Transverse structure of the Nucleon

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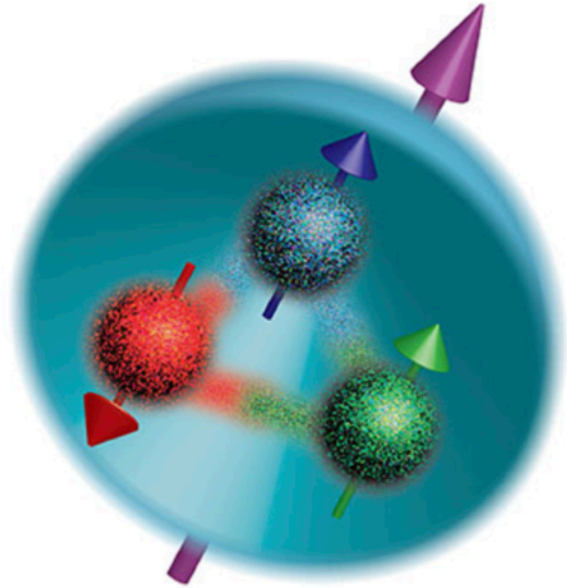
Spin structure of the Nucleon

Naive Understanding of the Nucleon Spin

- A nucleon consists of two up and one down quarks.
- Nucleon spin: 1/2
- Quark spin: 1/2



- Nucleon spin should come from the three quarks:

$$\frac{1}{2} \otimes \frac{1}{2} \otimes \frac{1}{2} = (0 \oplus 1) \otimes \frac{1}{2} = \frac{1}{2} \oplus \frac{1}{2} \oplus \frac{3}{2}$$

Picture in the NRQM

Figure taken from Eur. Phys. J. A (2016) 52: 268

Spin Crisis in 1988

A Measurement of the Spin Asymmetry and Determination of the Structure Function g(1) in Deep Inelastic Muon-Proton Scattering
European Muon Collaboration (J. Ashman (Sheffield U.) *et al.*). Dec 1987. 7 pp.
Published in **Phys.Lett. B206 (1988) 364**
CERN-EP-87-230
DOI: 10.1016/0370-2693(88)91523-7
Conference: C94-01-05.1, p.340-346 Proceedings

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service
Data: INSPIRE | HepData

Detailed record - Cited by 2094 records 1000+

$$\Delta\Sigma \sim 0.15 \quad (\Delta\Sigma_{\mathrm{NRQM}} = 1)$$

What's wrong with the NRQM?

$$\Delta\Sigma = g_A^0 = \Delta u + \Delta d + \Delta s$$

Sea-quark polarization

Spin structure of the nucleon

$$\Delta\Sigma|_{\mathrm{DIS}} = 0.33 - 0.36$$

Aidala etal, RMP, 85, 655 (2013)

The quark content of the nucleon spin: max(40 %)

Where does the nucleon spin come from?

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_G$$

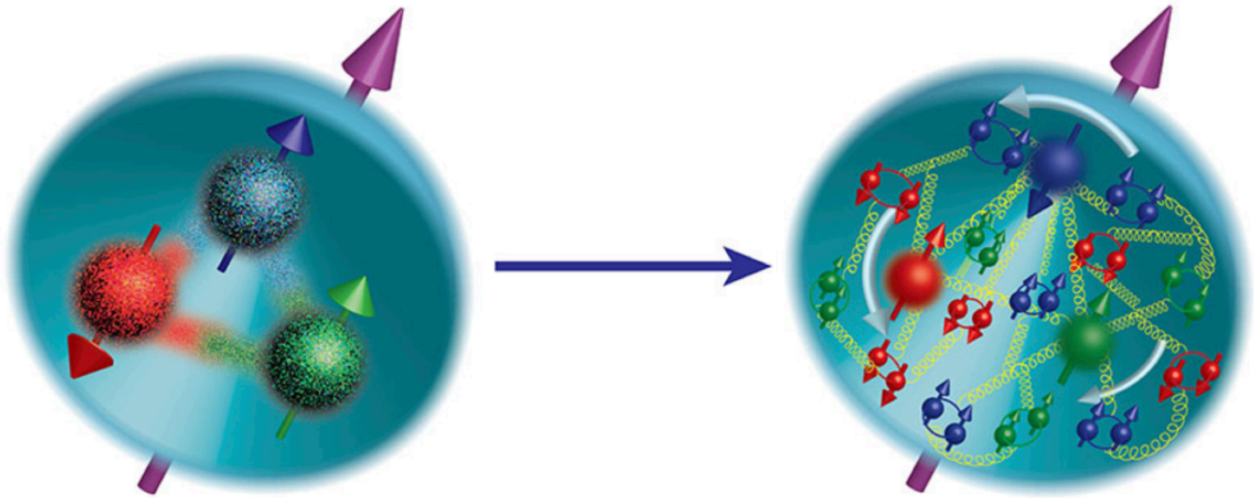
Gluon content

Angular momenta

One VI direction of hadronic physics in the future

Spin structure of the nucleon

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_G$$

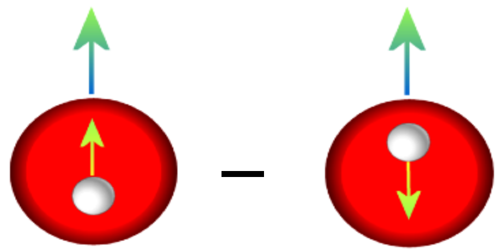


NRQM ⟶ NPQCD

Figure taken from Eur. Phys. J. A (2016) 52: 268

Transversity of the nucleon

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



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

- 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).

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

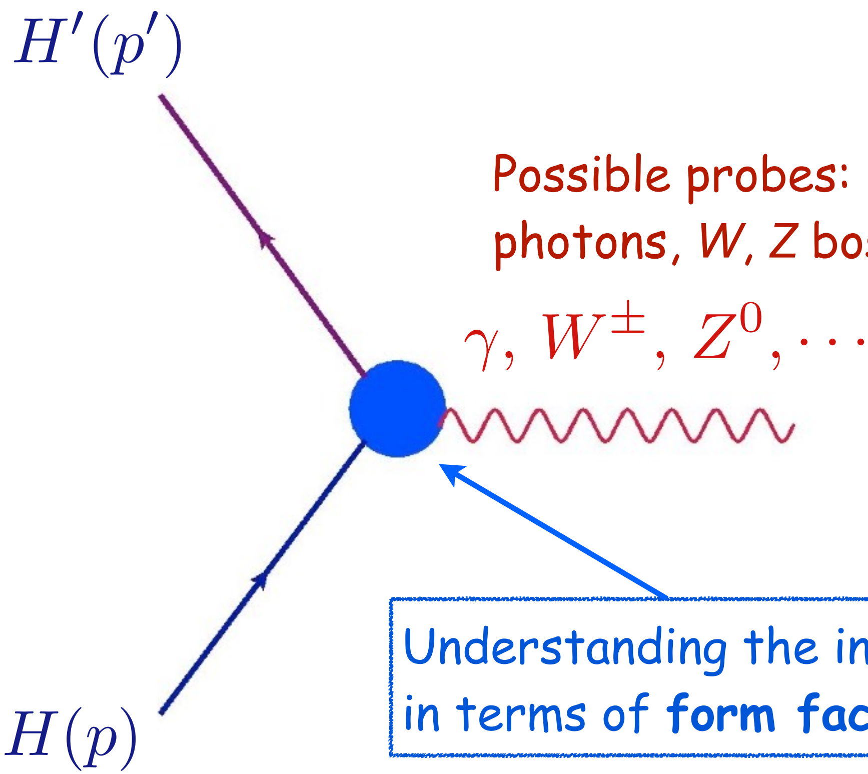
[16] M. Anselmino et al. Nucl. Phys. B, Proc. Suppl. 191, 98 (2009)

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

Modern Understanding of the Nucleon

Traditional way of a hadron structure

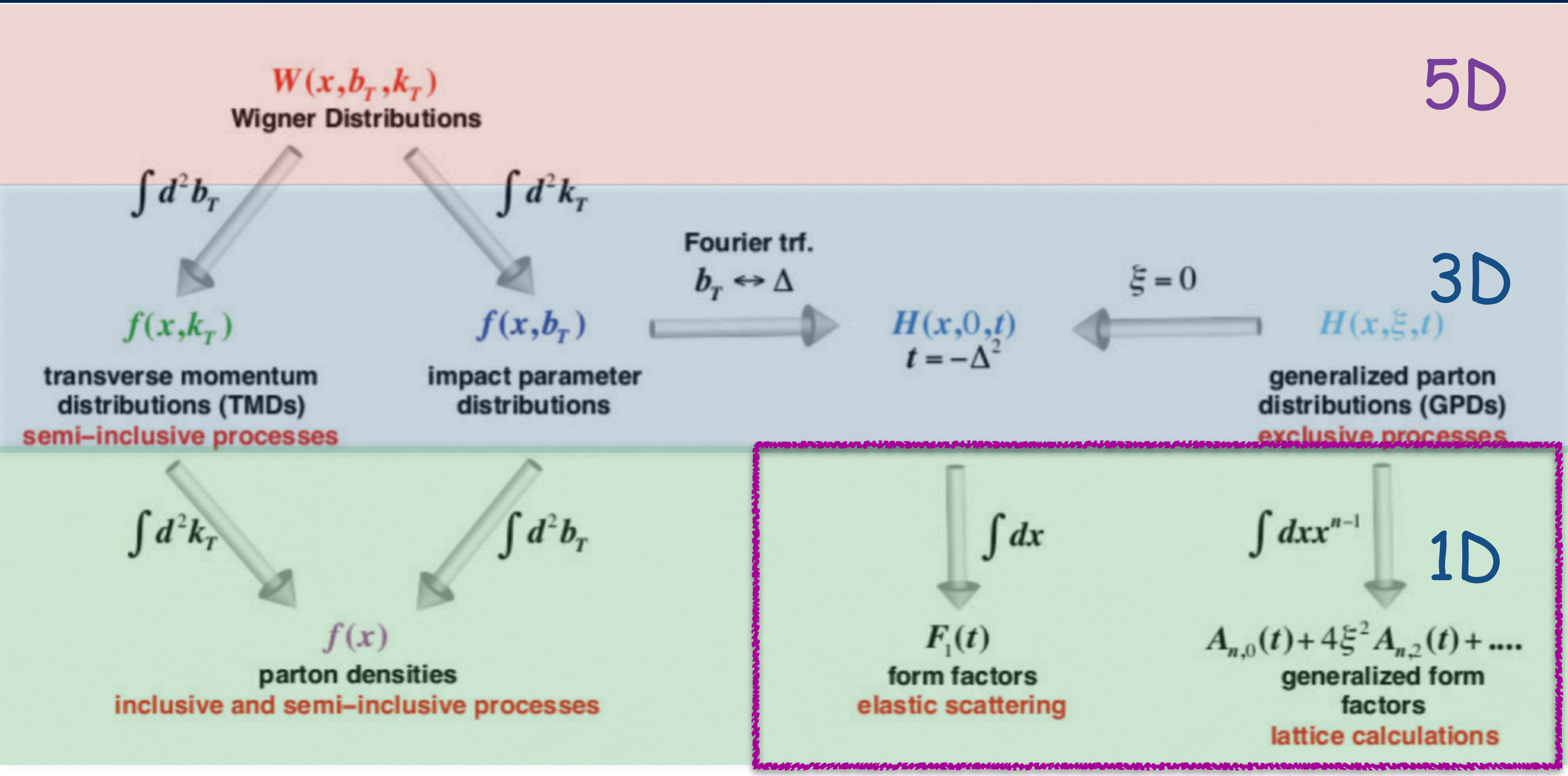
Traditional way of studying structures of hadrons



Possible probes:
photons, *W*, *Z* bosons, mesons, nucleons......

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

Modern understanding of a baryon structure



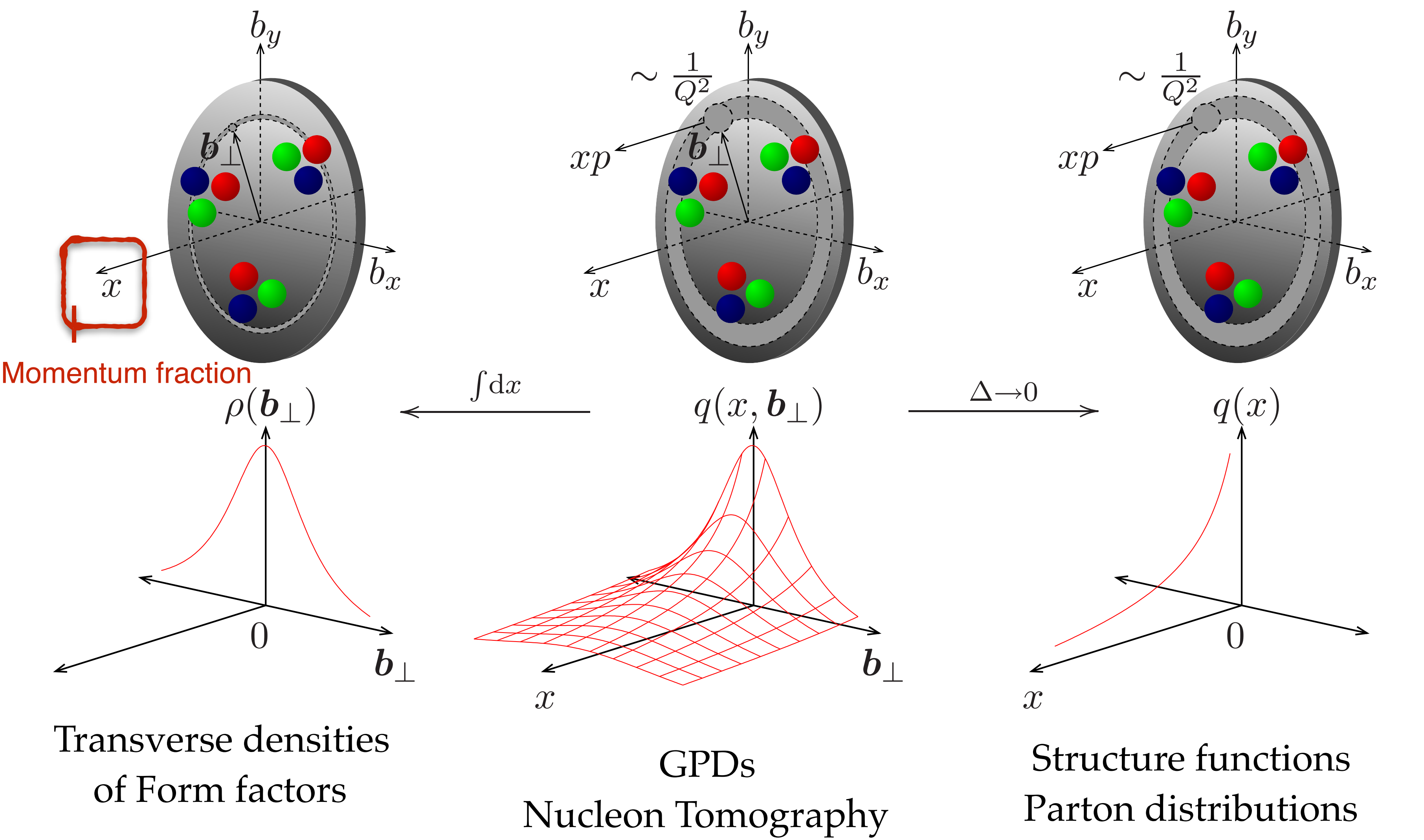
Today's topic to discuss

State of the art of the nucleon tomography

Figure taken from Eur. Phys. J. A (2016) 52: 268

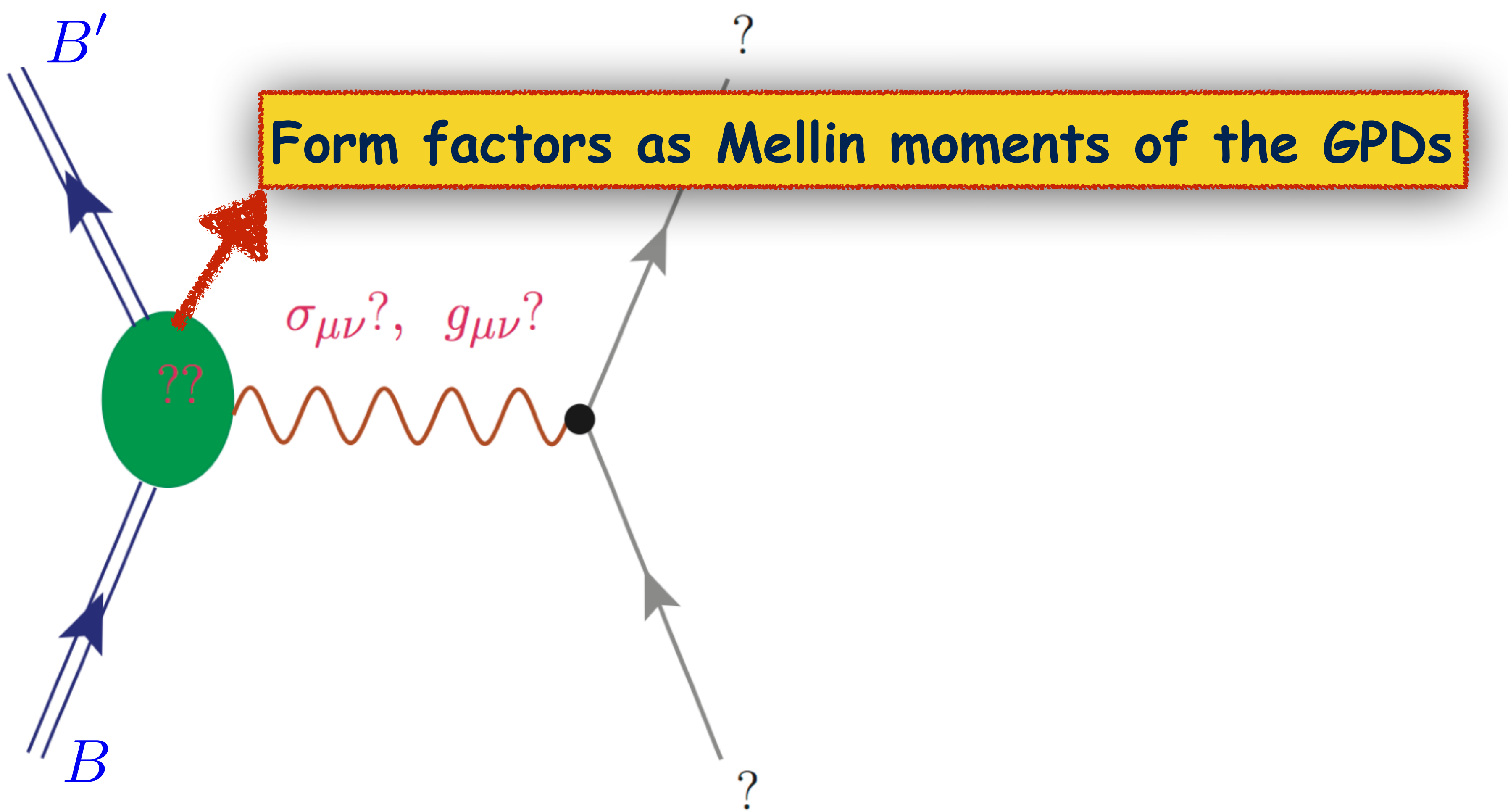
Modern understanding of a baryon structure

3D Nucleon Tomography



Modern understanding of a baryon structure

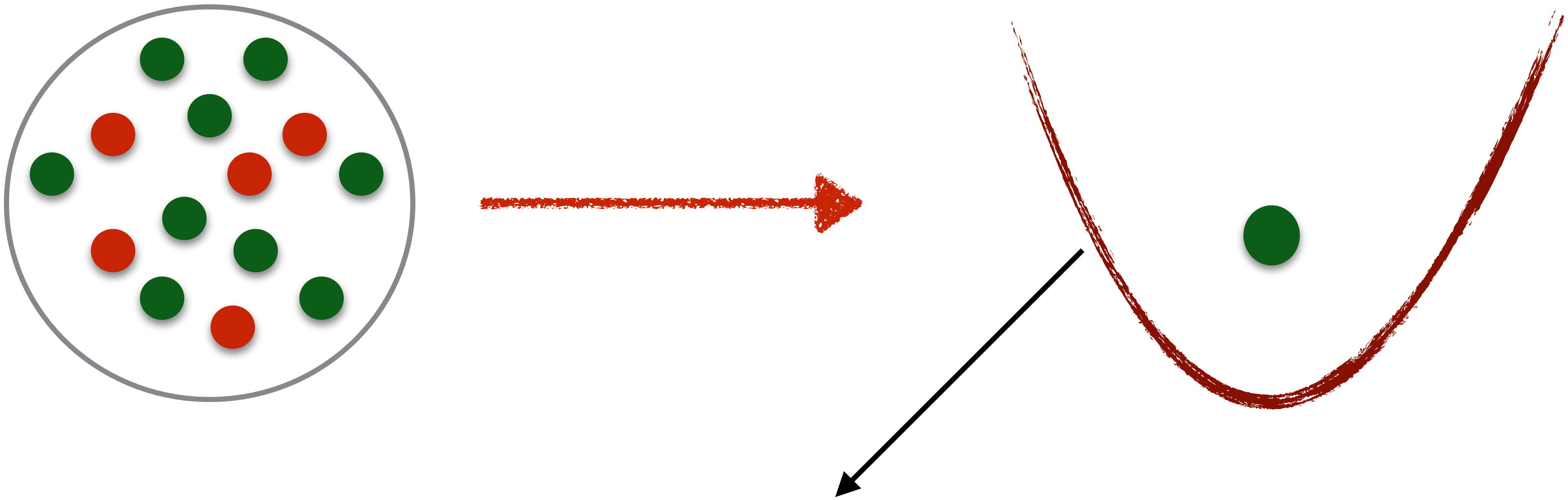
Probes are unknown for **Tensor form factors**
and the **Energy-Momentum Tensor form factors!**



Nucleon as Nc quarks bound by the pion mean fields

Mean-Field Approximation

Simple picture of a mean-field approximation



Mean-field potential that is produced by all other particles.

- Nuclear shell models
- Ginzburg-Landau theory for superconductivity
- Quark potential models for baryons

Mean-Field Approximation

More theoretically defined mean fields

Given action, $S[\phi]$

$$\left.\frac{\delta S}{\delta \phi}\right|_{\phi=\phi_0} = 0$$: Solution of this saddle-point equation ϕ_0

Key point: Ignore the quantum fluctuation.

→ How we can understand the structure of baryons, based on this mean field approach, this is the subject of the present talk.

Baryon in pion mean fields

* A baryon can be viewed as a state of Nc quarks bound by mesonic **mean fields** (E. Witten, NPB, 1979 & 1983).

→ Its mass is proportional to *Nc*, while its width is of order *O(1)*.
Mesons are weakly interacting (Quantum fluctuations are suppressed by 1/Nc: *O(1/Nc)*.

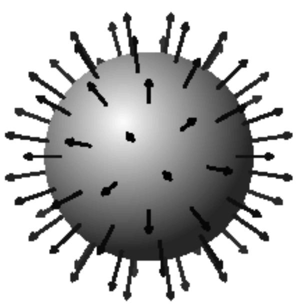
Meson mean-field approach (Chiral Quark-Soliton Model)

* Baryons as a state of Nc quarks bound by mesonic mean fields.

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

* Key point: Hedgehog Ansatz

$$\pi^a(\boldsymbol{r}) = \begin{cases} n^a F(r),\ n^a = x^a/r, & a = 1,\ 2,\ 3 \\ 0, & a = 4,\ 5,\ 6,\ 7,\ 8. \end{cases}$$



hedgehog

→ It breaks spontaneously $\mathrm{SU}(3)_{\mathrm{flavor}} \otimes \mathrm{O}(3)_{\mathrm{space}} \to \mathrm{SU}(2)_{\mathrm{isospin+space}}$

Baryon in pion mean fields

✱ Merits of the Chiral Quark-Soliton Model

- It is directly related to nonperturbative QCD via the Instanton vacuum.

  → Natural scale of the model given by the instanton size:

$$\rho \approx (600\,\mathrm{MeV})^{-1}$$

- Fully relativistic quantum-field theoretic model (we have a QCD vacuum):

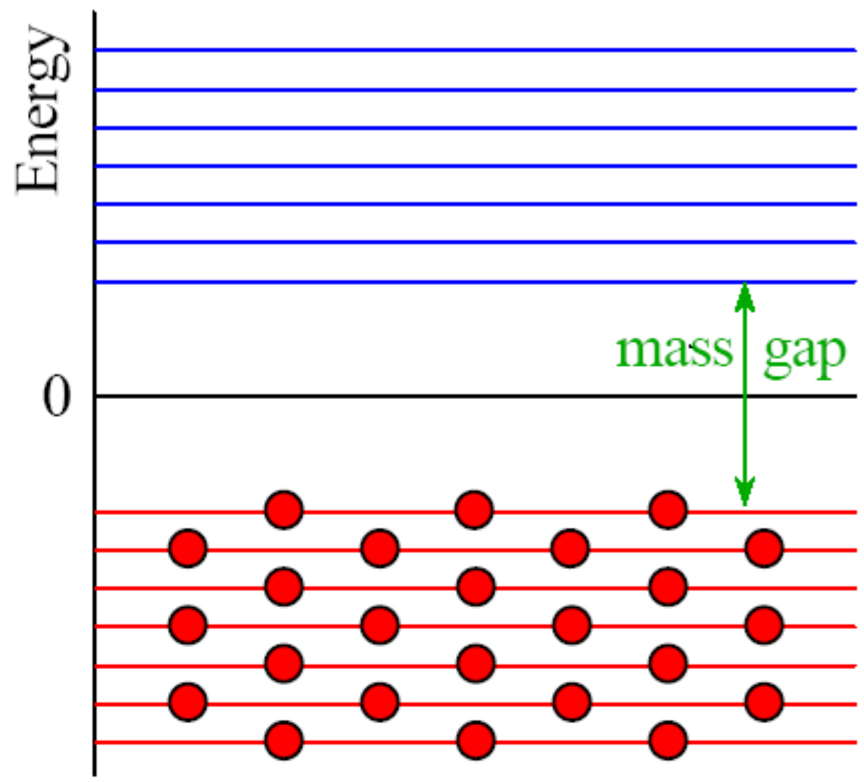
  It explains almost all properties of the lowest-lying baryons.

- It describes the light & heavy baryons on an equal footing

  (Advantage of the mean-field approach) .

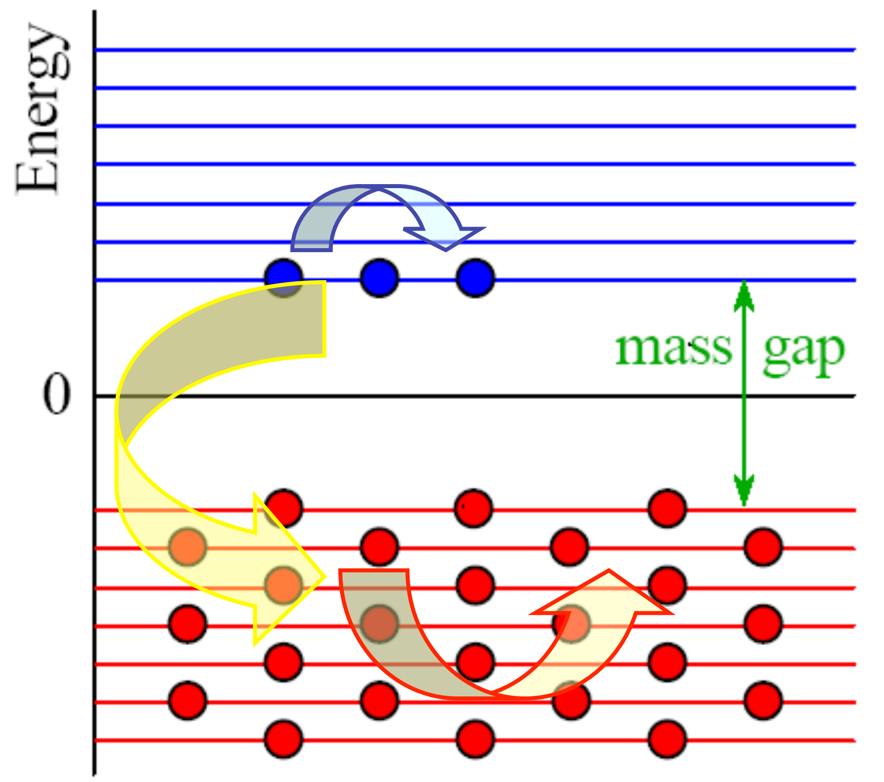
- Basically, no free parameter to fit the experimental data.
  Cutoff parameter is fixed by the pion decay constant, and
  Dynamical quark mass (M=420 MeV) is fixed by the proton
  radius.

Baryon in pion mean fields



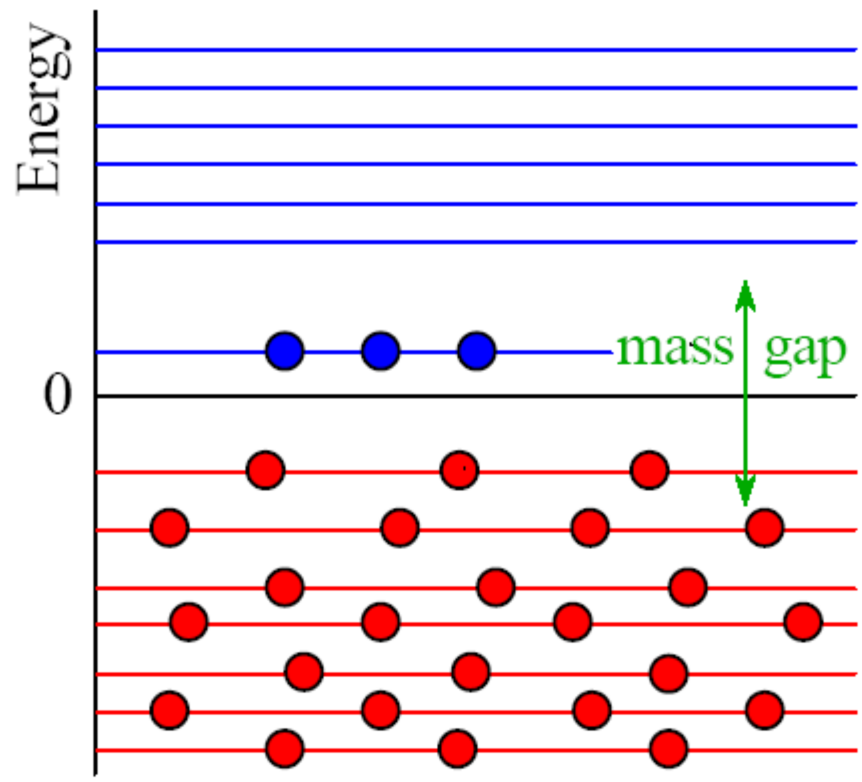
HChK et al. Prog. Part. Nucl. Phys. Vol.95, (1995)

Baryon in pion mean fields



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

Baryon in pion mean fields

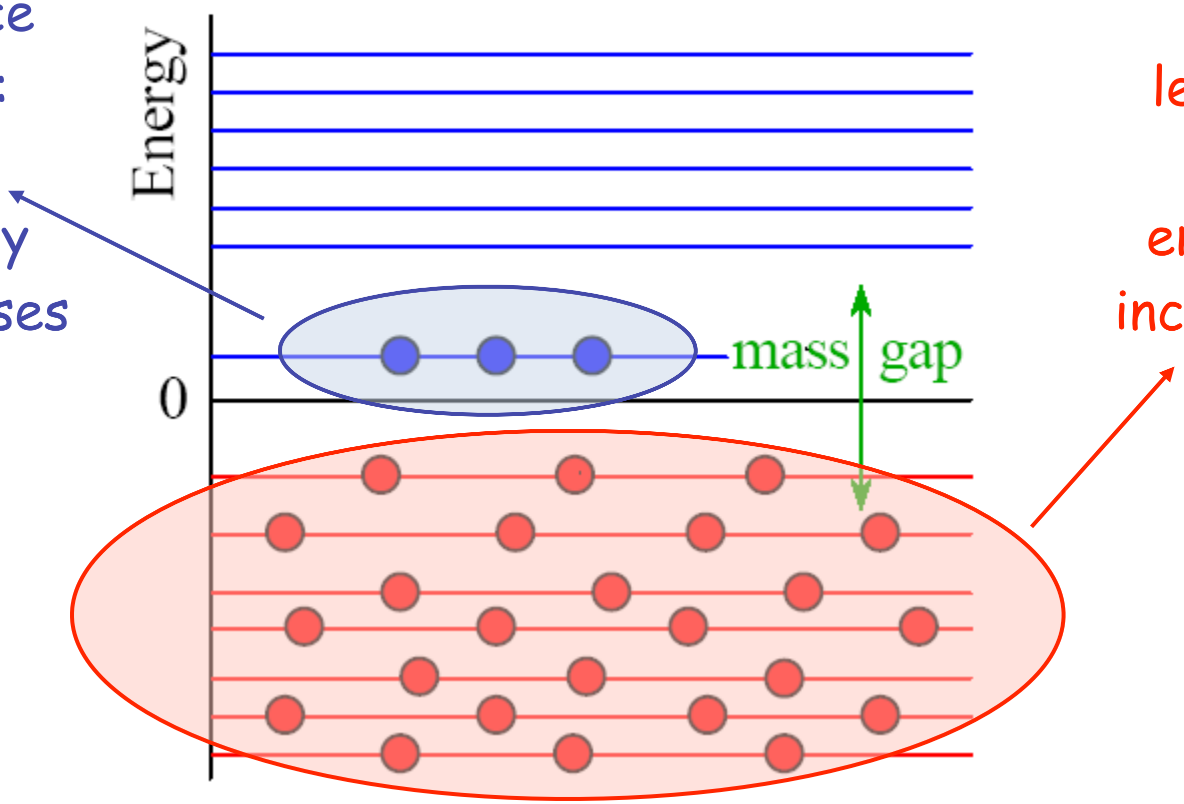


HChK et al. Prog. Part. Nucl. Phys. Vol.95, (1995)

Baryon in pion mean fields

valence level:

energy decreases



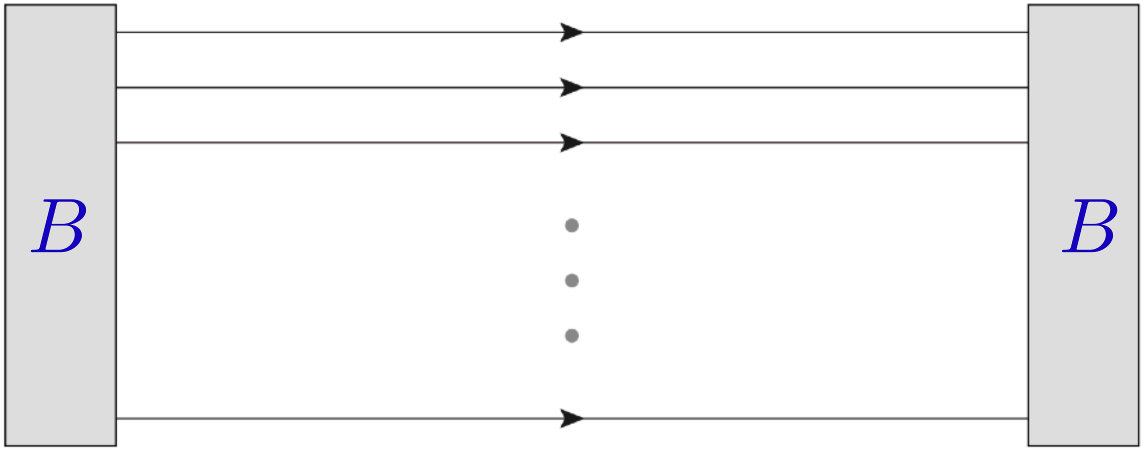
sea levels:

energy increases

system is stabilized

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

A light baryon in pion mean fields

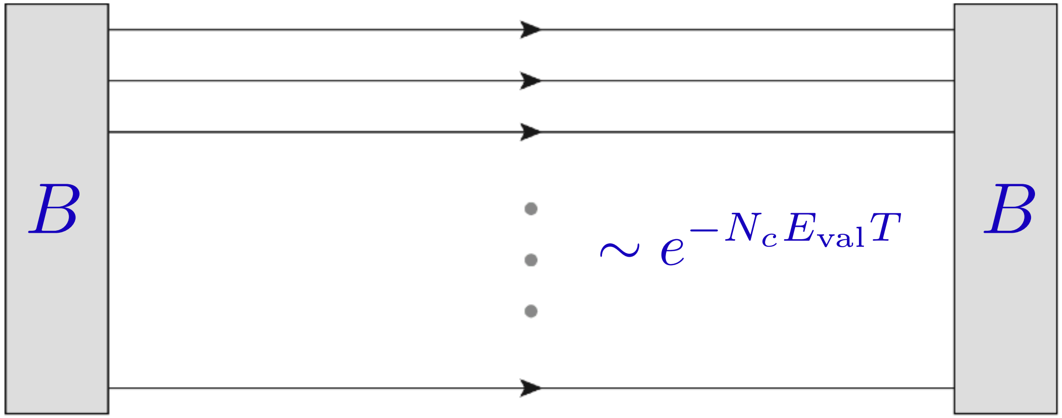


$$\langle J_B J_B^\dagger \rangle_0 \sim e^{-N_c E_{\rm val} T}$$

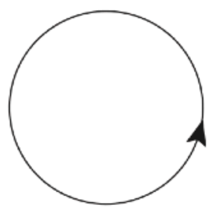
Presence of Nc quarks will polarize the vacuum or create mean fields.

Nc valence quarks → Vacuum polarization or meson mean fields

A light baryon in pion mean fields



$$E_{\rm cl} = N_c E_{\rm val} + E_{\rm sea}$$



$$\sim e^{-E_{\rm sea} T}$$

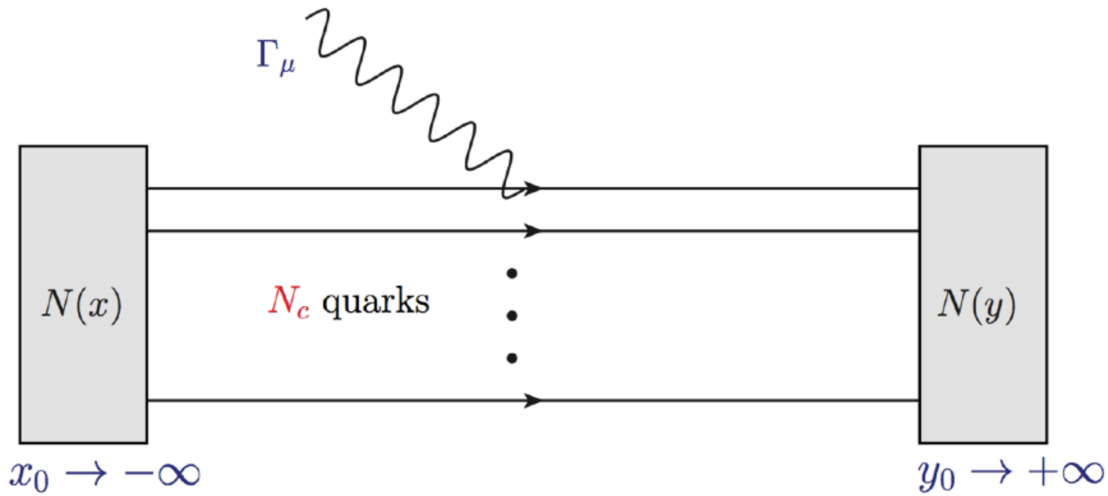
Classical Nucleon mass is described by the Nc valence quark energy and sea-quark energy.

$$\frac{\delta E_{cl}}{\delta U} = 0 \quad \longrightarrow \quad M_{\rm cl} \longrightarrow P(r)$$

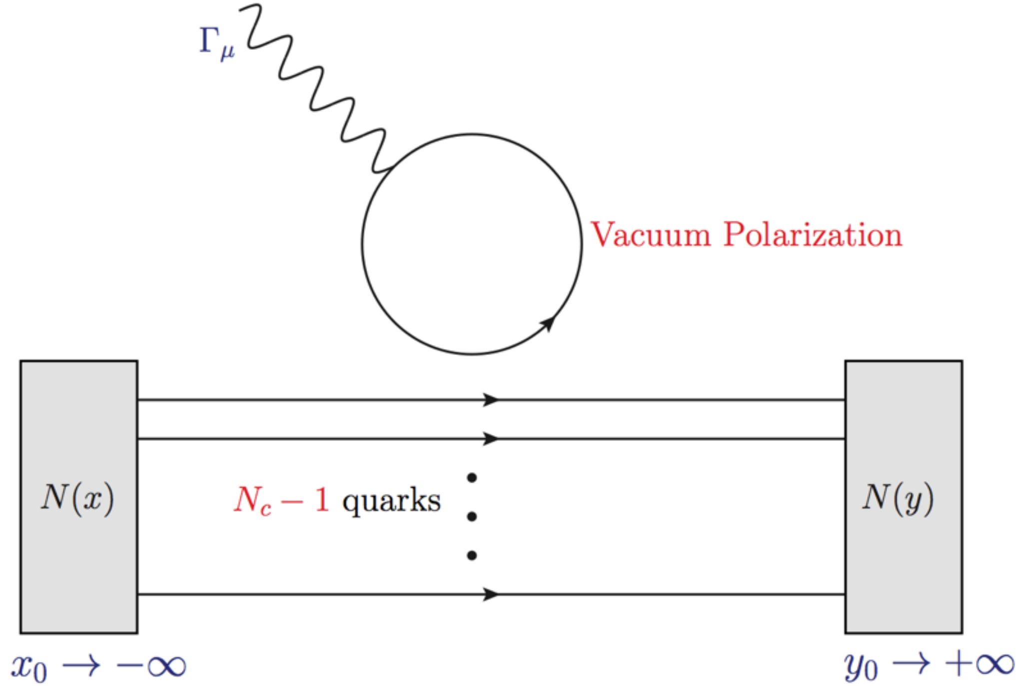
P(r): Soliton profile function or Soliton field

An observable for the light baryon

Valence part

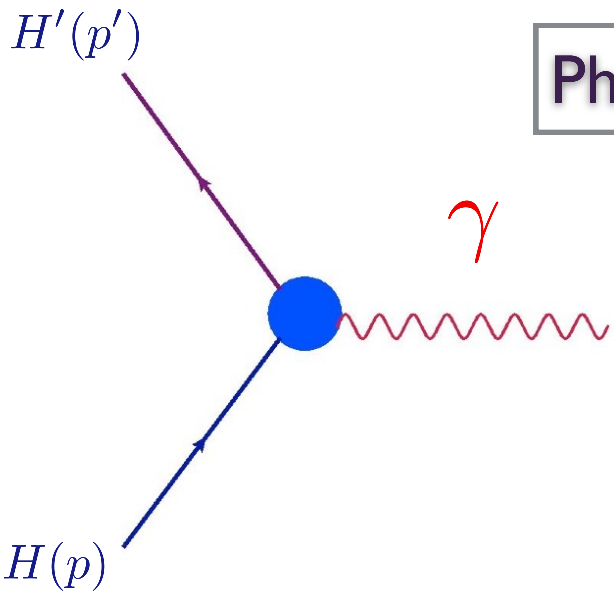


Sea part



EM Form factors
of
the Nucleon

Traditional definition of form factors



Photons → Charge & magnetic densities

$\nu,\ e_{PV}$

Neutrino or PV electron scattering

↓

Axial-Vector properties

No probe for the tensor & EMT (grav.) form factors!

$$\langle N(P')|\bar{q}(0)\gamma^{\mu}q(0)|N(P)\rangle = \overline{U}(P')\left\{\gamma^{\mu}F_1(t) + \frac{i\sigma^{\mu\nu}\Delta_{\nu}}{2m_N}F_2(t)\right\}U(P),$$

$$\langle N(P')|\bar{q}(0)\gamma^{\mu}\gamma_5 q(0)|N(P)\rangle = \overline{U}(P')\left\{\gamma^{\mu}\gamma_5 G_A(t) + \frac{\gamma_5\Delta^{\mu}}{2m_N}G_P(t)\right\}U(P),$$

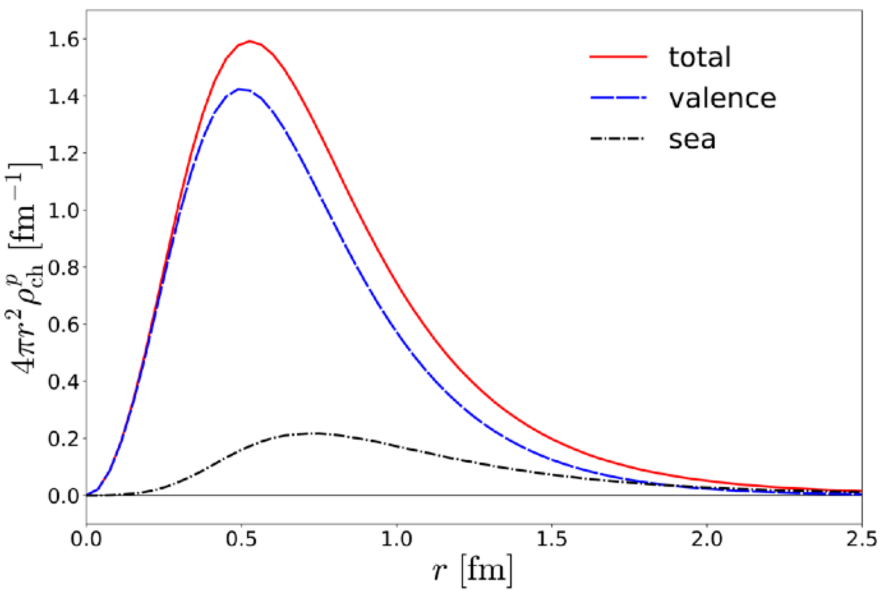
Traditional definition of form factors

$$G_E^{p,n}(Q^2) \Longleftrightarrow \rho_{\rm ch}^{p,n}(r^2)$$

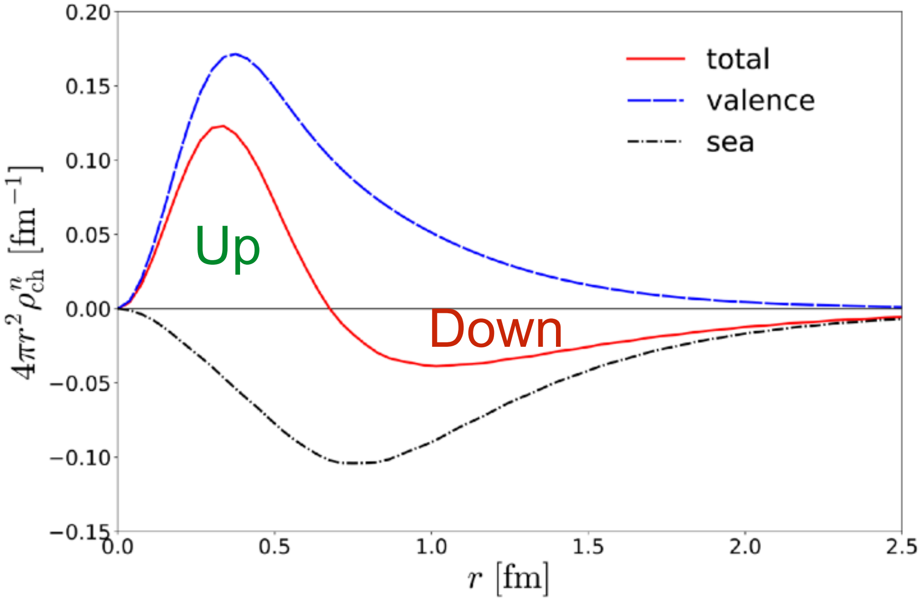
Fourier transform

Textbook physics since 1950s.

Proton



Neutron



New Definition

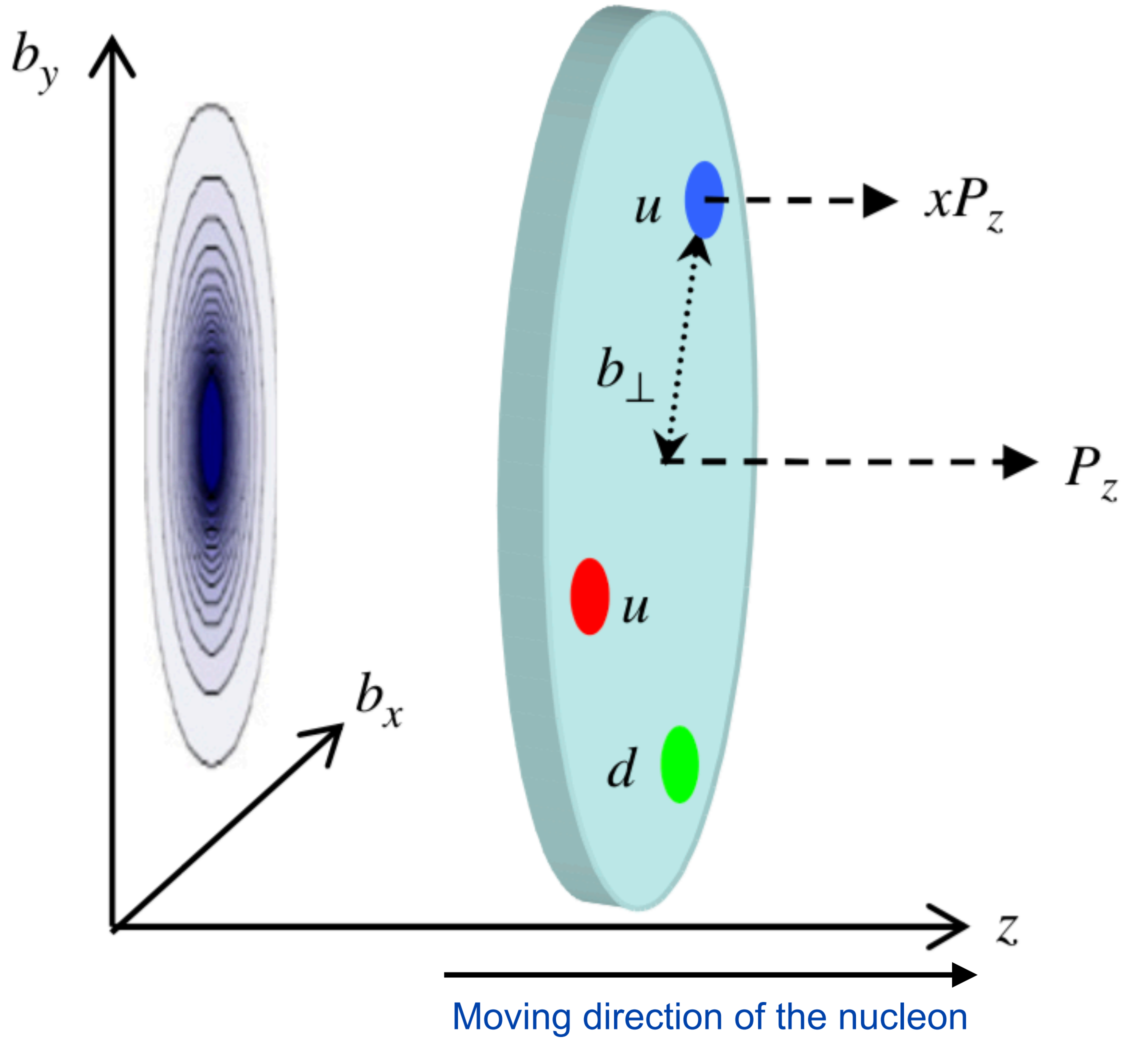
Generalized
Parton Distributions

Melin transform

Generalized
Form factors

2D Fourier transfor

Transverse
charge densities



Quark probabilities inside a nucleon

Transverse charge density

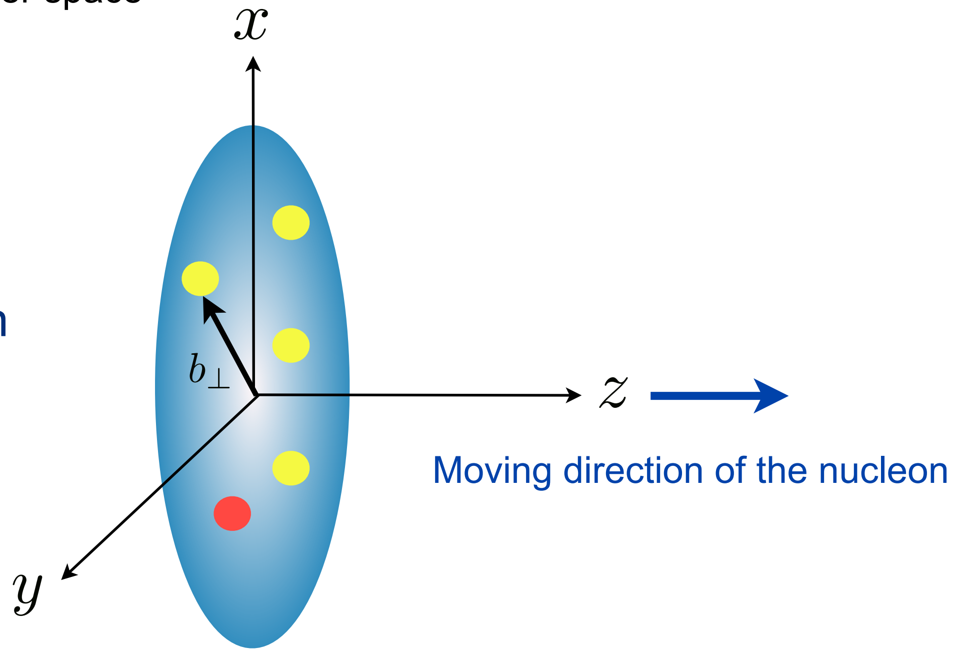
Why transverse charge densities?

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

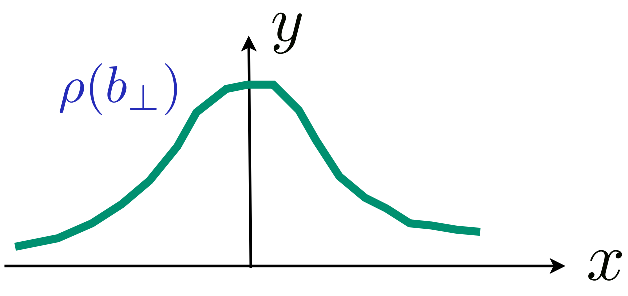
$$q(x,\,\mathbf{b}) = \int \frac{d^2q}{(2\pi)^2} e^{i\mathbf{q}\cdot\mathbf{b}} H_q(x,-\mathbf{q}^2)$$

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

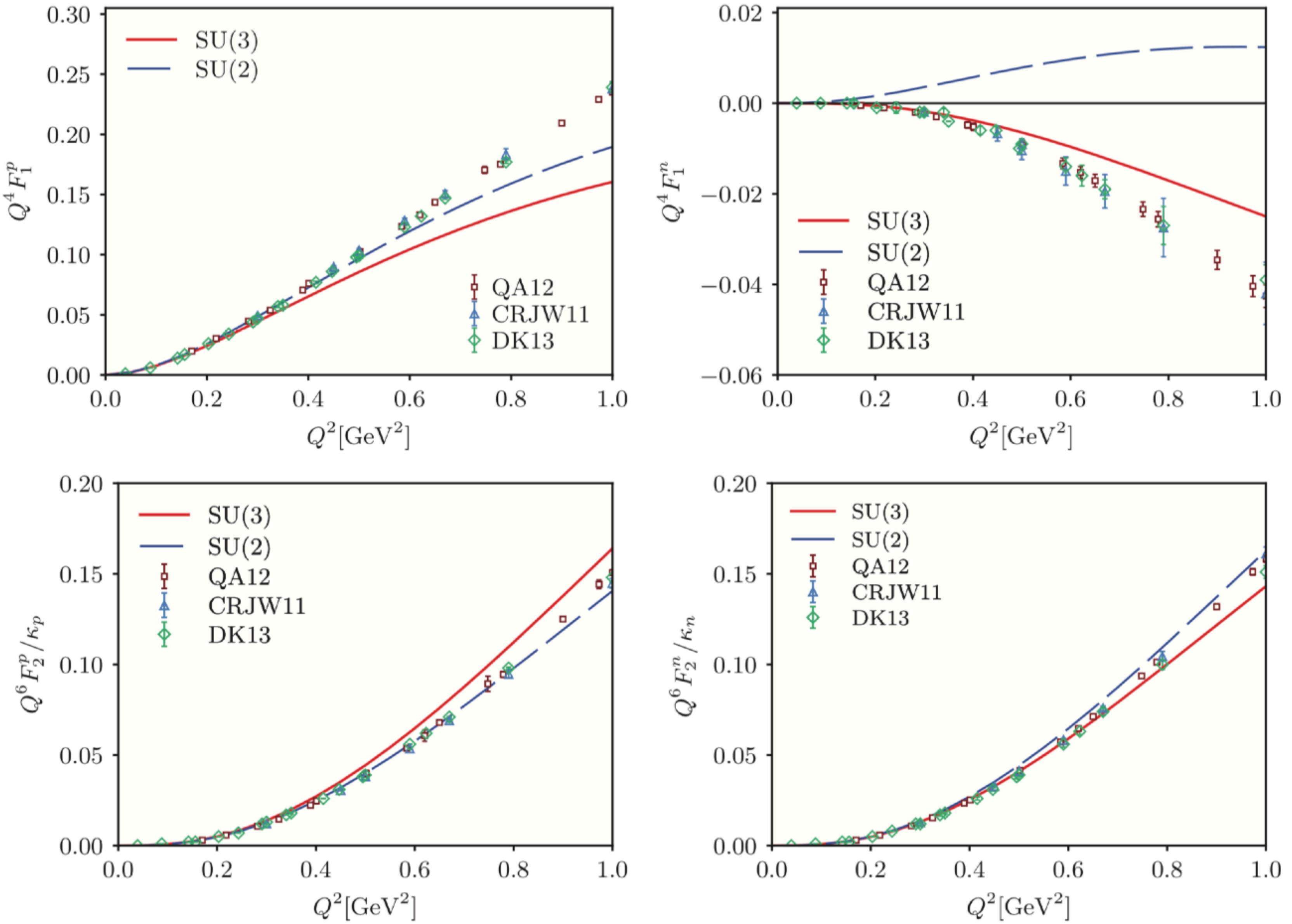
M. Burkardt, PRD **62**, 071503 (2000); Int. J. Mod. Phys. A **18**, 173 (2003).



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



Proton & neutron EM fom factors



Silva, Urbano, HChK, PTEP, 2018

Transverse charge density

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)

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

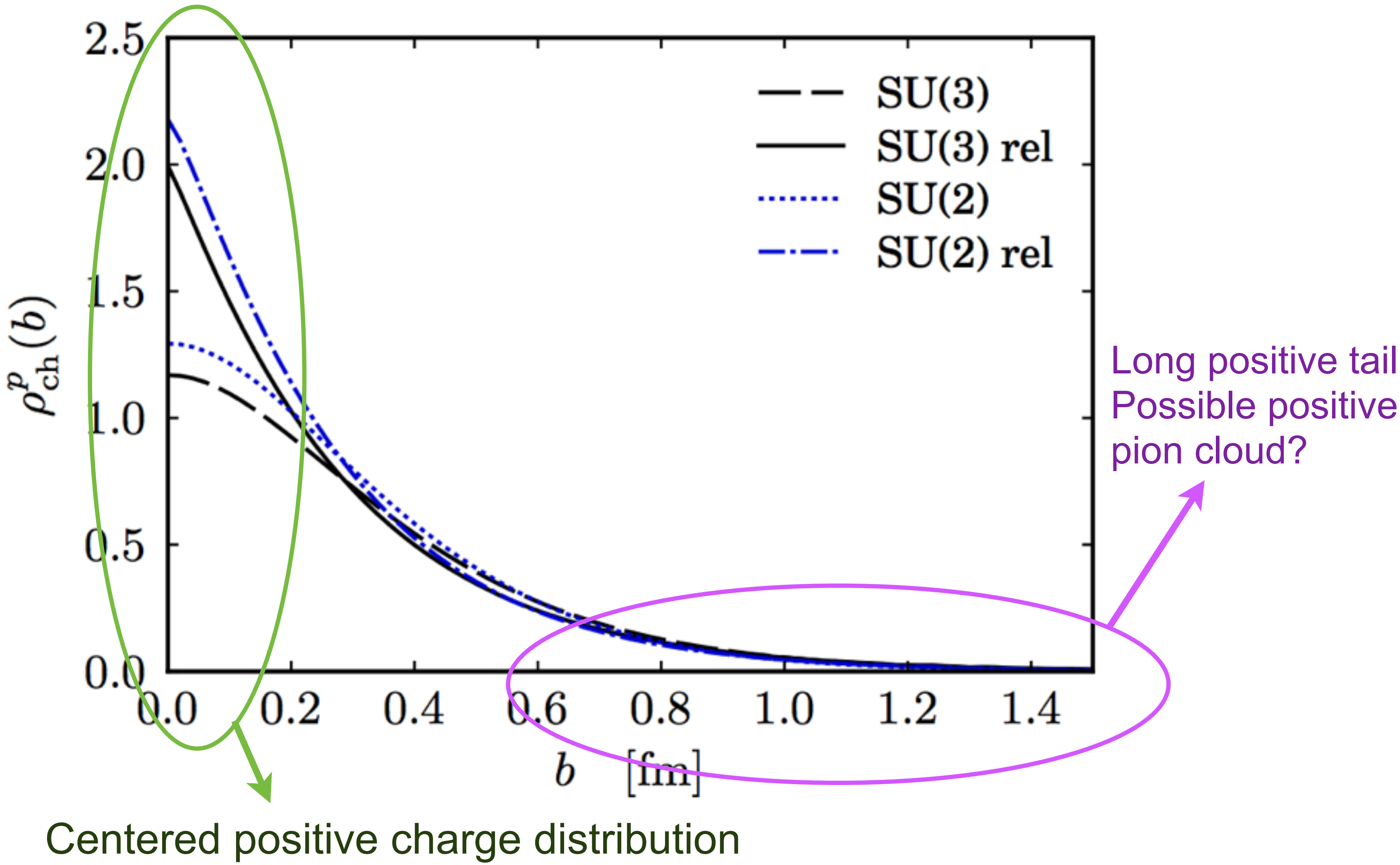
Inside an polarized nucleon

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

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

Proton & neutron transverse charge densities

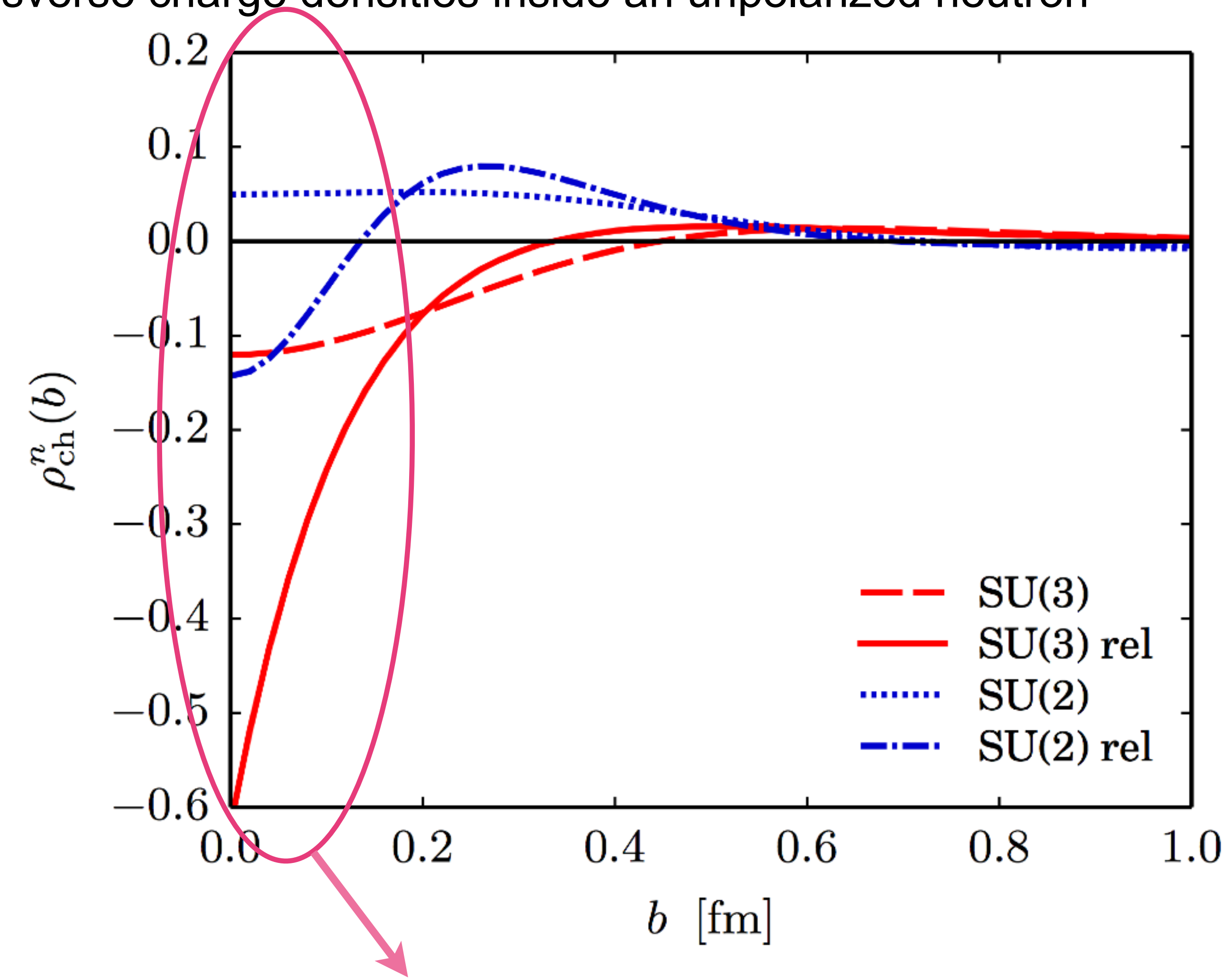
Transverse charge densities inside an unpolarized proton



Silva, Urbano, HChK, PTEP, (2018)

Proton & neutron transverse charge densities

Transverse charge densities inside an unpolarized neutron

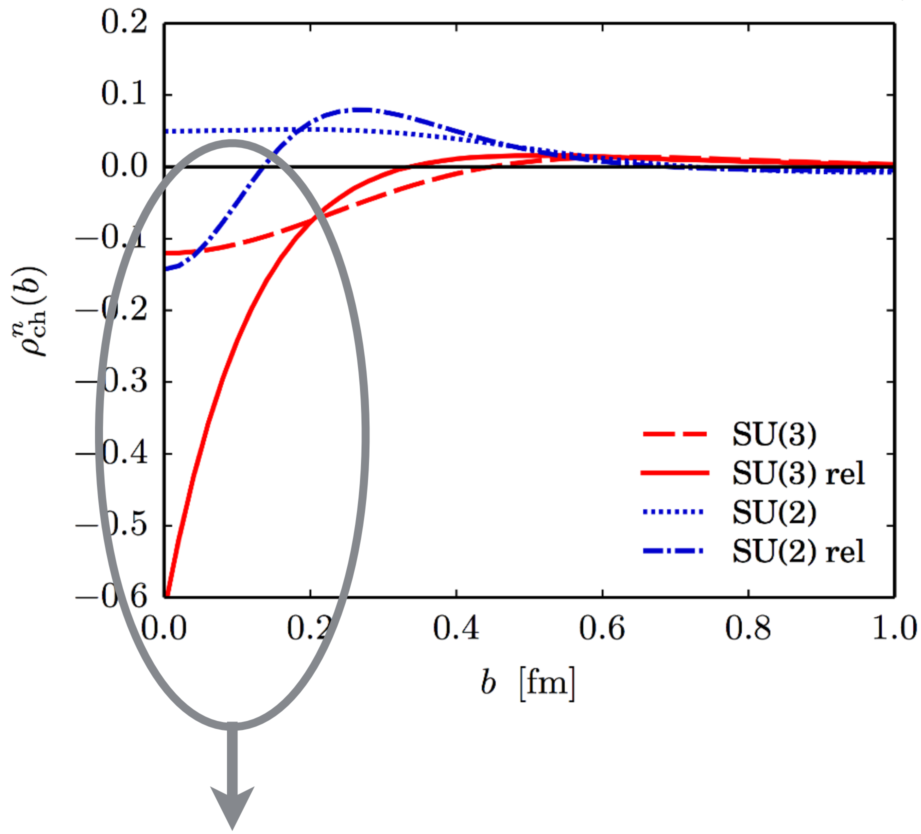


Surprisingly, negative charge distribution in the center of the neutron!

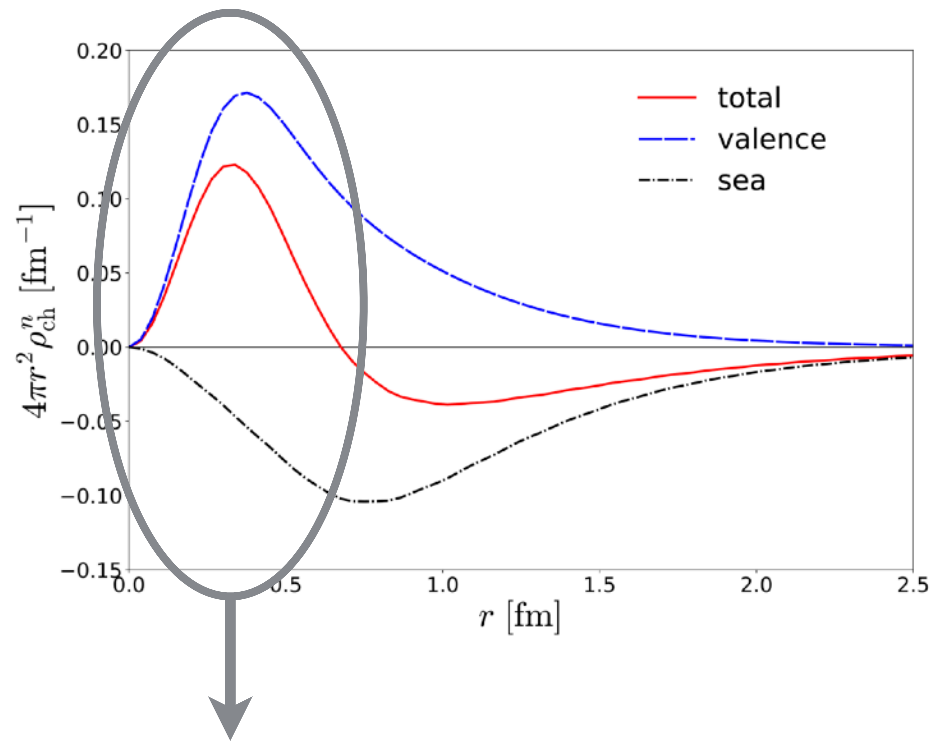
Silva, Urbano, HChK, PTEP, (2018)

Proton & neutron transverse charge densities

2D transverse charge density



3D charge density



Negative!

Relativistically invariant!

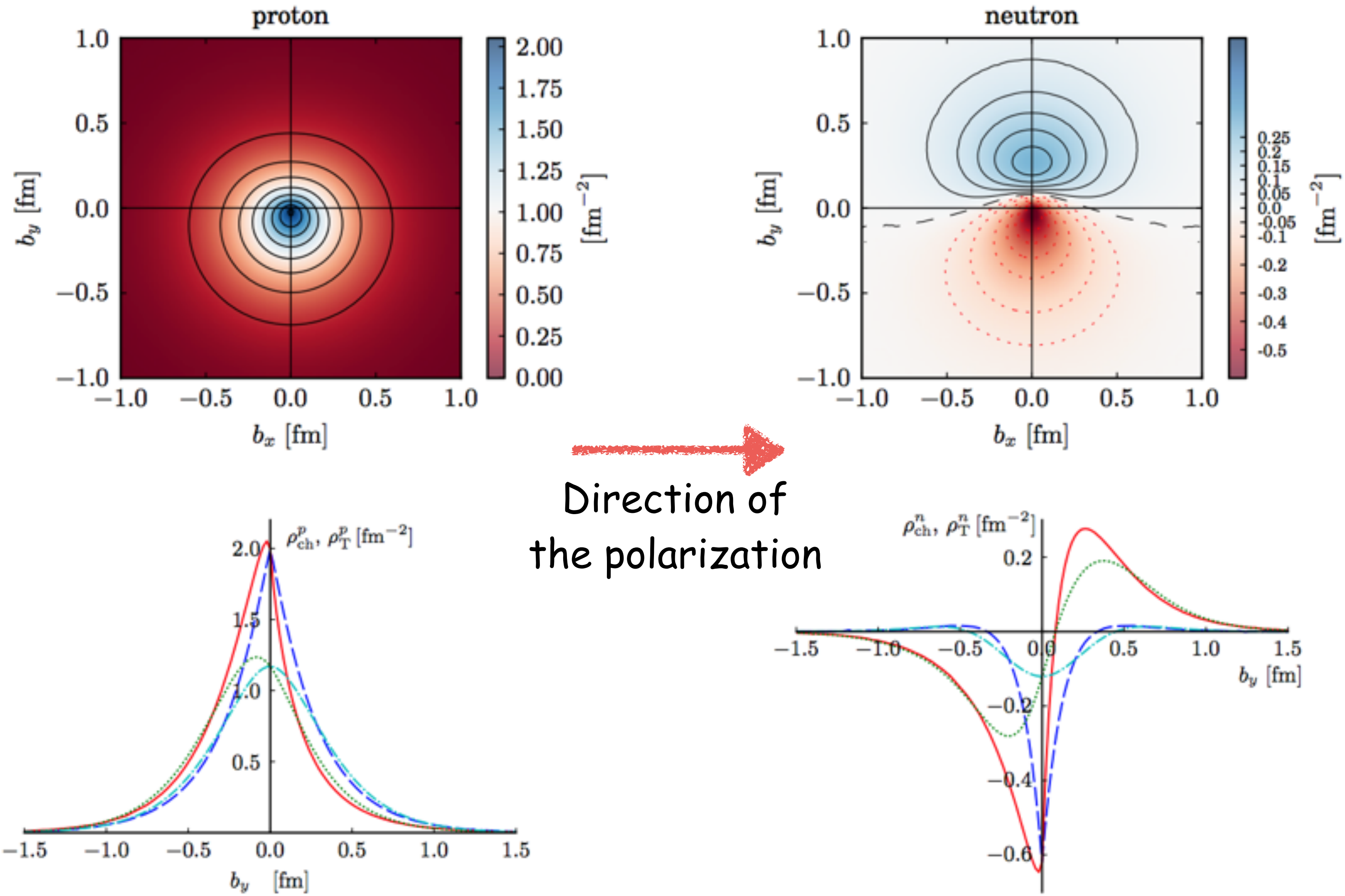
Positive!

Nonrelativistic!

Silva, Urbano, HChK, PTEP, (2018)

Proton & neutron transverse charge densities

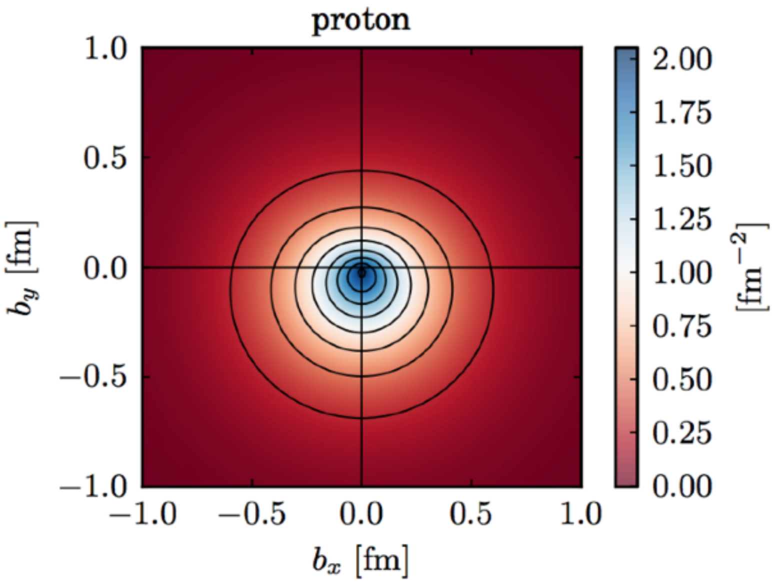
Transverse charge densities inside an **polarized** nucleon



Silva, Urbano, HChK, PTEP, (2018)

Proton & neutron transverse charge densities

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

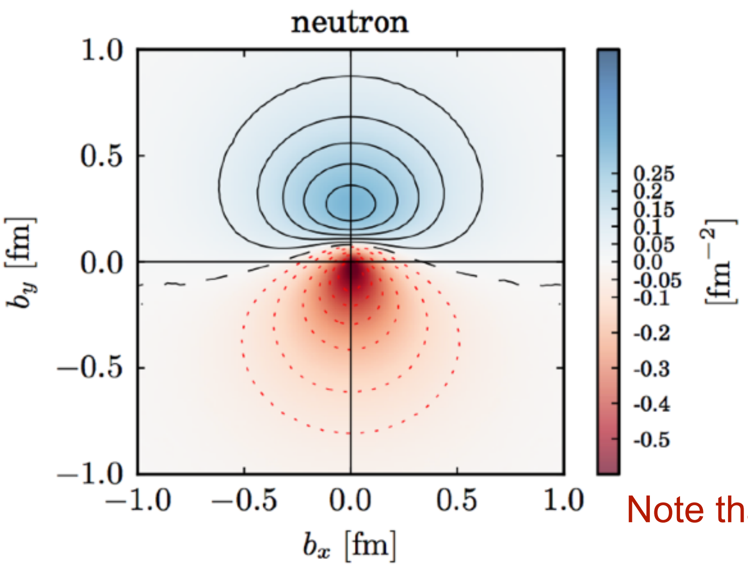


Nucleon polarization along the ***x*** axis:
Magnetic dipole field ***B***

$\vec{\mathbf{B}}$

b_x

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

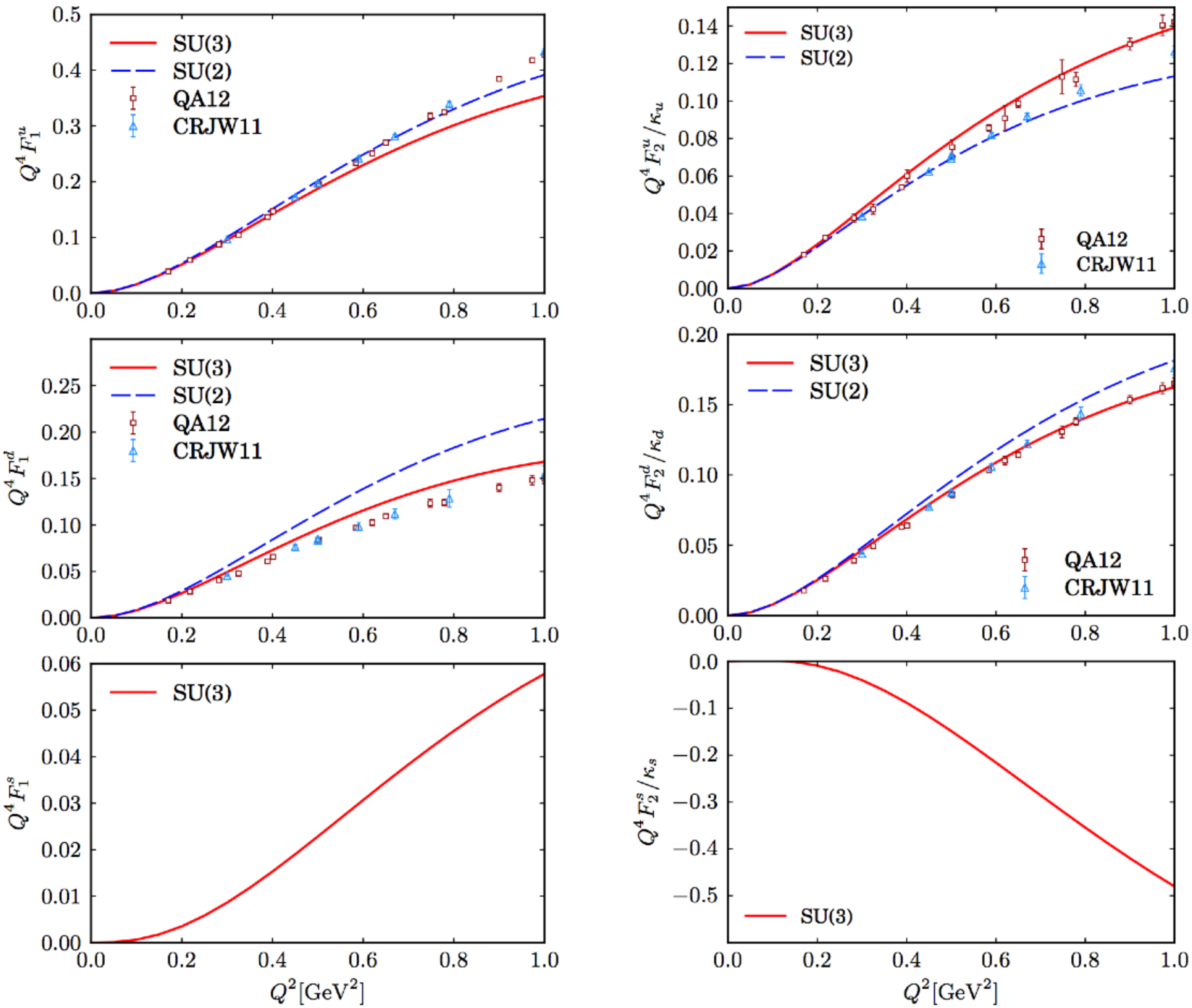


Induced electric dipole field along the negative ***y*** axis: Relativistic effects

Note that the neutron anomalous magnetic moment is negative!

Silva, Urbano, HChK, PTEP, (2018)

Flavor structure



Up quark FFs

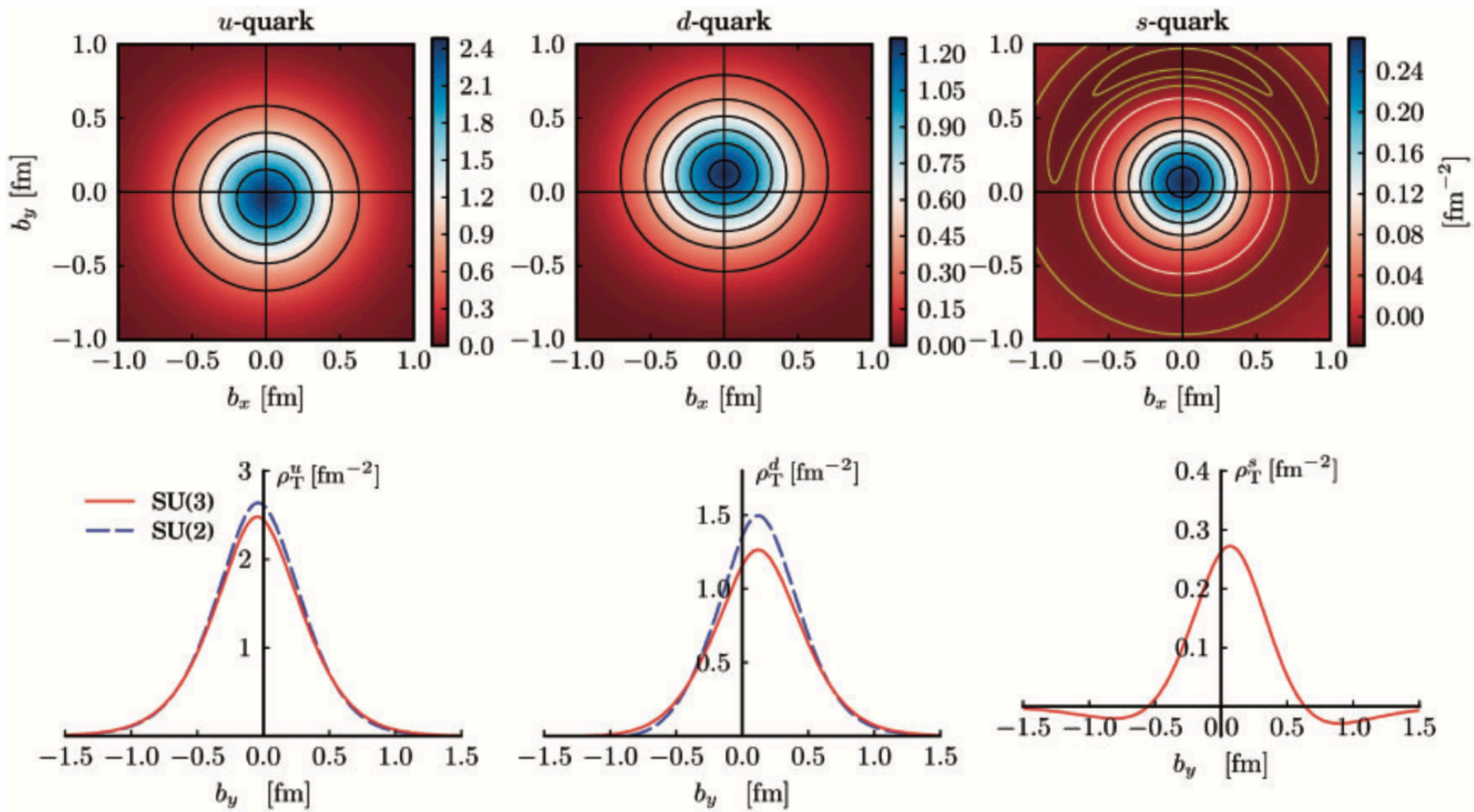
Down quark FFs

Strange quark FFs

Silva, Urbano, HChK, PTEP, (2018)

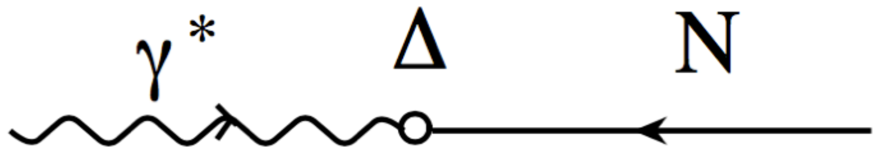
Flavor structure

Nucleon polarized along the x direction



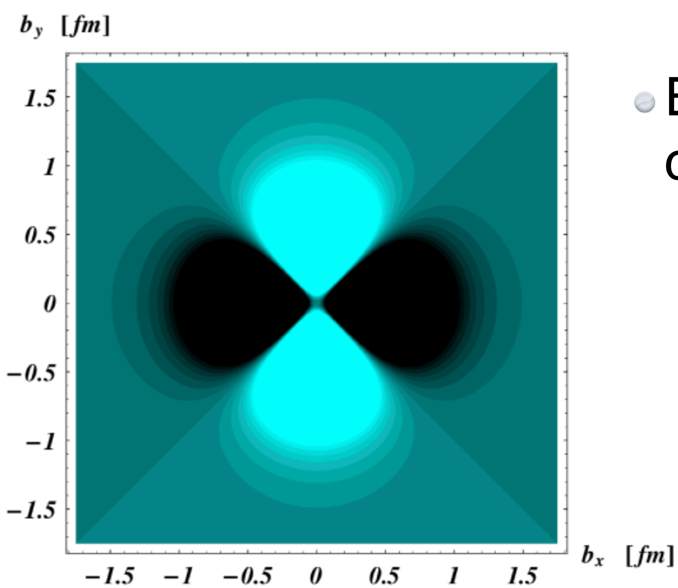
Silva, Urbano, HChK, PTEP, (2018)

EM transition form factors of the decuplet



$(\omega, \boldsymbol{q}) \qquad (E_\Delta, \boldsymbol{0}) \qquad (E_N, -\boldsymbol{q})$

- EM transition FFs provide information on how the Delta looks like.



- EM transition FFs are related to the VBB coupling constants through VDM & CFI.

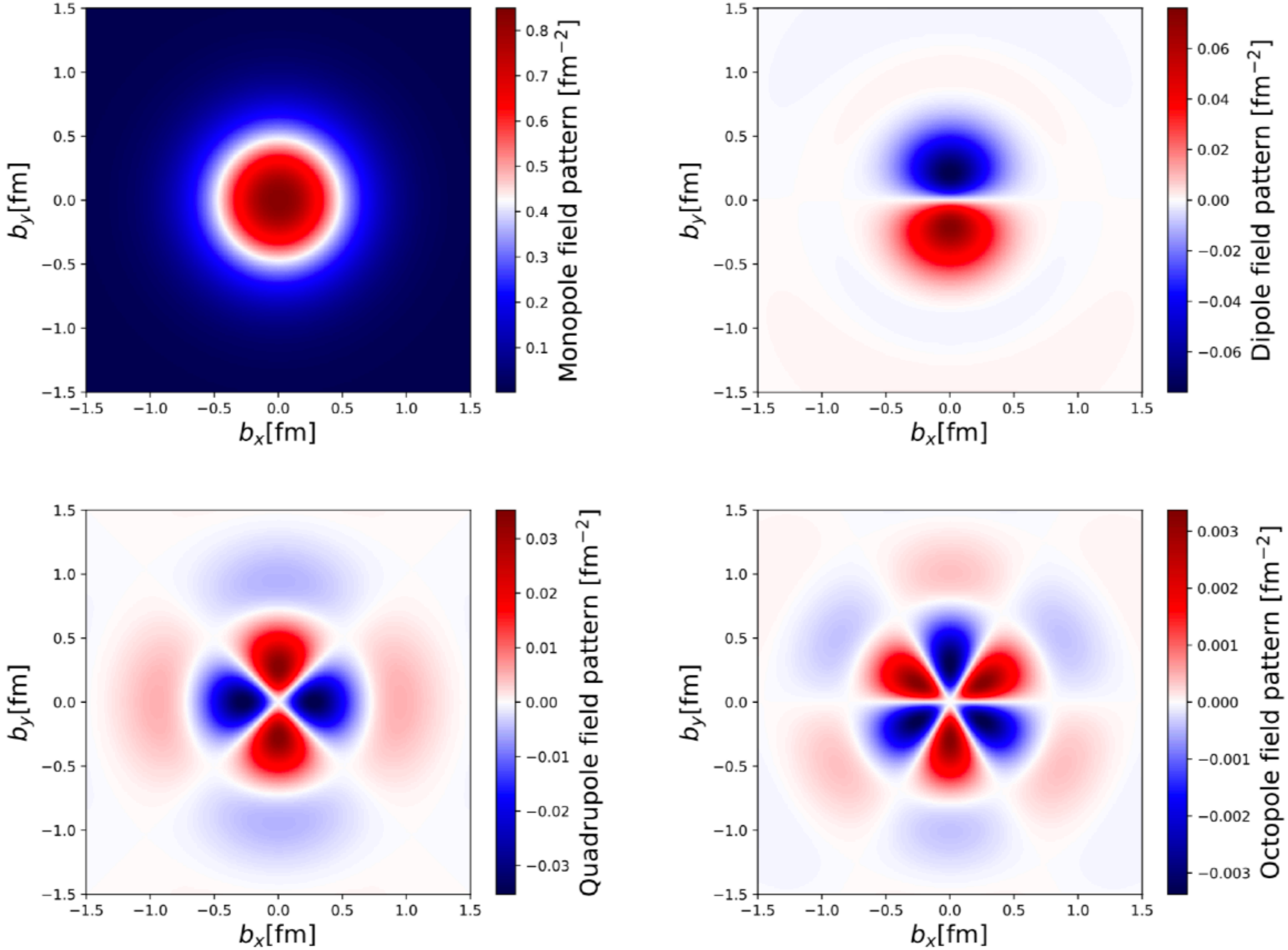
→ Essential to understand a production mechanism of hadrons.

Carlson & Vanderhaeghen, PRD 100 (2008) 032004

Multipole patter in the transverse plane

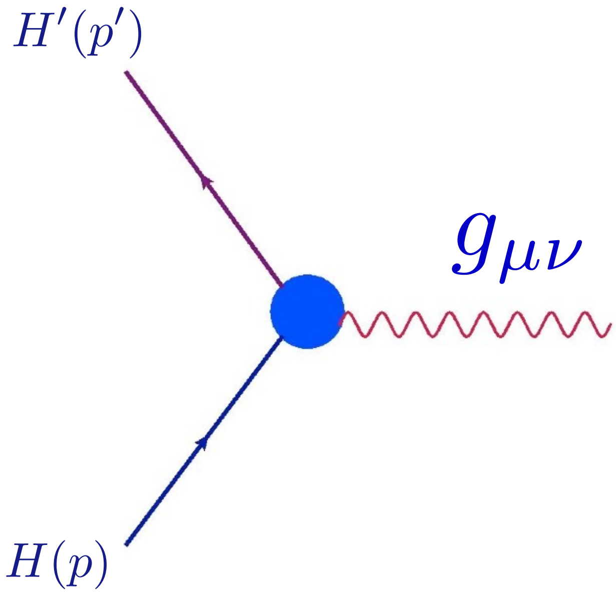
Δ^+

Preliminary results (J.-Y. Kim & HChK)



Gravitational Form factors
of
the pion & Nucleon

Gravitational form factors



Graviton: To weak to probe the EMT structure of a hadron

Given an action,

$$\frac{\delta S}{\delta g_{\mu\nu}} = 0 \quad \text{or}$$

$\delta S = 0$ under Poincaré transform

$$\langle \pi^a(p')|T_{\mu\nu}(0)|\pi^b(p)\rangle = \frac{\delta^{ab}}{2}[(tg_{\mu\nu} - q_\mu q_\nu)\Theta_1(t) + 2P_\mu P_\nu \Theta_2(t)]$$

Gravitational form factors

$$2\delta^{ab}H_\pi^{I=0}(x,\xi,t)=\frac{1}{2}\int\frac{d\lambda}{2\pi}e^{ix\lambda(P\cdot n)}\langle\pi^a(p')|\bar{\psi}(-\lambda n/2)\not{n}[-\lambda n/2,\lambda n/2]\psi(\lambda n/2)|\pi^b(p)\rangle$$

Gravitational or EMT form factors
as the second Melin moments of the EM GPD

$$\int dx x H_\pi^{I=0}(x,\xi,t)=A_{2,0}(t)+4\xi^2A_{2,2}(t)$$

$$\Theta_1=-4A_{2,2}^{I=0}\qquad\Theta_2=A_{2,0}^{I=0}$$

$$\langle\pi^a(p')|T_{\mu\nu}(0)|\pi^b(p)\rangle=\frac{\delta^{ab}}{2}[(tg_{\mu\nu}-q_\mu q_\nu)\Theta_1(t)+2P_\mu P_\nu\Theta_2(t)]$$

T^{00} : Mass form factor

T^{i0} : Angular momentum

T^{ij} : Shear force and Pressure → Stability of a particle: von Laue condition

Mechanics of a particle

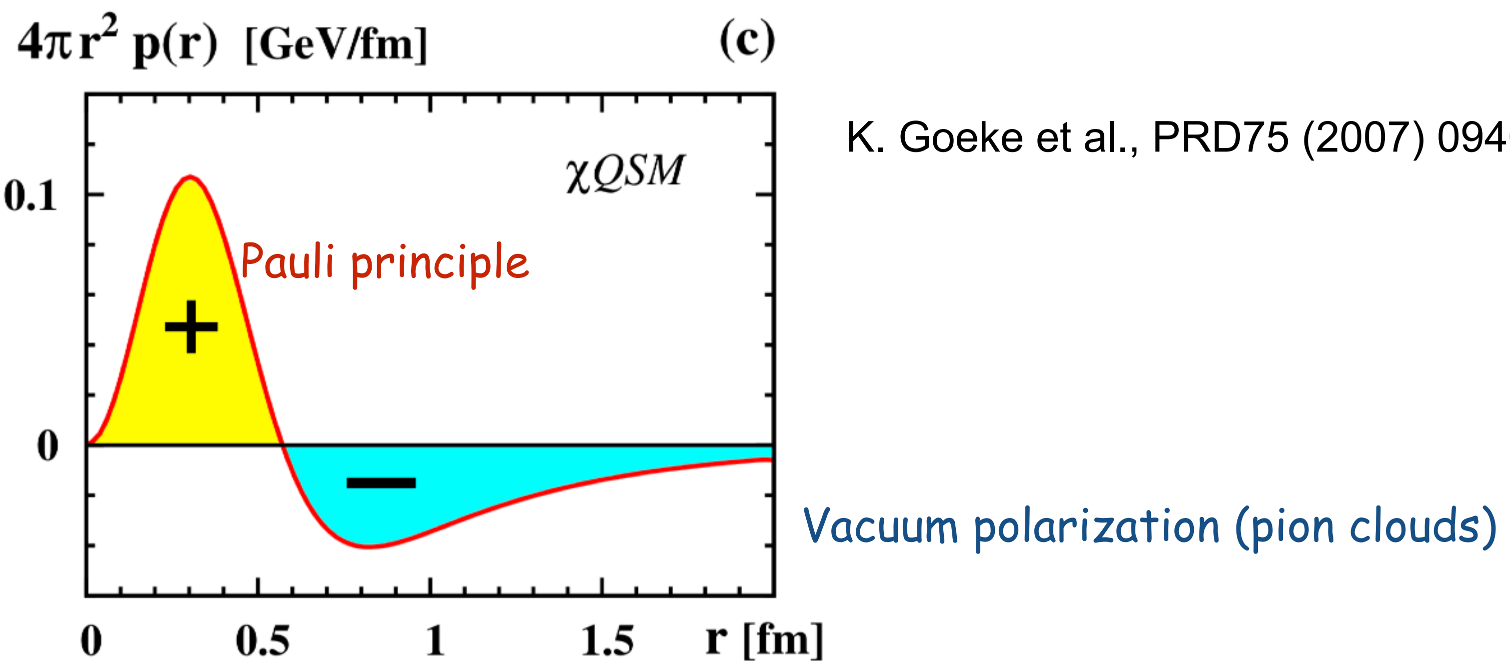
Stability

- Pion: The stability is guaranteed by the chiral symmetry and its spontaneous breakdown

H.D. Son & HChK, PRD 90 (2014) 111901

$$\mathcal{P} = \frac{3M}{f_\pi^2 \bar{M}} \left(m\langle \bar{\psi}\psi \rangle + m_\pi^2 f_\pi^2 \right) = 0$$

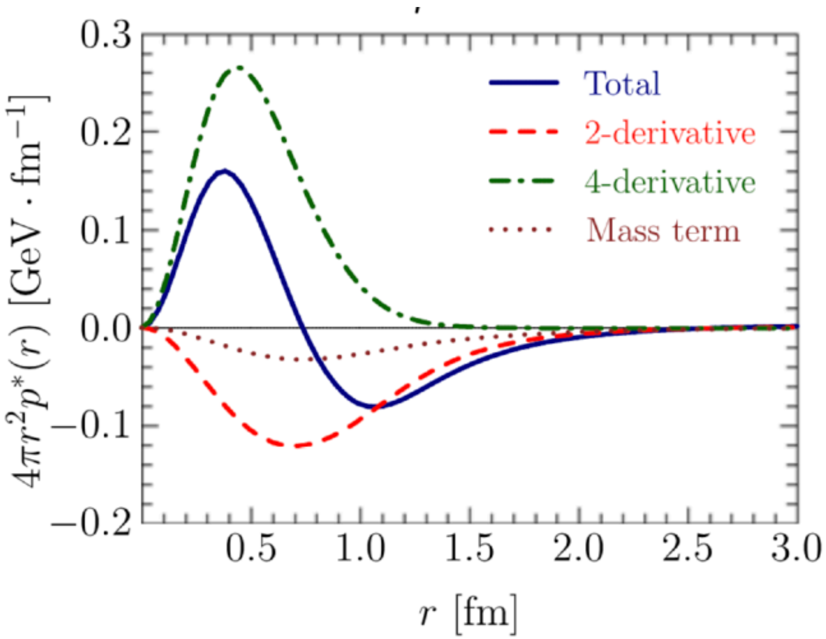
- Nucleon: The stability is guaranteed by the balance between the core valence quarks and the sea quarks (XQSM).



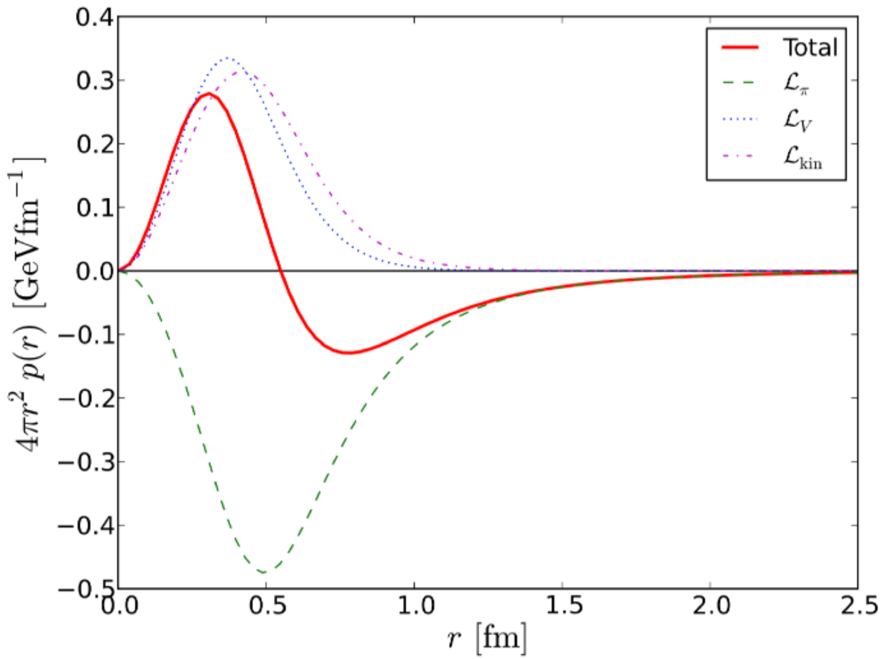
K. Goeke et al., PRD75 (2007) 094021

Stability

- Nucleon: The stability is guaranteed by the balance between the pion and rho mesons (Skyrme picture).



Original Skyrme model



pi-rho-omega model

Cebulla et al., NPA794 (2007) 87

HChK, P. Schweitzer, U. Yakhshiev, PLB 718 (2012) 625

J.H. Jung, U. Yakhshiev, HChK, J.Phys. G41 (2014) 055107

Spin structure
of
the Nucleon

Tensor form factors

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

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

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

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

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

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

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

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

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

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

Scale dependence

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).

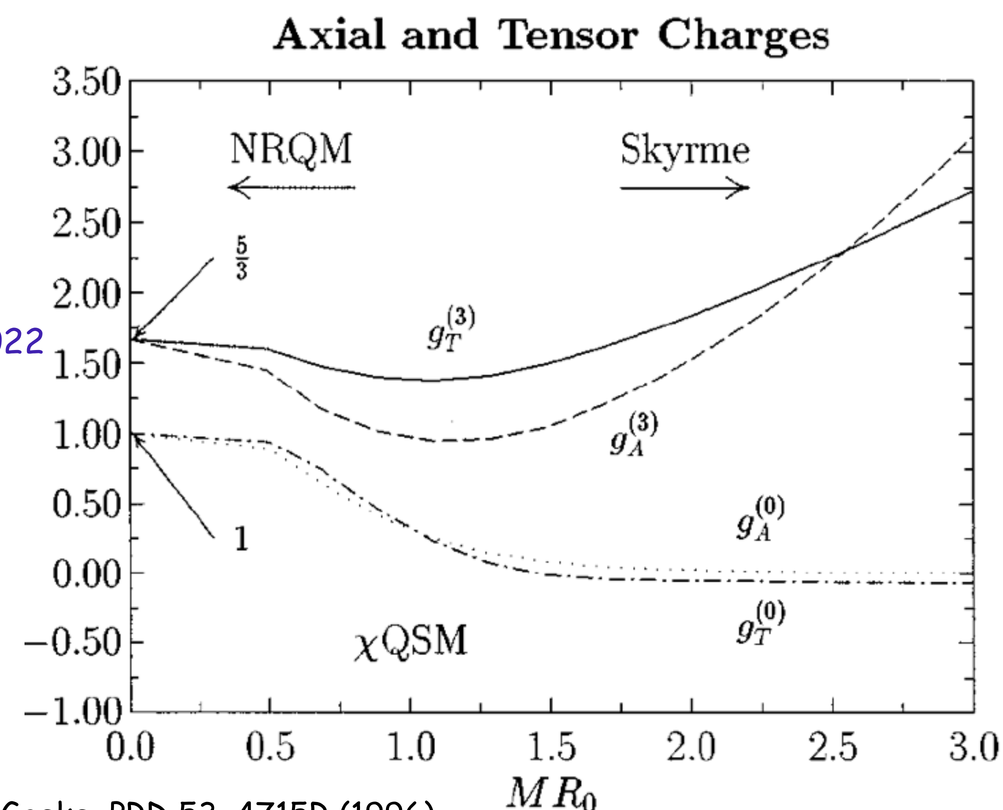
Comparison with Axial-vector constants

	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	$--$	$\frac{4}{3}$	$\frac{4}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	$--$	$--$

$$g_A^3 \sim (MR_0)^2 \qquad g_T^3 \sim MR_0$$
$$g_A^0 \sim \frac{1}{(MR_0)^4} \qquad g_T^0 \sim \frac{1}{MR_0}$$

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

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



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

Results

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

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

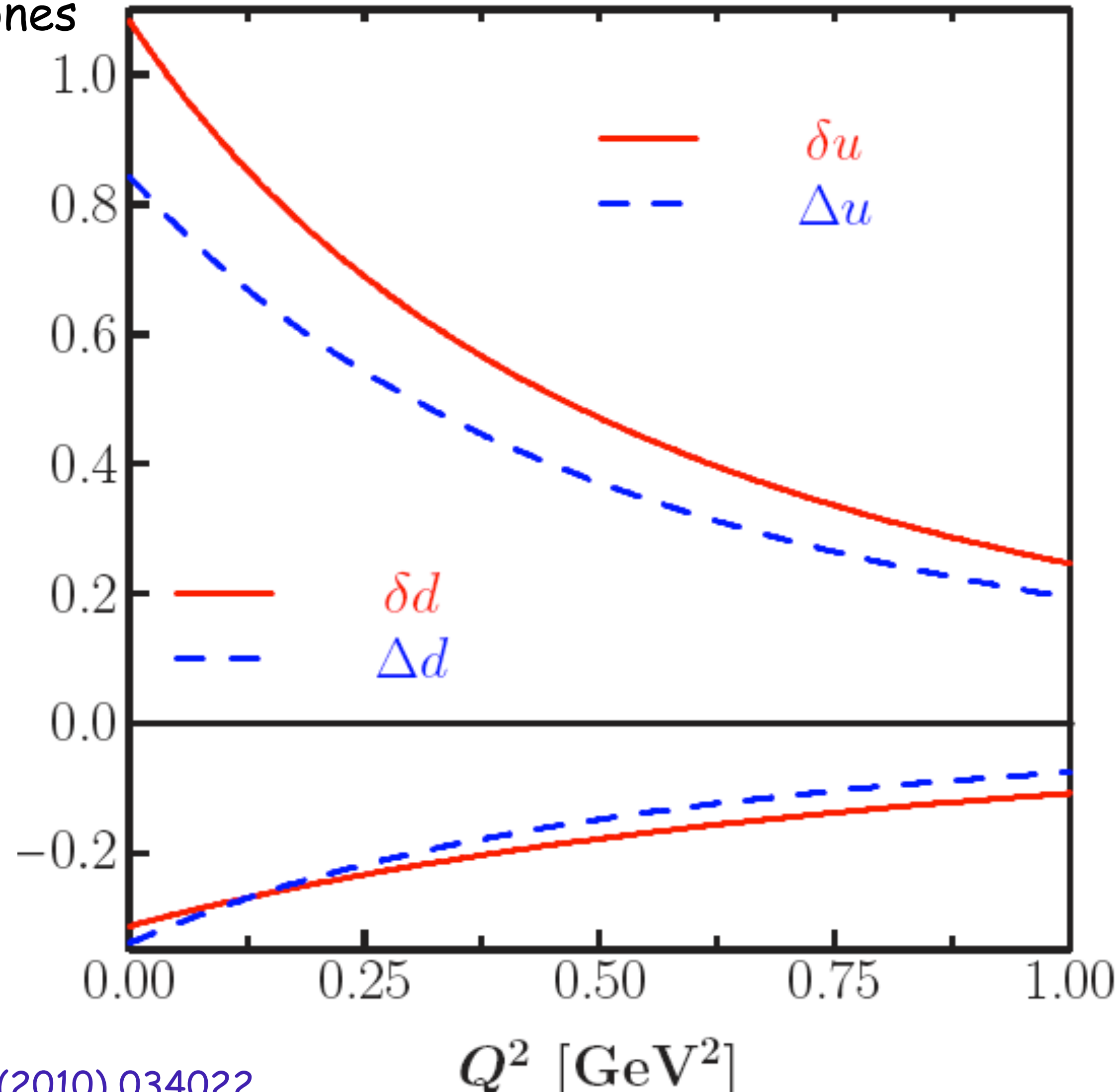
[16] M. Anselmino et al. Nucl. Phys. B, Proc. Suppl. 191, 98 (2009)

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

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

Results

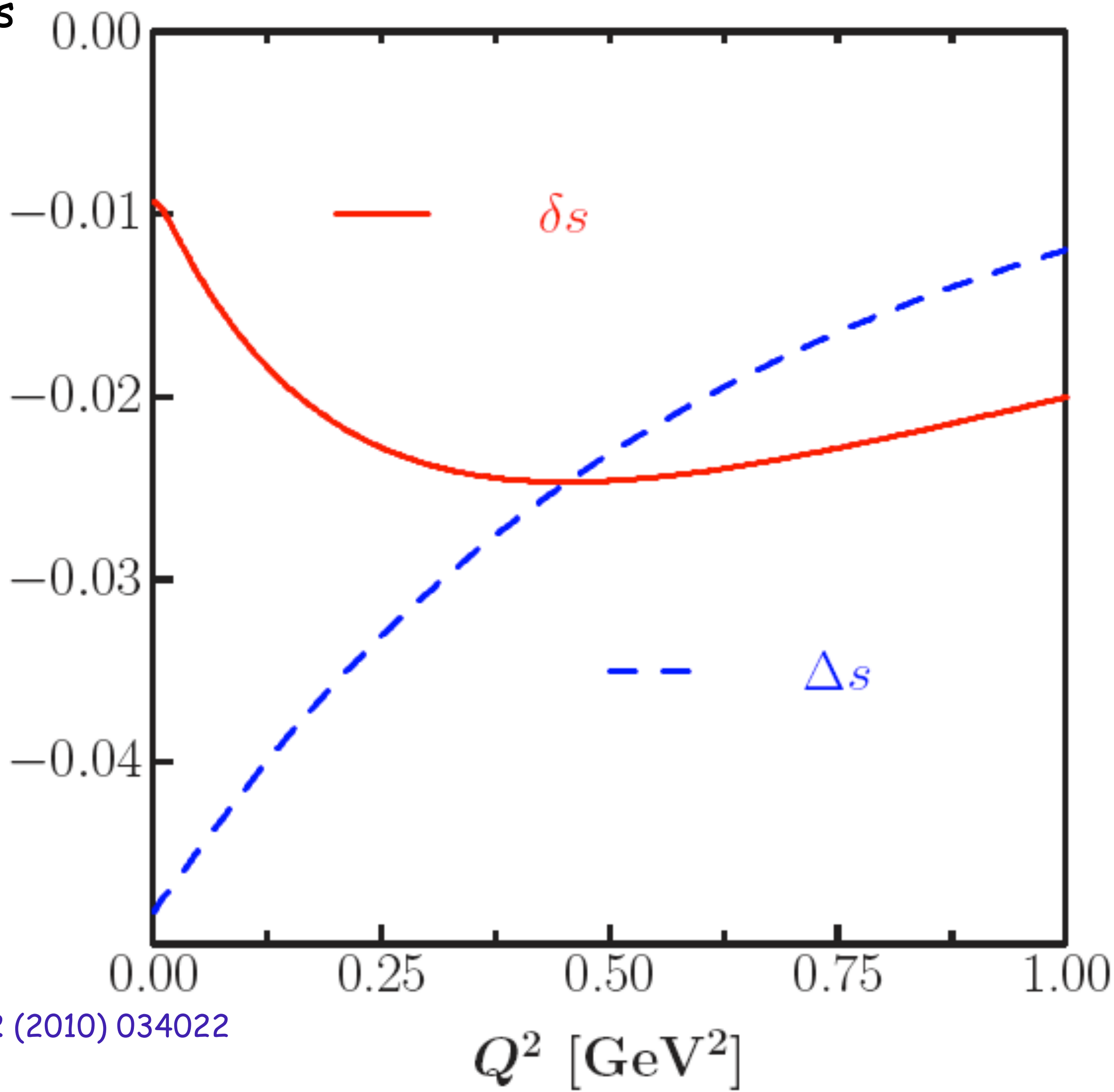
Up and down tensor form factors compared with the axial-vector ones



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

Transverse spin density

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

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

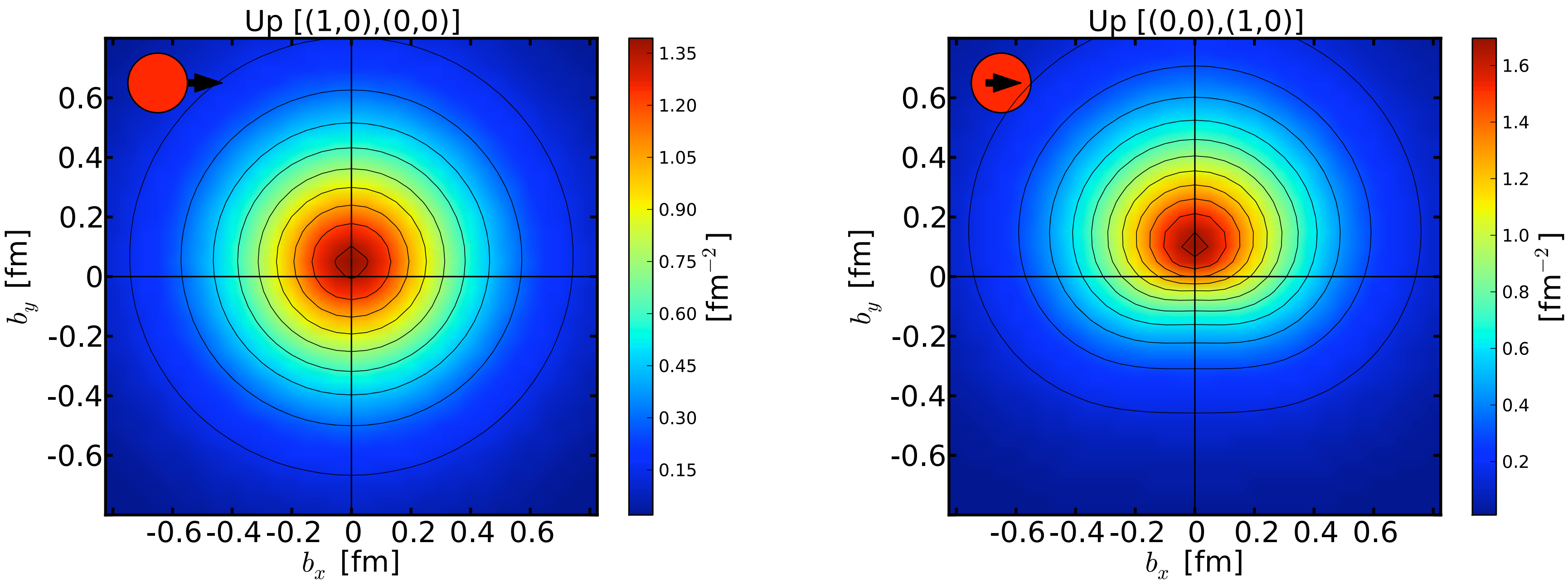
$$\mathcal{F}^{\chi}(b^2) = \int_0^{\infty} \frac{dQ}{2\pi} Q J_0(bQ) F^{\chi}(Q^2)$$

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

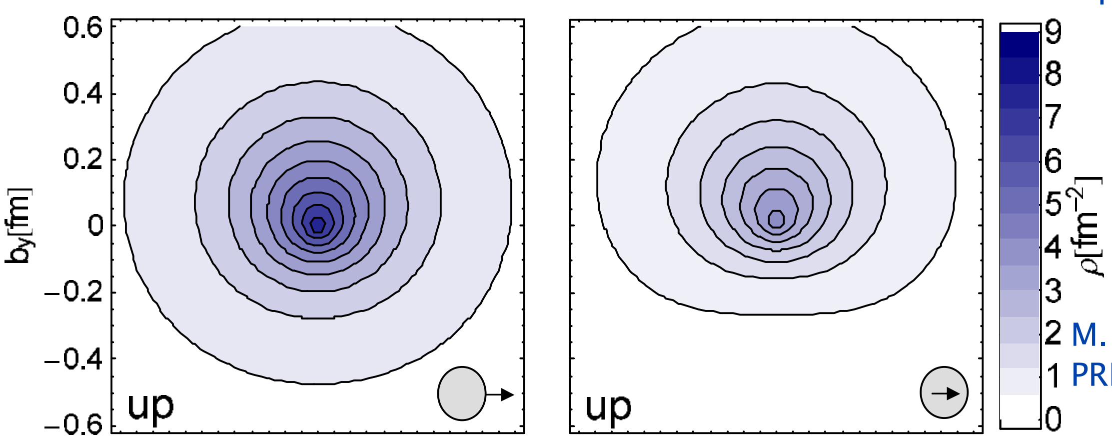
M. Diehl & Ph. Haegler, Euro.Phys. J., C 44 (2005) 87.

Transverse spin density

Up quark transverse spin density inside a nucleon



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

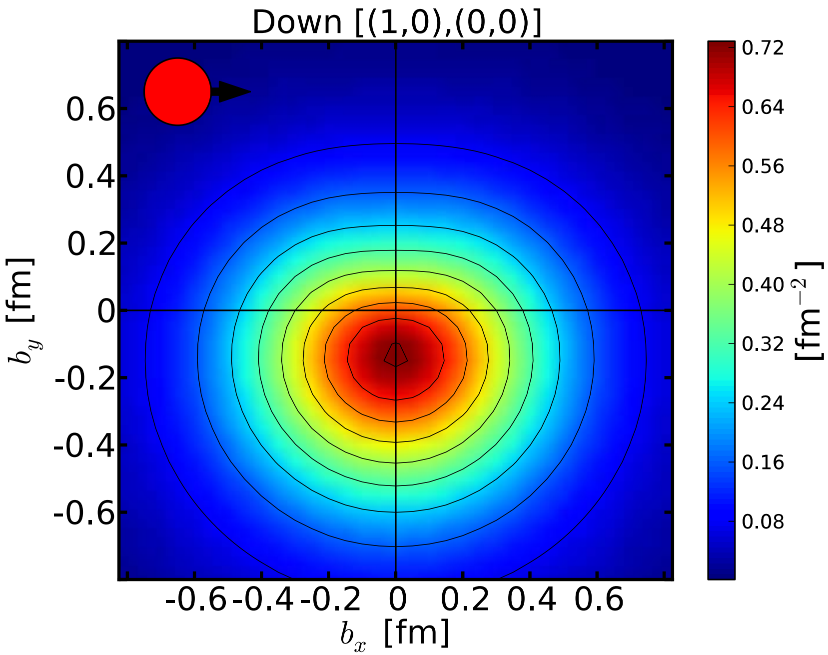


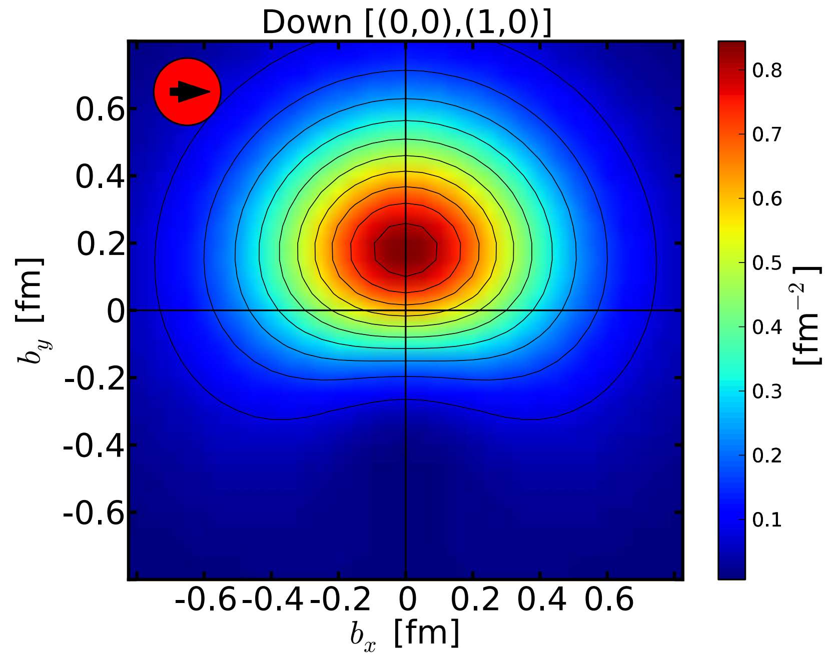
Lattice results

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

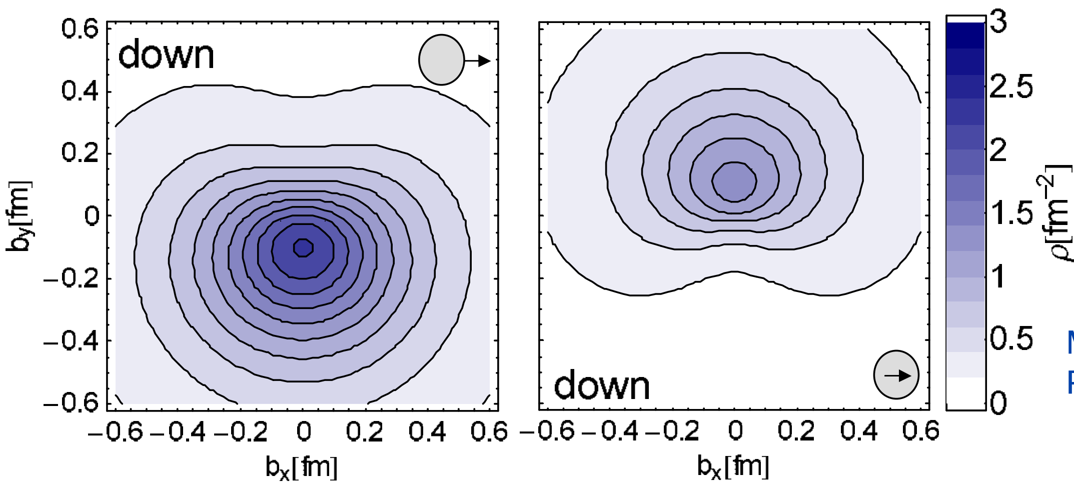
Transverse spin density

Down quark transverse spin density inside a nucleon





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

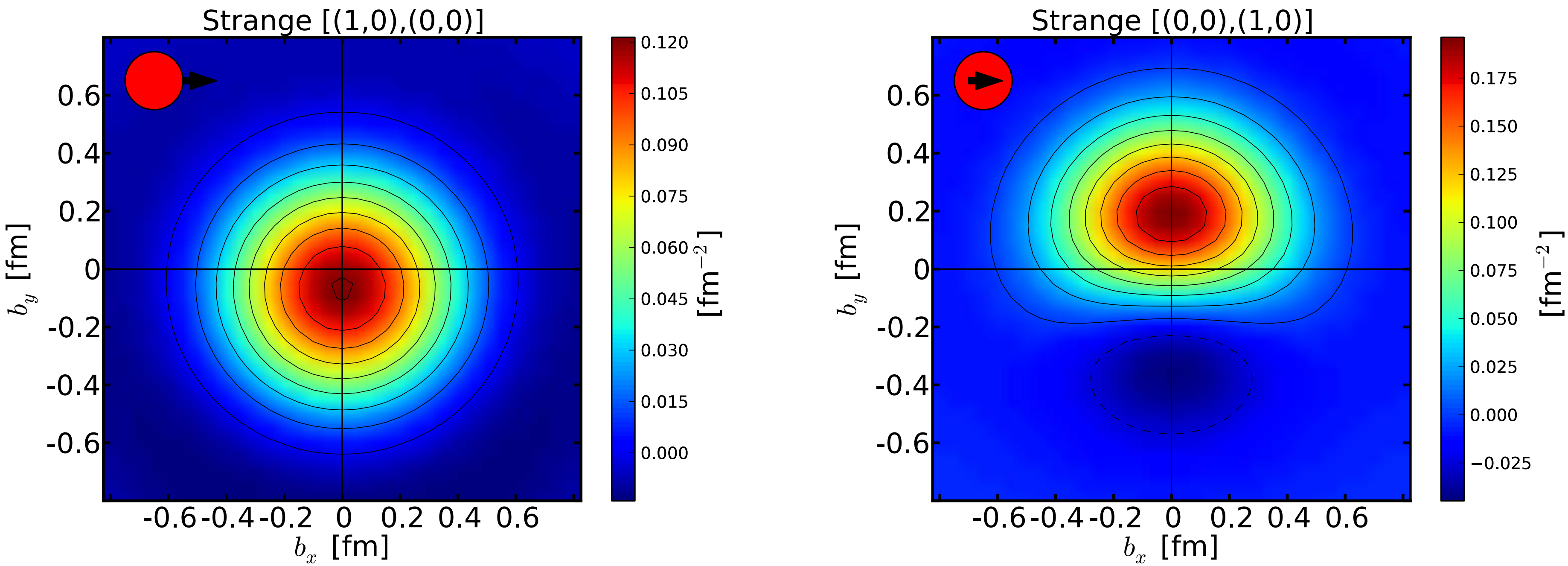


Lattice results

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

Transverse spin density

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

Spin structure
of
the Pion

What we know about the Pion

Experimentally, we know about the pion

- Pion Mass = 139.57 MeV
- Pion Spin: S = 0

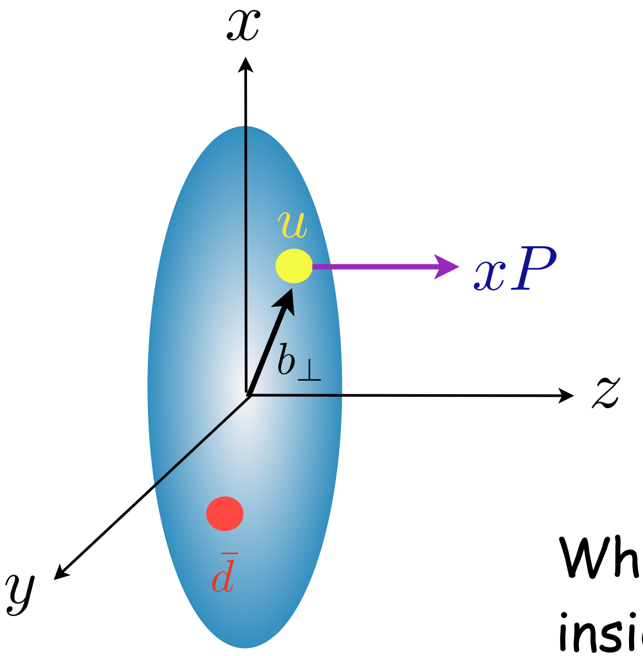
Theoretically

- pseudo-Goldstone boson
- The lowest-lying mesons
  (1 q + 1anti-q + sea quarks + gluons + …)

Their structures are simpler than that of the nucleon but messy enough!

The spin structure of the pion

Vector & Tensor Form factors of the pion



Pion: Spin S=0

Longitudinal spin structure is trivial.

$$\langle \pi(p') | \bar{\psi} \gamma_3 \gamma^5 \psi | \pi(p) \rangle = 0$$

What about the transversely polarized quarks inside a pion?

→ Internal spin structure of the pion

Comparison with Axial-vector constants

$$\rho_n(b_\perp, s_\perp) = \int_{-1}^{1} dx\, x^{n-1} \rho(x, b_\perp, s_\perp) = \frac{1}{2}\left[A_{n0}(b_\perp^2) - \frac{s_\perp^i \epsilon^{ij} b_\perp^j}{m_\pi} \frac{\partial B_{n0}(b_\perp^2)}{\partial b_\perp^2}\right]$$

Spin probability densities in the transverse plane

A_{n0}: Vector densities of the pion, B_{n0}: Tensor densities of the pion

$$\int_{-1}^{1} dx\, x^{n-1} H(x, \xi = 0, b_\perp^2) = A_{n0}(b_\perp^2), \quad \int_{-1}^{1} dx\, x^{n-1} E(x, \xi = 0, b_\perp^2) = B_{n0}(b_\perp^2)$$

Vector and Tensor form factors of the pion

$$\langle \pi(p_f) | \psi^\dagger \gamma_\mu \hat{Q} \psi | \pi(p_i) \rangle = (p_i + p_f) A_{10}(q^2)$$

$$\langle \pi^+(p_f) | \mathcal{O}_T^{\mu\nu\mu_1\cdots\mu_{n-1}} | \pi^+(p_i) \rangle = \mathcal{AS}\left[\frac{(p^\mu q^\nu - q^\mu p^\nu)}{m_\pi} \sum_{i=\text{even}}^{n-1} q^{\mu_1} \cdots q^{\mu_i} p^{\mu_{i+1}} \cdots p^{\mu_{n-1}} B_{ni}(Q^2)\right]$$

Gauged effective chiral action

Gauged Effective Nonlocal Chiral Action

$$S_{\mathrm{eff}} = -N_c \mathrm{Tr} \ln \left[i\not{D} + im + i\sqrt{M(iD,m)}U^{\gamma_5}\sqrt{M(iD,m)} \right]$$

$$D_\mu = \partial_\mu - i\gamma_\mu V_\mu$$

The nonlocal chiral quark model from the instanton vacuum

- Fully relativistically field theoretic model.
- "Derived" from QCD via the Instanton vacuum.
- Renormalization scale is naturally given.
- No free parameter

$\rho \approx 0.3\,\mathrm{fm},\ R \approx 1\,\mathrm{fm}$ $\mu \approx 600\,\mathrm{MeV}$

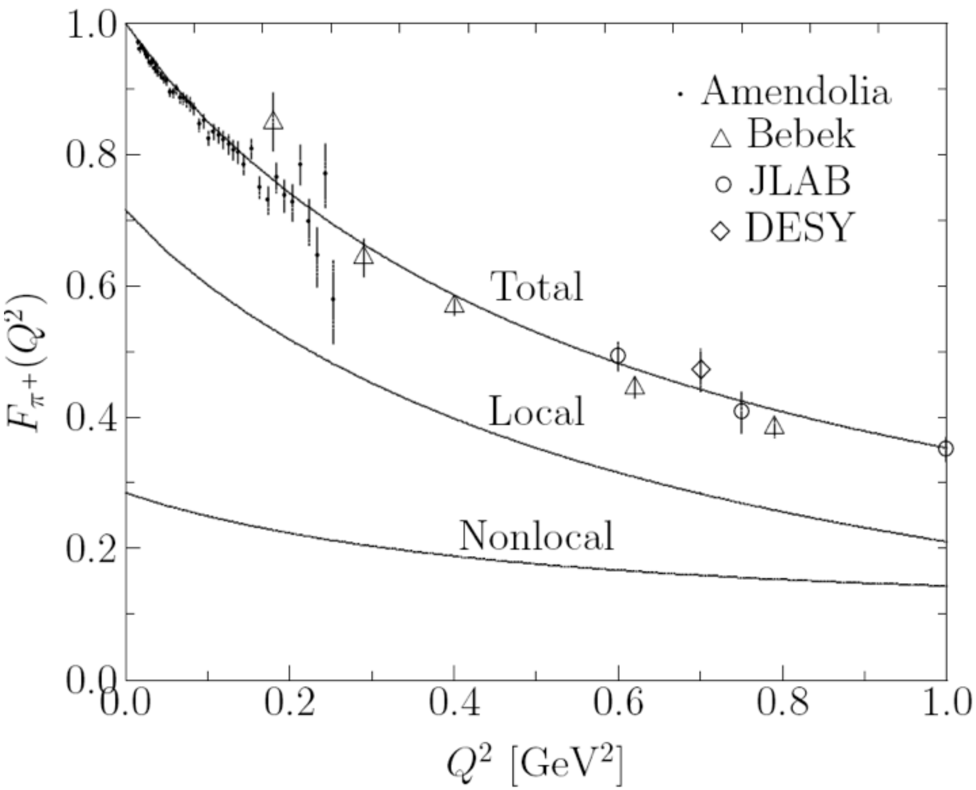
Dilute instanton liquid ensemble

D. Diakonov & V. Petrov Nucl.Phys. B272 (1986) 457
H.-Ch.K, M. Musakhanov, M. Siddikov Phys. Lett. B **608**, 95 (2005).
Musakhanov & H.-Ch. K, Phys. Lett. B **572**, 181-188 (2003)

EM form factors of the pion

EM form factor (A_{10})

$$\langle \pi(p_f)|\psi^\dagger\gamma_\mu\hat{Q}\psi|\pi(p_i)\rangle = (p_i+p_f)A_{10}(q^2)$$



$$\sqrt{\langle r^2\rangle} = 0.675\,\mathrm{fm}$$

$$\sqrt{\langle r^2\rangle} = 0.672\pm0.008\,\mathrm{fm}\ (\mathrm{Exp})$$

$$F_\pi(Q^2) = A_{10}(Q^2) = \frac{1}{1+Q^2/M^2}$$

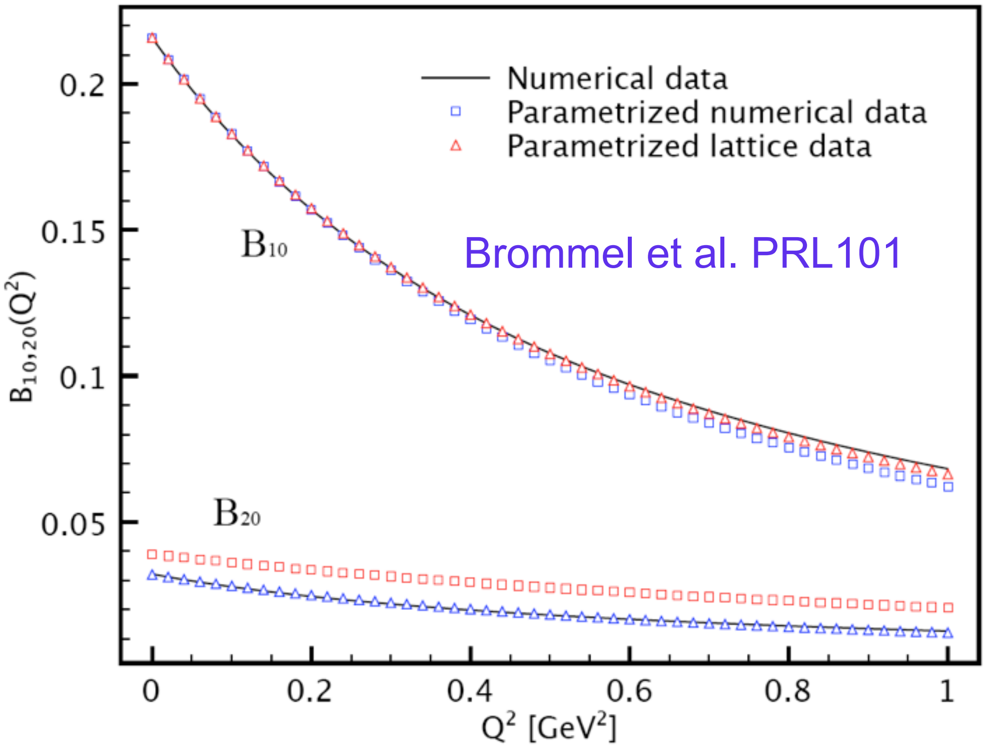
M(Phen.): 0.714 GeV

M(Lattice): 0.727 GeV

M(XQM): 0.738 GeV

S.i. Nam & HChK, Phys. Rev. D77 (2008) 094014

EM form factors of the pion



RG equation for the tensor form factor

$$B_{10}(Q^2,\,\mu) = B_{10}(Q^2,\,\mu_0)\left[\frac{\alpha(\mu)}{\alpha(\mu_0)}\right]^{\gamma/2\beta_0}$$

$$\gamma_1 = 8/3,\ \gamma_2 = 8,\ \beta_0 = 11N_c/3 - 2N_f/3$$

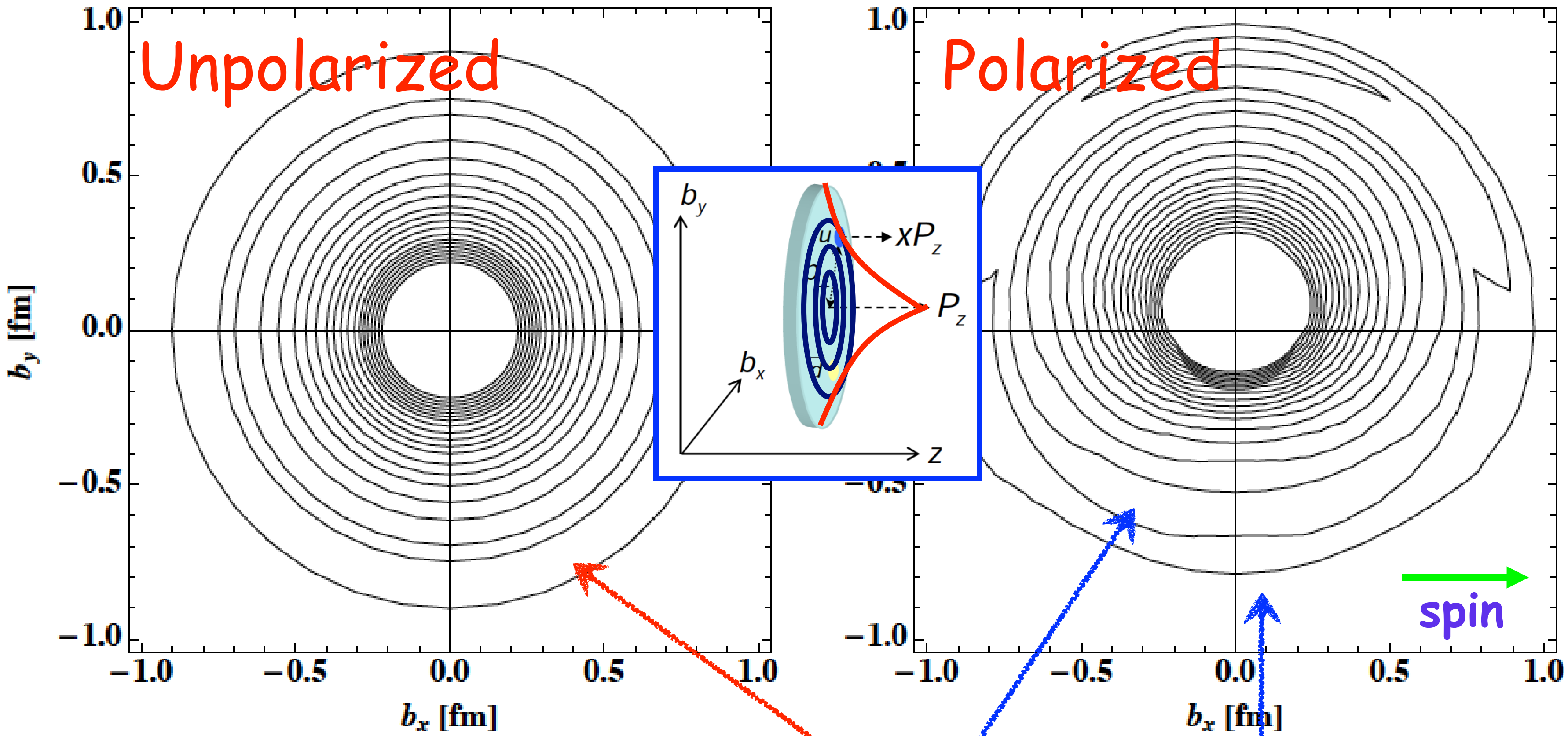
p-pole parametrization for the form factor

$$B_{10}(Q^2) \;=\; B_{10}(0)\left[1+\frac{Q^2}{pm_p^2}\right]^{-p}$$

S.i. Nam & H.-Ch.K, Phys. Lett. B **700**, 305 (2011).

For the kaon, S.i. Nam & HChK, Phys. Lett. **B**707, 546 (2012)

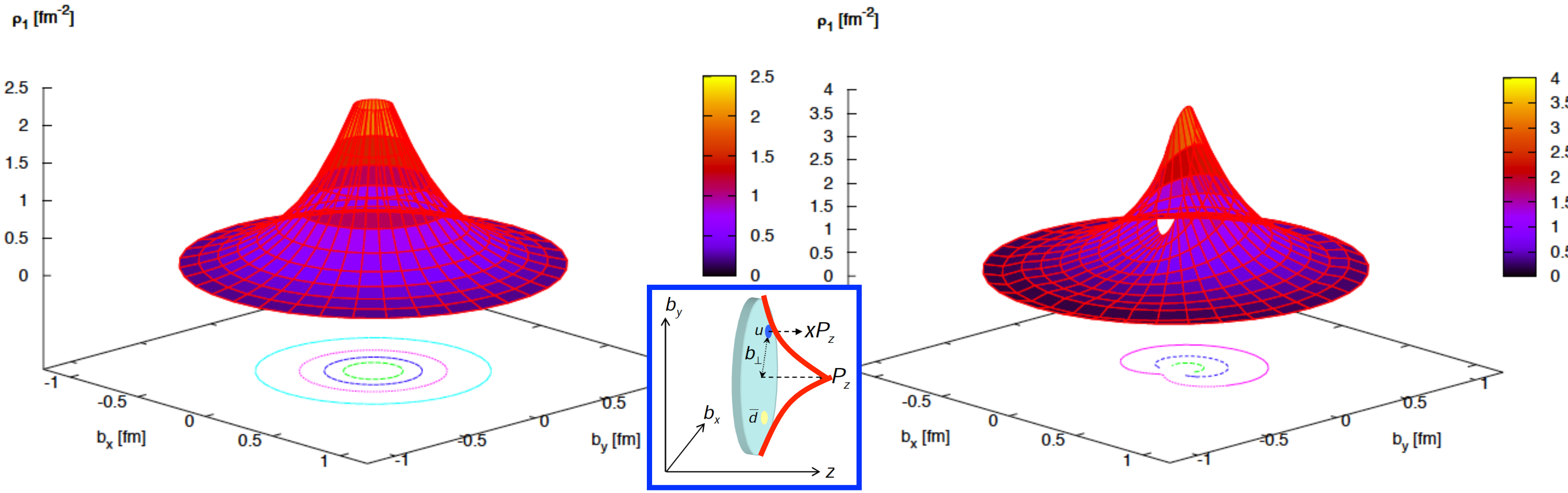
Spin density of the quark inside a pion



$$\rho_1\left(b_\perp, s_x = \pm\frac{1}{2}\right) = \frac{1}{2}\left[A_{10}(b^2) \mp \frac{b\sin\theta}{m_\pi} B'_{10}(b^2)\right]$$

Polarization

Spin density of the quark inside a pion



Significant distortion appears for the polarized quark!

$m_\pi = 140$ MeV	$B_{10}(0)$	m_{p_1} [GeV]	$\langle b_y \rangle$ [fm]	$B_{20}(0)$	m_{p_2} [GeV]
Present work	0.216	0.762	0.152	0.032	0.864
Lattice QCD [7]	0.216 ± 0.034	0.756 ± 0.095	0.151	0.039 ± 0.099	1.130 ± 0.265

Results are in a good agreement with the lattice calculation!

Summary & Outlook

Summary

- In the present talk, we aimed at reviewing a certain aspect on the transverse spin structure of the nucleon.
- We discussed first the transverse charge densities and its conceptual difference from the traditional 3D charge densities.
- We briefly discussed the gravitational form factors of the pion and nucleon.
- Finally, we presented recent results of the transverse spin structure of the nucleon and pion.
- Though we haven't shown the kaon, its spin structure was also studied.

Outlook

- The same method can be extended to heavy hadrons.
- Quasi parton distribution (Comparison with the lattice data)
- GPDs of the pion and nucleon
- TMDs of the nucleon
- Wigner functions in the XQSM

To investigate the spin structure of the nucleon, it is essential to use a field-theoretic approach such as the chiral quark-soliton model (both the valence-quark and vacuum polarization effects included).

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

Hamlet Act 2, Scene 2

by Shakespeare

Thank you very much for the attention!