Nucleon and Resonance Structure with Hard Exclusive Processes

29-31 May 2017, IPN Orsay

Insights into strong forces through GPDs

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Outline

- **Introduction**

  hard-exclusive reactions $\rightarrow$ GPDs(x, ξ, t)

  $\hookrightarrow$ $\underbrace{\text{tomography, Ji sum rule}}_{\xi=0}$ $+$ $\underbrace{\text{more than that}}_{\xi\neq 0}$

- **Energy-momentum tensor & D-term**

  last unknown global property(!)

  stress tensor, strong forces, stability

- **Applications**

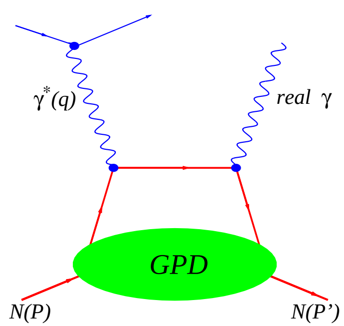
  pictorial : insights in strong forces

  principle: test correctness of models & effective approaches

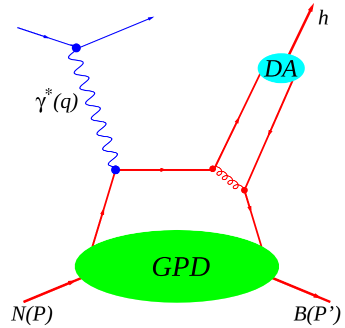
  practical: hard-exclusive reactions at JLab $\rightarrow$ $c\bar{c}$ pentaquark spectroscopy at LHCb

- **Outlook**

Introduction



DVCS



HMP

- hard-exclusive reactions
  factorization, access to **GPDs**
  Ji; Radyushkin; Collins, Frankfurt, Strikman

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

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

definitions for completeness:
$\xi = (n\cdot\Delta)/(n\cdot P), \quad t = \Delta^2$
$P = \frac{1}{2}(p'+p), \quad \Delta = p' - p$
$n^2 = 0,\ n\cdot P = 2,\ k = xP$
renormalization scale μ
analog gluon GPDs

- one day: we will know the GPDs.

- what will we learn?

Will learn a lot!

- GPDs generalize form factors, PDFs

  $\int \mathrm{d}x \; H^q(x,\xi,t) = F_1^q(t)$

  $\lim\limits_{\Delta\to 0} H^q(x,\xi,t) = f_1^q(x)$

- use impact parameter space $\to$ tomography (Ralston, Pire, Burkardt)

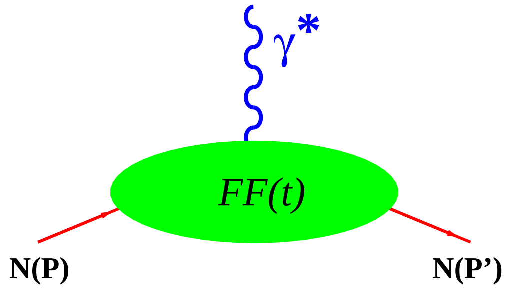
$$H^q(x,b_\perp) = \int \frac{\mathrm{d}^2\boldsymbol{\Delta}_\perp}{(2\pi)^2}\left[\lim_{\xi\to 0} H^q(x,\xi,t)\right] e^{i\boldsymbol{\Delta}_T \boldsymbol{b}_T}$$

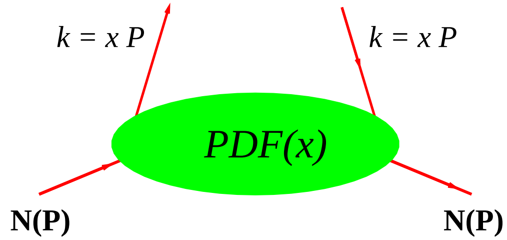
- polynomiality $\to$ access to **gravitational form factors**

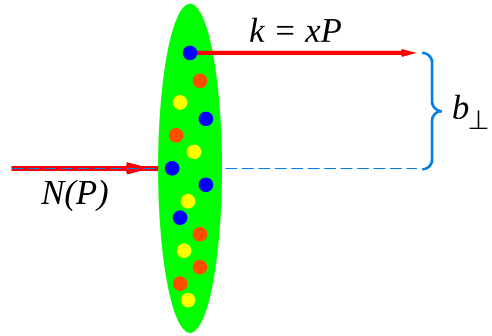
  $\int \mathrm{d}x \; x\, H^q(x,\xi,t) = \boldsymbol{A^q(t)} + \xi^2 \boldsymbol{D^q(t)}$

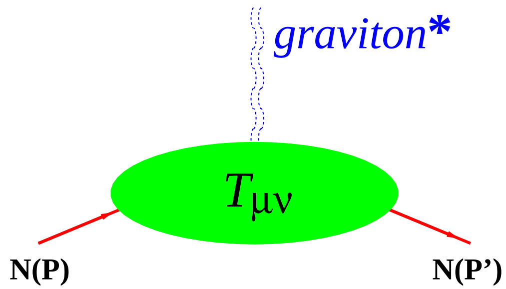
  $\int \mathrm{d}x \; x\, E^q(x,\xi,t) = \boldsymbol{B^q(t)} - \xi^2 \boldsymbol{D^q(t)}$

- and **gravity** couples to **energy momentum tensor** probably most fundamental quantity









Energy-momentum tensor (EMT)

- important: do you know introductory QFT text books which *do not* discuss EMT in first chapters?*

- generators of Poincaré group $\rightarrow$ matrix elements $\rightarrow$ $\underbrace{\textbf{mass}}_{!}$, $\underbrace{\textbf{spin}}_{!}$, $\underbrace{\textbf{D-term}}_{!?}$
  (in introductory books: free fields, solvable, instructive)

- even if not solvable, studies of EMT insightful
  prominent example: **Ji sum rule** PRL 78 (1997) 610

$$\int \mathrm{d}x\, x \Big(H^q(x,\xi,t) + E^q(x,\xi,t) \Big) = A^q(t) + B^q(t) \xrightarrow{t\to 0} 2J^q(0)$$

notice: ξ-dependence not explored, D-term is "first" if $\xi \neq 0$ considered: $\int \mathrm{d}x\, x H(x,\xi,t) = A(t) + \xi^2 D(t)$

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* interestingly, advanced QFT books discuss EMT in later chapters: *trace anomaly*
$\hat{T}^{\mu}_{\mu} \equiv \frac{\beta}{2g} F^{\mu\nu} F_{\mu\nu} + (1+\gamma_m) \sum_q m_q \bar{\psi}_q \psi_q$ Adler, Collins, Duncan, PRD15 (1977) 1712; Nielsen, NPB 120, 212 (1977); Collins, Duncan, Joglekar, PRD 16, 438 (1977)

definition of nucleon EMT form factors

$$\langle P'|\hat{T}^{q,g}_{\mu\nu}|P\rangle = \bar{u}(p')\Bigg[\; A^{q,g}(t)\,\frac{\gamma_\mu P_\nu + \gamma_\nu P_\mu}{2} + B^{q,g}(t)\,\frac{i(P_\mu\sigma_{\nu\rho} + P_\nu\sigma_{\mu\rho})\Delta^\rho}{4M_N} + D^{q,g}(t)\,\frac{\Delta_\mu\Delta_\nu - g_{\mu\nu}\Delta^2}{4M_N} \pm \bar{c}(t)g_{\mu\nu}\Bigg]u(p)$$

- $\hat{T}^q_{\mu\nu}$ and $\hat{T}^g_{\mu\nu}$ each gauge-invariant (not conserved)
- total EMT $\hat{T}_{\mu\nu} = \hat{T}^q_{\mu\nu} + \hat{T}^g_{\mu\nu}$ is conserved: $\partial_\mu \hat{T}^{\mu\nu} = 0$
- constraints: **mass** $\Leftrightarrow$ $A^q(0) + A^g(0) = 1$ (100 % of nucleon momentum carried by quarks + gluons)
  spin $\Leftrightarrow$ $B^q(0) + B^g(0) = 0$ (i.e. $J^q + J^g = \frac{1}{2}$ nucleon spin due to quarks + gluons)*
- property: **D-term** $\Leftrightarrow$ $D^q(0) + D^g(0) \equiv D$ $\rightarrow$ *fundamental quantity!*
  but unconstrained!
  Unknown!

* also expressed as: vanishing of total gravitomagnetic moment

notation: $A^q(t) = M_2^q(t)$, $A^q(t) + B^q(t) = 2\,J^q(t)$, $D^q(t) = \frac{4}{5}\,d_1^q(t) = \frac{1}{4}\,C^q(t)$ or $C^q(t)$

Last global unknown: How do we learn about nucleon?

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

em:	$\partial_\mu J^\mu_{\mathbf{em}} = 0$	$\langle N'\|J^\mu_{\mathbf{em}}\|N\rangle$	$\longrightarrow$	$Q,\ \mu,\ \ldots$
weak:	PCAC	$\langle N'\|J^\mu_{\mathbf{weak}}\|N\rangle$	$\longrightarrow$	$g_A,\ g_p,\ \ldots$
gravity:	$\partial_\mu T^{\mu\nu}_{\mathbf{grav}} = 0$	$\langle N'\|T^{\mu\nu}_{\mathbf{grav}}\|N\rangle$	$\longrightarrow$	$M,\ J,\ D,\ \ldots$

basic global properties:

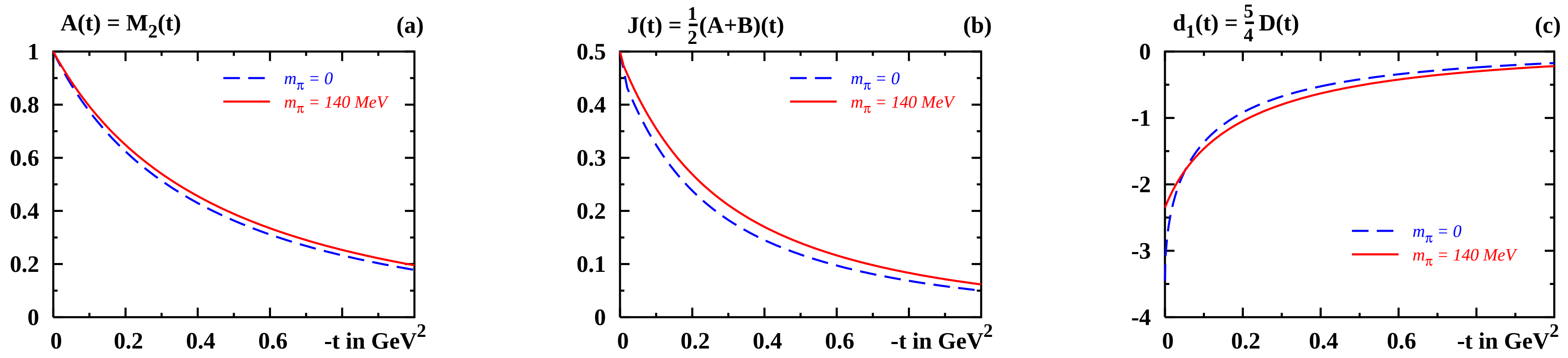
$$
\begin{aligned}
Q_{\text{prot}} &= 1.602176487(40)\times 10^{-19}\,\text{C} \\
\mu_{\text{prot}} &= 2.792847356(23)\,\mu_N \\
g_A &= 1.2694(28) \\
g_p &= 8.06(0.55) \\
M &= 938.272013(23)\,\text{MeV} \\
J &= \tfrac{1}{2} \\
\boldsymbol{D} &= \textbf{?}
\end{aligned}
$$

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

$\hookrightarrow$ $\boldsymbol{D} =$ *"last" global unknown*
which value does it have?
what does it mean?

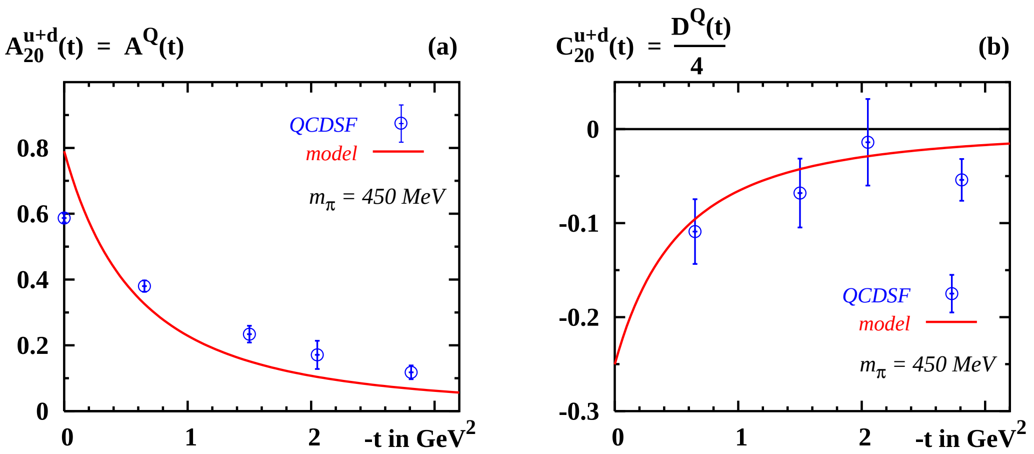
EMT form factors & D-term of nucleon:

- nature: **unknown!**
- model: e.g. chiral quark soliton model, Goeke et al, PRD75 (2007) 094021



well-tested model, many nucleon properties vs data within 30 % ✓

- lattice: QCDSF Collaboration, Göckeler et al, PRL92 (2004) 042002 & hep-ph/0312104 $\rightarrow$ test models



lattice QCD, bag model, Skyrme model,
chiral quark soliton model: $D_{\text{nucleon}} < 0$

other particles:
nuclei, pions, photons, Q-balls, Q-cloud, Higgs(!)
have also negative D-terms! (in theory!)

One day we will know $D(t)$ from **experiment!**

what will we learn?

interpretation of Fourier transforms of form factors as 3D-densities

- Breit frame $\Delta^\mu = (0, \vec{\Delta})$ and $t = -\vec{\Delta}^2$
- analog to electric form factor $G_E(\vec{\Delta}^2) = \int d^3\vec{r}\, \rho_E(\vec{r})\, e^{i\vec{\Delta}\,\vec{r}} \to$ charge distribution
  Sachs, PR126 (1962) 2256
  $\hookrightarrow Q = \int d^3\vec{r}\, \rho_E(\vec{r})$
- static EMT $T_{\mu\nu}(\vec{r}, \vec{s}) = \int \frac{d^3\vec{\Delta}}{2E(2\pi)^3}\, e^{i\vec{\Delta}\,\vec{r}}\, \langle P'|\hat{T}_{\mu\nu}|P\rangle \to$ mechanical properties of nucleon
  M.V.Polyakov, PLB 555 (2003) 57
  $\hookrightarrow M_N = \int d^3\vec{r}\, T_{00}(\vec{r})$

limitations of 3D densities ($\exists$ in contrast to 2D $\leftrightarrow$ tomography)

well known since earliest days (Sachs, 1962)
comprehensive studies, e.g. by
- Belitsky & Radyushkin, Phys. Rept. 418, 1 (2005), Sec. 2.2.2
- X.-D. Ji, PLB254 (1991) 456 (Skyrme model, not dramatic)
- G. Miller, PRC80 (2009) 045210 (toy model, dramatic)

No doubt: mathematical operation is well-defined
The question: is the concept justified? Answer:
yes of course, modulo **corrections**!
how large are these corrections?

are corrections large? Look at simplest framework

$\mathcal{L} = \frac{1}{2}(\partial_\mu\Phi)(\partial^\mu\Phi) - \frac{1}{2}m^2\Phi^2$ free neutral elementary point-like scalar particle

("Higgs" modulo standard model corrections)

evaluate EMT:

$$\langle \vec{p}\,'|\hat{T}^{\mu\nu}(x)|\vec{p}\,\rangle = e^{i(p'-p)x}\,\frac{1}{2}\Big\{P^\mu P^\nu A(t) + \Big(\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2\Big)D(t)\Big\}, \qquad A(t) = -D(t) = 1$$

compute **energy density**

$$T_{00}(\vec{r}) \equiv m^2 \int \frac{\mathrm{d}^3\Delta}{E(2\pi)^3}\, e^{i\vec{\Delta}\vec{r}} \left[A(t) - \frac{t}{4m^2}(A(t)+D(t))\right]$$ in Breit frame $E = E' = \sqrt{m^2 + (\vec{\Delta}/2)^2}$

$$\overset{\text{here}}{=} \frac{m}{\sqrt{1-\vec{\nabla}^2/(4m^2)}}\,\delta^{(3)}(\vec{r})$$

reproduces correctly $\int \mathrm{d}^3r\, T_{00}(\vec{r}) \overset{!}{=} m$

but yields $\langle r_E^2\rangle = \frac{1}{m}\int \mathrm{d}^3r\, r^2 T_{00}(\vec{r}) \overset{??}{=} \frac{3}{4m^2}$

mean square radius $\neq 0$ for point-like particle???
effect of relativistic "recoil" corrections
bad concept for point-like particle

However . . .

- take **heavy mass limit** to recover "correct" description

$$T_{00}(\vec{r}) \longrightarrow m\,\delta^{(3)}(\vec{r}) \quad \text{for } m \to \text{large} \ldots$$ large with respect to what?

- let's give particle a **finite size R** (i.e. "smear out" δ-function, such that reduces to $\delta^{(3)}(\vec{r})$ for $R \to 0$)

$$T_{00}(\vec{r})_{\text{true}} \overset{\text{e.g.}}{=} m\,\frac{e^{-r^2/R^2}}{\pi^{3/2}\,R^3} \quad \text{"true energy density"}$$

$$\to \quad \langle r_E^2\rangle = \langle r_E^2\rangle_{\text{true}}\left(1+\delta_{\text{corr}}\right) \simeq \langle r_E^2\rangle_{\text{true}} \quad \text{with } \delta_{\text{corr}} \equiv \frac{1}{2m^2R^2} \ll 1 \qquad \langle r_E^2\rangle_{\text{true}} = \tfrac{3}{2}R^2 \text{ for Gaussian}$$

- **nuclei** $(m_A \simeq m_N A,\ R_A = R_0\,A^{1/3},\ R_0 \sim 1.3\,\text{fm}) \ \to\ \delta_{\text{corr}} \sim 0.16\,A^{-8/3} \lesssim 4\times10^{-3}$ (^{4}He, ...)

- **for nucleon** $(m_p \sim 938\,\text{MeV},\ R_p \sim 0.875\,\text{fm}) \ \to\ \delta_{\text{corr}} \sim 0.03 \overset{!?}{\ll} 1$ small enough!?

- **large-N_c nucleon** $(m_N \sim N_c,\ R_N \sim N_c^0) \ \to\ \delta_{\text{corr}} \sim \dfrac{1}{N_c^2} \overset{!!}{\ll} 1$ small!! Why?

remark: $\dfrac{1}{N_c}$ *is the only available (known) small parameter in QCD at* ***all*** *energies*

(large-N powerful theoretical method, much more general than QCD)

- **interpretation as 3D-densities** (M.V.Polyakov, PLB 555 (2003) 57)

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

interpretation in terms of 3D-densities subject to corrections, BUT all formulae correct!

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

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

$$-\frac{5M_N}{8} \int d^3r \left(r^i r^j - \frac{r^2}{3}\delta^{ij}\right) T_{ij}(\vec{r}) \equiv D \qquad \textbf{new!}$$

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

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

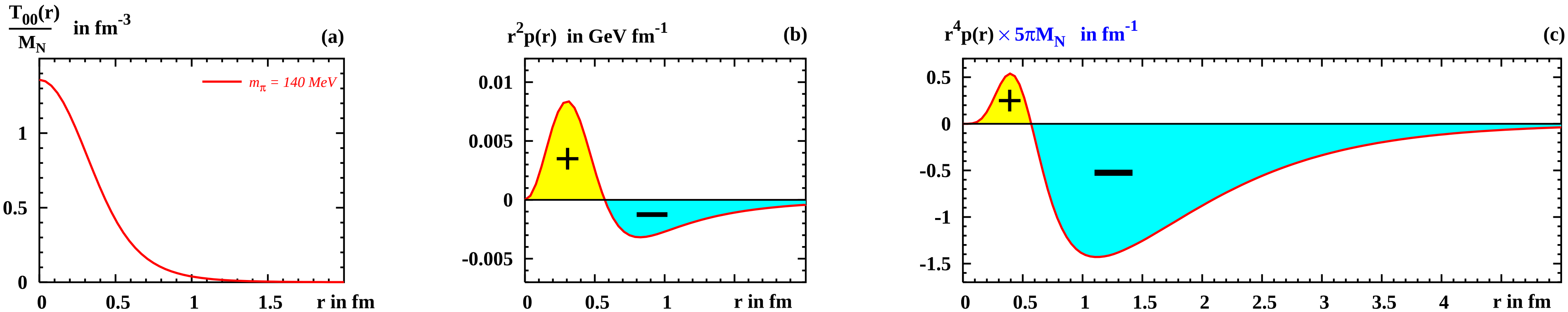
- **relation to stability**: EMT conservation $\Leftrightarrow$ $\partial^\mu \hat{T}_{\mu\nu} = 0$ $\Leftrightarrow$ $\nabla^i T_{ij}(\vec{r}) = 0$

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

$$D = -\frac{16\pi}{15} M_N \int_0^\infty \mathrm{d}r\, r^4 s(r) = 4\pi M_N \int_0^\infty \mathrm{d}r\, \boldsymbol{r^4\, p(r)}$$

$\hookrightarrow$ shows how internal forces balance

- lessons from model



energy density — pressure: $r^2 p(r)$ — $r^4 p(r)$ $\rightsquigarrow$ sign of d_1 negative

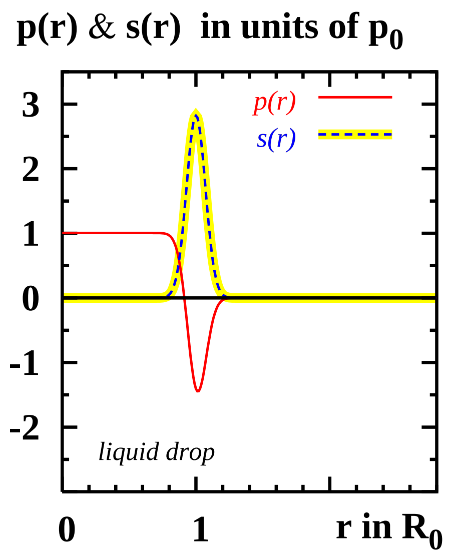
$T_{00}(0) = 1.70\,\mathrm{GeV/fm^3} \approx 3 \times 10^{15}\,\rho(\mathrm{H_2O}) \approx 13 \times$ (nuclear density)

$p(0) = 0.23\,\mathrm{GeV/fm^3} \approx 4 \times 10^{34}\,\mathrm{N/m^2}$ $\gtrsim 100\times$(pressure in center of neutron star)

in chiral quark soliton model (Goeke et al, PRD75 (2007) 094021)

... *how does it look like in QCD? Would be fascinating to know!*

- **intuition on shear forces and pressure**



liquid drop

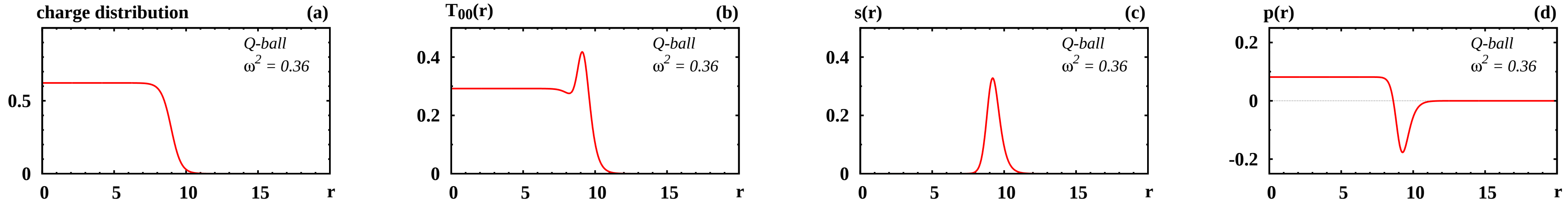
radius R_0
inside pressure p_0
surface tension $\gamma = \frac{1}{2} p_0 R_0$

$$s(r) = \gamma\, \delta(r - R_0)$$

$$p(r) = p_0\, \Theta(R_0 - r) - \tfrac{1}{3} p_0 R_0\, \delta(r - R_0)$$

application: liquid drop model of nucleus
(M.V.Polyakov, PLB 555 (2003) 57)

realized in field theoretical Q-ball system



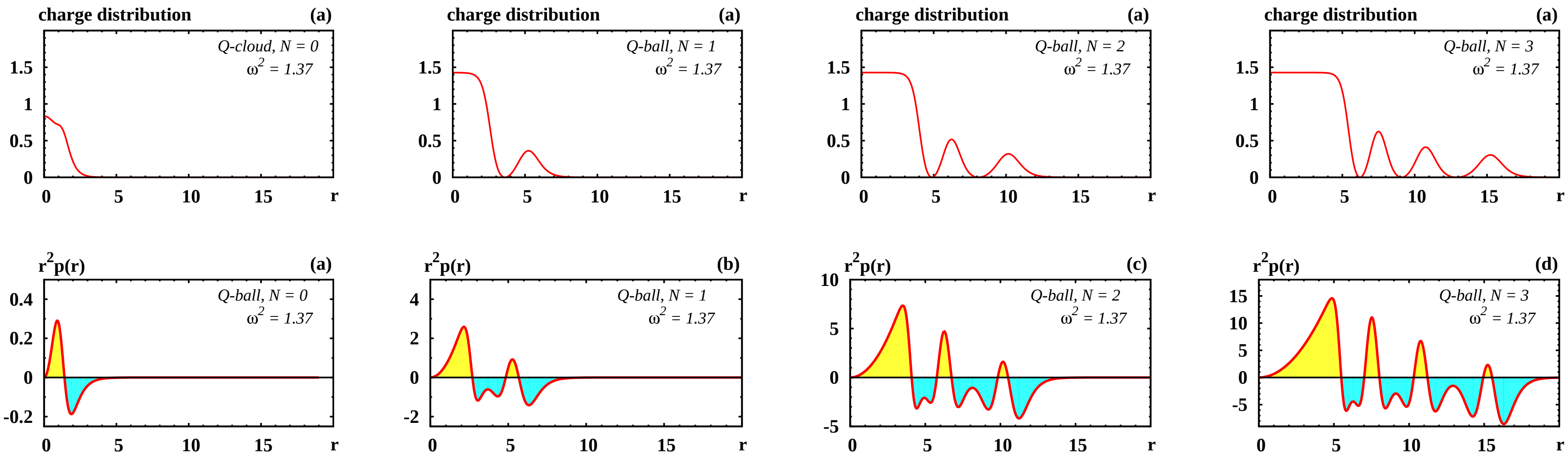
$\mathcal{L} = \frac{1}{2}(\partial_\mu \Phi^*)(\partial^\mu \Phi) - V$ with U(1) global symm., $V = A\,(\Phi^*\Phi) - B\,(\Phi^*\Phi)^2 + C\,(\Phi^*\Phi)^3$, $\Phi(t,\vec{r}) = e^{i\omega t}\,\phi(r)$
S. R. Coleman, NPB262 (1985) 263, 269 (1986) 744E; M. Mai, PS PRD86 (2012) 076001

to satisfy $\int_0^\infty \mathrm{d}r\; r^2 p(r) = 0 \;\to\; p(r)$ **must have a zero! Could it have more zeros?**

N^{th} radial excitations of Q-balls

$N = 0$ ground state,
$N = 1$ first excited state, etc

Mai, PS PRD86 (2012) 096002
charge density exhibits N shells
$p(r)$ exhibits $(2N+1)$ zeros



$N > 0$ radial excitations all unstable
→ decay to ground state Q-balls of smaller total energy and same total charge

nevertheless $\int_0^\infty \mathrm{d}r\, r^2 p(r) = 0$ always valid
→ necessary (not sufficient) condition ⇔ (local vs global minimum of action)

D-term always negative!
→ is it a theorem? → for Q-balls yes Mai, PS PRD86 (2012) 076001
→ rigorous proof that $d_1 < 0$ for hadrons in QCD and other particles still awaiting

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

(Q-**cloud:** most extreme instability(!); parametric limit where Q-balls dissociate in free quanta; still $D < 0$)

Application I: investigating forces

prominent property of proton:
life time $\tau_{\text{prot}} > 2.1 \times 10^{29}$ years!

question: how do strong forces balance to produce stability?

- answer in **model:** strong cancellation of repulsive forces due to quark core, and attractive forces from pion cloud

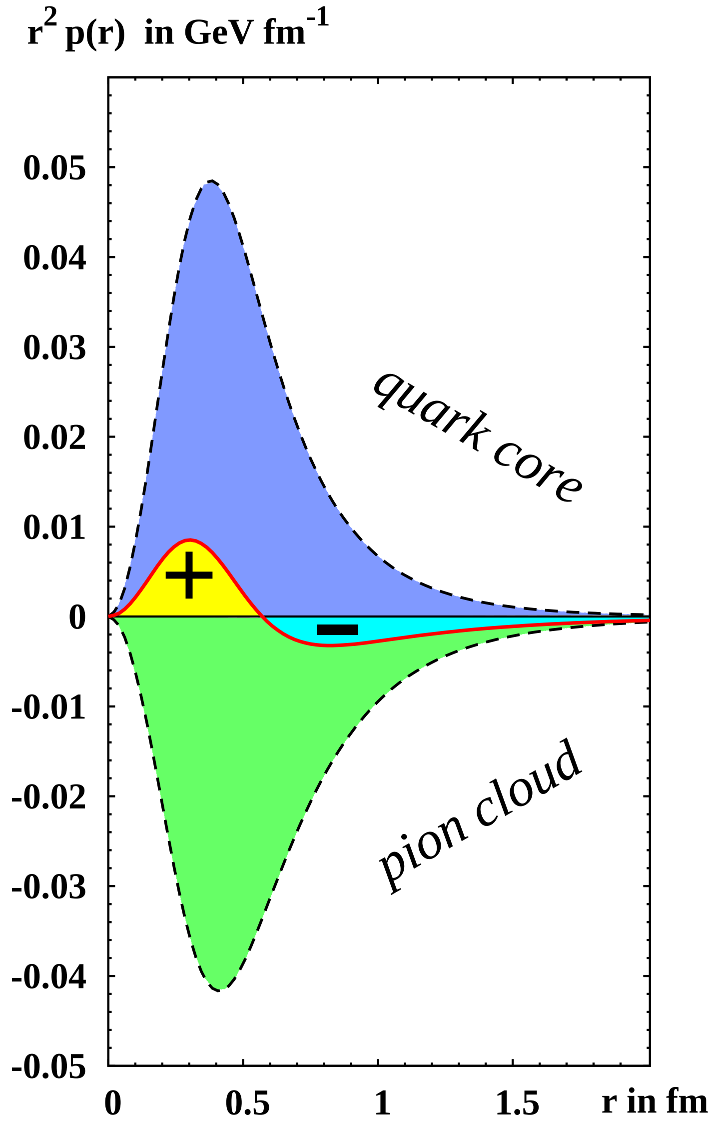
- answer in **QCD:** we do not know
nice pictures, attractive insights
underexplored propaganda(?)

be aware: same for neutron,
$\tau_{\text{neut}} = 14\,\text{min}\,40\,\text{sec} \gg 10^{-23}\,\text{sec}$
and even the same picture for Δ ...
$\tau_{\Delta} \sim 10^{-23}\,\text{sec} \rightarrow$ necessary condition!

- as motivation for GPD program: okay

... but is there any practical use of that?

answer: in principle yes!



in chiral quark soliton model
chiral symmtry breaking ✓
realization of QCD in large-N_c ✓
built on instanton vacuum calculus ✓
not bad, but after all a model ...
Goeke et al, PRD75 (2007)

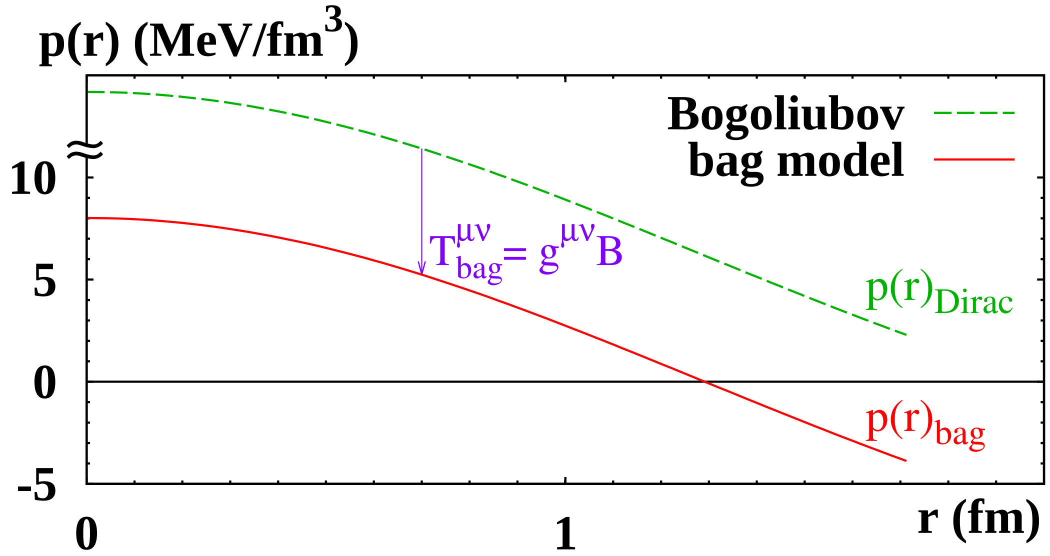
Application II: test models or effective theories

Whether you like 3D densities or not:

- you can evaluate EMT form factor: $D(t)$
- take Fourier transform $\to p(r)$
  (do not call it pressure, if you do not like it)
- check that $\displaystyle\int_0^\infty \mathbf{d}r\, r^2 p(r) = 0$ (must be due to $\partial_\mu T^{\mu\nu} = 0$)

  if true: consistent model, nucleon exists
  (e.g. chiral quark soliton model, bag model, Skyrme model LO, ...)

  if not: something is screwed up, no nucleon exists
  (e.g. Bogolyubov model, spectator model, Skyrme model NLO, ...)
- depending on answer use model (with due care)
  or improve/repair (if you know how)
  or discard



Bogoliubov model (1967)

Thomas & Weise,

"Structure of Nucleon,"

Sec. 8.4.1

Bogoliubov: $M_N = \dfrac{3\omega_0}{R_{\text{bag}}}$ where R_{bag} fixed by hand

bag model: $M_N = \dfrac{3\omega_0}{R_{\text{bag}}} + \dfrac{4\pi}{3} R^3_{\text{bag}} B \quad \rightarrow \quad R_{\text{bag}}$ from $\delta M_N = 0 \;\Leftrightarrow\; \displaystyle\int_0^{R_{\text{bag}}} \mathrm{d}r\, r^2 p(r) = 0$

try to minimize M_N in Bogoliubov model $\Rightarrow$ $R_{\text{bag}} \rightarrow \infty$ due to $p(r)_{\text{Dirac}} > 0$ **Explosion!!**

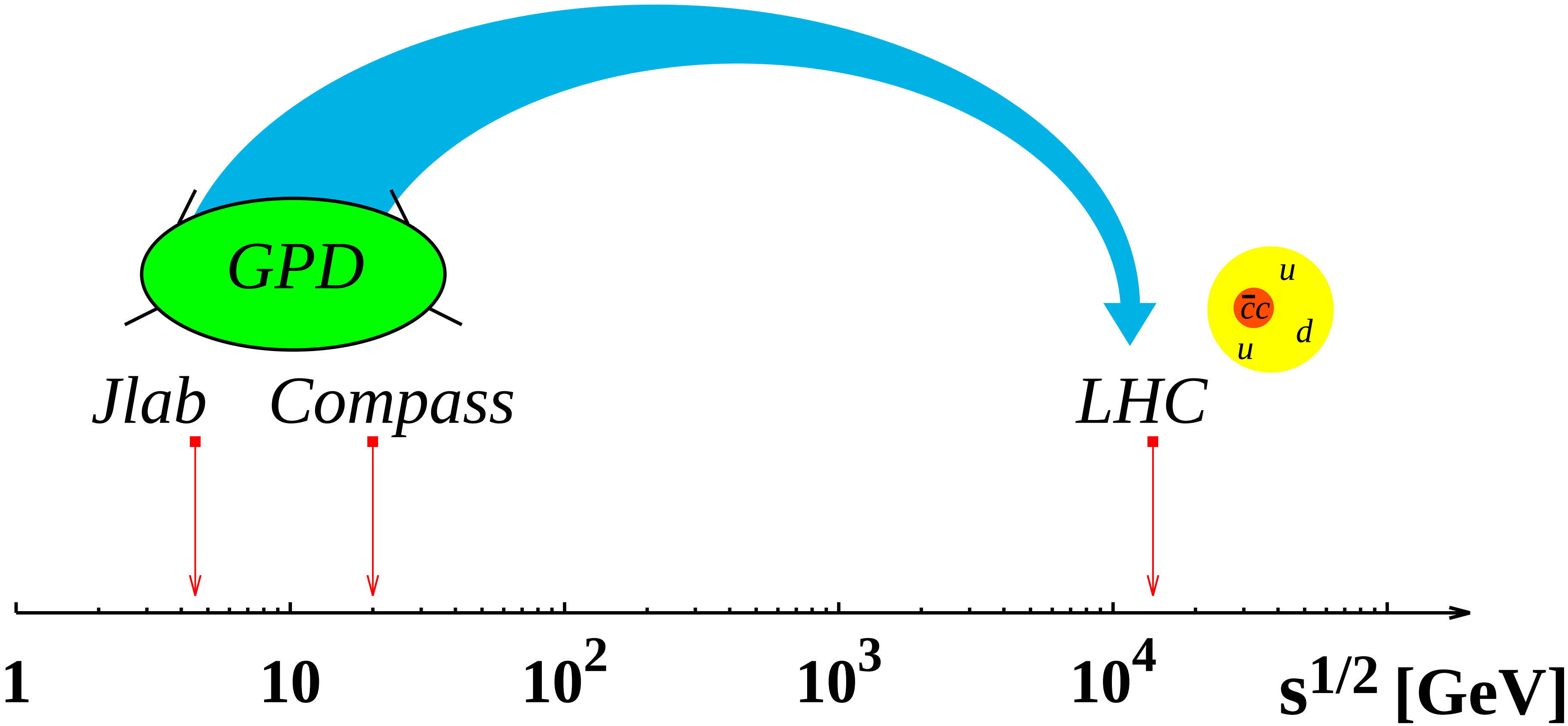
Notice that D_{Bogo} positive! But unphysical system. Model discarded!

(has done its job, paved the way for bag model)

Why bag model in 21 century? Because still insightful!

And enthusiastic undergraduate students can handle it!

Application III: amazing!



from hard-exclusive reactions at JLab, COMPASS ...

... to spectroscopy of $\bar{c}c$-pentaquarks at LHCb

not usual hadrons, not just any exotic hadron

only $\bar{c}c$-baryon bound states $\rightarrow$ rich enough!

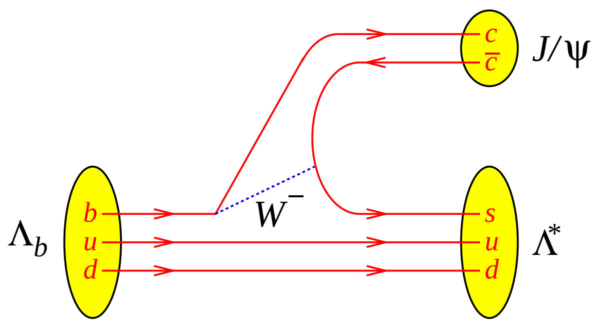
- **discovery of charmonium pentaquarks in Λ_b^0 decays at LHCb**

Aaij *et al.* PRL 115, 072001 (2015)

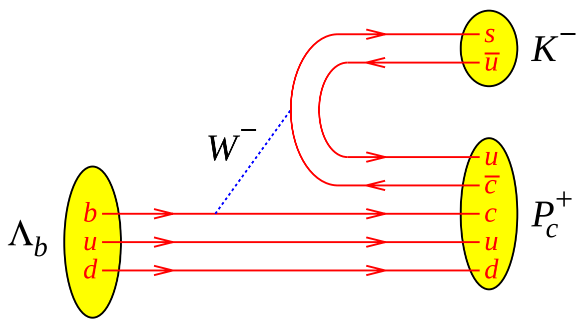
Λ_b^0 $m = 5.6$ GeV, $\tau = 1.5$ ps
J/Ψ $m = 3.1$ GeV, $\Gamma = 93$ keV, $\Gamma_{\mu^+\mu^-} = 6\,\%$
Λ^* $m = 1.4$ GeV or more, $\Lambda^* \to K^- p$ in 10^{-23}s

$\Lambda_b^0 \longrightarrow J/\Psi\, p\, K^-$ seen

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



$\longrightarrow J/\Psi\, P_c^+$



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 $\frac{3}{2}^{-}$

Appealing approach to new pentaquarks

Eides, Petrov, Polyakov, PRD**93**, 054039 (2016)
Perevalova, Polyakov, PS, PRD**94**, 054024 (2016)

- **theoretical approach**

  $R_{J/\psi} \ll R_N \;\Rightarrow$ non-relativistic multipole expansion Gottfried, PRL 40 (1978) 598
  baryon-quarkonium interaction dominated by 2 virtual chromoelectric dipole gluons

  $V_{\text{eff}} = -\frac{1}{2}\,\alpha\,\vec{E}^2$ Voloshin, Yad. Fiz. **36**, 247 (1982)

- **chromoelectric polarizability**

$$\alpha(1S) \approx 0.2\,\text{GeV}^{-3}\ \text{(pert)},$$
$$\alpha(2S) \approx 12\,\text{GeV}^{-3}\ \text{(pert)},$$
$$\alpha(2S\to 1S) \approx \begin{cases} -0.6\,\text{GeV}^{-3}\ \text{(pert)},\\ \pm 2\,\text{GeV}^{-3}\ \text{(pheno)},\end{cases}$$

in heavy quark mass limit & large-N_c limit
$\rightsquigarrow$ "perturbative result" Peskin, NPB 156 (1979) 365

value for $2S \to 1S$ transition from
phenomenological analysis of $\psi' \to J/\psi\,\pi\,\pi$ data
Voloshin, Prog. Part. Nucl. Phys. 61 (2008) 455

- **chromoelectric field strength:**

$$\vec{E}^2 = g^2\left(\frac{8\pi^2}{bg^2}\,T^\mu{}_\mu + T^G_{00}\right)$$

$b = \frac{11}{3}N_c - \frac{2}{3}N_F$ leading coeff. of β-function
$g =$ strong coupling at low (nucleon) scale $\lesssim 1$ GeV
$g_s =$ strong coupling at scale of heavy quark ($g_s \neq g$)
$T^G_{00} = \xi T_{00}$ with $\xi =$ fractional contributions of gluon to M_N
$T^\mu{}_\mu = T^{00} - T^{ii}$, stress tensor $T^{ij} = \left(\frac{r^i}{r}\frac{r^j}{r} - \frac{1}{3}\,\delta^{ij}\right)s(r) + \delta^{ij}\,p(r)$

- **universal effective potential**

$$V_{\text{eff}} = -\tfrac{1}{2}\,\alpha\,\frac{8\pi^2}{b}\,\frac{g^2}{g_s^2}\Big[\nu\,T_{00}(r) + 3p(r)\Big], \quad \nu = 1 + \xi_s\,\frac{b\,g_s^2}{8\pi^2}$$

$\nu \approx 1.5$ estimate by Eides et al, op. cit.
Novikov & Shifman, Z.Phys.C8, 43 (1981);
X. D. Ji, Phys. Rev. Lett. **74**, 1071 (1995)

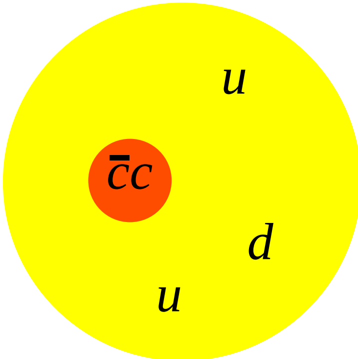
- **in future GPDs can help:** GPDs ⇒ EMT form factors ⇒ EMT densities
  ⇒ universal potential V_{eff} for quarkonium-baryon interaction!

- **currently:** e.g. chiral quark soliton model, Skyrme model

- **compute quarkonium-nucleon bound state**

  solve $$\left(-\frac{\vec{\nabla}^2}{2\mu}+V_{\text{eff}}(r)\right)\psi = E_{\text{bind}}\,\psi$$

  $\mu =$ reduced quarkonium-baryon mass



- **results:**

  nucleon and J/ψ form no bound state

  nucleon and $\psi(2S)$ form 2 bound states with nearly degenerate masses around 4450 MeV
  in $L=0$ channel, $J^P = \frac{1}{2}^-$ and $\frac{3}{2}^-$ if $\alpha(2S) \approx 17\ \text{GeV}^{-3}$ (consistent with guideline from pert. calc.)
  robust! Largely model-independent

- **decay of $P_c(4450)$**

  cannot decay directly to $\psi(2S)$ and nucleon, as $M_{\psi(2S)} + M_N > 4450\,\text{MeV}$

  instead transition $(2S) \to (1S)$ governed by the same $\boldsymbol{V_{\text{eff}}}$
  but with small $\alpha(2S \to 1S)$ transition polarizability
  $\Rightarrow$ it "takes time"

  after the transition is "completed,"
  prompt decay to $J/\psi +$ nucleon
  (observed final states)

  estimated width is tens of MeV $\to$ compatible with data!

- first found in χQSM (Eides et al)
  confirmed in Skyrme model (Perevalova et al)

- prediction: also **Δ and $\psi(2S)$ form isospin-$\frac{3}{2}$ bound state**
  mass $= 4.5$ GeV, $\Gamma_{\Delta\bar{c}c} \sim 60$ MeV
  negative parity ($l = 0$), spin $\frac{1}{2} \leq J \leq \frac{5}{2}$
  (states degenerate in heavy quark limit)

  possibly also a broad isospin-$\frac{3}{2}$ resonance
  mass $= 4.9$ GeV, $\Gamma_{\Delta\bar{c}c} \sim 150$ MeV
  positive parity ($l = 1$), spin $\frac{1}{2} \leq J \leq \frac{7}{2}$

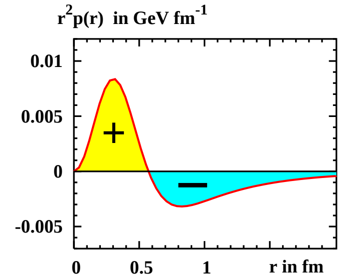
  decays $\rightarrow J/\psi + \underbrace{\text{nucleon} + \text{pion}}_{\Delta\text{-resonance}}$

  hyperon-quarkonium bound states are also possible! (Perevalova et al)

- what about $P_c^+(4380)$?
  cannot be charmonium-nucleon bound state
  broader, more possibilities, threshold cusp effect

Summary & Outlook

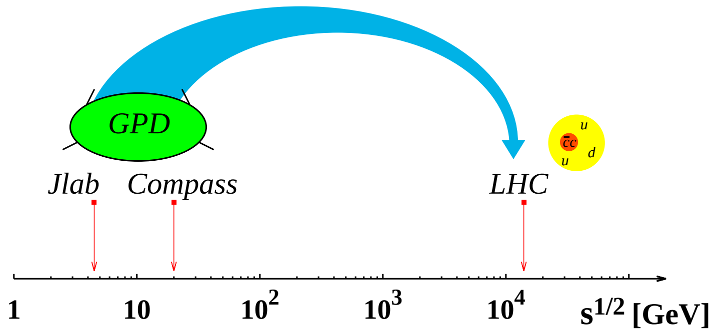
- GPDs $\hookrightarrow$ form factors of **energy momentum tensor**
  mass decomposition, spin decomposition, and D-term!



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

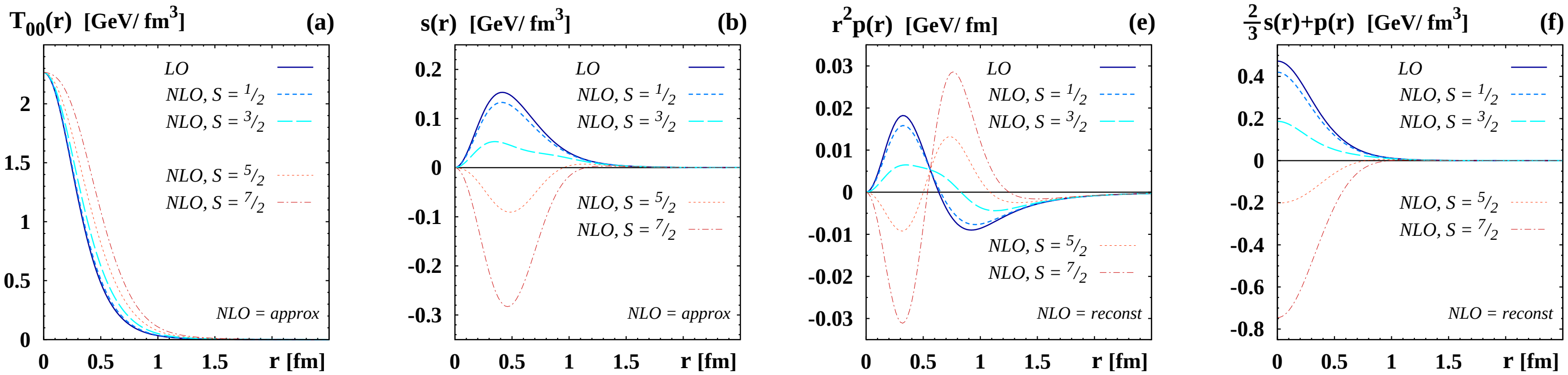
- recent development: knowledge of EMT densities
  $\to$ **quarkonium-baryon interaction V_{eff}**

- naturally explains properties of $P_c^+(4450)$ observed at LHCb
  rich potential, new predictions, ongoing work



Thank you!

support slide



EMT densities from the Skyrme model as functions of r. The LO results are valid for any $S = I$ in the large-N_c limit. The estimates of NLO corrections in the $1/N_c$-expansion are shown for states with the quantum numbers $S = I = \frac{1}{2}, \frac{3}{2}, \frac{5}{2}, \frac{7}{2}$.

The Figures show:

(a) energy density $T_{00}(r)$,

(b) shear forces $s(r)$,

(e) $r^2 p(r)$ with NLO corrections reconstructed from $s(r)$.

(f) the local stability criterion $\frac{2}{3}\, s(r) + p(r) > 0$ (if it holds)

States with the exotic quantum numbers $S = I \geq 5/2$ do not satisfy $\frac{2}{3}\, s(r) + p(r) > 0$
and have a positive D-term!! That's why they do not exist!
(Perevalova, Polyakov, PS, PRD**94**, 054024)