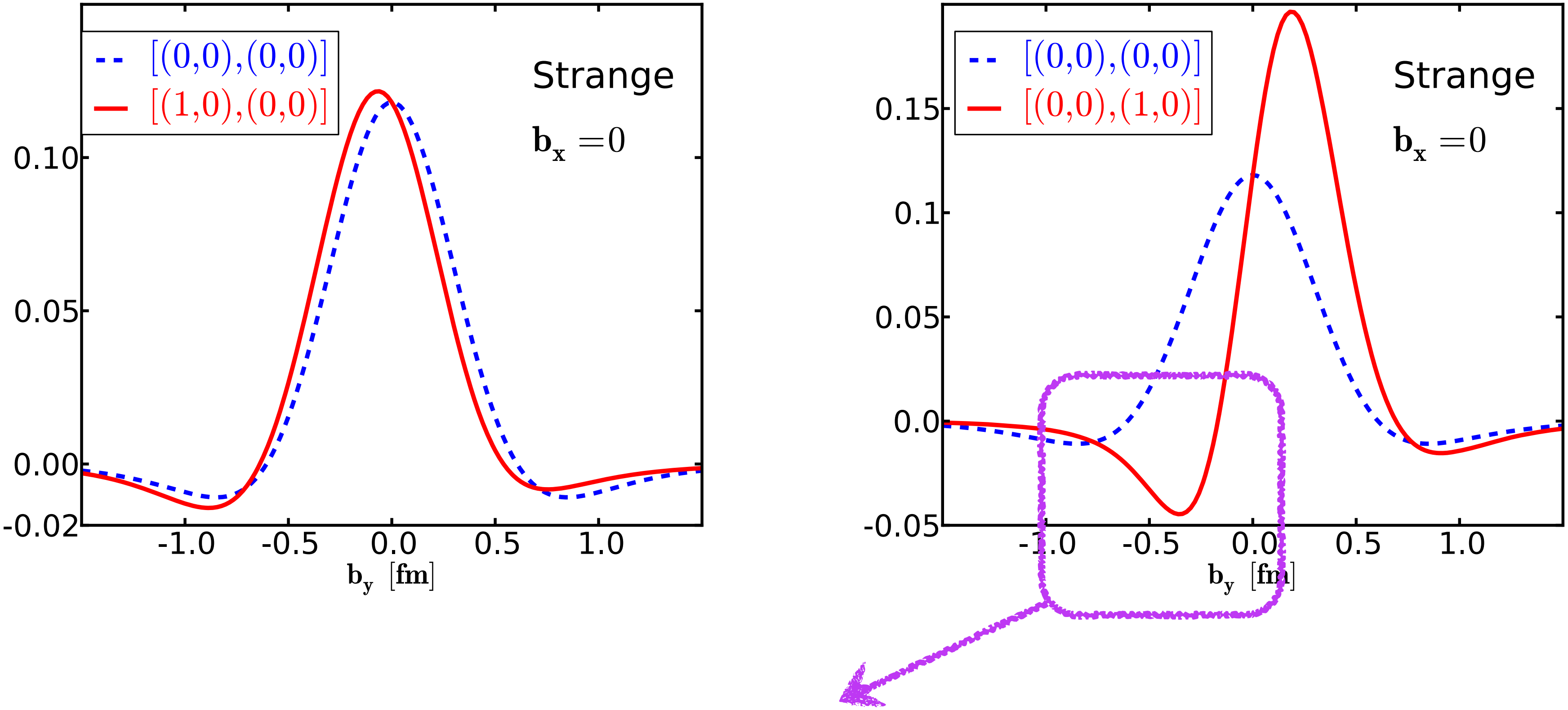


Polarized to the negative direction in the b plane.

Summary

- We have reviewed recent investigations on the charge and spin structures of the nucleon, based on the chiral quark-soliton model.
- We have derived the EM and tensor form factors of the nucleon, from which we have obtained their transverse charge & spin densities. The results are compared with the lattice and "experimental" data.
- The first strange anomalous tensor magnetic moment was obtained, though it is compatible with zero.
- The strange quark transverse spin density was first announced in this work.
- We also extended the investigation to nuclear matter case.

Though this be madness,
yet there is method in it.

Hamlet Act 2, Scene 2

Thank you very much!

Chiral quark-soliton model

$$S_{\rm eff} = -N_c \mathrm{Tr} \ln(i\partial\!\!\!/ + iMU^{\gamma_5} + i\hat{m})$$

Nucleon consisting of Nc quarks

$$\Pi_N = \langle 0 | J_N(0, T/2) J_N^\dagger(0, -T/2) | 0 \rangle$$

$$J_N(\vec{x}, t) = \frac{1}{N_c!} \varepsilon^{\beta_1 \cdots \beta_{N_c}} \Gamma^{\{f\}}_{JJ_3Y'TT_3Y} \psi_{\beta_1 f_1}(\vec{x}, t) \cdots \psi_{\beta_{N_c} f_{N_c}}(\vec{x}, t)$$

$$\lim_{T\to\infty} \Pi_N(T) \simeq e^{-M_N T}$$

$$\Pi_N(\vec{x}, t) = \Gamma_N^{\{f\}} \Gamma_N^{\{g\}*} \frac{1}{Z} \int dU \prod_{i=1}^{N_c} \left\langle 0, T/2 \left| \frac{1}{D(U)} \right| 0, -T/2 \right\rangle_{f,g} e^{-S_{\rm eff}}$$

$$\lim_{T\to\infty} \frac{1}{Z} \prod_{i=1}^{N_c} \left\langle 0, T/2 \left| \frac{1}{D(U)} \right| 0, -T/2 \right\rangle \sim e^{-(N_c E_{\rm val}(U) + E_{\rm sea}(U))T}$$

Baryonic correlation functions

Baryonic observables

$$\lim_{x_0 \to -\infty} \langle 0 | J_N(x) \Gamma_\mu(z) J_N^\dagger(y) | 0 \rangle = \lim_{\substack{x_0 \to -\infty \\ y_0 \to \infty}} \mathcal{K}_\mu$$

$$\mathcal{K}_\mu = \frac{1}{\mathcal{Z}} \int D\psi D\psi^\dagger DU \, J_N \Gamma_\mu J_N^\dagger$$
$$\times \exp\left[\int d^4x \psi^\dagger \left(i\partial\!\!\!/ + iMU^{\gamma_5} + i\hat{m} \right)] \psi \right]$$

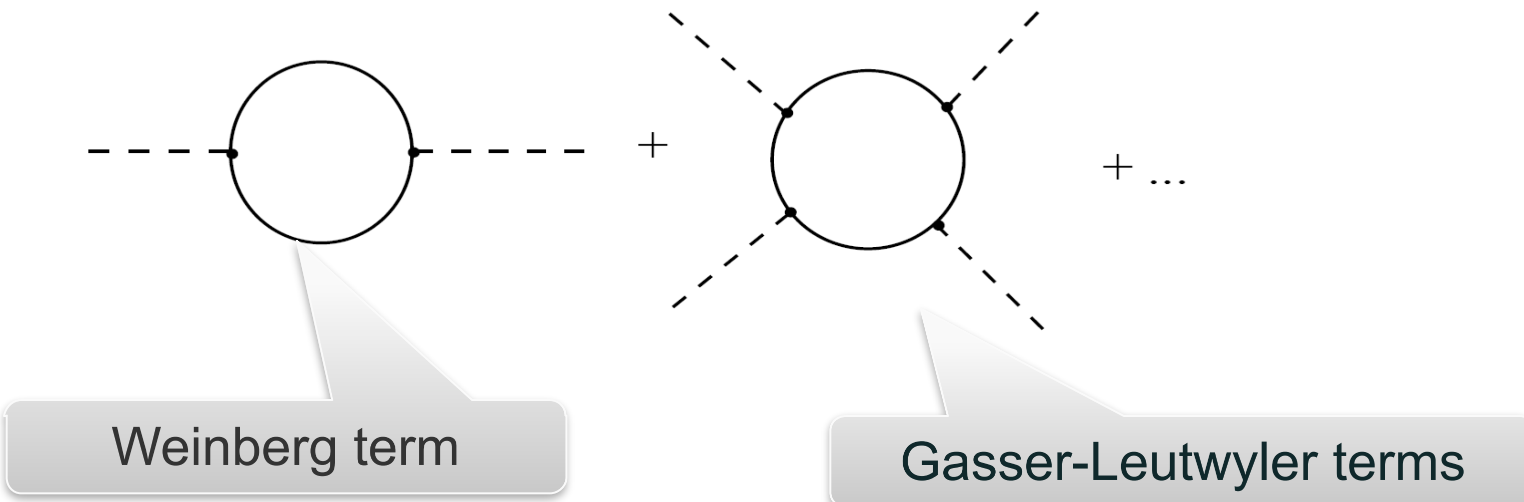
HChK et al. Prog. Part. Nucl. Phys. Vol.95, (1995)

Skyrme model as a limit of the XQSM

Effective Chiral Lagrangian and LECs

$$S_{\mathrm{eff}} = -N_c \mathrm{Tr}\ln\left(i\partial\!\!\!/ + i\sqrt{M(i\partial)}U^{\gamma_5}\sqrt{M(i\partial)}\right)$$

Derivative expansions: pion momentum as an expansion parameter



HChK et al. Prog. Part. Nucl. Phys. Vol.37, 91 (1996)

Effective chiral Lagrangian

Weinberg Lagrangian

$\mathcal{O}(p^2)$

$$\mathrm{Re}S_{\mathrm{eff}}^{(2)}[\pi^a] - \mathrm{Re}S_{\mathrm{eff}}^{(2)}[0] = \int d^4x \mathcal{L}^{(2)}$$

$$\mathcal{L}^{(2)} = \frac{F_\pi^2}{4}\left\langle D^\mu U^\dagger D_\mu U \right\rangle + \frac{F_\pi^2}{4}\left\langle \mathcal{X}^\dagger U + \mathcal{X} U^\dagger \right\rangle$$

Gasser-Leutwyler Lagrangian

$\mathcal{O}(p^4)$

$$\mathcal{L}^{(4)} = L_1 \langle L_\mu L_\mu \rangle^2 + L_2 \langle L_\mu L_\nu \rangle^2 + L_3 \langle L_\mu L_\mu L_\nu L_\nu \rangle$$

H.A. Choi and HChK, PRD 69, 054004 (2004)

Low-energy constants

Gasser-Leutwyler Lagrangian

	M_0(MeV)	Λ(MeV)	$L_1(\times 10^{-3})$	$L_2(\times 10^{-3})$	$L_3(\times 10^{-3})$
local χQM	350	1905.5	0.79	1.58	-3.17
DP	350	611.7	0.82	1.63	-3.09
Dipole	350	611.2	0.82	1.63	-2.97
Gaussian	350	627.4	0.81	1.62	-2.88
GL			0.9 ± 0.3	1.7 ± 0.7	-4.4 ± 2.5
Bijnens			0.6 ± 0.2	1.2 ± 0.4	-3.6 ± 1.3
Arriola			0.96	1.95	-5.21
VMD			1.1	2.2	-5.5
Holdom(1)			0.97	1.95	-4.20
Holdom(2)			0.90	1.80	-3.90
Bolokhov et al.			0.63	1.25	2.50
Alfaro et al.			0.45	0.9	-1.8

H.A. Choi and HChK, PRD 69, 054004 (2004)

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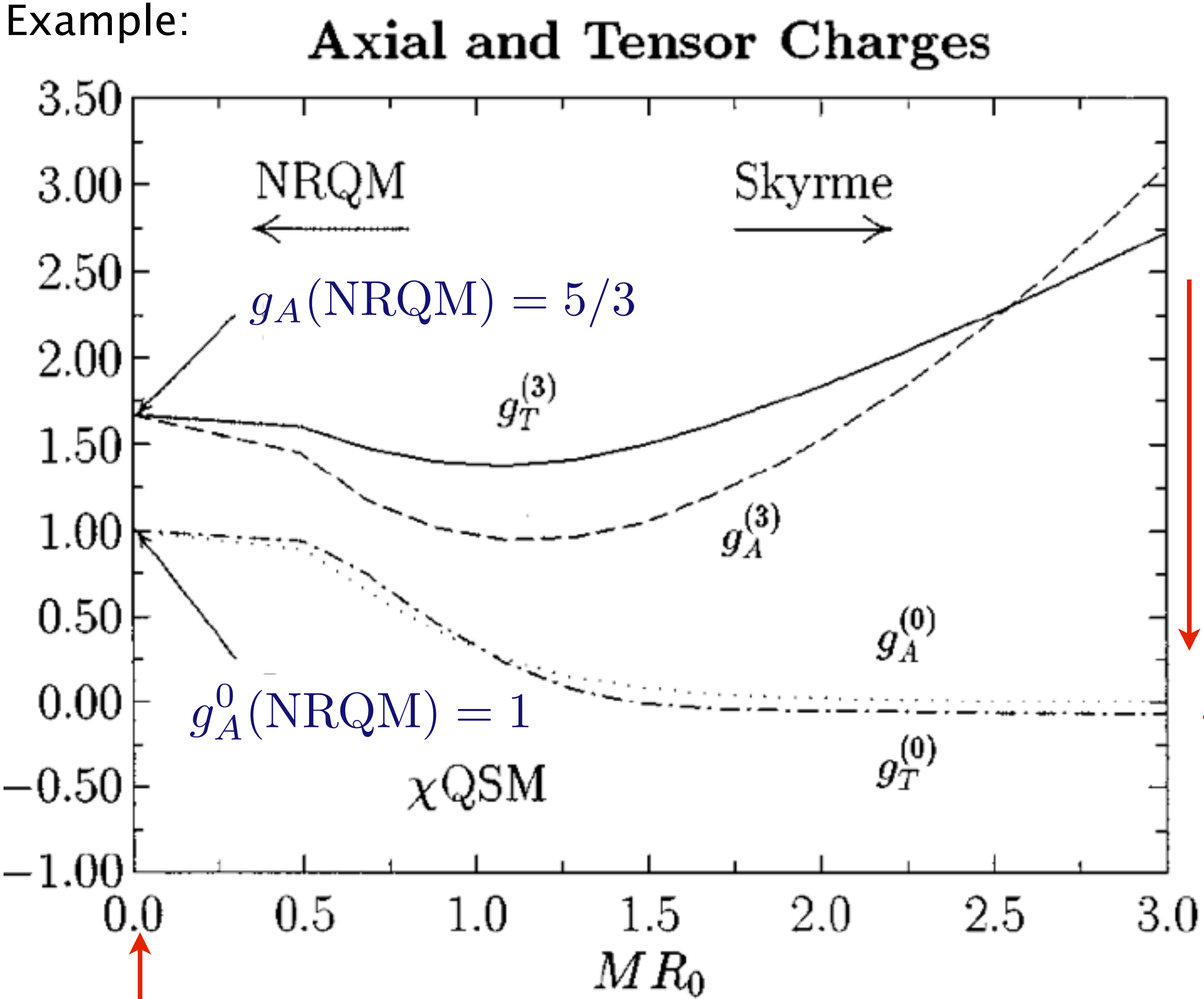
Limit to the Skyrme model

Example:



Large soliton size: Valence quarks dive into the Dirac sea– No quark and topological winding number=1.

$g_A^0(\mathrm{Skyrme}) \approx 0$

zero soliton size: NRQM

HChK, M. Polyakov, K. Goeke, PRD 53 (1996) 4715R

Medium-modified Skyrme model

Medium-modified effective chiral Lagrangian

$$\mathcal{L}^* = \frac{F_\pi^2}{4}\mathrm{Tr}\left(\frac{\partial U}{\partial t}\right)\left(\frac{\partial U^\dagger}{\partial t}\right) - \frac{F_\pi^2}{16}\alpha_p(\mathbf{r})\mathrm{Tr}\left(\nabla U\right)\cdot\left(\nabla U^\dagger\right)$$
$$+\frac{1}{32e^2\gamma(\mathbf{r})}\mathrm{Tr}\left[U^\dagger\partial_\mu U,\, U^\dagger\partial_\nu U\right]^2$$
$$+\frac{F_\pi^2 m_\pi^2}{16}\alpha_s(\mathbf{r})\mathrm{Tr}(U+U^\dagger-2)$$

U. Yakhshiev and HChK, PRC **83**, 038203 (2011)

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$$+ \frac{1}{32e^2\gamma(\mathbf{r})}\mathrm{Tr}\left[U^\dagger\partial_\mu U,\, U^\dagger\partial_\nu U\right]^2$$
$$+ \frac{F_\pi^2 m_\pi^2}{16}\alpha_s(\mathbf{r})\mathrm{Tr}(U + U^\dagger - 2)$$

$$\alpha_p(\mathbf{r}) = 1 - \chi_p(\mathbf{r})$$

$$\alpha_s(\mathbf{r}) = 1 + \chi_s(\mathbf{r})/m_\pi^2$$

$\chi_{p,\,s}$: pion dipole susceptibility in medium

The parameters are fixed by pion-nucleus scattering data.

(See Ericson and Weise, “Pions in Nuclei”.)

U. Yakhshiev and HChK, PRC **83**, 038203 (2011)

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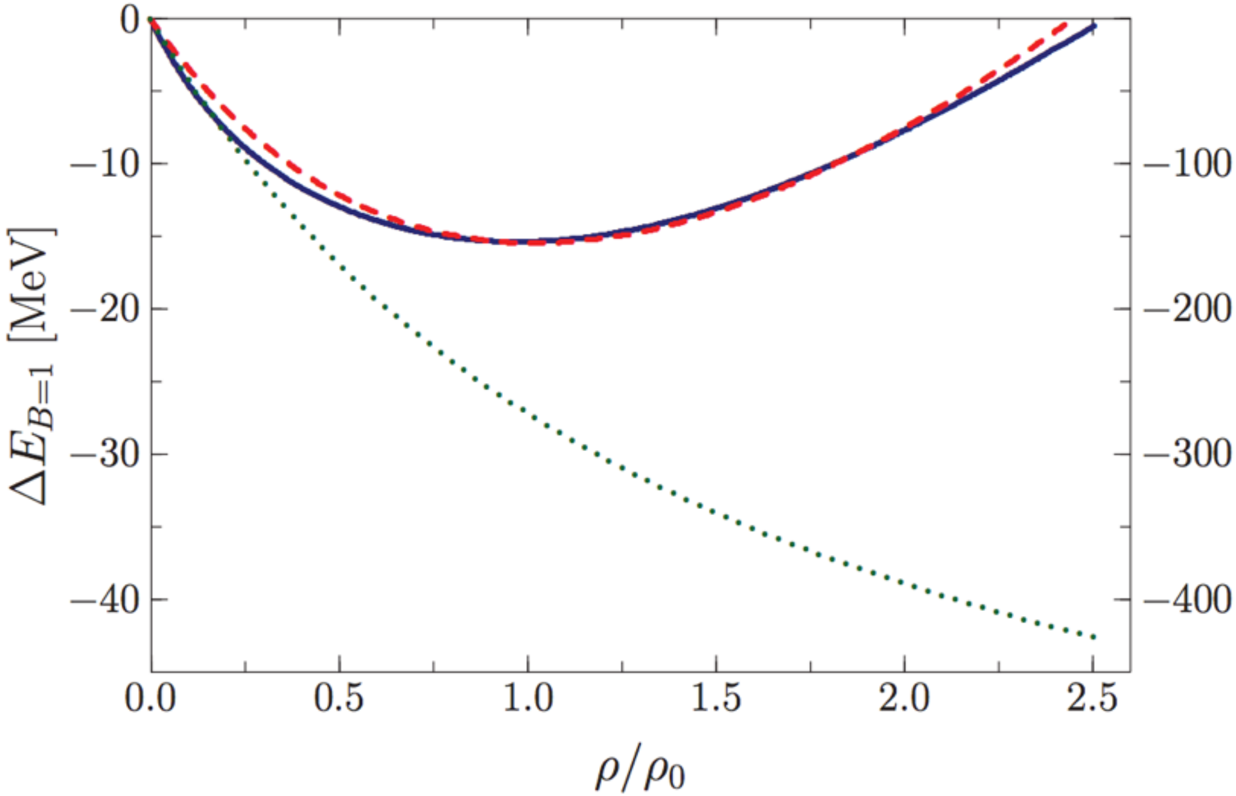
$$\gamma(\mathbf{r}) = \exp\left(-\frac{\gamma_{\mathrm{num}}\rho(\mathbf{r})}{1+\gamma_{\mathrm{den}}\rho(\mathbf{r})}\right)$$

Fitted to the volume term of the semi-empirical mass formula.

U. Yakhshiev and HChK, PRC **83**, 038203 (2011)

Medium-modified Skyrme model

Binding Energy per nucleon

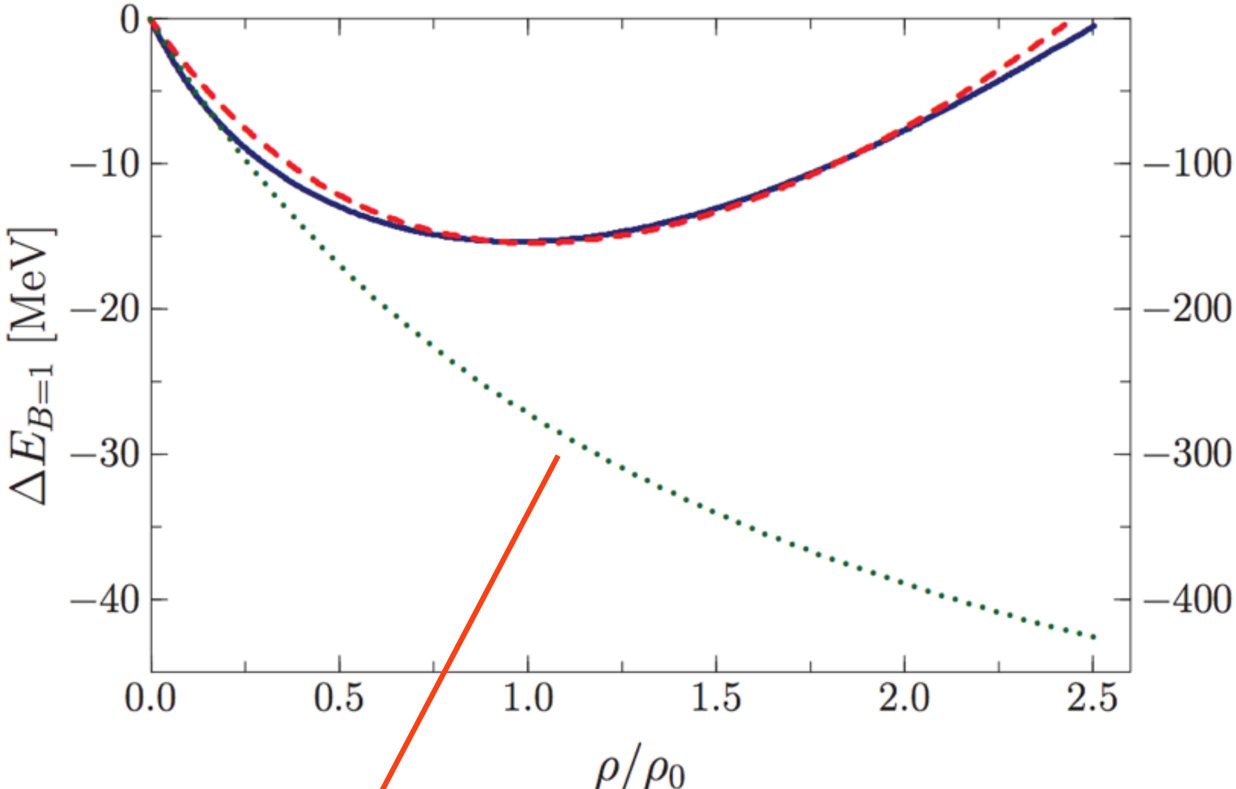


$$\gamma_{\mathrm{num}} = 0.47 m_\pi^{-3}$$

$$\gamma_{\mathrm{den}} = 0.17 m_\pi^{-3}$$

Medium-modified Skyrme model

Binding Energy per nucleon



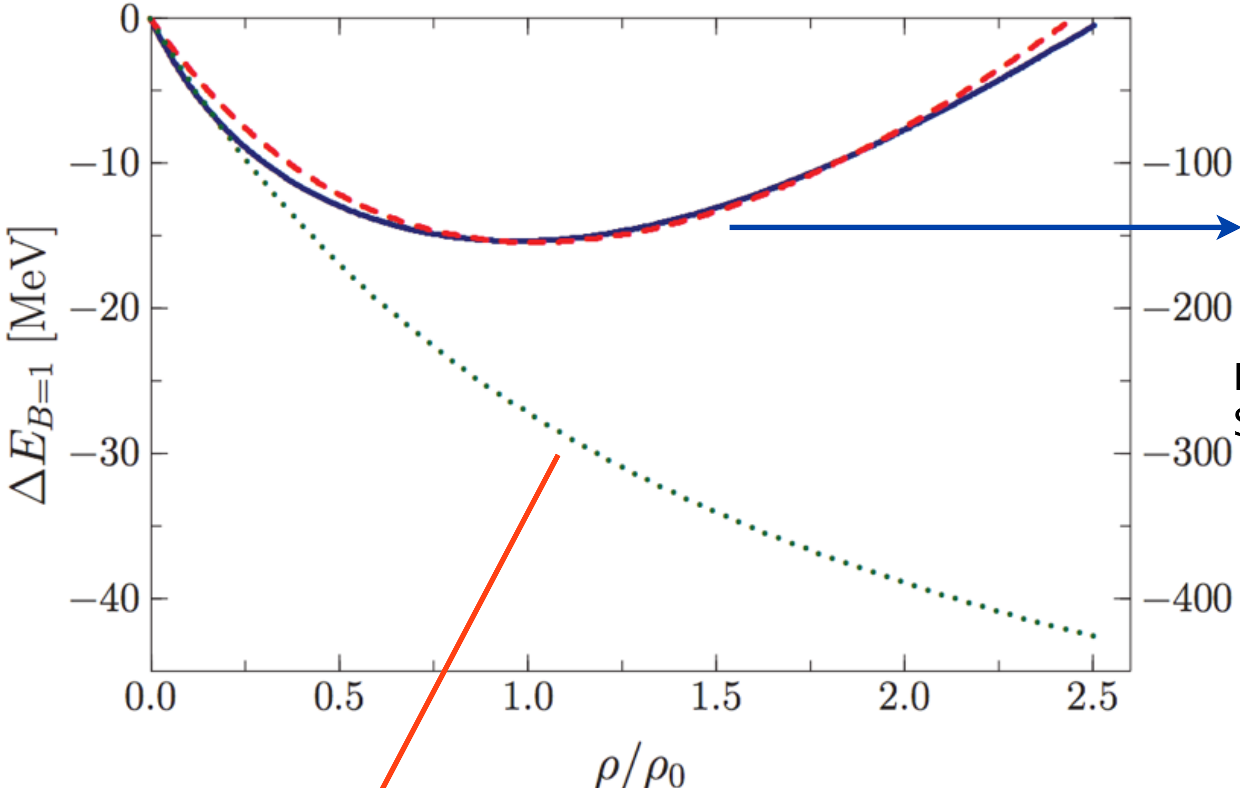
No modification of the Skyrme term

$$\gamma_{\rm num} = 0.47 m_\pi^{-3}$$

$$\gamma_{\rm den} = 0.17 m_\pi^{-3}$$

Medium-modified Skyrme model

Binding Energy per nucleon



With the Skyrme term modified

It is required to protect the Skyrmion from the collapse!

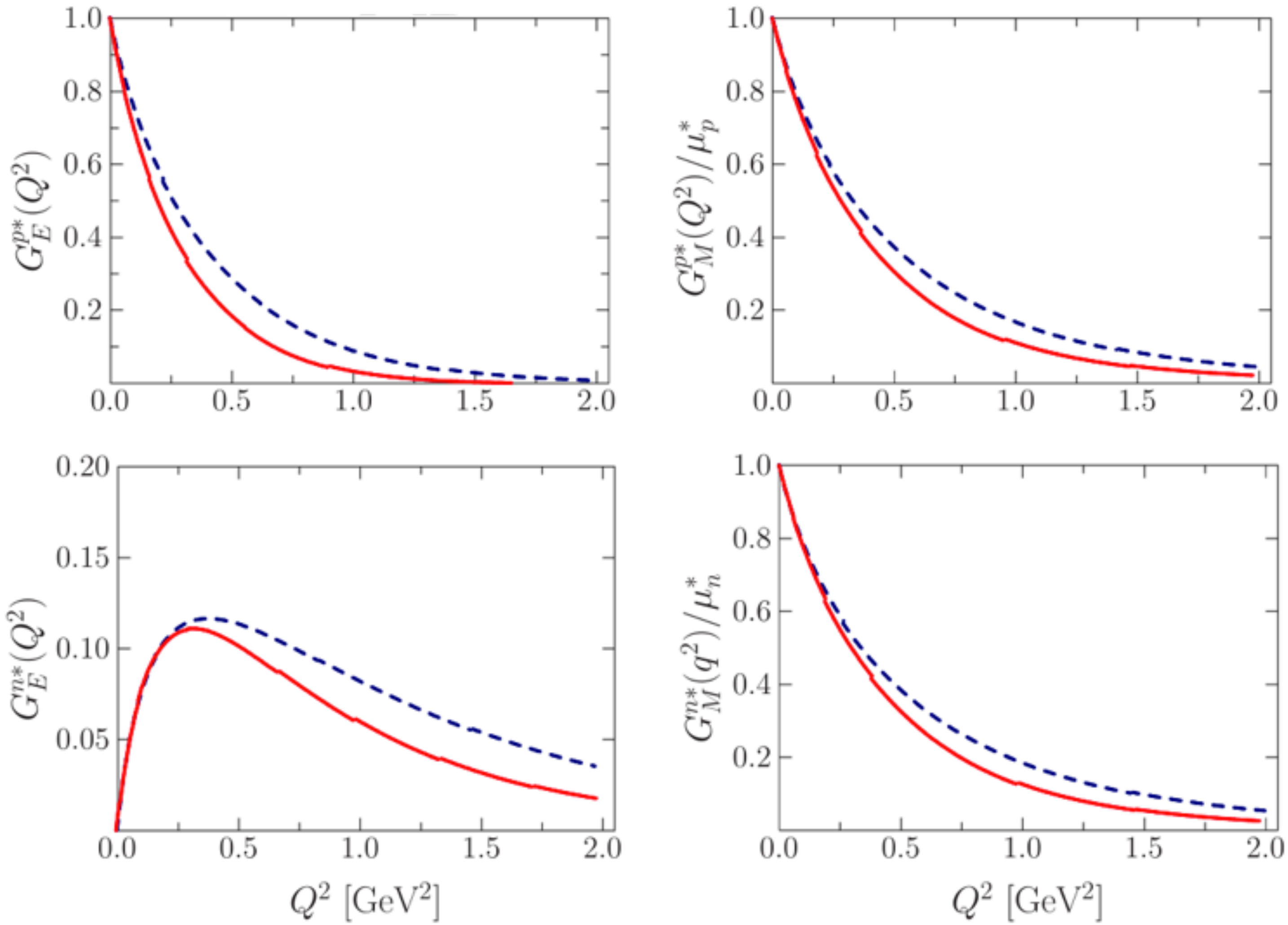
No modification of the Skyrme term

$$\gamma_{\rm num} = 0.47 m_\pi^{-3}$$

$$\gamma_{\rm den} = 0.17 m_\pi^{-3}$$

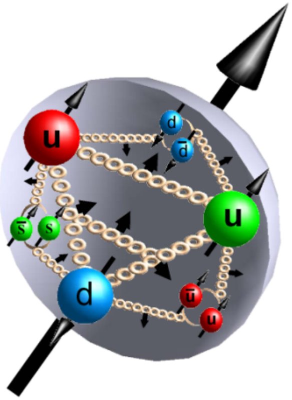
Results

Electromagnetic form factors of the nucleon in nuclear matter

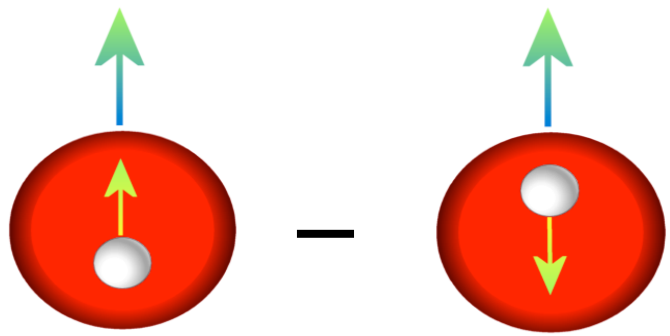


U. Yakhshiev and HChK, PLB, (2013)

Transversity: Tensor Charges



$$\delta \mathbf{q}(\mathbf{x}) =$$



$$\left\langle N \left| \bar{\psi} \sigma_{\mu\nu} \lambda^{\chi} \psi \right| N \right\rangle \sim \text{Tensor charges}$$

- No explicit probe for the tensor charge! Difficult to be measured.
- Chiral-odd Parton Distribution Function can get accessed via the SSA of SIDIS (HERMES and COMPASS).

A. Airapetian et al. (HERMES Coll.), PRL 94, 012002 (2005).

E.S. Ageev et al. (COMPASS Coll.), NPB 765, 31 (2007).

CLAS & CLAS12 Coll.

ppbar Drell-Yan process (PAX Coll.): Technically too difficult for the moment (polarized antiproton: hep-ex/0505054).

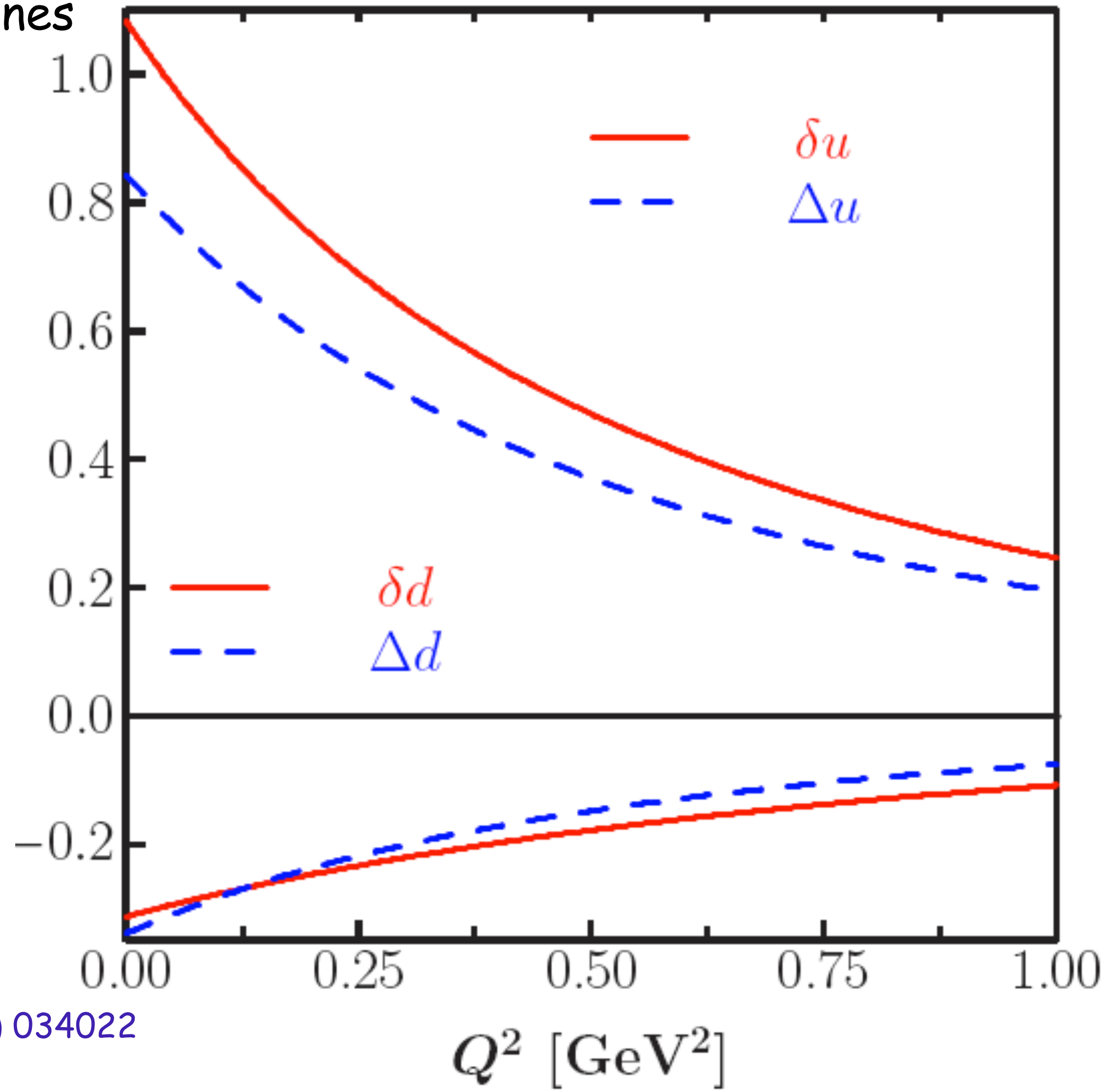
Transversity: Tensor Charges

$$\delta u = 0.60^{+0.10}_{-0.24}\,, \quad \delta d = -0.26^{+0.1}_{-0.18} \text{ at } 0.36\,\mathrm{GeV}^2$$

Based on SIDIS (HERMES) data:
M. Anselmino et al. Nucl. Phys. B, Proc. Suppl. 191, 98 (2009)

Results

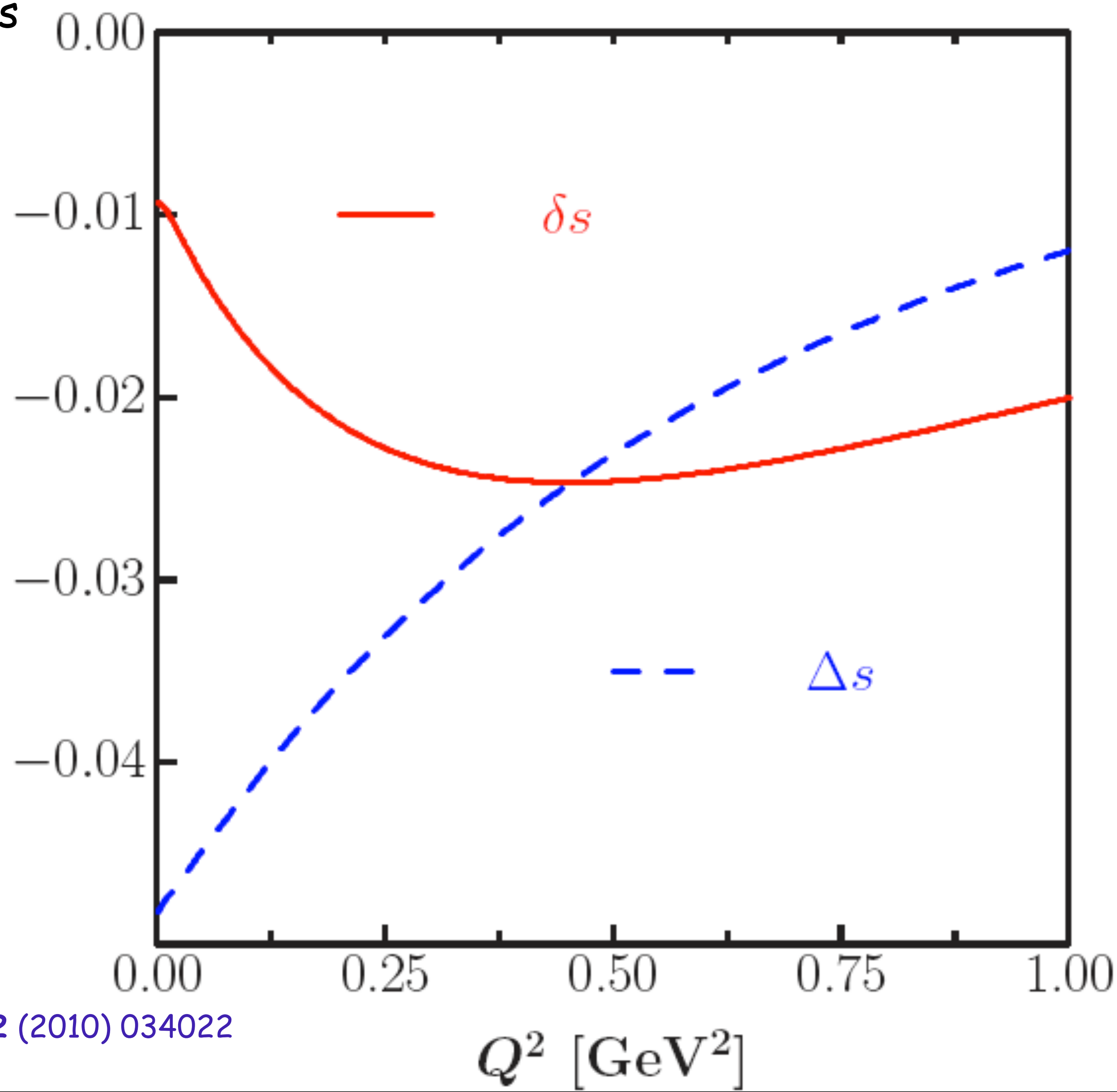
Up and down tensor form factors compared with the axial-vector ones



T. Ledwig, A. Silva, HChK, Phys. Rev. D **82** (2010) 034022

Results

Strange tensor form factors compared with the axial-vector ones

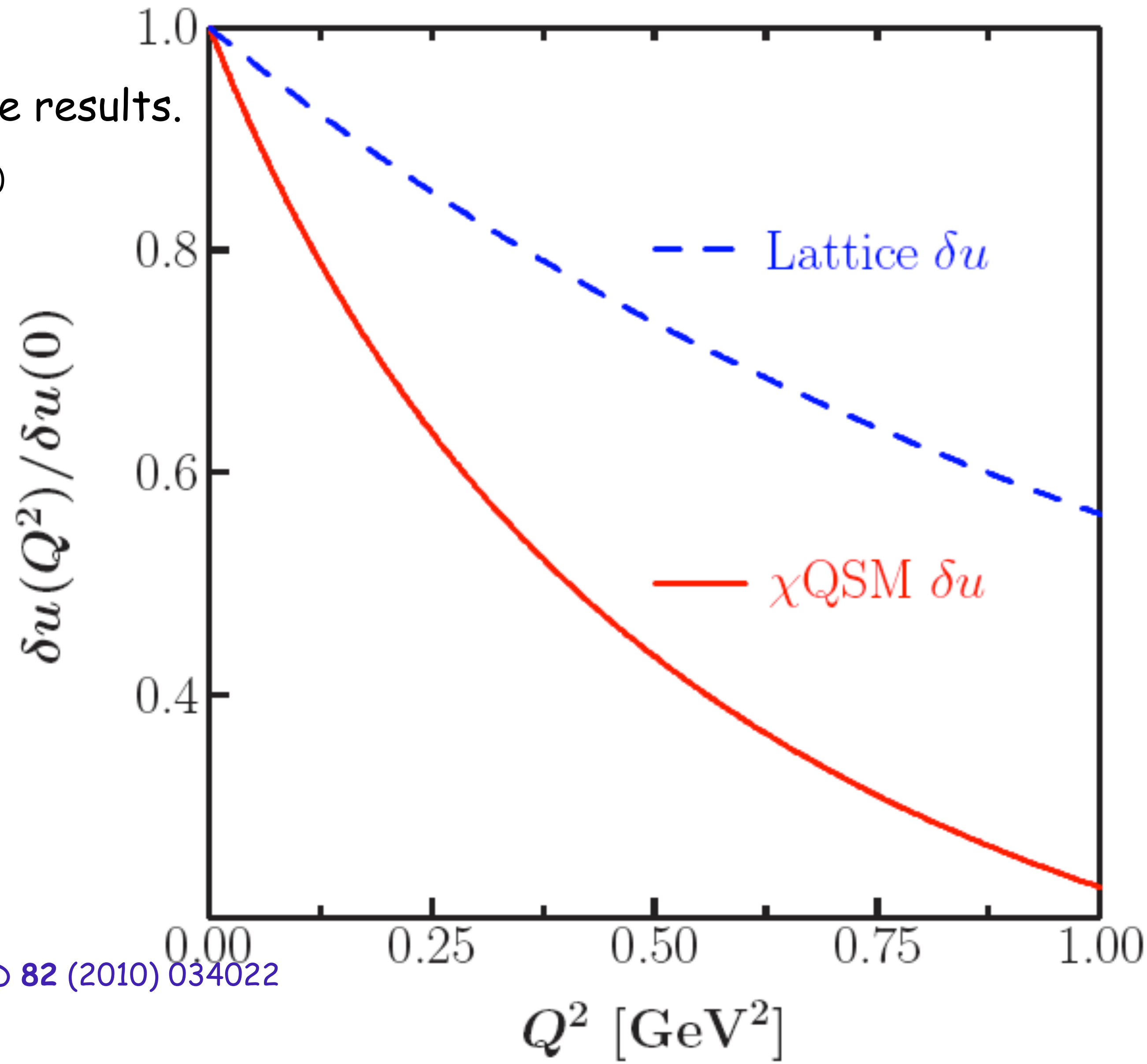


T. Ledwig, A. Silva, HChK, Phys. Rev. D **82** (2010) 034022

Results

Comparison with the lattice results.

M. Goeckeler et al., PLB 627, 113 (2005)



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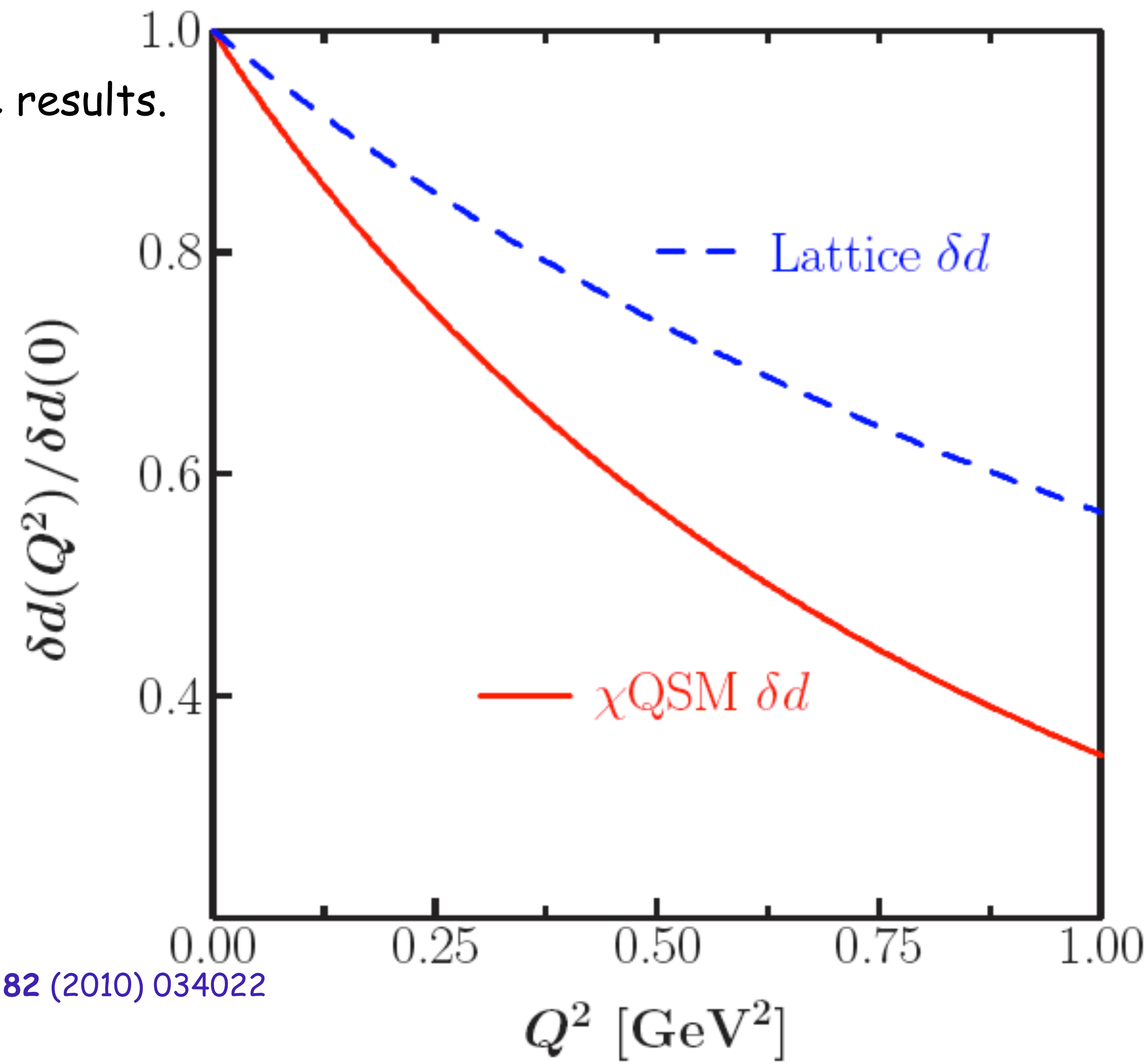

T. Ledwig, A. Silva, HChK, Phys. Rev. D **82** (2010) 034022

Results

	$p(uud)$	$n(ddu)$	$\Lambda(uds)$	$\Sigma^+(uus)$	$\Sigma^0(uds)$	$\Sigma^-(dds)$	$\Xi^0(uss)$	$\Xi^-(dss)$
δu	1.08	−0.32	−0.03	1.08	0.53	−0.02	−0.32	−0.02
δd	−0.32	1.08	−0.03	−0.02	0.53	1.08	−0.02	−0.32
δs	−0.01	−0.01	0.79	−0.29	−0.29	−0.29	1.06	1.06

Isospin relations

$$\begin{aligned} \delta u_p &= \delta d_n, & \delta u_n &= \delta d_p, & \delta u_\Lambda &= \delta d_\Lambda, & \delta u_{\Sigma^+} &= \delta d_{\Sigma^-}, \\ \delta u_{\Sigma^0} &= \delta d_{\Sigma^0}, & \delta u_{\Sigma^-} &= \delta d_{\Sigma^+}, & \delta u_{\Xi^0} &= \delta d_{\Xi^-}, & \delta u_{\Xi^-} &= \delta d_{\Xi^0}, \\ \delta s_p &= \delta s_n, & \delta s_{\Sigma^\pm} &= \delta s_{\Sigma^0}, & \delta s_{\Xi^0} &= \delta s_{\Xi^-}, \end{aligned}$$

SU(3) relations

$$\begin{aligned} \delta u_p &= \delta d_n = \delta u_{\Sigma^+} = \delta d_{\Sigma^-} = \delta s_{\Xi^0} = \delta s_{\Xi^-}, \\ \delta u_n &= \delta d_p = \delta u_{\Xi^0} = \delta d_{\Xi^-} = \delta s_{\Sigma^\pm} = \delta s_{\Sigma^0}. \end{aligned}$$

T. Ledwig, A. Silva, HChK, Phys. Rev. D **82** (2010) 034022

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δs	−0.01	−0.01	0.79	−0.29	−0.29	−0.29	1.06	1.06

Isospin relations

$$\begin{aligned} \delta u_p &= \delta d_n, & \delta u_n &= \delta d_p, & \delta u_\Lambda &= \delta d_\Lambda, & \delta u_{\Sigma^+} &= \delta d_{\Sigma^-}, \\ \delta u_{\Sigma^0} &= \delta d_{\Sigma^0}, & \delta u_{\Sigma^-} &= \delta d_{\Sigma^+}, & \delta u_{\Xi^0} &= \delta d_{\Xi^-}, & \delta u_{\Xi^-} &= \delta d_{\Xi^0}, \\ \delta s_p &= \delta s_n, & \delta s_{\Sigma^\pm} &= \delta s_{\Sigma^0}, & \delta s_{\Xi^0} &= \delta s_{\Xi^-}, \end{aligned}$$

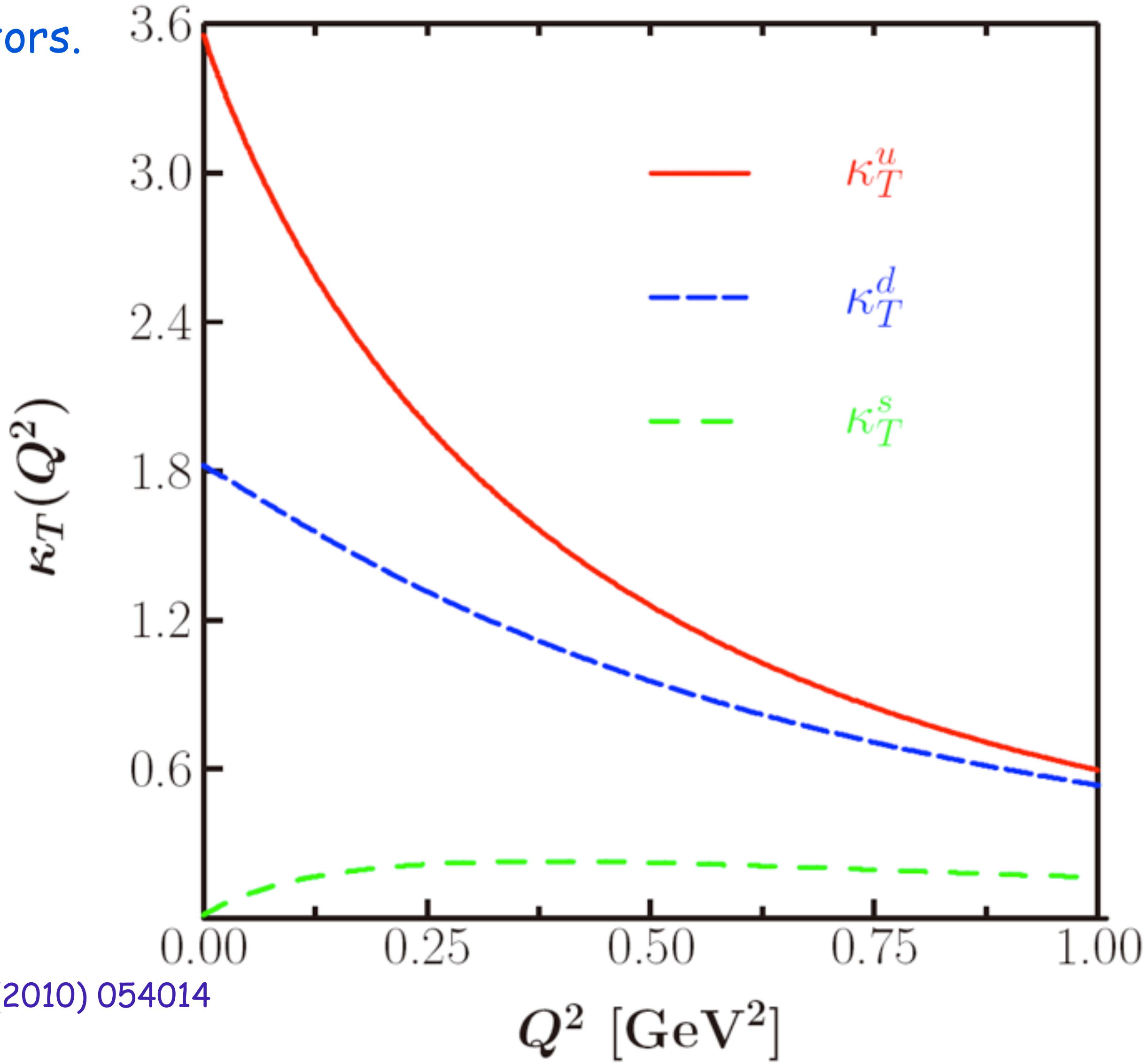
SU(3) relations → Effects of SU(3) symmetry breaking are almost negligible!

$$\begin{aligned} \delta u_p &= \delta d_n = \delta u_{\Sigma^+} = \delta d_{\Sigma^-} = \delta s_{\Xi^0} = \delta s_{\Xi^-}, \\ \delta u_n &= \delta d_p = \delta u_{\Xi^0} = \delta d_{\Xi^-} = \delta s_{\Sigma^\pm} = \delta s_{\Sigma^0}. \end{aligned}$$

T. Ledwig, A. Silva, HChK, Phys. Rev. D **82** (2010) 034022

Results

Flavor decomposition of the anomalous tensor magnetic form factors.

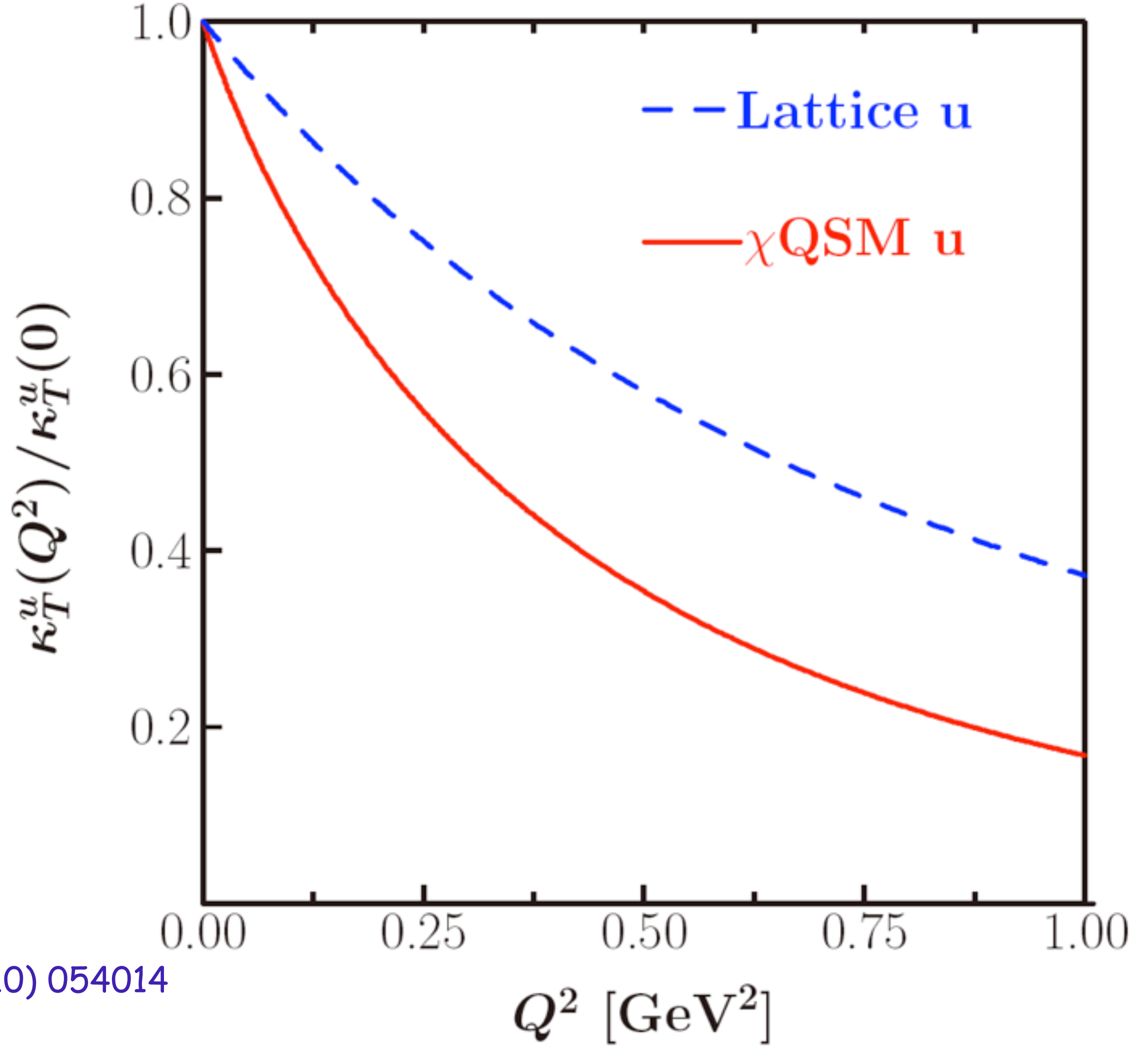


. Ledwig, A. Silva, HChK, Phys. Rev. D **82** (2010) 054014

Results

Up anomalous tensor magnetic form factors compared with the lattice one.

M. Goeckeler et al. [QCDSF Coll. and UKQCD Coll.] PRL 98, 222001 (2007)

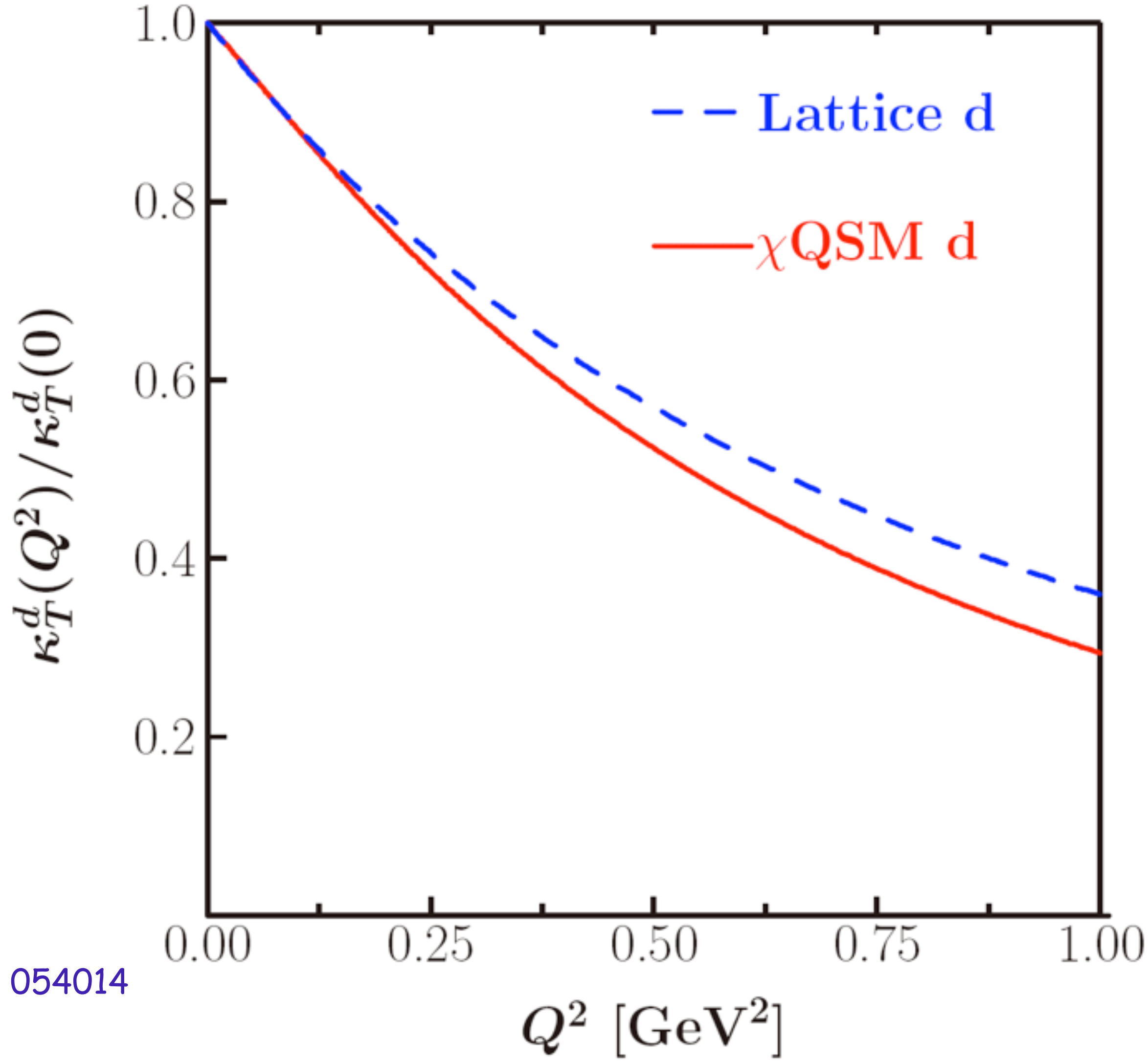


Ledwig, A. Silva, HChK, Phys. Rev. D **82** (2010) 054014

Results

Down anomalous tensor magnetic form factors compared with the lattice one.

M. Goeckeler et al. [QCDSF Coll. and UKQCD Coll.] PRL 98, 222001 (2007)



Ledwig, A. Silva, HChK, Phys. Rev. D **82** (2010) 054014