Femtoscopy of the $J/\psi-$nucleon interaction

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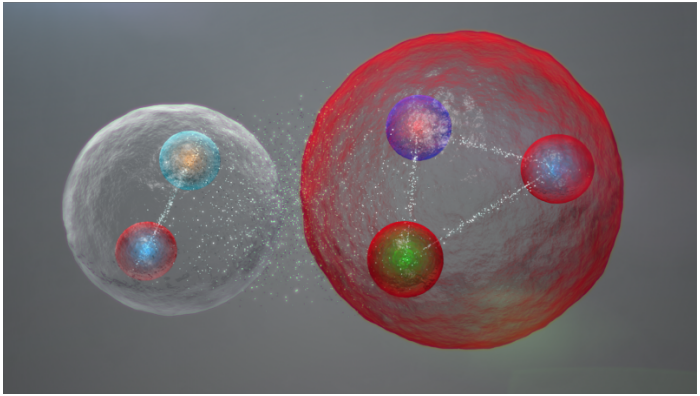
Outline

1. Motivation: trace anomaly, proton mass
2. Heavy quarkonium-nucleon scattering
3. J/ψ-nucleon @ LHC - Femtoscopy
4. Predictions for $J/\psi-$nucleon femtoscopy
5. Conclusions & Perspectives

Work with T. C. Peixoto

1. Quarkonium-nucleon scattering

Access to trace anomaly matrix element: $\langle N|(gE^a)^2|N\rangle$
(small QN relative momentum)



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

Trace anomaly - Nucleon mass

$$m_N = \underbrace{\frac{\beta(g)}{2g}\langle N|G^a_{\mu\nu}G^{a\mu\nu}|N\rangle}_{\Downarrow \;\simeq 880\ \mathrm{MeV}} + \underbrace{\sum_{l=u,d,s}\langle N|m_l(1+\gamma_{m_l})\bar{q}_l q_l|N\rangle}_{\Downarrow \;\simeq 60\ \mathrm{MeV}\ (\sigma-\text{term})}$$

$$\beta(g) \simeq -b\frac{g^3}{16\pi^2}, \qquad b = 11 - \frac{2n_l}{3}$$ (heavy quarks integrated out)

Experimental access to $\langle N|G^a_{\mu\nu}G^{a\mu\nu}|N\rangle$?

Inequality (almost saturated, chromomagnetic part suppressed)*:

$$-\frac{1}{2}\langle N|g^2 G^a_{\mu\nu}(x)G^{a\mu\nu}(x)|N\rangle = \langle N|\left[(g\boldsymbol{E}^a)^2 - (g\boldsymbol{B}^a)^2\right]|N\rangle \leqslant \langle N|(g\boldsymbol{E}^a)^2|N\rangle$$

Shifman, Vainshtein & Zakharov (1978)

*Sibirtsev & Voloshin (2005)

2. 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)

Peskin (1978), Bhanot & Peskin (1978), Voloshin (1979), Novikov & Shifman (1981), Kaidalov & Volkovitsky (1992), Luke, Manohar & Savage (1992)

QN scattering amplitude

QCD multipole expansion

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

- μ_{QN} reduced mass, $\boldsymbol{p},\boldsymbol{p}'$ relative c.m. momenta
- α_Q quarkonium color polarizability
- $T_F = 1/2$, $N_c = 3$
- Note that: forward ($\boldsymbol{p}' = \boldsymbol{p}$) amplitude enters here

Kaidalov & Volkovitsky (1992), Kharzeev (1996), Sibirtseev & Voloshin (2005)

Experimental access to $\langle N|(gE^a)^2|N\rangle$ —Will focus on $Q = J/\psi$

Lattice QCD simulations and models point toward a weakly attractive, $S-$wave dominated $J/\psi\, N$ interaction

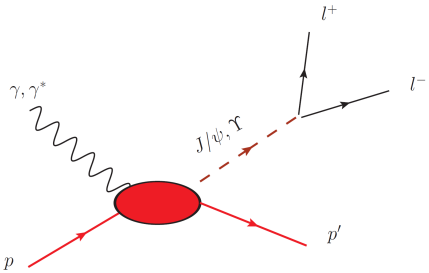
$\Downarrow$ small relative $J/\psi\, N$ momenta: $f_{\text{forw.}} \simeq -a_{J/\psi N}$

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

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, Eur. Phys. J. A 57, 56 (2021)

3. J/ψ-nucleon @ LHC - Femtoscopy

Production yields and leptonic decay rates relatively high

Knowledge from lattice QCD and phenomenological models

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: $J/\psi, N = (p, n), \pi$

Models:

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

*J. Tarrús Castellà & GK, Phys. Rev. D 98, 014029 (2018)

Femtoscopy: basics

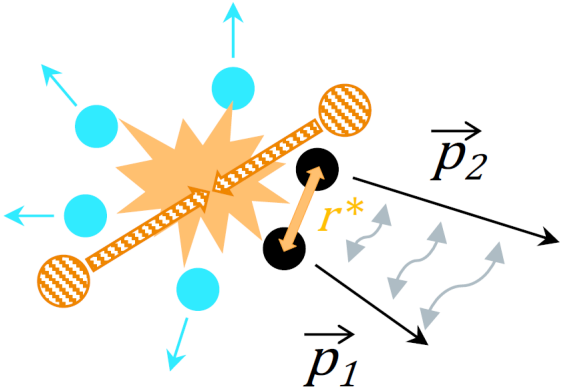


Figure from:
Unveiling the strong interaction among hadrons at the LHC
ALICE Coll., Nature 588, 232 (2020)

Momentum correlation function

Experimental extraction

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

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

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

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

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

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

Correlation function

Theoretical interpretation

— Koonin-Pratt formula

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

$S_{12}(\boldsymbol{r})$: 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 $0 \leqslant r \leqslant \infty$, <u>not asymptotic as in scattering</u>

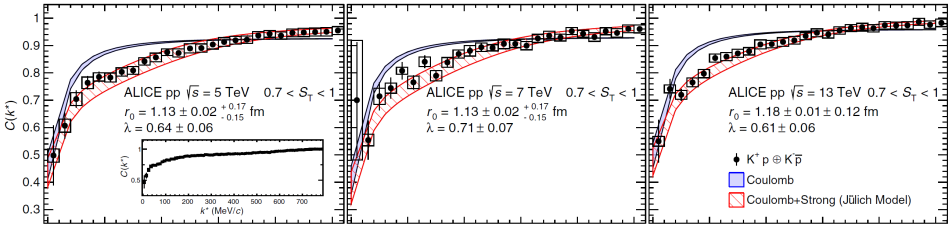
— $\psi(\boldsymbol{k},\boldsymbol{r})$: properties of the interaction

Femtoscopy of the KN interaction

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)

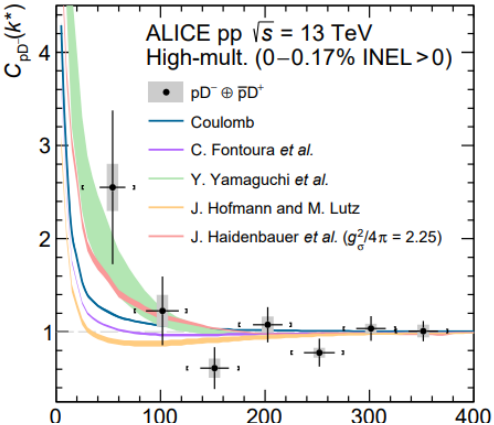


Red band (theory prediction):
J. Haidenbauer, G. Krein, U.-G. Meißner and L. Tólos
Eur. Phys. J. A 47, 18 (2011)

Femtoscopy of the DN interaction

First study of the two-body scattering involving charm hadrons

ALICE Collaboration*



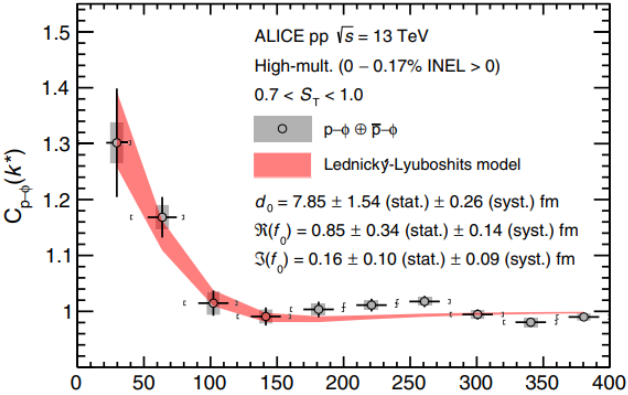
Femtoscopy of the ϕN interaction

PHYSICAL REVIEW LETTERS **127,** 172301 (2021)

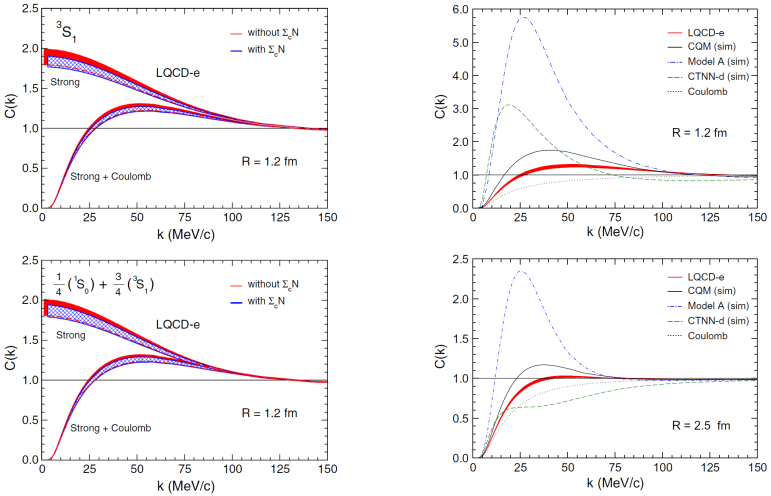
Editors' Suggestion

Experimental Evidence for an Attractive *p*-ϕ Interaction

S. Acharya *et al.*[*]
(ALICE Collaboration)



Femtoscopy of the $\Lambda_c N$ - prediction



J. Haidenbauer & 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: $R = 1\ \mathrm{fm} - 1.3\ \mathrm{fm}\,(p\bar{p})$, $\quad R = 1.5\ \mathrm{fm} - 4.0\ \mathrm{fm}\,(pA, AA)$

— Correlation function:

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

Source size $\times$ 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

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

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

Validity: $r0 \ll R$

Universal formula, independent of interaction details

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

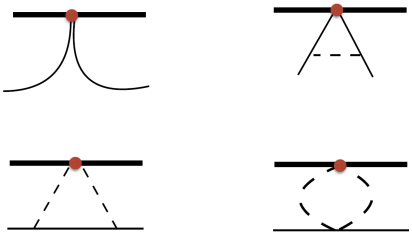
LL for small k:

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

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

*Under validity of LL model

Quarkonium-nucleon EFT (QNEFT)



Degrees of freedom – Scales – Power counting

— DOF: nucleons (N), quarkonia (ϕ), pions ($\boldsymbol{\pi}$)

— Scales: $E_N, E_\phi, E_\pi \ll \Lambda_\chi \simeq 1$ GeV

— Power counting: powers of $\dfrac{m_\pi}{\Lambda_\chi}$

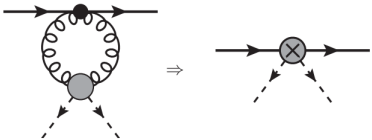
— Loops: dimensional regularization

J. Tarrús Castellà & GK, Phys. Rev. D 98, 014029 (2018)

QNEFT input: $\phi - \pi$ vertex

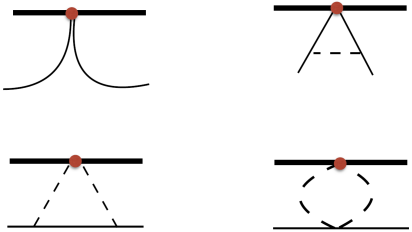
pNRQCD → gWEFT (J/ψ polarizabilityt)

gWEFT → χEFT (trace anomaly)



[1] A. Vairo, in QCHS IV, ed. W. Lucha and K. M. Maung (World Scientific, 2002)
[2] N. Brambilla, GK, J. Tarrús Castellà, A. Vairo, Phys. Rev. D 93 054002 (2016)

QNEFT predictions



QNEFT: J/ψ polarizability + χEFT

- Weakly attractive
- Tail: van der Waals type of force

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

- $S-$wave dominated:

Effective range expansion (ERE):

$$f_0(k) = \frac{1}{k\cot\delta - ik} = \frac{1}{-\frac{1}{\boldsymbol{a}_0} + \frac{1}{2}\boldsymbol{r}_0\, k^2 - ik} \begin{cases} -0.71 \text{ fm} \leqslant \boldsymbol{a}_0 \leqslant -0.35 \text{ fm} \\ 1.29 \text{ fm} \leqslant \boldsymbol{r}_0 \leqslant 1.35 \text{ fm} \end{cases}$$

Phenomenological 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 (phenom. models)

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

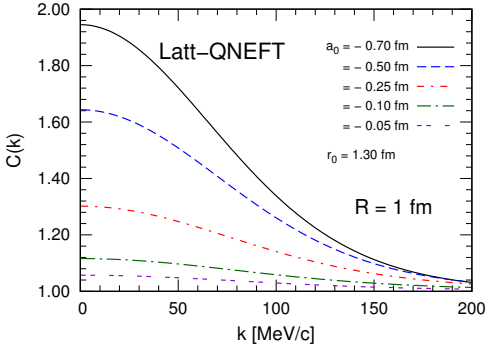
ERE parameters (in fm) for different $\alpha_{J/\psi}$ (in GeV^{-3})

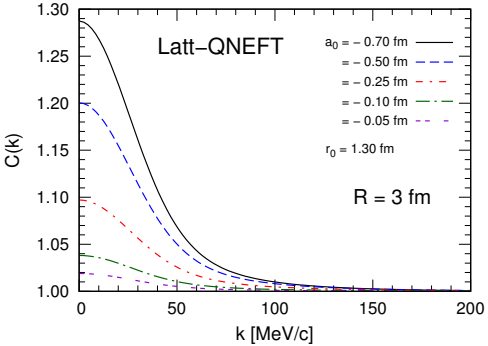
	Finite well*		χSQM	
$\alpha_{J/\psi}$	a_0	r_0	a_0	r_0
2.00	-0.68	1.59	-0.42	1.86
1.60	-0.47	1.86	-0.30	2.25
0.54	-0.12	4.50	-0.08	6.00
0.24	-0.05	9.46	-0.03	13.05

*$R_N = 1$ fm

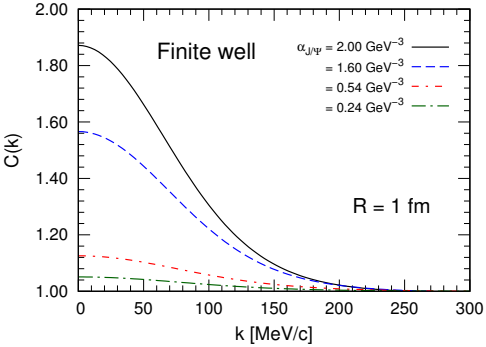
4. Predictions J/ψ−nucleon femtoscopy

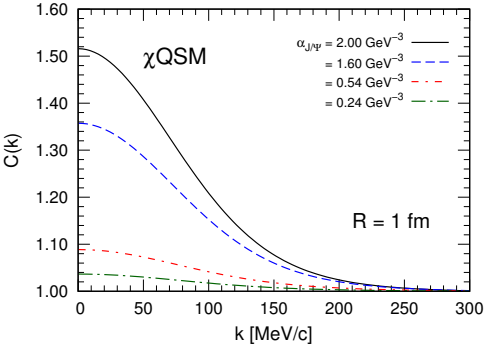
Use of ERE





Full wave function





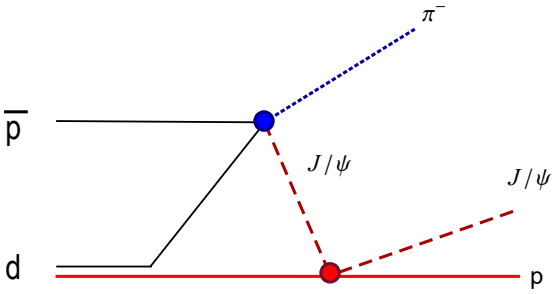
5. Conclusions & Perspectives

1. Trace anomaly: how QCD "explains" proton's mass
2. Femtoscopy of $J/\psi-$nucleon: access key matrix element
3. Femtoscopy sensitive to interaction if $\alpha_{J/\psi} \geqslant 0.25\ \mathrm{GeV}^{-3}$
4. How about quarkonium-pion?
5. Open issues:

   Theory: LL model & multipole expansion, lattice QCD, models

   Experiment: source size, nonfemtoscopic correlations, etc
6. Prospects: cautiously optimistic !

$\bar{p}d \to J/\psi\, p\, \pi^-$: $\overline{\text{P}}$ANDA @ FAIR, AMBER @ CERN



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

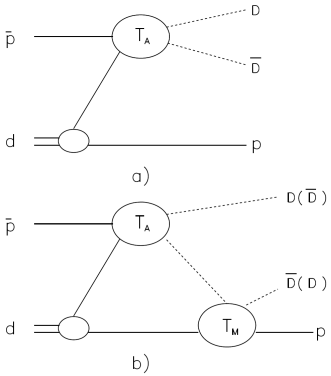


Fig. 1. Contributions to the reaction $\bar{p}d \to D\bar{D}N$: a) the Born (nucelon exchange) diagram. T_A denotes the annihilation amplitude. b) Meson rescattering diagram. T_M denotes the meson-nucleon scattering amplitude. Note that both DN and $\bar{D}N$ scatterings contribute to the reaction amplitude.

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

Thank you

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