Origin of most of universe's visible matter – Theory and experiment

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Understand origin of the matter that amounts to
5% of the mass of the universe

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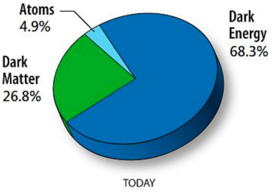

Actually:

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What is the origin of the mass of protons and neutrons (nucleons)?

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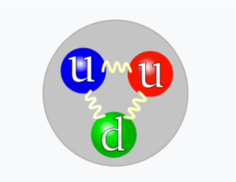


Computers gave an answer to the question

Nucleon mass comes from quarks and gluons

Quarks and gluons

— degrees of freedom of Quantum Chromodynamics: Q C D

$$\mathcal{L}_{\mathrm{QCD}} = \mathcal{L}_{\mathrm{G}} + \mathcal{L}_{\mathrm{light}} + \mathcal{L}_{\mathrm{heavy}}$$

$$= -\frac{1}{4} G^a_{\mu\nu}(x) G^{a\mu\nu}(x) + \overline{q}(x) \left(i\not{D} - m_{\mathrm{light}}\right) q(x) + \overline{Q}(x) \left(i\not{D} - m_{\mathrm{heavy}}\right) Q(x)$$

$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g f^{abc} A^b_\mu A^c_\nu$$

$$m_{\mathrm{light}} = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_d & 0 \\ 0 & 0 & m_s \end{pmatrix} \qquad m_{\mathrm{heavy}} = \begin{pmatrix} m_c & 0 & 0 \\ 0 & m_b & 0 \\ 0 & 0 & m_t \end{pmatrix}$$

$$m_u, m_d, m_s \simeq \mathcal{O}(\mathrm{MeV}) \qquad m_c, m_b \sim \mathcal{O}(\mathrm{GeV}) \qquad m_t \simeq 173 \ \mathrm{GeV}$$

Light-hadron masses

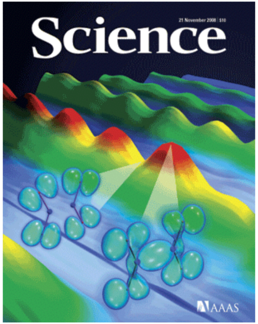
Science

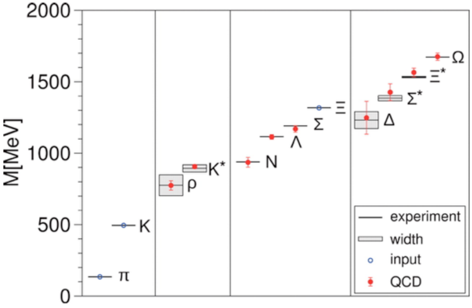
2008

Ab Initio Determination of Light Hadron Masses

S. Dürr, Z. Fodor, J. Frison, C. Hoelbling, R. Hoffmann, S. D. Katz, S. Krieg, T. Kurth, L. Lellouch, T. Lippert, K. K. Szabo and G. Vulvert

Science **322** (5905), 1224-1227.
DOI: 10.1126/science.1163233





Hadron-mass differences

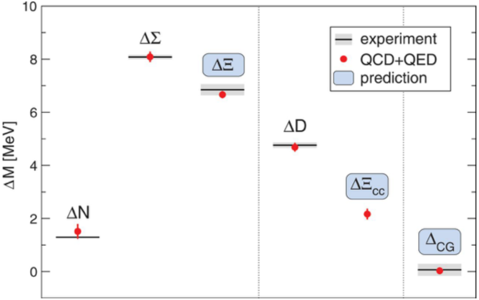
Science

2015

Ab initio calculation of the neutron-proton mass difference

Sz. Borsanyi, S. Durr, Z. Fodor, C. Hoelbling, S. D. Katz, S. Krieg, L. Lellouch, T. Lippert, A. Portelli, K. K. Szabo and B. C. Toth

Science **347** (6229), 1452-1455.
DOI: 10.1126/science.1257050



Nucleon weak axial charge

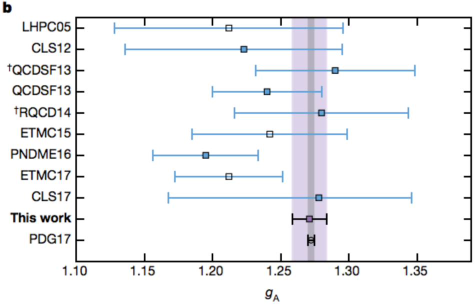
nature
International journal of science

2018

A per-cent-level determination of the nucleon axial coupling from quantum chromodynamics

C. C. Chang, A. N. Nicholson, E. Rinaldi, E. Berkowitz, N. Garron, D. A. Brantley, H. Monge-Camacho, C. J. Monahan, C. Bouchard, M. A. Clark, B. Joó, T. Kurth, K. Orginos, P. Vranas & A. Walker-Loud

Nature **558**, 91–94 (2018)



Hadron mass computation

$h(x)$: hadron interpolating field e.g. $\pi^+(x) = \overline{d}(x)\gamma_5 u(x)$

$$\langle h(x)h^\dagger(x+T)\rangle = \frac{\int [\mathcal{D}\psi\overline{\psi}A_\mu]\; h(x)h^\dagger(x+T)\; e^{-\int d^4x\, \mathcal{L}_{\mathrm{QCD}}}}{\int [\mathcal{D}\psi\overline{\psi}A_\mu]\; e^{-\int d^4x\, \mathcal{L}_{\mathrm{QCD}}}}$$

$$\boxed{\lim_{T\to\infty} \langle h(x)h^\dagger(x+T)\rangle \sim e^{-M_h T}}$$

Yet, we are not satisfied

We want to know more:

How did it happen?*

*F. Wilczek, *The lightness of being: Mass, ether, and the unification of forces* (Basic Books, 2008)

Back $\sim$ 40 years

— $|h(\boldsymbol{p})\rangle$: hadron state*, $p = (E_h(\boldsymbol{p}), \boldsymbol{p})$

*Normalized such that expectation value of T^{00} gives the hadron energy

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  Classical action is scale invariant: $x^\mu \to \lambda x^\mu$

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Since $\partial_\mu T^{\mu\nu}(x) = 0 \to \partial_\mu J^\mu_{\mathrm{D}}(x) = 0 \to T^\mu_\mu(x) = 0 \Rightarrow m_h = 0$

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Back $\sim$ 40 years - cont'd

— Quantum action IS NOT scale invariant: $\alpha_s = g^2/4\pi \xrightarrow{\text{reg.}} \alpha_s(\mu)$

$$\boxed{T^\mu_\mu(x) = \frac{\beta(\alpha_s)}{2\alpha_s}\, G^a_{\mu\nu}(x) G^{a\mu\nu}(x)}$$

This is the trace anomaly

— For $m_{\text{light}} = 0$ and $m_{\text{heavy}} = \infty$: $m_h = \frac{\beta(\alpha_s)}{2\alpha_s} \langle h | G^a_{\mu\nu}(x) G^{a\mu\nu}(x) | h \rangle$

— For $m_{\text{light}} \neq 0$ and m_{heavy} finite

$$\begin{aligned} m_h &= \frac{\beta(\alpha_s)}{2\alpha_s} \langle h | G^a_{\mu\nu} G^{a\mu\nu} | h \rangle + \langle h | \bar{q} m_{\text{light}} q | h \rangle \\ m_N &= \qquad\qquad \Downarrow \qquad\qquad\qquad\qquad \Downarrow \\ & \qquad \simeq 860 \text{ MeV} \qquad\qquad \simeq 80 \text{ MeV (Higgs)} \end{aligned}$$

How about the pion?

When $m_{\text{light}} = 0 \rightarrow m_\pi = 0$

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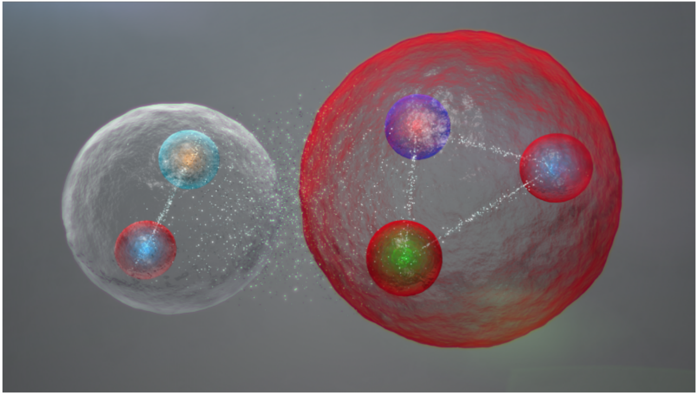
How does this happen?

Heavy quarkonium - nucleon scattering

Small QN relative momentum



Quarkonium: $\underbrace{\phi(s\bar{s})}_{\text{light}}, \underbrace{\eta_c(c\bar{c}), J/\psi(c\bar{c}), \eta_b(b\bar{b}), \Upsilon(b\bar{b})}_{\text{heavy}}$

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Low QN momentum interaction

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- QCD multipole expansion ($\sim$ OPE)

QN forward scattering amplitude*

QCD multipole expansion

$$
\begin{aligned}
f_{QN}(\boldsymbol{p},\boldsymbol{p}')|_{\boldsymbol{p}'=\boldsymbol{p}} &= \frac{\mu_{QN}}{2\pi}\,\frac{1}{2}\left[\frac{2T_F}{3N_c}\langle\varphi_Q|\boldsymbol{r}\,\frac{1}{E_b+H_{\rm octet}}\,\boldsymbol{r}|\varphi_Q\rangle\right]\langle N(\boldsymbol{p})|(g\boldsymbol{E}^a)^2|N(\boldsymbol{p})\rangle \\
&= \frac{\mu_{QN}}{2\pi}\,\frac{1}{2}\,\alpha_Q\,\langle N(\boldsymbol{p})|(g\boldsymbol{E}^a)^2|N(\boldsymbol{p})\rangle
\end{aligned}
$$

— μ_{QN} reduced mass, $\boldsymbol{p},\boldsymbol{p}$' relative c.m. momenta

— α_Q quarkonium color polarizability

— $T_F = 1/2,\ N_c = 3$

* Peskin, Bhanot & Peskin, Kaidalov & Volkovitsky, Kharzeev, Luke et al., Voloshin, . . .

Trace anomaly and $\langle N|(gE^a)^2|N\rangle$

$$\frac{\beta(\alpha_s)}{2\alpha_s}\,\langle N|G^a_{\mu\nu}(x)G^{a\mu\nu}(x)|N\rangle = m_N\,, \qquad \beta(\alpha_s) \overset{N_f=3}{=} -\,\frac{9}{4\pi}\,\alpha_s^2$$

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Inequality (almost saturated)*:

$$\begin{aligned}
\langle N|\left[(g\boldsymbol{E}^a)^2-(g\boldsymbol{B}^a)^2\right]|N\rangle &= -\frac{1}{2}\langle N|g^2G^a_{\mu\nu}(x)G^{a\mu\nu}(x)|N\rangle \\
&= \frac{16\pi^2}{9}\,m_N \\
&\leqslant \langle N|(g\boldsymbol{E}^a)^2|N\rangle
\end{aligned}$$

* Sibirtsev & Voloshin

Theory: J/ψ-nucleon

Lattice:

- $J/\psi N$ interaction: attractive, not very strong
- Used quenched confs. or large quark masses, need extrapolation to physical masses
- Extrapolation: use effective field theory (EFT) - QNEFT*
- QNEFT degrees of freedom: $J/\psi, N = (p, n), \pi$

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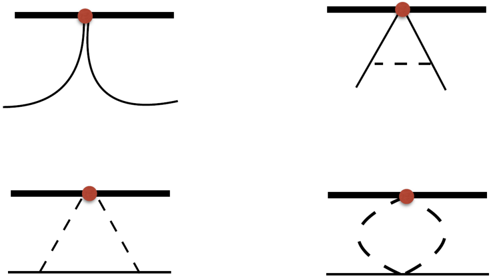
Models:

- Phenomenological spherical well, simple but insightful
- QCD multipole expansion + chiral soliton model (χCSQM)

J. T. Castellà and G. Krein, Phys. Rev. D 98, 014029 (2018)

Effective field theory for QN: QNEFT

Q polarizability + Chiral EFF (χEFT)



J. T. Castellà and GK, Phys. Rev. D 98, 014029 (2018)

Degrees of freedom, scales & power counting

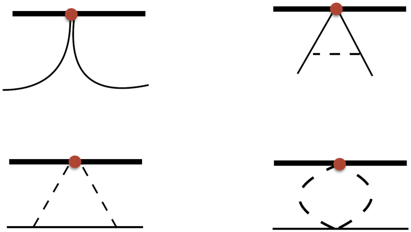
D.O.F.: nucleons, quarkonia, pions

Scales: $E_N, E_Q \sim m_\pi \ll \Lambda_\chi \sim 1$ GeV

P.C.: **(Weinberg)** Lagrangian in powers of m_π/Λ_χ

Loops: dimensional regularization

QNEFT predictions



QNEFT: J/ψ polarizability + χEFT

- Weakly attractive, relatively short-ranged
- van der Waals type of force

$$V_{\mathrm{vdW}}(r) \xrightarrow{r \gg 1/2m_\pi} \frac{3g_A^2 m_\pi^4 (c_{di} + c_m)}{128\pi^2 F^2} \frac{e^{-2m_\pi r}}{r^2}$$

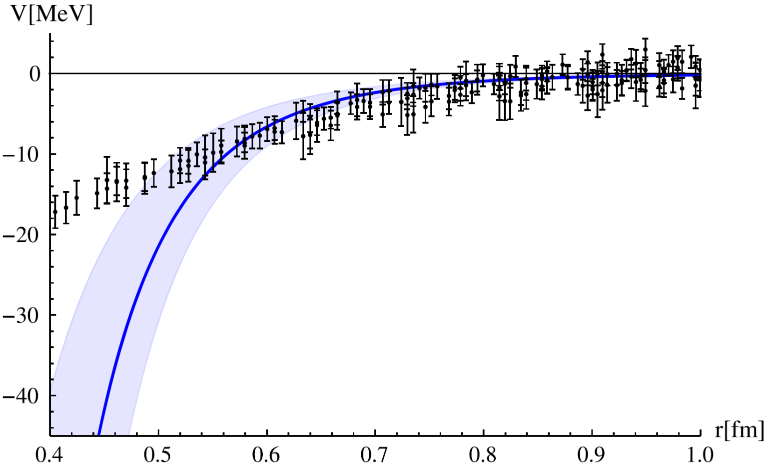
- $s-$wave dominated:

Effective range expansion (ERE):

$$f_0(k) = \frac{1}{k \cot\delta - ik} = \frac{1}{-\frac{1}{a_0} + \frac{1}{2} r_0 k^2 - ik} \left\{ \begin{array}{l} -0.71 \text{ fm} \leqslant a_0 \leqslant -0.35 \text{ fm} \\ 1.29 \text{ fm} \leqslant r_0 \leqslant 1.35 \text{ fm} \end{array} \right.$$

J. T. Castellà and GK, Phys. Rev. D 98, 014029 (2018)

$J/\psi N$ van der Waals force (Latt-QNEFT)



Models

Finite well[1]:

$$V(r) = \begin{cases} -\frac{2\pi}{3}\left(\frac{\alpha_{J/\psi}}{R_N^3}\right) m_N & \text{for} \quad r < R_N \\ 0 & \text{for} \quad r > R_N \end{cases}$$

Multipole expansion + χSQM[2]

$$V(r) = -\alpha_{J/\psi}\frac{4\pi^2}{b}\left(\frac{g^2}{g_s^2}\right)\left[\nu\rho_E(r) - 3p(r)\right] \begin{cases} \rho_E(r), p(r) : \text{energy density, pressure} \\ b = 27/3, \quad g^2/g_s^2 = 1, \quad \nu = 1.5 \end{cases}$$

[1] J. Ferretti, E. Santopinto, M. N Anwar and M. Bedolla, Phys. Lett. B 789, 562 (2019)

[2] M.I. Eides, V.Y. Petrov and M.V. Polyakov, Eur. Phys. J. C 78, 36 (2018)

ERE parameters - models

Essentially one unknown parameter: $\alpha_{J/\psi}$

ERE parameters (in fm) for different $\alpha_{J/\psi}$ (in GeV^{-3})

	Finite well*		χSQM	
$\alpha_{J/\psi}$	a_0	r_0	a_0	r_0
2.00	-0.68	1.59	-0.42	1.86
1.60	-0.47	1.86	-0.30	2.25
0.54	-0.12	4.50	-0.08	6.00
0.24	-0.05	9.46	-0.03	13.05

*$R_N = 1$ fm

Experimental access to $\langle \boldsymbol{N}|(\boldsymbol{g}\boldsymbol{E}^{\boldsymbol{a}})^2|\boldsymbol{N}\rangle$

—Will focus on $Q = J/\psi$

Lattice QCD simulations and models point toward a

weakly attractive, $S-$wave dominated

$J/\psi\, N$ interaction

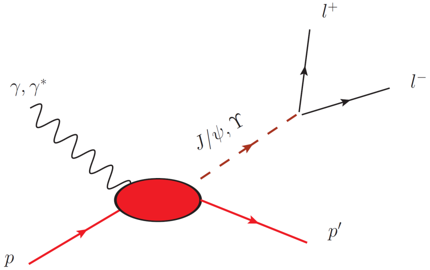
$\Downarrow$ small relative $J/\psi\, N$ momenta: $f_{\text{forw.}} \simeq -a_{J/\psi N}$

$$\boxed{a_{J/\psi N} = -\frac{\mu_{J/\psi N}}{2\pi}\,\frac{1}{2}\,\alpha_{J/\psi}\,\langle N|(g\boldsymbol{E}^a)^2|N\rangle}$$

Need to measure $a_{J/\psi\, N}$

(But to obtain $\langle N|(g\boldsymbol{E}^a)^2|N\rangle$ need to know $\alpha_{J/\psi}$)

Electro- and photoproduction @ JLab, EIC, EicC



Analyses of recent Glue-X experiment*

- Extracted very small values of scattering length

  $0.003 \text{ fm} \leqslant |a_{J/\psi N}| \leqslant 0.025 \text{ fm}$

  100 times smaller than some of earlier theoretical estimates

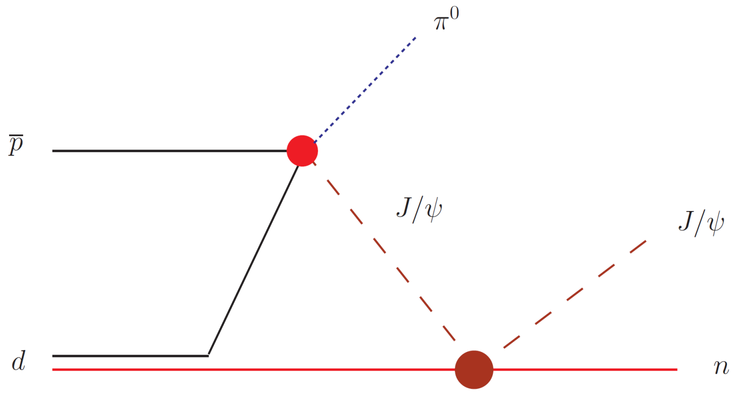
- **Issues:**

  No forward scattering, $t_{\text{thr.}} \simeq 1.5 \text{ GeV}^2$

  Vector meson dominance problematic, not enough time for J/ψ to be formed

* I.I. Strakovsky, D. Epifanov, and L. Pentchev, PRD 101, 042201 (2020)
L. Pentchev and I.I. Strakovsky, arXiv:2009.04502v1

$\bar{p}d \to J/\psi\, n\, \pi^0$ @ AMBER (?)



Input: $\bar{p}d \to J/\psi\, \pi^0$

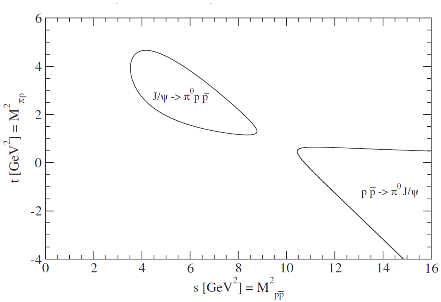


FIG. 3. Kinematically allowed regions for the three-body decay $J/\psi \to \pi^0 p\bar{p}$ and the related charmonium production reaction $p\bar{p} \to \pi^0 J/\psi$.

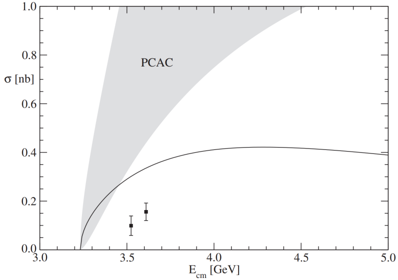


FIG. 4. Theoretical and experimental cross sections for $p\bar{p} \to \pi^0 J/\psi$. The theoretical predictions are the constant amplitude result Eq. (7) (solid) and the range of PCAC cross sections, from Eq. (8) (filled). The experimental points are from E760 [9].

Taken from: A. Lundborg, T. Barnes, and U. Wiedner, PRC 73, 096003 (2006)

Similar to $\bar{p}d \to D\,\overline{D}N$ @ $\overline{\text{P}}$ANDA

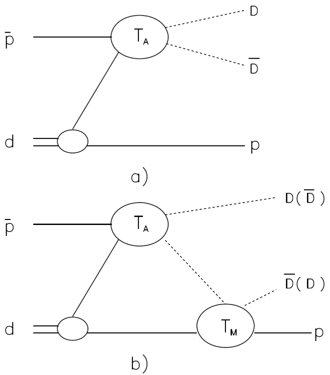


Fig. 1. Contributions to the reaction $\bar{p}d \to D\bar{D}N$: a) the Born (nucelon exchange) diagram. T_A denotes the annihilation amplitude. b) Meson rescattering diagram. T_M denotes the meson-nucleon scattering amplitude. Note that both DN and $\bar{D}N$ scatterings contribute to the reaction amplitude.

J. Haidenbauer, GK, U.-G. Meißner, and A. Sibirtsev, Eur. Phys. J. A 37, 55 (2008)

Femtoscopy in heavy-ion collisions @ LHC

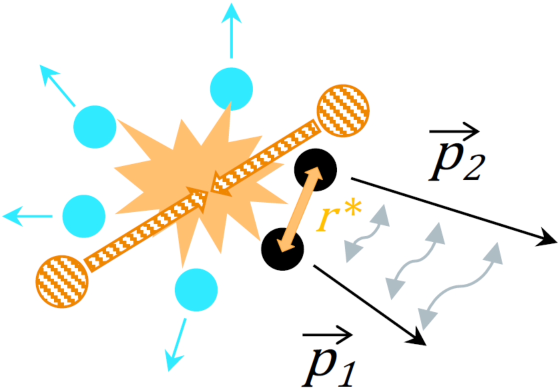


Figure from:
A new laboratory to study hadron-hadron interactions
ALICE collaboration, arXiv:2005.11495

Correlation function

Experimental extraction

— $\boldsymbol{p}_1, \boldsymbol{p}_2$: measured hadron momenta m_1, m_2: hadron masses

$$\boldsymbol{P} = \boldsymbol{p}_1 + \boldsymbol{p}_2, \quad \boldsymbol{k} = \frac{m_2\boldsymbol{p}_1 - m_1\boldsymbol{p}_2}{m_1 + m_2}$$: c.m. and relative momenta

Correlation function

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— Pair's c.m. frame: $\boldsymbol{P} = 0 \to \boldsymbol{p}_1 = -\boldsymbol{p}_2 \Rightarrow \boldsymbol{k} = \boldsymbol{p}_1 = -\boldsymbol{p}_2$

$$C(k) = \frac{A(k)}{B(k)} \begin{cases} A(k) : \text{yield from same event (coincidence yield)} \\ B(k) : \text{yield from different events (background)} \end{cases}$$

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— Corrections: nonfemtoscopic correlations, momentum resolution, etc $\leftarrow \xi(k)$

$$C(k) = \xi(k) \, \frac{A(k)}{B(k)}$$

Correlation function

Theoretical interpretation

- Kooning-Pratt formula

$$C(k) = \xi(k)\,\frac{A(k)}{B(k)} = \int d^3r\, S_{12}(\boldsymbol{r})\,|\psi(\boldsymbol{k},\boldsymbol{r})|^2$$

  $S(\boldsymbol{r})$: source, pair's relative distance distribution function (in pair's frame)

  $\psi(\boldsymbol{k},\boldsymbol{r})$: pair's relative wave function

- One needs here $\psi(\boldsymbol{k},\boldsymbol{r})$ for $0 \leqslant r \leqslant \infty$, not asymptotic as in scattering

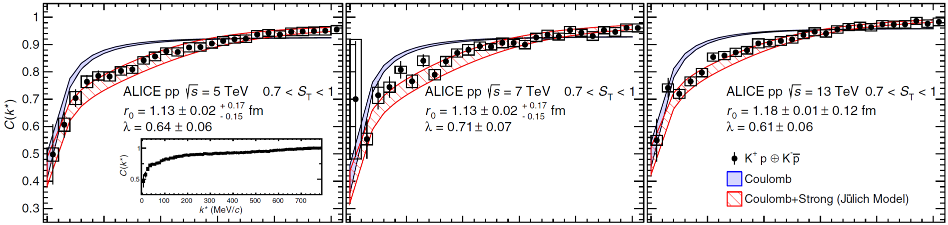
- $\psi(\boldsymbol{k},\boldsymbol{r})$: properties of the interaction

Prediction confirmed by femtoscopy

PHYSICAL REVIEW LETTERS **124,** 092301 (2020)

Scattering Studies with Low-Energy Kaon-Proton Femtoscopy in Proton-Proton Collisions at the LHC

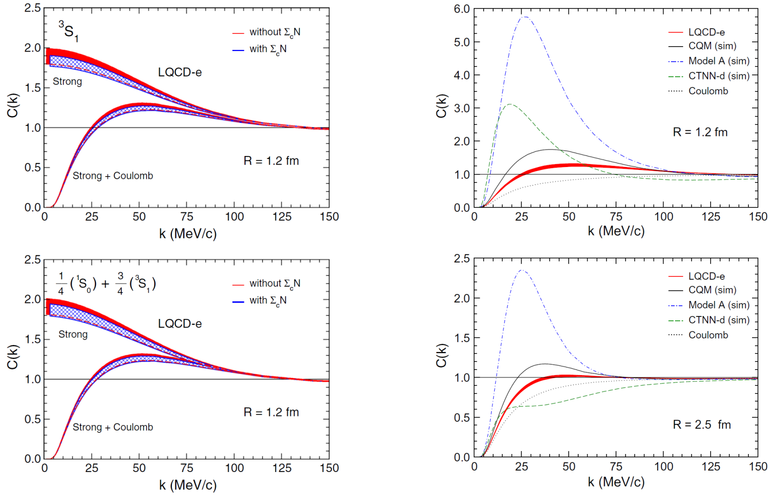
S. Acharya *et al.**
(A Large Ion Collider Experiment Collaboration)



Red band (theory prediction):
J. Haidenbauer, GK, U.-G. Meißner and L. Tólos
Eur. Phys. J. A 47, 18 (2011)

Recent prediction: $\Lambda_c N$

184 Page 6 of 8 Eur. Phys. J. A (2020) 56:184



J. Haidenbauer and GK, Eur. Phys. J. A 56, 184 (2020)

Femtoscopy of $J/\psi-$nucleon

— Interaction: weakly attractive, $s-$wave dominated

$$\psi(\boldsymbol{k},\boldsymbol{r}) = e^{i\boldsymbol{k}\cdot\boldsymbol{r}} + \psi_0(k,r) - j_0(kr)$$

$\psi_0(k,r)$ contains the effects of the interaction

— Simplification (not unrealistic):

$$S_{12}(r) = \frac{1}{(4\pi R^2)^{3/2}}\, e^{-r^2/4R^2}$$

Normally used: $R = 1$ fm $- 1.3$ fm $(p\bar{p})$, $\quad R = 1.5$ fm $- 4.0$ fm (pA, AA)

— Correlation function:

$$C(k) = 1 + \frac{4\pi}{(4\pi R^2)^{3/2}} \int_0^\infty dr\, r^2\, e^{-r^2/4R^2}\left[|\psi_0(k,r)|^2 - |j_0(kr)|^2\right]$$

GK and T.C. Peixoto, Few Body Syst. 61, 49 (2020)

Source size × interaction range

If emission happens outside "interaction range": $\psi_0(k,r) \to \psi_0^{\rm asy}(k,r)$

$$\psi_0^{asy}(k,r) = \frac{\sin(kr+\delta_0)}{kr} = e^{-i\delta_0}\left[j_0(kr) + f_0(k)\frac{e^{ikr}}{r}\right]$$

$$f_0(k) = \frac{e^{i\delta_0}\sin\delta_0}{k} \overset{k\to 0}{\approx} \frac{1}{-1/a_0 + r_0\,k^2/2 - ik}$$

Lednicky-Lyuboshits (LL) model

$$C(k) = 1 + \frac{|f_0(k)|^2}{2R^2}\left(1 - \frac{r_0}{2\sqrt{\pi}R}\right) + \frac{2\mathrm{Re}f_0(k)}{\sqrt{\pi}R}F_1(2kR) - \frac{\mathrm{Im}f_0(k)}{R}F_2(2kR)$$

$$F_1(x) = \frac{1}{x}\int_0^x dt\, e^{\,t-x}, \qquad F_2(x) = \frac{1}{x}\left(1 - e^{-x^2}\right)$$

Validity: $r0 \ll R$

Universal formula, independent of interaction details

Correlation and $\langle (g\boldsymbol{E})^2 \rangle_N$

LL for $k \to 0$:

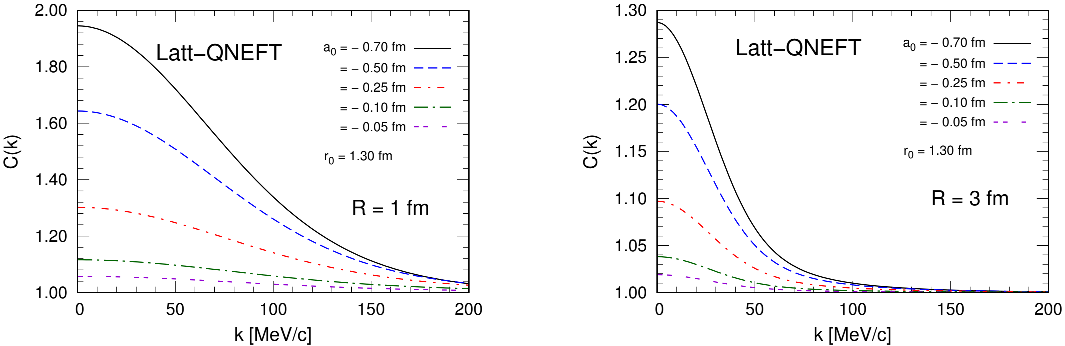
$$\boxed{C(k) = 1 - \frac{1}{2\pi^{3/2}} \left(1 - \frac{8}{3} k^2 R^2\right) \frac{\mu_{J/\psi N}\, \alpha_{J/\psi} \langle (g\boldsymbol{E})^2 \rangle_N}{R}}$$

$\boldsymbol{C}(k)$ gives direct access to $\langle (g\boldsymbol{E})^2 \rangle_N$*

*Under validity of LL model, Gaussian source

Predictions for J/ψ–nucleon correlation

Lattice QCD data extrapolated to the physical pion mass by QNEFT*



Used here LL & ERE

* J. T. Castellà and GK, Phys. Rev. D 98, 014029 (2018)

Summary & Perspectives

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— <u>Did not touch on:</u> validity of multipole expansion, factorization

Thank you

Funding

FAPESP
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CNPq
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