Role of near-threshold heavy-quarkonia production in providing access to QCD trace anomaly

Gastão Krein

Instituto de Física Teórica, São Paulo

AMBER@CERN
September 30 - December 04, 2020

What is the origin of the mass

of the hadrons ?

Computers gave an answer to the question

The mass of the hadrons comes from the gluons and nearly massless quarks

Light-hadron masses

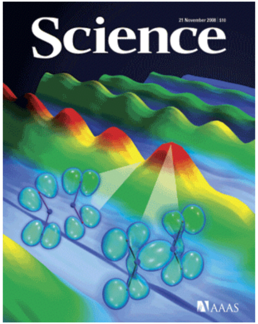
Science

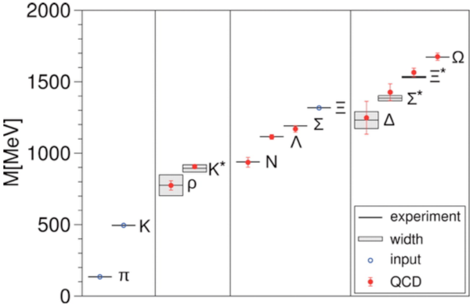
2008

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





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

Back $\sim$ 40 years

- $|h(\boldsymbol{p})\rangle$: hadron state*, $p = (E_h(\boldsymbol{p}), \boldsymbol{p})$
- $\langle h(\boldsymbol{p})|T^{\mu\nu}(x)|h(\boldsymbol{p})\rangle = p^\mu p^\nu / E_h(\boldsymbol{p})$, $\quad T^{\mu\nu}(x)$: en.-mom. tensor

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

Back $\sim$ 40 years

- $|h(\boldsymbol{p})\rangle$: hadron state*, $p = (E_h(\boldsymbol{p}), \boldsymbol{p})$
- $\langle h(\boldsymbol{p})|T^{\mu\nu}(x)|h(\boldsymbol{p})\rangle = p^\mu p^\nu / E_h(\boldsymbol{p})$, $\quad T^{\mu\nu}(x)$: en.-mom. tensor
- $\langle h(\boldsymbol{p})|T^\mu_\mu(x)|h(\boldsymbol{p})\rangle = p^\mu p_\mu / E_h(\boldsymbol{p}) = m_h^2 / E_h(\boldsymbol{p})$

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

Back $\sim$ 40 years

- $|h(\boldsymbol{p})\rangle$: hadron state*, $p = (E_h(\boldsymbol{p}), \boldsymbol{p})$
- $\langle h(\boldsymbol{p})|T^{\mu\nu}(x)|h(\boldsymbol{p})\rangle = p^\mu p^\nu / E_h(\boldsymbol{p})$, $\quad T^{\mu\nu}(x)$: en.-mom. tensor
- $\langle h(\boldsymbol{p})|T^\mu_\mu(x)|h(\boldsymbol{p})\rangle = p^\mu p_\mu / E_h(\boldsymbol{p}) = m_h^2 / E_h(\boldsymbol{p})$
- Take $m_{\text{light}} = 0$ and $m_{\text{heavy}} = \infty$ in QCD Lagrangian:

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

Back $\sim$ 40 years

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

— $\langle h(\boldsymbol{p})|T^{\mu\nu}(x)|h(\boldsymbol{p})\rangle = p^\mu p^\nu / E_h(\boldsymbol{p})$, $\quad T^{\mu\nu}(x)$: en.-mom. tensor

— $\langle h(\boldsymbol{p})|T^\mu_\mu(x)|h(\boldsymbol{p})\rangle = p^\mu p_\mu / E_h(\boldsymbol{p}) = m_h^2 / E_h(\boldsymbol{p})$

— Take $m_{\mathrm{light}} = 0$ and $m_{\mathrm{heavy}} = \infty$ in QCD Lagrangian:

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

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

Back $\sim$ 40 years

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

— $\langle h(\boldsymbol{p})|T^{\mu\nu}(x)|h(\boldsymbol{p})\rangle = p^\mu p^\nu / E_h(\boldsymbol{p})$, $\quad T^{\mu\nu}(x)$: en.-mom. tensor

— $\langle h(\boldsymbol{p})|T^\mu_\mu(x)|h(\boldsymbol{p})\rangle = p^\mu p_\mu / E_h(\boldsymbol{p}) = m_h^2 / E_h(\boldsymbol{p})$

— Take $m_{\text{light}} = 0$ and $m_{\text{heavy}} = \infty$ in QCD Lagrangian:

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

Conserved current: $\partial_\mu J^\mu_{\text{D}}(x) = 0 \text{ where } J^\mu_{\text{D}}(x) = x_\nu T^{\mu\nu}(x)$

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

Back $\sim$ 40 years

- $|h(\boldsymbol{p})\rangle$: hadron state*, $p = (E_h(\boldsymbol{p}), \boldsymbol{p})$
- $\langle h(\boldsymbol{p})|T^{\mu\nu}(x)|h(\boldsymbol{p})\rangle = p^\mu p^\nu / E_h(\boldsymbol{p})$, $T^{\mu\nu}(x)$: en.-mom. tensor
- $\langle h(\boldsymbol{p})|T^\mu_\mu(x)|h(\boldsymbol{p})\rangle = p^\mu p_\mu / E_h(\boldsymbol{p}) = m_h^2 / E_h(\boldsymbol{p})$
- Take $m_{\text{light}} = 0$ and $m_{\text{heavy}} = \infty$ in QCD Lagrangian:

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

  Conserved current: $\partial_\mu J^\mu_{\text{D}}(x) = 0 \text{ where } J^\mu_{\text{D}}(x) = x_\nu T^{\mu\nu}(x)$

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

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

Back $\sim$ 40 years - cont'd

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

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

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

$$m_h = \frac{\beta(\alpha_s)}{2\alpha_s} \langle h | G^a_{\mu\nu} G^{a\mu\nu} | h \rangle + \langle h | \bar{q} m_{\text{light}} q | h \rangle$$

$$m_N = \qquad \Downarrow \qquad\qquad \Downarrow$$

$$\simeq 860 \text{ MeV} \qquad \simeq 80 \text{ MeV (Higgs)}$$

How about the pion?

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

(pion is a Goldstone boson)

How about the pion?

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

(pion is a Goldstone boson)

$$\frac{\beta(\alpha_s)}{2\alpha_s} \langle N(\boldsymbol{p})|G^a_{\mu\nu}(x)G^{a\mu\nu}(x)|N(\boldsymbol{p})\rangle = \frac{m_N^2}{E_N(\boldsymbol{p})} \neq 0$$

$$\frac{\beta(\alpha_s)}{2\alpha_s} \langle \pi(\boldsymbol{p})|G^a_{\mu\nu}(x)G^{a\mu\nu}(x)|\pi(\boldsymbol{p})\rangle = \frac{m_\pi^2}{E_N(\boldsymbol{p})} = 0$$

How about the pion?

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

(pion is a Goldstone boson)

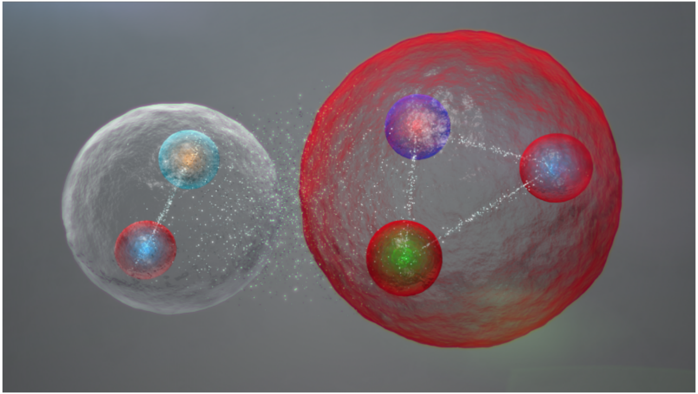
$$\frac{\beta(\alpha_s)}{2\alpha_s} \langle N(\boldsymbol{p})|G^a_{\mu\nu}(x)G^{a\mu\nu}(x)|N(\boldsymbol{p})\rangle \quad = \quad \frac{m_N^2}{E_N(\boldsymbol{p})} \neq 0$$

$$\frac{\beta(\alpha_s)}{2\alpha_s} \langle \pi(\boldsymbol{p})|G^a_{\mu\nu}(x)G^{a\mu\nu}(x)|\pi(\boldsymbol{p})\rangle \quad = \quad \frac{m_\pi^2}{E_N(\boldsymbol{p})} = 0$$

How does this happen?

Heavy quarkonium - nucleon scattering

Small QN relative momentum



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

Heavy quarkonium - nucleon (QN)

Low QN momentum interaction

- Heavy quarkonium: small object, radius r_Q

Heavy quarkonium - nucleon (QN)

Low QN momentum interaction

— Heavy quarkonium: small object, radius r_Q

— Interacts by exchanging gluons with nucleon's light quarks

Heavy quarkonium - nucleon (QN)

Low QN momentum interaction

- Heavy quarkonium: small object, radius r_Q
- Interacts by exchanging gluons with nucleon's light quarks
- Low relative momentum, gluon wavelength $\lambda_g \sim r_N$ (nucleon radius)

Heavy quarkonium - nucleon (QN)

Low QN momentum interaction

- Heavy quarkonium: small object, radius r_Q
- Interacts by exchanging gluons with nucleon's light quarks
- Low relative momentum, gluon wavelength $\lambda_g \sim r_N$ (nucleon radius)
- $r_Q \ll r_N$: quarkonium small dipole in soft gluon fields

Heavy quarkonium - nucleon (QN)

Low QN momentum interaction

- Heavy quarkonium: small object, radius r_Q
- Interacts by exchanging gluons with nucleon's light quarks
- Low relative momentum, gluon wavelength $\lambda_g \sim r_N$ (nucleon radius)
- $r_Q \ll r_N$: quarkonium small dipole in soft gluon fields
- 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 $\langle N|(gE^a)^2|N\rangle$

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

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

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

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

Experimental access to $\langle N|(g\boldsymbol{E}^a)^2|N\rangle$
—Will focus on $Q = J/\psi$

Lattice QCD simulations and models point toward a

weakly attractive, $S-$wave dominated

$J/\psi\,N$ interaction

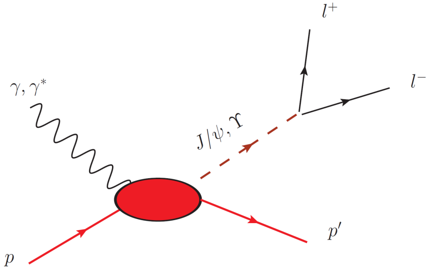
$\Downarrow$ small relative $J/\psi\,N$ momenta: $f_{\rm forw.} \simeq -a_{J/\psi N}$

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

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

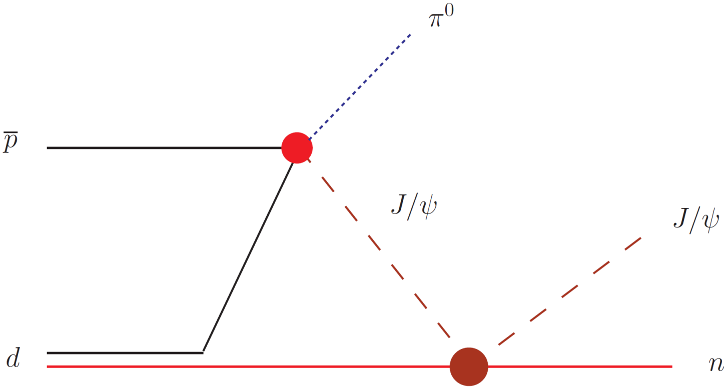
- **Issues:**

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

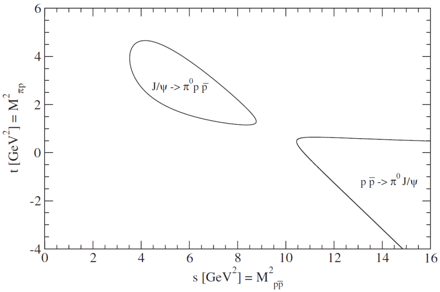


FIG. 3. Kinematically allowed regions for the three-body decay $J/\psi \to \pi^0 p\bar{p}$ and the related charmonium production reaction $p\bar{p} \to \pi^0 J/\psi$.

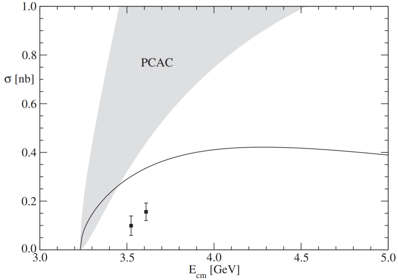


FIG. 4. Theoretical and experimental cross sections for $p\bar{p} \to \pi^0 J/\psi$. The theoretical predictions are the constant amplitude result Eq. (7) (solid) and the range of PCAC cross sections, from Eq. (8) (filled). The experimental points are from E760 [9].

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

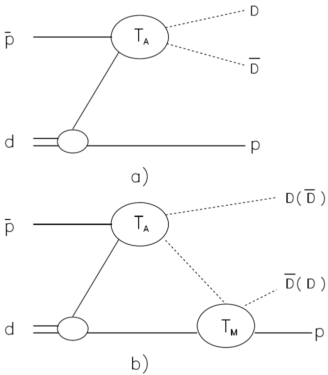


Fig. 1. Contributions to the reaction $\bar{p}d \to D\bar{D}N$: a) the Born (nucelon exchange) diagram. T_A denotes the annihilation amplitude. b) Meson rescattering diagram. T_M denotes the meson-nucleon scattering amplitude. Note that both DN and $\bar{D}N$ scatterings contribute to the reaction amplitude.

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

Femtoscopy in heavy-ion collisions @ LHC

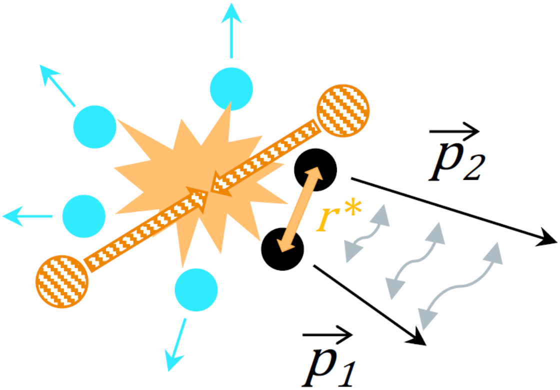


Figure from:
A new laboratory to study hadron-hadron interactions
ALICE collaboration, arXiv:2005.11495

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

Experimental extraction

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

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

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

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

Correlation function

Experimental extraction

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

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

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

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

- 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

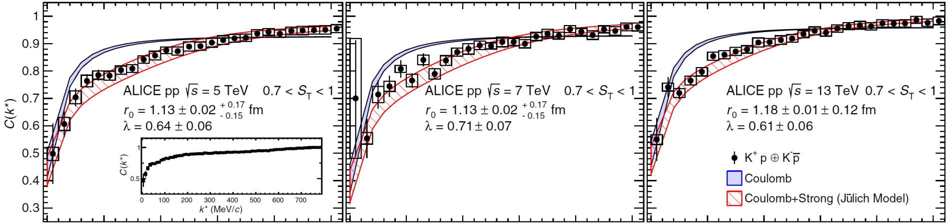
— $\psi(\boldsymbol{k},\boldsymbol{r})$: properties of the interaction

Prediction confirmed by femtoscopy

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

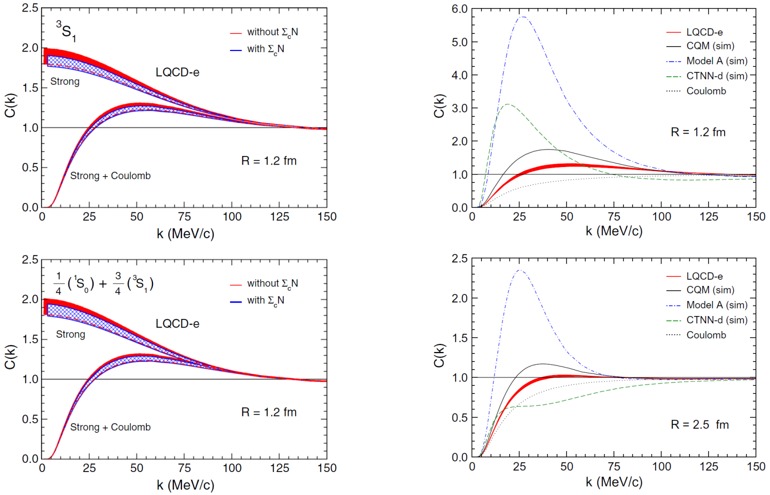
Scattering Studies with Low-Energy Kaon-Proton Femtoscopy in Proton-Proton Collisions at the LHC

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: $\Lambda_c N$



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

— 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": $\psi_0(k,r) \to \psi_0^{\text{asy}}(k,r)$

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

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

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 $k \to 0$:

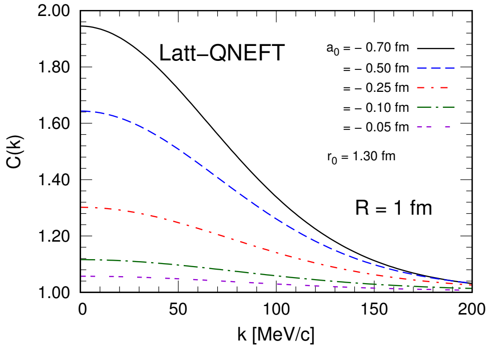
$$C(k) = 1 - \frac{1}{2\pi^{3/2}} \left(1 - \frac{8}{3}k^2 R^2\right) \frac{\mu_{J/\psi N}\, \alpha_{J/\psi} \langle (g\boldsymbol{E})^2 \rangle_N}{R}$$

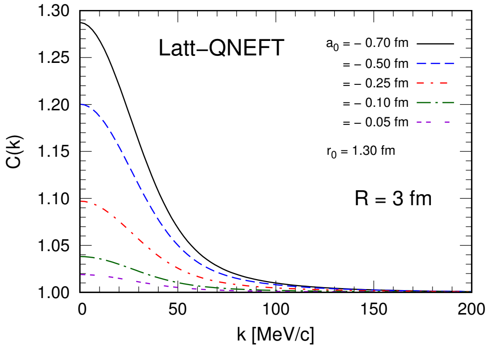
$\boldsymbol{C}(k)$ gives direct access to $\langle (g\boldsymbol{E})^2 \rangle_N$ *

*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

Summary & Perspectives

— Origin of hadrons' mass: QCD trace anomaly (known for 40 years)

Summary & Perspectives

- Origin of hadrons' mass: QCD trace anomaly (known for 40 years)
- Experimental access to a key matrix element, $\langle N|(g\boldsymbol{E}^a)^2|N\rangle$

Summary & Perspectives

- Origin of hadrons' mass: QCD trace anomaly (known for 40 years)
- Experimental access to a key matrix element, $\langle N|(g\boldsymbol{E}^a)^2|N\rangle$
- Electro- and photoproduction of $J/\psi, \Upsilon$

Summary & Perspectives

- Origin of hadrons' mass: QCD trace anomaly (known for 40 years)
- Experimental access to a key matrix element, $\langle N|(g\boldsymbol{E}^a)^2|N\rangle$
- Electro- and photoproduction of $J/\psi, \Upsilon$

  -Issues due to extrapolation, vector meson dominance

Summary & Perspectives

- Origin of hadrons' mass: QCD trace anomaly (known for 40 years)
- Experimental access to a key matrix element, $\langle N|(g\boldsymbol{E}^a)^2|N\rangle$
- Electro- and photoproduction of $J/\psi, \Upsilon$

  -Issues due to extrapolation, vector meson dominance
- $\bar{p}d \to J/\psi N\pi^0$ @ AMBER (?)

Summary & Perspectives

— Origin of hadrons' mass: QCD trace anomaly (known for 40 years)

— Experimental access to a key matrix element, $\langle N|(g\boldsymbol{E}^a)^2|N\rangle$

— Electro- and photoproduction of $J/\psi, \Upsilon$

-Issues due to extrapolation, vector meson dominance

— $\overline{p}d \to J/\psi N\pi^0$ @ AMBER (?)

— Femtoscopy in high energy pp and heavy-ion collisions

Summary & Perspectives

- Origin of hadrons' mass: QCD trace anomaly (known for 40 years)
- Experimental access to a key matrix element, $\langle N|(g\boldsymbol{E}^a)^2|N\rangle$
- Electro- and photoproduction of $J/\psi, \Upsilon$

  -Issues due to extrapolation, vector meson dominance
- $\overline{p}d \to J/\psi N\pi^0$ @ AMBER (?)
- Femtoscopy in high energy pp and heavy-ion collisions
- How about the pion? $J/\psi\,\pi$ Femtoscopy?

Summary & Perspectives

- Origin of hadrons' mass: QCD trace anomaly (known for 40 years)
- Experimental access to a key matrix element, $\langle N|(g\boldsymbol{E}^a)^2|N\rangle$
- Electro- and photoproduction of $J/\psi, \Upsilon$

  -Issues due to extrapolation, vector meson dominance
- $\overline{p}d \to J/\psi N \pi^0$ @ AMBER (?)
- Femtoscopy in high energy pp and heavy-ion collisions
- How about the pion? $J/\psi\,\pi$ Femtoscopy?
- Did not touch on: validity of multipole expansion, factorization

Thank you

Funding

FAPESP
SÃO PAULO RESEARCH FOUNDATION

CNPq
Conselho Nacional de Desenvolvimento Científico e Tecnológico