

A technique for studying J/ψ -hadron interactions using femtoscopic correlations

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① J/ψ - a probe of QGP

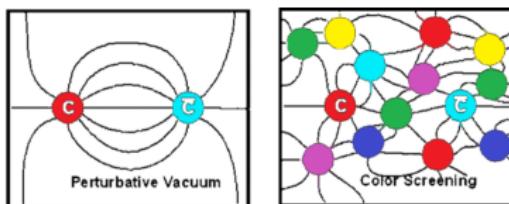
② J/ψ -hadron femtoscopy

③ Feasibility study

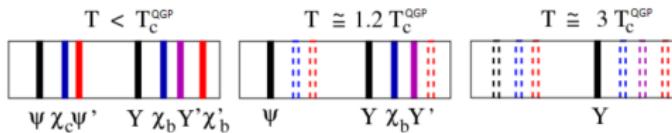
④ Results

⑤ Summary

- High temperature in QGP causes J/ψ to dissociate via process of Debye-like screening of color charges
 - J/ψ suppression, a signature of QGP formation [Phys.Lett.B 178(4), 416-422(1986)]



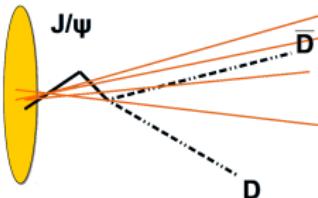
- Looking at quarkonium suppression pattern allows to study QGP properties



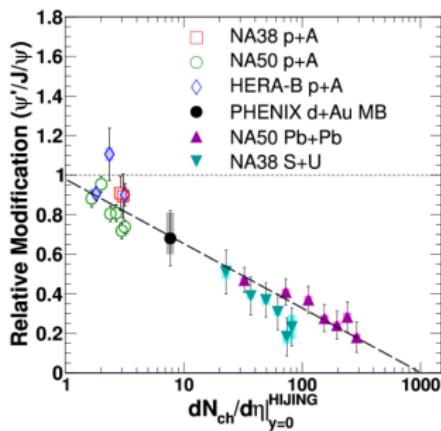
- Production/suppression affected by many other competing effects
 - Production mechanism - not fully understood
 - Feed-down contributions: $\psi(nS) \rightarrow J/\psi \pi^+ \pi^-$, $\chi_{cJ} \rightarrow \gamma J/\psi$
 - Regeneration/coalescence [Phys.Rev.C, 63(5), 054905]
 - Shadowing/anti-shadowing
 - Break-up in the final state: comover interactions, nuclear absorption

Comover interactions

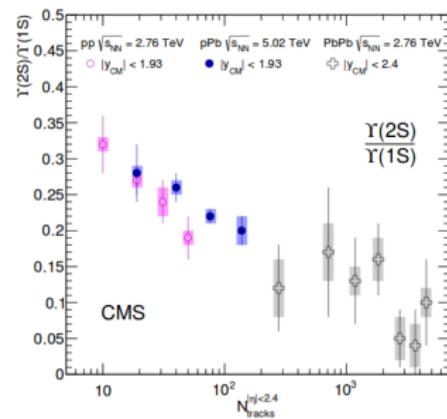
- J/ψ can be broken-up in interactions with comoving hadrons



- Estimated indirectly by measuring ratios vs. N_{ch} :



[Phys. Rev. Lett. 111, 202301(2013)]

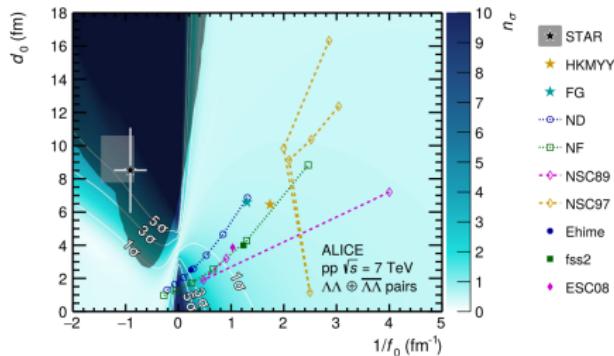
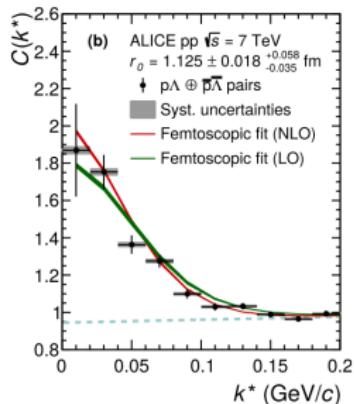


[JHEP. 2014, 103(2014)]

- Perhaps the cross section for J/ψ -hadron interactions can be measured directly.

- Femtoscopy allows to measure final state interaction parameters or cross sections for any particles a and b by calculating a correlation function:

$$C(p_a, p_b) = \frac{P_2(p_a, p_b)}{P_1(p_a)P_1(p_b)}$$



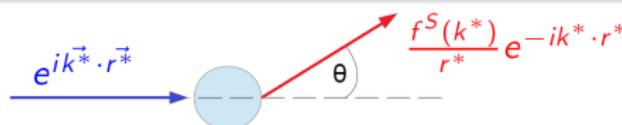
[Phys. Rev. C, 99(2), 024001(2019)]

- We propose to apply femtoscopic correlations analysis to J/ψ -hadron system in order to directly measure cross section for their elastic and inelastic interactions.

J/ψ -hadron scattering - idea

- J/ψ -hadron interaction wavefunction: incoming plane wave + scattered spherical wave:

$$\Psi(\vec{r}^*, k^*) \doteq e^{ik^* \cdot \vec{r}^*} + \frac{f^S(k^*)}{r^*} e^{-ik^* \cdot \vec{r}^*}$$



- k^* - relative momentum in pair center-of-mass frame
- r^* - relative distance in c.m. frame
- f^S - s-wave scattering amplitude

- Apply partial wave analysis:

$$\Psi(\theta) = \sum_l (2l+1) f_l P_l(\cos(\theta))$$

- Scattering amplitude for small values of k^* and with effective range approximation (neglects the shape of the potential) [A. Deloff, *Fundamentals in Hadronic Atom Theory* (2013)]:

$$f^S(k^*) = \left(\frac{1}{f_0^S} + \frac{1}{2} d_0^S k^{*2} - ik^* \right)^{-1}$$

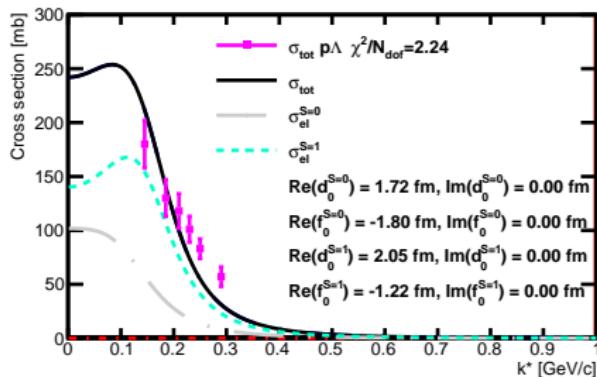
Cross sections

- Elastic $\sigma_e = 4\pi \sum_l (2l+1) |f_l|^2 = 4\pi |f_{k^*}|^2$
- Inelastic $\sigma_r = 4\pi \left(\frac{\text{Im}(f_{k^*})}{k^*} - |f_{k^*}|^2 \right)$

- f_0^S - scattering length
- d_0^S - effective radius

Cross-check and range of applicability

- Cross-check with measured $p - \Lambda$ data [Phys. Rev. 173, 1452 (1968)]

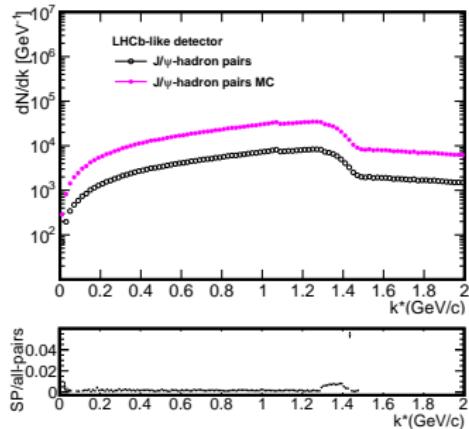


- Elastic cross sections for singlet and triplet states using parameters from [Nucl.Phys.A 779, 244-266 (2006)]
- Good description of the data for $k^* < 0.25 \text{ GeV}/c$

J/ψ-hadron

- Correlation effect limited to $k^* < 0.3 \text{ GeV}/c$ in our simulation
- This corresponds to $\sqrt{s} = 4.3 - 4.6 \text{ GeV}$

- ① Use PYTHIA8 simulation to generate k^* distributions for $J/\psi - h$ pairs in 2 cases:
 - LHCb setup
 - STAR setup
- ② $N_{J/\psi}$ is taken from the above previous measurements and scaled to the expected luminosity



Bottom: $B \rightarrow J/\psi$ contribution < 1% and outside range of correlation effect

| Detector | Decay channel | \sqrt{s} [TeV] | Published raw yield and L_{int} | | Expected raw yield and L_{int} | | | Expected pairs | |
|----------|----------------------------------|------------------|-----------------------------------|----------------------------|----------------------------------|--------------------------|-----------------------|--|--|
| | | | J/ψ yield | $L_{int} [\text{pb}^{-1}]$ | $L_{int} [\text{pb}^{-1}]$ | $N_{J/\psi} \times 10^6$ | $\langle N_h \rangle$ | $\langle N_{J/\psi-h} \rangle \times 10^6$ | |
| LHCb | $J/\psi \rightarrow \mu^+ \mu^-$ | 8 | 2.6×10^6 | 18.4 | 2082 | 294 | 5.31 | 1562 | |
| STAR | $J/\psi \rightarrow e^+ e^-$ | 0.5 | 9581 | 22.1 | 400 | 0.173 | 4.82 | 0.83 | |
| STAR | $J/\psi \rightarrow e^+ e^-$ | 0.51 | 9581 | 22.1 | 2200 | 0.95 | 4.82 | 4.6 | |
| STAR | $J/\psi \rightarrow \mu^+ \mu^-$ | 0.51 | 1154 | 22.0 | 2200 | 0.115 | 4.82 | 0.56 | |

- ③ Use Lednicky-Lyuboshitz model to calculate the correlation effect and sample the obtained k^* distributions

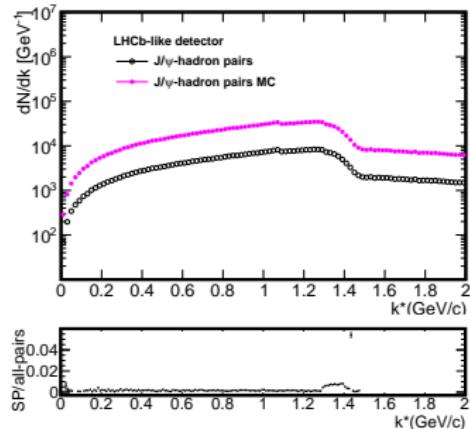
[Sov.J.Nucl.Phys., 35, 1316–1330 (1981)]

$$C(k^*) = 1 + \sum_S \rho_S \left[\frac{1}{2} \left| \frac{f^S(k^*)}{r_0} \right|^2 \left(1 - \frac{d_0^S}{2\sqrt{\pi}r_0} \right) + \right.$$

$$\left. \frac{2 \operatorname{Re}(f^S(k^*))}{\sqrt{\pi}r_0} F_1(Qr_0) - \frac{\operatorname{Im}(f^S(k^*))}{r_0} F_2(Qr_0) \right]$$

$$Q = 2k^*, F_1(z) = \int_0^z dx e^{x^2 - z^2} / z, F_2(z) = (1 - e^{-z^2}) / z$$

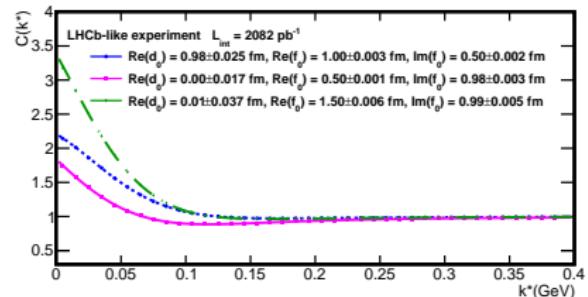
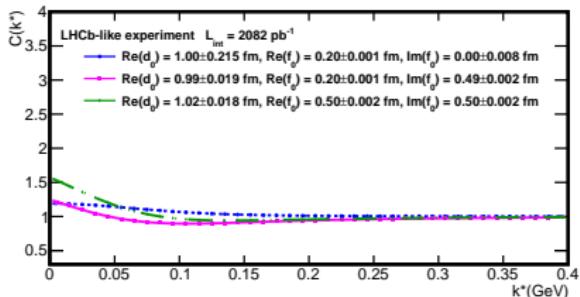
- Assume initial values of interaction parameters f_0^S and d_0^S , set $r_0 = 1.25$ fm
- ④ Obtain the $J/\psi - h$ correlation functions and fit them with the Lednicky-Lyuboshitz formula to see if we can recover the input values of interaction parameters.
 - ⑤ Calculate cross sections



Bottom: $B \rightarrow J/\psi$ contribution < 1% and outside the range of correlation effect

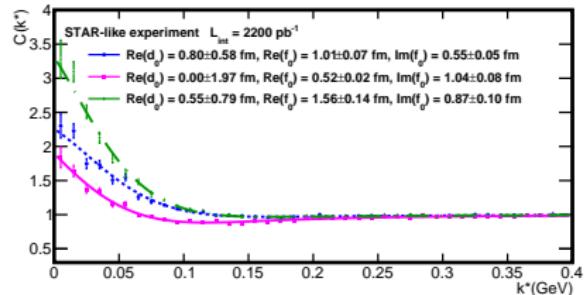
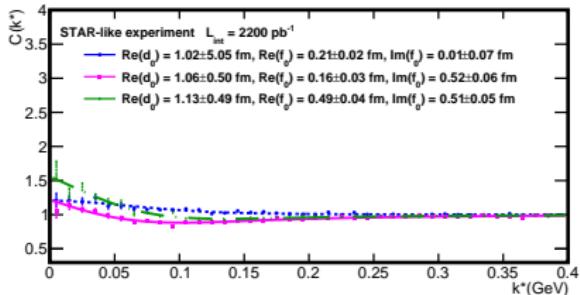
| Set No. | $\operatorname{Re}(d_0^S)$ [fm] | $\operatorname{Re}(f_0^S)$ [fm] | $\operatorname{Im}(f_0^S)$ [fm] |
|---------|---------------------------------|---------------------------------|---------------------------------|
| 1 | 1.0 | 0.2 | 0.0 |
| 2 | 1.0 | 0.2 | 0.5 |
| 3 | 1.0 | 0.5 | 0.5 |
| 4 | 1.0 | 1.0 | 0.5 |
| 5 | 0.0 | 0.5 | 1.0 |
| 6 | 0.0 | 1.5 | 1.0 |

Results - correlation functions



- Good fits! Input values recovered.
- Possible to measure $J/\psi - h$ femtoscopic correlations at LHCb with existing data!

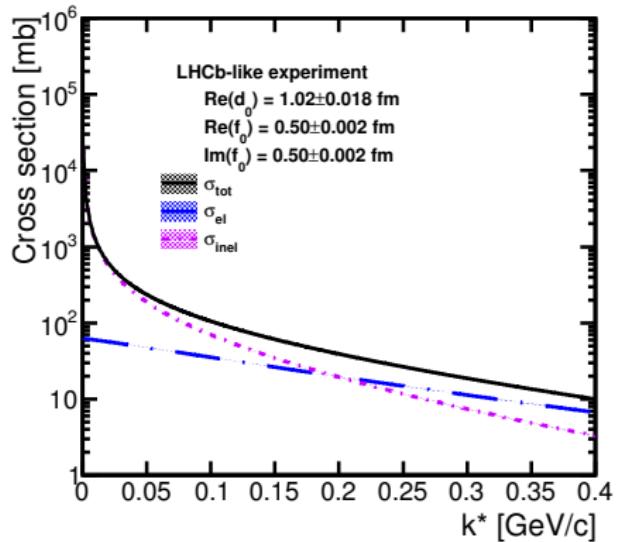
Results - correlation functions



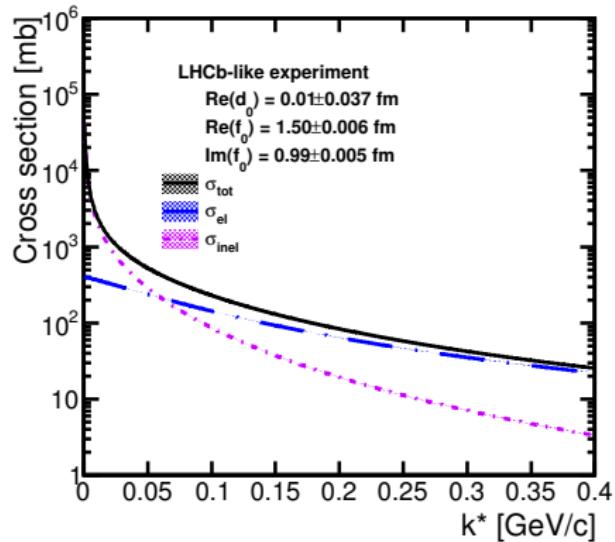
- Large uncertainties for STAR-like setup, but should be possible with planned data taking in 2023.

Results - cross sections

Set 3



Set 6



- Elastic and inelastic cross sections calculated using parameters obtained from fits.
- For LHC Run 3 and Run 4 it should be possible to study even $\Upsilon - h$ correlations at LHCb and CMS with 300 fb^{-1} .

- We propose a new method for direct measurement of J/ψ -hadron elastic and inelastic interaction cross sections
- Performed a feasibility study for LHCb and STAR-like experiments
- Results show that it should be possible to measure J/ψ -hadron femtoscopic correlations at LHCb already and at STAR in the future
- Run 3 and Run 4 data planned to be collected at LHCb and CMS will allow even Υ -hadron correlations to be measured

M. Bahmani, D. Kikola, L. Kosarzewski, "**A technique to study the elastic and inelastic interaction of quarkonium with hadrons using femtoscopic correlations**"

[*arXiv:2012.11250 [hep-ph]*] (*submitted to EPJC*)

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Thank you for your attention!

BACKUP

Scattering amplitude and cross sections

$$f_l = \frac{S_l - 1}{2ik} = i \frac{1 - S_l}{2k} \quad (1)$$

$$f_l = \frac{\eta_l \sin 2\delta_l}{2k} + i \frac{1 - \eta_l \cos 2\delta_l}{2k} \quad (2)$$

$$S_l = \eta_l e^{i2\delta_l} \quad (3)$$

Reformulate Eq. 1 in order to get S_l :

$$S_l = 1 + 2ikf_l \quad (4)$$

$$|S_l|^2 = (1 + 2ikf_l)(1 - 2ikf_l^*) = 1 + 2ikf_l - 2ikf_l^* + 4k^2|f_l|^2 = 1 - 4k \operatorname{Im}(f_l) + 4k^2|f_l|^2 \quad (5)$$

$$\sigma_e = 4\pi \sum_l (2l + 1)|f_l|^2 = 4\pi|f_k|^2 \quad (6)$$

Scattering amplitude and cross sections 2

Plugging in Eq. 5 into σ_r :

$$\sigma_r = \frac{\pi}{k^2} \sum_l (2l+1)(1 - |S_l|^2) = \frac{\pi}{k^2} \sum_l (2l+1)(1 - 1 + 4k \operatorname{Im}(f_l) - 4k^2|f_l|^2) \quad (7)$$

$$\sigma_r = 4\pi \sum_l (2l+1) \left(\frac{\operatorname{Im}(f_l)}{k} - |f_l|^2 \right) \quad (8)$$

Substituting $f_l \rightarrow f_k$:

$$\sigma_r = 4\pi \left(\frac{\operatorname{Im}(f_k)}{k} - |f_k|^2 \right) \quad (9)$$

In order to calculate the total cross section σ_T add Eq. 6 and Eq. 8

$$\sigma_T = \sigma_r + \sigma_e = \frac{4\pi}{k} \sum_l (2l+1) \operatorname{Im}(f_l) = \frac{4\pi}{k} \operatorname{Im}(f_k) \quad (10)$$

$$\sigma_T = \frac{4\pi}{k} \sum_l (2l+1) \frac{1 - \operatorname{Re}(S_l)}{2k} = \frac{2\pi}{k^2} \sum_l (2l+1)(1 - \operatorname{Re}(S_l)) \quad (11)$$