D-term of nucleon

Peter Schweitzer (UConn)

Outline

- **Introduction**
  energy momentum tensor $T^{\mu\nu}$ (EMT)
  D-term last unknown fundamental global property

- **What do we know from theory & experiment?**
  soft pion theorems, chiral theory, models, lattice
  first extractions of π^0 and nucleon D-term from data

- **What do we learn?**
  interpretation: internal forces, stability, mechanical properties
  applications: visualization of dynamics, hadrocharmonia, large-N_c baryon

- **Outlook**

recent review: M.V.Polyakov, PS, Int. J. Mod. Phys. A **33**, 1830025 (2018) [arXiv:1805.06596]

supported by NSF

Introduction: Energy momentum tensor (EMT)

- $T^{\mu\nu}$: conserved $\partial^\mu \hat{T}_{\mu\nu} = 0$, Noether current of translations, couples to gravity
- **Poincaré group generators:** $\hat{P}^\mu = \int d^3x\, \hat{T}^{0\mu}$, $\hat{M}^{\kappa\nu} = \int d^3x\, (x^\kappa \hat{T}^{0\nu} - x^\nu \hat{T}^{0\kappa})$
- **Casimir operators:** $\hat{P}^\mu \hat{P}_\mu \to m^2$, $\hat{W}^\mu \hat{W}_\mu \to m^2 J(J+1)$ where $\hat{W}^\kappa = -\frac{1}{2}\varepsilon^{\kappa\mu\nu\sigma}\hat{M}_{\mu\nu}\hat{P}_\sigma$ $\to$ **mass & spin**
- **QCD:** quark & gluon gauge-invariant, total $\hat{T}_{\mu\nu} = \sum_q T^q_{\mu\nu} + \hat{T}^g_{\mu\nu}$ conserved, trace anomaly

form factors

nucleon (Kobzarev, Okun, Pagels 1960s)

- $$\langle p'|\hat{T}^a_{\mu\nu}|p\rangle = \bar{u}(p')\Bigg[A^a(t,\mu^2)\,\frac{P_\mu P_\nu}{M} + J^a(t,\mu^2)\,\frac{i(P_\mu \sigma_{\nu\rho} + P_\nu \sigma_{\mu\rho})\Delta^\rho}{2M} + D^a(t,\mu^2)\,\frac{\Delta_\mu \Delta_\nu - g_{\mu\nu}\Delta^2}{4M} + \bar{c}^a(t,\mu^2) g_{\mu\nu}\Bigg] u(p)$$

$2P = (p'+p)$, $\Delta = (p'-p)$, $t = \Delta^2$
total form factors scale invariant
$A(t) = \sum_a A^a(t,\mu^2)$, $J(t)$, $D(t)$;
and $\sum_a \bar{c}^a(t,\mu^2) = 0$

- constraints: **mass** $\Leftrightarrow$ $A(0) = 1$ $\Leftrightarrow$ quarks + gluons carry 100 % of nucleon momentum

  spin $\Leftrightarrow$ $J(0) = \frac{1}{2}$ $\Leftrightarrow$ quarks + gluons carry 100 % of nucleon spin *

  D-term $\Leftrightarrow$ $D(0) \equiv D$ $\to$ unconstrained! **Last global unknown!**

Higher spin $J = 0, \frac{1}{2}, 1, \ldots$ $\to$ more form factors. Each particle has a D-term.
Cosyn, Cotogno, Freese, Lorcé; Polyakov, Sun 2019; Peter Lowdon's poster yesterday on constraints

D on same footing as mass, spin, charge:

$|N\rangle$ = strong–interaction particle. Use other forces to probe it!

em:	$\partial_\mu J^\mu_{\rm em} = 0$	$\langle N'\lvert J^\mu_{\rm em}\rvert N\rangle$	$\longrightarrow$	$G_E(t),\ G_M(t)$	$\longrightarrow$	$\boldsymbol{Q},\ \boldsymbol{\mu},$	...
weak:	PCAC	$\langle N'\lvert J^\mu_{\rm weak}\rvert N\rangle$	$\longrightarrow$	$G_A(t),\ G_P(t)$	$\longrightarrow$	$\boldsymbol{g_A},\ \boldsymbol{g_p},$	...
gravity:	$\partial_\mu T^{\mu\nu}_{\rm grav} = 0$	$\langle N'\lvert T^{\mu\nu}_{\rm grav}\rvert N\rangle$	$\longrightarrow$	$A(t),\ J(t),\ D(t)$	$\longrightarrow$	$\boldsymbol{M},\ \boldsymbol{J},\ \boldsymbol{D},$	...

global properties:

$$
\begin{aligned}
Q_{\rm prot} &= 1.602176487(40)\times 10^{-19}\,{\rm C}\\
\mu_{\rm prot} &= 2.792847356(23)\,\mu_N\\
g_A &= 1.2694(28)\\
g_p &= 8.06(0.55)\\
M &= 938.272013(23)\ {\rm MeV}\\
J &= \tfrac{1}{2}\\
\boldsymbol{D} &= \ ?
\end{aligned}
$$

and more:
t-dependence ... ...
parton structure, etc ...

$\hookrightarrow$ *D = "last" global unknown*
which value does it have?
how can it be measured?
what does it mean?

D-term in theory

- **spin 0:** free Klein-Gordon field $D = -1$
  (Pagels 1966; Hudson, PS 2017)

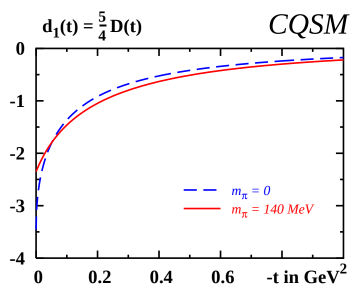
- **spin 0:** Goldstone bosons of chiral symmetry breaking $D = -1$
  Novikov, Shifman; Voloshin, Zakharov (1980); Polyakov, Weiss (1999); Donoghue, Leutwyler (1991)
  $D_\pi \approx -0.97 \pm 0.01$, $D_K \approx -0.77 \pm 0.15$ Hudson, PS (2017)

- **spin $\frac{1}{2}$:** free theory $D = 0$ (analog to $g = 2$ magnetic moment)
  implicit in Donoghue et al (2002), explicit in Hudson, PS PRD97 (2018) 056003

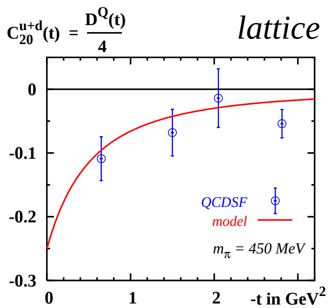
- **models** help understanding Hudson, PS PRD97 (2018)
  chiral quark-soliton model: "switch off strong chiral interaction" $\Rightarrow$ $D \to 0$
  bag model: free fermions $\to$ "introduce boundary" (interaction!) $\Rightarrow$ negative $D \neq 0$ emerges!

- **distinction boson vs fermion:** $\begin{cases} \text{non-interacting boson } D = -1 \\ \text{non-interacting fermion } D = 0 \end{cases}$ ... is there a deeper reason?

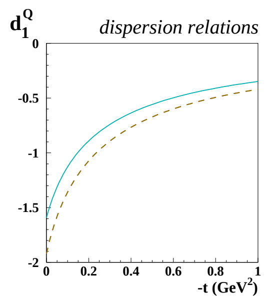
- **results:** (cf. Adam Freese in parallel session)



chiral quark soliton
Goeke et al, PRD75 (2007)
and PRC75 (2007)



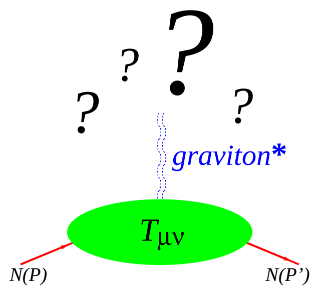
lattice QCD
QCDSF, PRL92 (2004)
recently gluon $D^g(t) < 0$
Shanahan, Detmold, (2019)



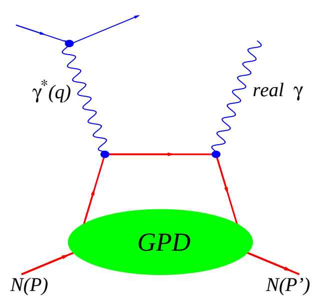
dispersion relations
Pasquini et al (2014)
pion PDFs input, 4 GeV^2

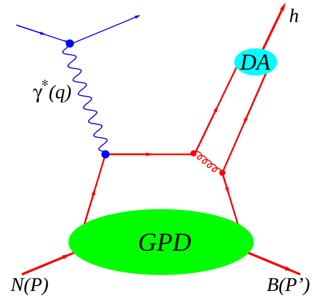
How to measure?

- **direct probe: graviton**
  (in principle only)



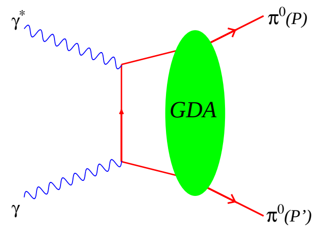
- **indirect probe: photon $\to$ GPDs**
  D.Müller et al, (1994)





$$\int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle N'(p')|\overline{\psi}_q(-\tfrac{\lambda n}{2})\, n_\mu \gamma^\mu \, \mathcal{W}\, \psi_q(\tfrac{\lambda n}{2})\,|N(p)\rangle$$

$$= \overline{u}(p')\left[n_\mu\gamma^\mu\, H^q(x,\xi,t) + \frac{i\sigma^{\mu\nu}n_\mu\Delta_\nu}{2M} E^q(x,\xi,t)\right] u(p)$$



- DVCS, hard meson production
  Ji, (1997); Radyushkin, (1996). Collins et al (1997)

- generalized distribution amplitudes
  $t > 2m^2$, study unstable particles e.g. π^0

polynomiality

$$\int dx\, x\, H^q(x,\xi,t) = \boldsymbol{A^q(t)} + \xi^2 \boldsymbol{D^q(t)}$$
$$\int dx\, x\, E^q(x,\xi,t) = \boldsymbol{B^q(t)} - \xi^2 \boldsymbol{D^q(t)}$$

$$B^q(t) = 2J^q(t) - A^q(t)$$

- GPDs convoluted in **Compton form factors** (e.g. DVCS, LO)

$$\mathcal{H}(\xi,t,\mu^2) = \sum_q e_q^2 \int dx \left[\frac{1}{x-\xi-i\varepsilon} - \frac{1}{x+\xi-i\varepsilon}\right] H^q(x,\xi,t,\mu^2)$$

model-independent extraction of $A^q(t)$, $J^q(t)$ ($\to$ Ji sum rule) diffucult in forseeable future
for $D(t)$ situation better!

- **dispersion relation**

$$\Re\mathrm{e}\, \mathcal{H}(\xi,t,\mu^2) = \tfrac{1}{\pi}\, \mathrm{PV} \int dx \left[\frac{1}{\xi - x} - \frac{1}{\xi + x}\right] \mathcal{I}m\, \mathcal{H}(x,t,\mu^2) - \Delta(t,\mu^2)$$

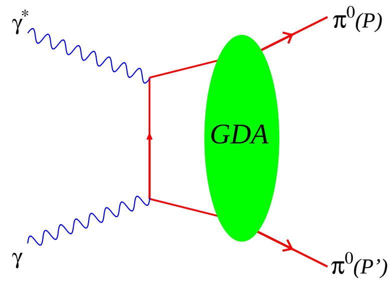
$\mathcal{R}e \rightsquigarrow$ unpol. σ(DVCS)
$\mathcal{I}m \rightsquigarrow$ beam-spin asymmetry
$\Delta(t,\mu^2) \;\to\; D(t)$ for $\mu \to \infty$
Teryaev; Diehl, Ivanov; Polyakov

first insights from experiment

- ***D*-term of π^0** $\gamma\gamma^* \to \pi^0\pi^0$ in e^+e^- Bell data: Masuda et al, PRD 93 (2016)

  $D^Q_{\pi^0} \approx -0.7$ at $\langle Q^2 \rangle = 16.6$ GeV^2 Kumano, Song, Teryaev, PRD97 (2018)

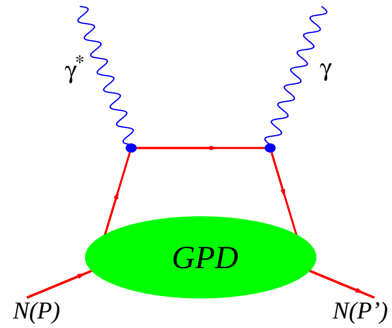
  chiral symmetry: total $D_{\pi^0} \approx -1$ (gluons contribute the rest)

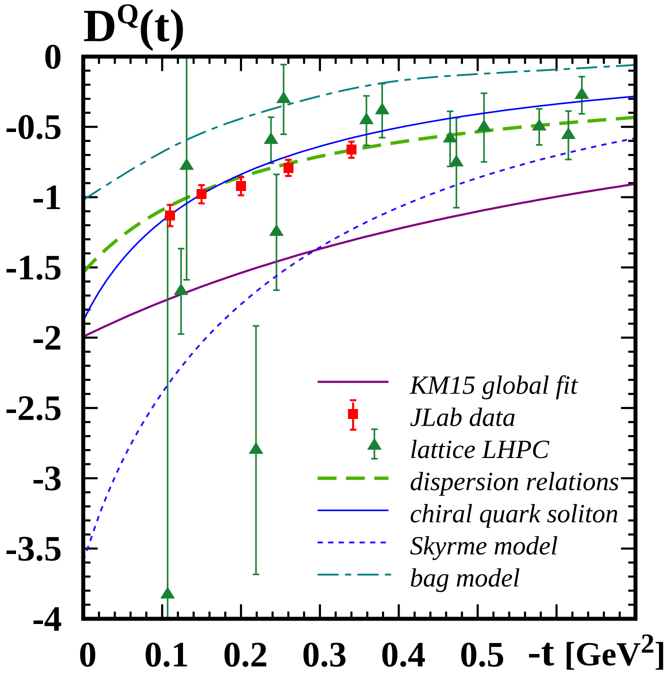


- ***D*-term of nucleon** Burkert, Elouadrhiri, Girod, **Nature** 557, 396 (2018)

  JLab data: PRL100 (2008) & PRL115 (2015)

  beam–spin asym.→$\mathcal{I}m\,\mathcal{H}$ unpol. cross sect.→$\mathcal{R}e\,\mathcal{H}$





$\Delta(t, \mu^2) \to D^Q(t)$ under assumptions!

Model-dependent (very first attempt)
But proof of principle: method works
K. Kumeričk, **Nature** 570, 7759 (2019)
cf. talk by Paweł Sznajder
explore scale dependence of $\Delta(t, \mu^2) \to$ EIC

What will we learn from this last unknown fundamental property?

interpretation as 3D-densities (okay for nuclei and nucleon) M.V.Polyakov, PLB 555 (2003) 57

Breit frame: $\Delta^\mu = (0, \vec{\Delta})$: static EMT $\boldsymbol{T_{\mu\nu}(\vec{r})} = \int \frac{d^3\vec{\Delta}}{2E(2\pi)^3}\, e^{i\vec{\Delta}\,\vec{r}}\, \langle P'|\hat{T}_{\mu\nu}|P\rangle$

$$\int d^3r\, T_{00}(\vec{r}) = M \qquad \text{known}$$

$$\int d^3r\, \varepsilon^{ijk}\, s_i\, r_j\, T_{0k}(\vec{r},\, \vec{s}) = \frac{1}{2} \qquad \text{known}$$

$$-\frac{2}{5} M \int d^3r \left(r^i r^j - \frac{r^2}{3}\delta^{ij}\right) T_{ij}(\vec{r}) \equiv \boldsymbol{D} \qquad \textbf{new!}$$

with: $$\boldsymbol{T_{ij}(\vec{r}) = s(r)\left(\frac{r_i r_j}{r^2} - \frac{1}{3}\,\delta_{ij}\right) + p(r)\,\delta_{ij}} \qquad \textbf{stress tensor}$$

$\boldsymbol{s(r)}$ related to distribution of *shear forces*
$\boldsymbol{p(r)}$ distribution of *pressure* inside hadron
$\longrightarrow$ **"mechanical properties"**

- EMT conserved $\Leftrightarrow$ $\partial^\mu \hat{T}_{\mu\nu} = 0$ $\Leftrightarrow$ $\nabla^i T_{ij}(\vec{r}) = 0$

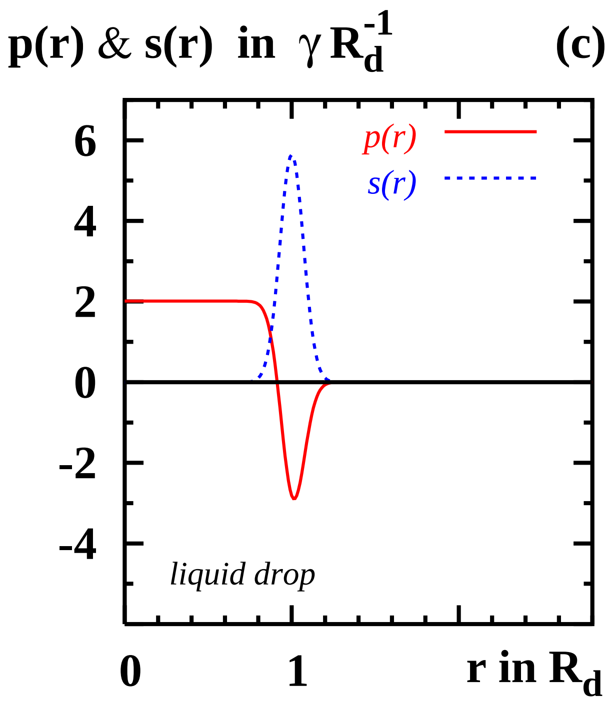
$\hookrightarrow$ necessary condition for **stability** $\int_0^\infty dr\, \boldsymbol{r^2\, p(r)} = 0$ (von Laue, 1911)

$$\boldsymbol{D} = -\frac{16\pi}{15}\, m \int_0^\infty dr\, r^4 s(r) = 4\pi m \int_0^\infty dr\, \boldsymbol{r^4\, p(r)}$$ $\rightarrow$ shows how internal forces balance
(already sign insightful! So far always negative)

remark on 2D densities: exact partonic probability densities M. Burkardt (2000)
applied to EMT form factors in works by Cédric Lorcé, Arek Trawiński, Harvey Moutarde
poster by Arek on Monday, talk by Cédric on Thursday

intuition from models:

- **liquid drop model of nucleus**



radius $R_A = R_0\, A^{1/3}$, $m_A = m_0\, A$

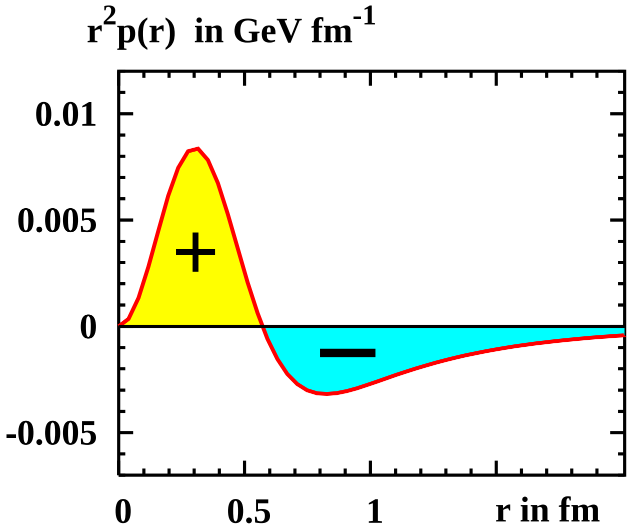
surface tension $\gamma = \frac{1}{2} p_0 R_A$, $s(r) = \gamma\, \delta(r - R_A)$

pressure $p(r) = p_0\, \Theta(R_A - r) - \frac{1}{3} p_0 R_A\, \delta(r - R_A)$

D-term $\boldsymbol{D = -\frac{4\pi}{3}\, m_A\, \gamma\, R_A^4 \approx -0.2\, A^{7/3}}$

M.V.Polyakov PLB555 (2003);
tested in Walecka model Guzey, Siddikov (2006)
alternative result in Liuti, Taneja, PRC 72 (2005)

- **chiral quark soliton model of nucleon**



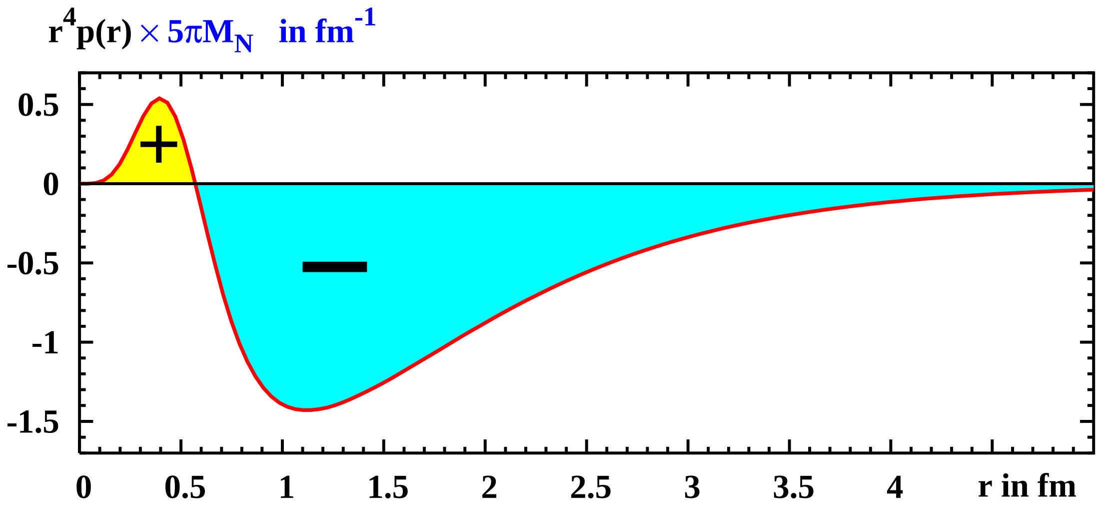
- $p(0) = 0.23\,\text{GeV/fm}^3 \approx 4 \times 10^{34}\,\text{N/m}^2$

  $\gtrsim$ 10-100×(pressure in center of neutron star)

- $p(r) = 0$ at $r = 0.57\,\text{fm}$ change of sign in pressure

- $p(r) = -\left(\frac{3g_A^2}{8\pi f_\pi}\right)^2 \frac{1}{r^6}$ at large r in chiral limit $m_\pi \to 0$

  Goeke et al, PRD75 (2007) 094021



recall: $\int_0^\infty \mathrm{d}r\, \boldsymbol{r^2\, p(r)} = 0$

$\boldsymbol{D} = 4\pi m \int_0^\infty \mathrm{d}r\, \boldsymbol{r^4\, p(r)} < 0$

negative sign of $D \;\Leftrightarrow\;$ **stability** (necessary condition)

mechanical radius

- $T_{ij}(\vec{r}) = s(r)\left(\frac{r_i r_j}{r^2} - \frac{1}{3}\,\delta_{ij}\right) + p(r)\,\delta_{ij} =$ symmetric 3×3 matrix $\rightarrow$ diagonalize:

  $\frac{2}{3}\,s(r) + p(r) =$ normal "force" (eigenvector $\vec{e}_r$)

  $-\frac{1}{3}\,s(r) + p(r) =$ tangential "force" ($\vec{e}_\theta$, $\vec{e}_\phi$, degenerate for spin 0 and $\frac{1}{2}$)

- mechanical stability $\Leftrightarrow$ normal force directed towards outside

  $\Leftrightarrow T^{ij} e_r^j\, dA = \underbrace{[\frac{2}{3}\,s(r) + p(r)]}_{>0} e_r^i\, dA \quad \Rightarrow \quad$ $\boldsymbol{D < 0}$ **(proof!)** Perevalova et al (2016)

- define: $\langle \boldsymbol{r}^2 \rangle_{\mathrm{mech}} = \dfrac{\int d^3r\ r^2[\frac{2}{3}\,s(r) + p(r)]}{\int d^3r\ [\frac{2}{3}\,s(r) + p(r)]} = \dfrac{6D(0)}{\int_{-\infty}^{0} \mathrm{d}t\, D(t)}$ vs $\langle r^2_{\mathrm{ch}} \rangle = \frac{6\,G_E'(0)}{G_E(0)}$ "anti-derivative"

  intuitive result for large nucleus $\frac{2}{3}\,s(r) + p(r) = p_0\,\Theta(R_A - r) \rightarrow \langle r^2 \rangle_{\mathrm{mech}} = \frac{3}{5}\,R_A^2$

  M.Polyakov, PS arXiv:1801.05858 (Kumano, Song, Teryaev PRD (2018) used $D'(0)$ but inadequate)

- in chiral limit $\langle r^2 \rangle_{\mathrm{mech}}$ finite vs $\langle r^2_{\mathrm{ch}} \rangle$ divergent (better concept)

- neutron $\langle r^2 \rangle_{\mathrm{mech}}$ same as proton(!) $\langle r^2_{\mathrm{ch}} \rangle = -\,0.11\,\mathrm{fm}^2$ inappropriate concept for neutron size
  (see also recent work Lorcé, Moutarde, Trawiński)

- proton: $\langle \boldsymbol{r}^2 \rangle_{\mathrm{mech}} \approx \boldsymbol{0.75}\,\langle \boldsymbol{r}^2_{\mathrm{ch}} \rangle$ in chiral quark soliton model

Summary & Outlook

- **GPDs, GDAs** $\rightarrow$
  form factors of **energy momentum tensor**

- **D-term**: last unknown global property,
  related to forces, attractive and physically appealling $\rightarrow$ "motivation"

- **first results**(!) from experiment/phenomenology for proton, π^0
  compatible with results from theory and models

- define **pressure, forces & mechanical radius**
  $\rightarrow$ unique, appealing, complementary information!

- **applications:**
  imaging of nucleon structure
  hadrocharmonia pentaquarks & tetraquarks
  and more applications

- rich **potential**, new **predictions**, some work is done
  lots of work still ahead of us

- I hope this talk showed:
  appealing, interesting topics, to be continued!

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Thank you!

Support slides

- **dispersion relation**

for $D(t)$ $\rightarrow$ situation better: dispersion relation. How this helps?

$$\Re\mathrm{e}\,\mathcal{H}(\xi,t,\mu^2) = \frac{1}{\pi}\,\mathrm{PV}\int \mathrm{d}x \left[\frac{1}{\xi-x} - \frac{1}{\xi+x}\right] \mathcal{I}m\,\mathcal{H}(x,t,\mu^2) - \Delta(t,\mu^2)$$

$\mathcal{R}\mathrm{e}\,\mathcal{H}(\xi,t,\mu^2) \rightsquigarrow$ unpolarized DVCS cross section

$\mathcal{I}m\,\mathcal{H}(\xi,t,\mu^2) \rightsquigarrow$ beam-spin asymmetry in DVCS

$$\Delta(t,\mu^2) = 4\sum_q e_q^2 \left[d_1^q(t,\mu^2) + d_3^q(t,\mu^2) + d_5^q(t,\mu^2) + \dots\right]$$

Teryaev hep-ph/0510031
Anikin, Teryaev, PRD76 (2007)
Diehl and Ivanov, EPJC52 (2007)
Radyushkin, PRD83, 076006 (2011)
M.V.Polyakov, PLB 555 (2003) small x

$$\lim_{\mu\to\infty} d_1^Q(t,\mu^2) = d_1(t)\,\frac{N_f}{N_f+4C_F}$$

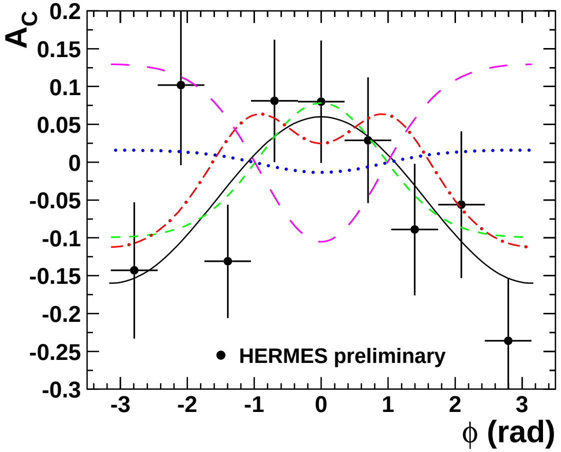
$$\lim_{\mu\to\infty} d_1^g(t,\mu^2) = d_1(t)\,\frac{4C_F}{N_f+4C_F}$$

$$\lim_{\mu\to\infty} d_i^a(t,\mu^2) \to 0 \quad \text{for } i = 3,5,\dots$$

$$\frac{4}{5}\,d_1(t) = D(t) \qquad C_F = \frac{N_c^2-1}{2N_c}$$

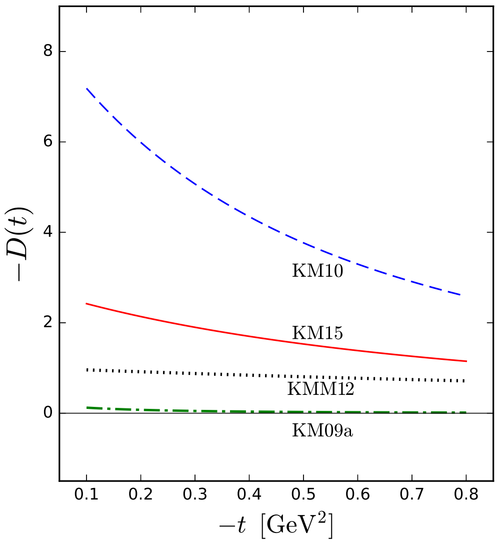
Results from experiment & phenomenology

- HERMES proceeding NPA711, 171 (2002) (model-dependent)



beam charge asymmetry (DVCS e^+ vs e^-)
dotted line: VGG model without D-term (ruled out)
dashed line: VGG model + positive D-term (ruled out)
dashed-dotted: VGG model + **negative** D-term (yeah!)
(cf. Belitsky, Müller, Kirchner, NPB 629 (2002) 323)

- fits by Kresimir Kumerički, Dieter Müller et al: $D < 0$ needed! (model-independent)

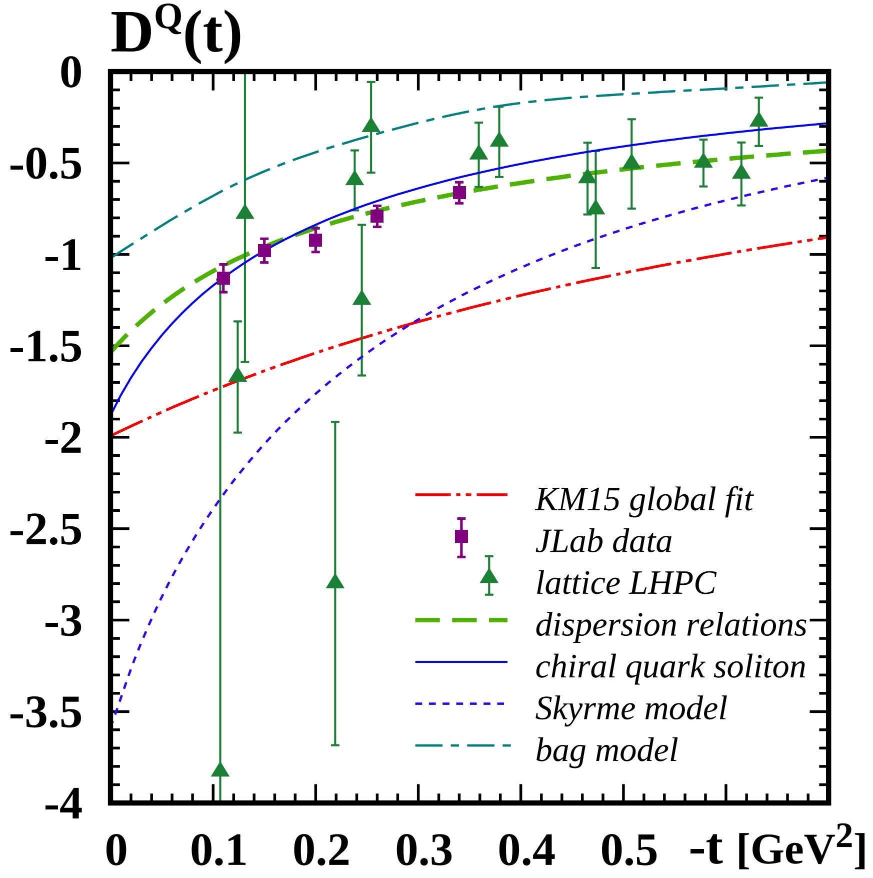


DVCS parametrizations from:
Kumerički, Müller, NPB 841 (2010) 1
Kumerički, Müller, Murray, Phys. Part. Nucl. 45 (2012) 723
Kumerički, Müller, EPJ Web Conf. 112 (2016) 01012
Fig. 9 in ECT* workshop proceeding 1712.04198
statistical uncertainty of D in KMM12: $\sim 50\,\%$,
statistical uncertainty of D in KM15: $\sim 20\,\%$.
unestimated systematic uncertainty
K.Kumerički private communication

- D-term of nucleon

Burkert, Elouadrhiri, Girod, **Nature 557, 396 (2018)** based on:
Girod et al PRL 100 (2008) 162002 and Jo et al PRL 115 (2015) 212003

beam–spin asymmetry→$\mathcal{I}m\,\mathcal{H}$ — unpol. cross section→$\mathcal{R}e\,\mathcal{H}$



$$\Delta(t,\mu^2) = 4\sum_q e_q^2\left[d_1^q(t,\mu^2) + \dots\right]$$

assumptions:

- neglect power corrections, NLO corrections at $E_{\text{beam}} = 6\,\text{GeV}$ and $\langle Q^2\rangle = 1.5\,\text{GeV}^2$
- only $\mathcal{H}$, neglect $\mathcal{E}$, etc
- $\Delta(t,\mu^2) = 4\sum_q e_q^2 d_1^q(t,\mu^2)$
  with $d_i^q(t,\mu^2)$ for $i = 3, 5, \dots$ neglected
  (in CQSM $d_3^Q/d_1^Q \sim 0.3$, $d_5^Q/d_1^Q \sim 0.1$
  (Kivel, Polyakov, Vanderhaeghen (2001))
- assume $d_1^u \approx d_1^d$
  (okay in CQSM, to be tested in experiment)

  $\rightsquigarrow\ D^Q(t,\mu^2) \approx \frac{18}{25}\Delta(t,\mu^2)$
- how good are these approximations?
  will see: JLab12, COMPASS, EIC, future experiments

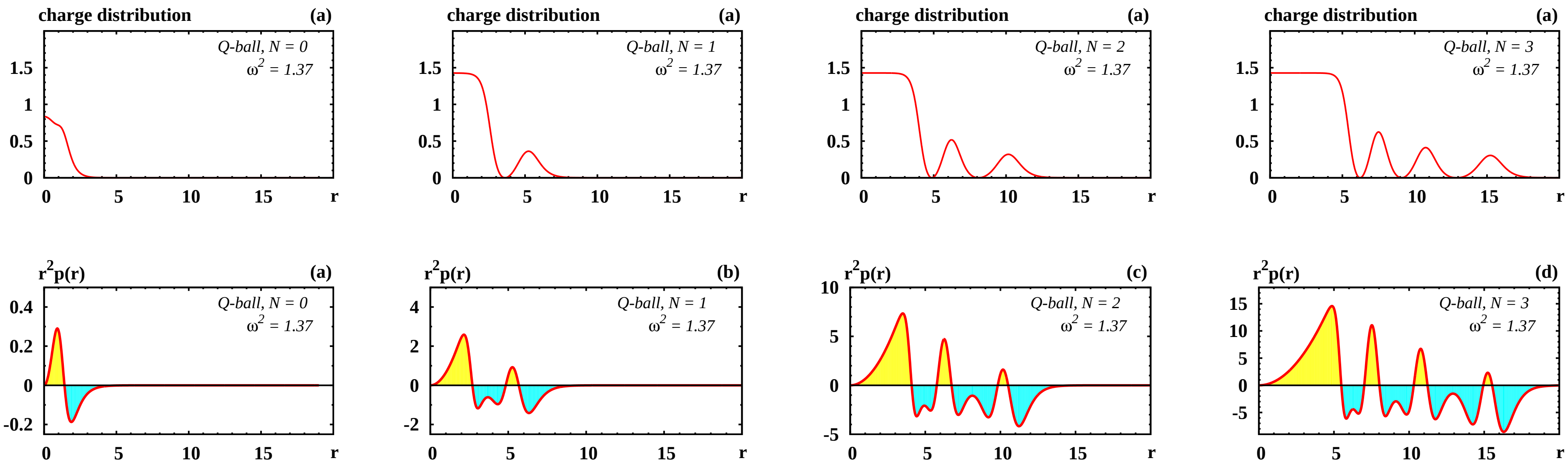
⇒ CLAS, KM-fits, dispersion relations, models, lattice: ***D*-term negative**

- **more intuition from toy system: Q-ball**

  $\mathcal{L} = \frac{1}{2}(\partial_\mu\Phi^*)(\partial^\mu\Phi) - V$ with U(1) global symm., $V = A\,(\Phi^*\Phi) - B\,(\Phi^*\Phi)^2 + C\,(\Phi^*\Phi)^3$, $\Phi(t,\vec{r}) = e^{i\omega t}\,\phi(r)$

  $N=0$ ground state, $N=1$ first excited state, etc Volkov & Wohnert (2002), Mai, PS PRD86 (2012)

  charge density exhibits N shells, $p(r)$ exhibits $(2N+1)$ zeros



  excited states unstable, but $\int_0^\infty dr\; r^2 p(r) = 0$ always valid, and D-term always negative!

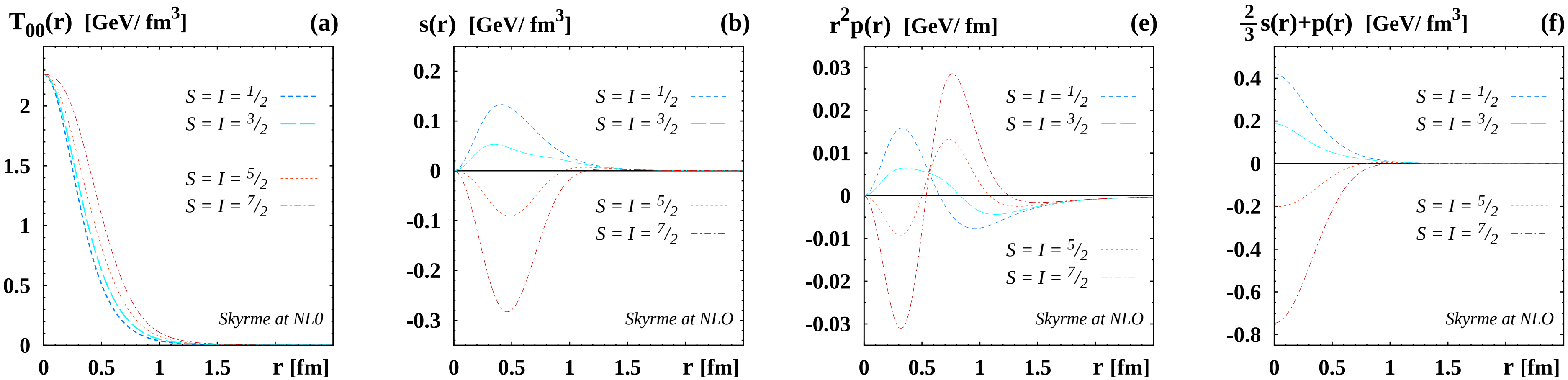
  so far **all D-terms** negative: pions, nucleons, nuclei, nucleons in nuclear matter, photons, Q-balls, Q-clouds

  could Roper resonance look like this? (possible to measure??) (transition GPDs???)
  However e.g. Δ-resonance, similar to nucleon! (lowest state for $J = T = \frac{3}{2}$, see below)

- side remark: you won't believe in how many models of the nucleon "the nucleon **does not** exist!!"
  (explodes or implodes within $t < 10^{-23}$s vs $t_{\text{proton}} > 10^{32}$ years ...)

Application I: nucleon, Δ, large-N_c artifacts Witten 1979

in large N_c baryons = rotational excitations of soliton with $S = I = \underbrace{\frac{1}{2}, \frac{3}{2}}_{\text{observed}}, \underbrace{\frac{5}{2}, \ldots}_{\text{artifacts}}$



$$M_B = M_{\text{sol}} + \frac{S(S+1)}{2\Theta}$$

nucleon $s(r) \neq \gamma\delta(r-R)$
Δ much more diffuse

$$\int_0^\infty dr\, r^2 p(r) = 0$$

stability needs more:
$p(r) > 0$ in center,
negative outside
okay for nucleon, Δ
$\Longrightarrow$ implies $D < 0$

mechanical stability
$T^{ij}\, da^j \geq 0$
$\Leftrightarrow \frac{2}{3}s(r) + p(r) \geq 0$
artifacts do not satisfy!
$\Rightarrow$ **have positive D-term!!**
That's why they do not exist!
EMT: dynamical understanding
Perevalova et al (2016)

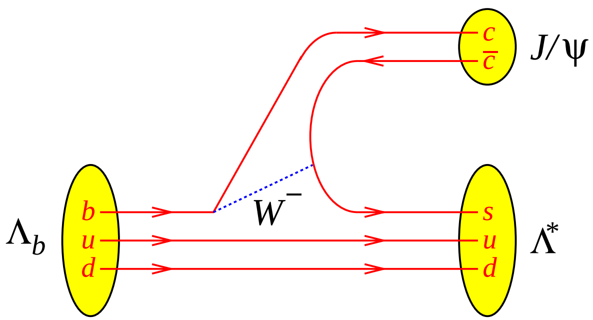
$\Rightarrow$ particles with positive D unphysical!!!

Application II: hidden-charm pentaquarks as hadrocharmonia

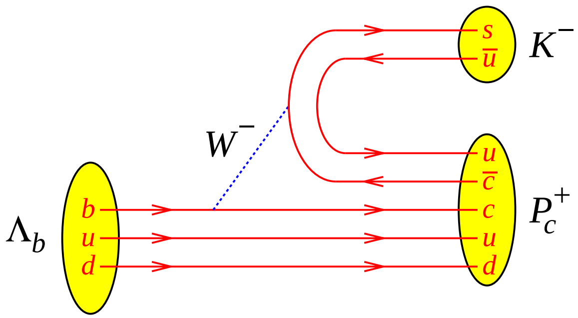
$\Lambda_b^0 \longrightarrow J/\Psi\, p\, K^-$ seen
Aaij *et al.* PRL 115 (2015)

Λ_b^0 $m = 5.6\,\text{GeV}$, $\tau = 1.5\,\text{ps}$
J/Ψ $m = 3.1\,\text{GeV}$, $\Gamma = 93\,\text{keV}$, $\Gamma_{\mu^+\mu^-} = 6\,\%$
Λ^* $m = 1.4\,\text{GeV}$ or more, $\Lambda^* \to K^- p$ in 10^{-23}s

$\longrightarrow J/\Psi\, \Lambda^*$



$\longrightarrow P_c^+\, K^-$



state	m [MeV]	Γ [MeV]	Γ_{rel}	mode	J^P
$P_c^+(4380)$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$(4.1 \pm 0.5 \pm 1.1)\,\%$	$J/\psi\, p$	$\frac{3}{2}^{\mp}$ or $\frac{5}{2}^{+}$
$P_c^+(4450)$	$4450 \pm 2 \pm 3$	$39 \pm 5 \pm 19$	$(8.4 \pm 0.7 \pm 4.2)\,\%$	$J/\psi\, p$	$\frac{5}{2}^{\pm}$ or $\frac{3}{2}^{-}$

Hadrocharmonium approach Eides, Petrov, Polyakov, PRD93, 054039 (2016)

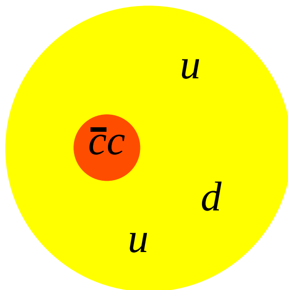
- **theoretical approach:** in heavy quark limit $\Rightarrow$ $V_{\text{eff}} = -\frac{1}{2}\,\alpha\,\vec{E}^2$ Voloshin, Yad. Fiz. **36**, 247 (1982)

- **chromoelectric polarizability** property of charmonium
  $\alpha(1S) \approx (1.6 \pm 0.8)\,\text{GeV}^{-3}$ Polyakov, PS PRD98 (2018); Sugiura et al, arXiv:1711.11219
  $\alpha(2S) \approx 17\,\text{GeV}^{-3}$ Eides et al; Perevalova, Polyakov, PS, PRD 94, 054024 (2016)
  $|\alpha(2S \to 1S)| \approx 2\,\text{GeV}^{-3}$ Voloshin, Prog. Part. Nucl. Phys. 61 (2008) 455
  cf. quarkonia = Coulomb systems Peskin NPB 156 (1979) 365

- **chromoelectric field strength:** $\vec{E}^2 \to T_{00}(r),\ p(r)$ from CQSM, Skyrme

- **compute quarkonium-nucleon bound state:** $\left(-\frac{\vec{\nabla}^2}{2\mu} + V_{\text{eff}}(r)\right)\psi = E_{\text{bind}}\,\psi$

- **results:** N and J/ψ form no bound state
  N and $\psi(2S)$ form **two** bound states
  with nearly degenerate masses $\sim 4450\,\text{MeV}$
  mass-splitting $\mathcal{O}(10\text{–}20)\,\text{MeV}$, $J^P = \frac{1}{2}^-$ and $\frac{3}{2}^-$,
  important: partial width $\Gamma = |\alpha(2S \to 1S)|^2 \times \cdots =$ few tens of MeV



- **update:** `26 March 2019, Observation of new pentaquarks, Moriond conference`:
  previous $P_c^+(4450)$ resolved in:
  $P_c^+(4440)$ $m = (4440.3 \pm 1.3^{+4.1}_{-4.7})$MeV, $\Gamma = (20.6 \pm 4.9^{+8.7}_{-10.1})$MeV
  $P_c^+(4457)$ $m = (4457.3 \pm 0.6^{+4.1}_{-1.7})$MeV, $\Gamma = (6.4 \pm 2.0^{+5.7}_{-1.9})$MeV **exciting!**

- **predictions:** bound states of $\psi(2S)$ with Δ and hyperons $\leftarrow$ test approch