A method for the measurement of J/ψ cross section in hadronic matter using femtoscopy.

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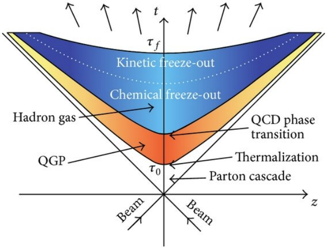
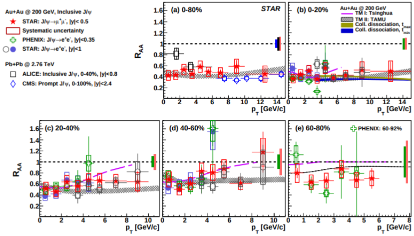
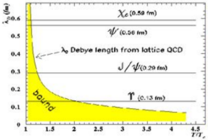
- Quark Gluon Plasma (QGP) exists for short time in high energy nuclear collision

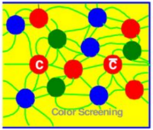


- It cools down and partons form hadrons which will be registered by Experiments. Hence hadronic phase always accompany the QGP signal.
- Physicists developed a variety of approaches to access the properties of QGP.

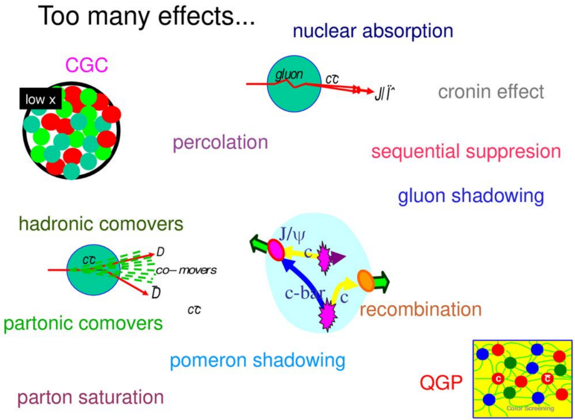
- One of the approaches is suppression of quarkonium production (Matsui & Satz (1986)), suppression happens due to color Debye screening.
- Suppression of a given state depends on the energy density (hence the temperature) of the partonic matter.
- Simulates measurement of production of J/ψ, $\psi(2s)$, $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ and other quarkonium states could provide information about thermodynamic properties of the QGP.
- Another approach is using open heavy flavour meson as a tool for probing QGP.







- But, there are other ways of quarkonium interaction with partonic matter.
- A lot of data, yet no complete theoretical model.
- One of important factor interaction of quarkonium with hadronic matter.



- Measurement of femtoscopic correlations (low relative momenta) of J/ψ-hadron give access to the cross section for elastic and inelastic interactions of J/ψ with hadrons.
- Femtoscopic correlations of D^0 with hadrons provide information about the size of the volume from which the correlated pair of a D^0 and a hadron is emitted.
- Femtoscopic correlations is sensitive to effects from Final State Interaction (FSI) and also Size of the emission source.
- It offers a formalism to calculate the parameters of interaction.
- The breakup cross section of quarkonium in hadronic matter (elastic and inelastic) is obtained using the parameter of interaction
- This study will provide a good opportunity to test the measurement of charmonium-hadron interaction and improve models of quarkonium production in HIC.

- femtoscopic correlation function for two particles:

$$C(p_1, p_2) = \frac{P_2(p_1, p_2)}{P_1(p_1)P_1(p_2)} \tag{1}$$

P_1 and P_2 are the probability of observing particles with a given momentum

- For nonidentical particles the effective interactions:

$$C(k^*) = \int d^3r^* S(r^*)|\Psi_{(\vec{r^*}, k^*)}|^2 \tag{2}$$

k^* is pair c.m.s ($k^* = p_1^* = -p_2^* \equiv Q/2$) and $S(r^*)$ is the source function

$$\Psi(\vec{r^*}, -k^*) \doteq e^{i\vec{k^*}\cdot\vec{r^*}} + \frac{f^S(k^*)}{r^*} e^{-ik^*\cdot r^*}, \tag{3}$$

which represents the stationary solution of the scattering problem.

The s-wave scattering amplitude in the effective range approximation:

$$f^S(k^*) = (\frac{1}{f_0^S} + \frac{1}{2} d_0^S k^{*2} - ik^*)^{-1}, \tag{4}$$

assuming $\vec{r^*}$ with Gaussian distribution according to Lednicky and Lyuboshitz analytical model,
the correlation function can be calculated analytically:

$$C(k^*) = 1 + \sum_S \rho_S \left[\frac{1}{2} \left| \frac{f^S(k^*)}{r_0} \right|^2 \left(1 - \frac{d_0^S}{2\sqrt{\pi} r_0} \right) + \frac{2\,\mathrm{Re}(f^S)(k^*)}{\sqrt{\pi} r_0} F_1(Qr_0) - \frac{\mathrm{Im}(f^S(k^*))}{r_0} F_2(Qr_0) \right], \tag{5}$$

where $F_1(z) = \int_0^z dx e^{x^2 - z^2}/z$ and $F_2(z) = (1 - e^{-z^2})/z$.
This model relates the two-particle correlation functions with source sizes and scattering amplitudes.

- Elastic and inelastic cross section for J/ψ-hadron interaction can be calculated from the scattering amplitude.
- The scattering amplitude can be extracted from experimental data by fitting the J/ψ-hadron femtoscopic correlation function.
- Measurement of J/ψ breakup cross section due to its interaction with hadrons.

$$\sigma_{tot} = \sigma_{inel} + \sigma_{el} = \frac{4\pi}{k^*}\,\mathrm{Im}(f^S(k^*))$$

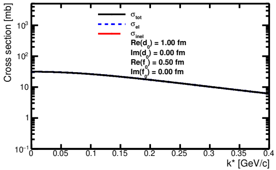
Feasibility study for J/ψ -hadron cross section measurement

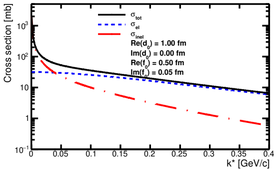
The expected number of J/ψ-hadron pairs for LHCb-like and STAR-like experiments for the data collected with LHCb in 2012 data taking period, and STAR in 2017 and the foreseen run in 2023 For obtaining the $N_{J/\psi-h}$ for each experiment:
$< N_{J/\psi-h} >=< N_{J/\psi} >< N_h >$

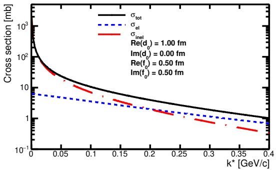
			Published raw J/ψ yield and L_{int}		Expected raw J/ψ yield and L_{int}			Expected number of pairs
Detector	Decay channel	$\sqrt{s}$ [TeV]	J/ψ yield	$L_{int}\,[pb^{-1}]$	$L_{int}\,[pb^{-1}]$	$N_{J/\psi}\times10^6$	N_h	$N_{J/\psi-h}\times10^6$
LHCb	$J/\psi\to\mu^+\mu^-$	8	2.6×10^6	18.4	2082	294	5.31	1562
STAR	$J/\psi\to e^+e^-$	0.5	9581	22.1	400	0.173	4.82	0.83
STAR	$J/\psi\to e^+e^-$	0.51	9581	22.1	2200	0.95	4.82	4.6
STAR	$J/\psi\to\mu^+\mu^-$	0.51	1154	22.0	2200	0.115	4.82	0.56

- For each parameter set we assume $r_0 = 1.25$ fm and $\mathrm{Im}(d_0^S) = 0$
  PhysRevC.99.024001, PhysRevD.87.052016, PhysRevC.83.064905.
- The sensitivity of inelastic cross section for J/ψ -hadron interaction to the parameter of interaction, the imaginary part of scattering length.

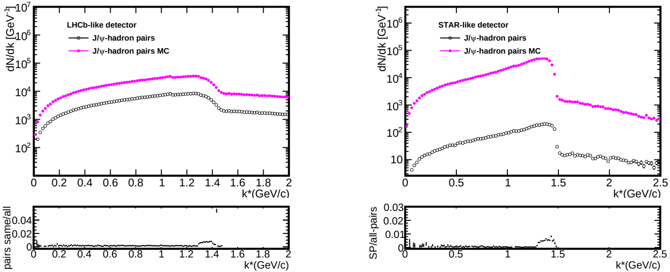
Set No.	$\mathrm{Re}(d_0^S)$ [fm]	$\mathrm{Re}(f_0^S)$ [fm]	$\mathrm{Im}(f_0^S)$[fm]
1	1.0	0.2	0.0
2	1.0	0.2	0.5
3	1.0	0.5	0.5
4	1.0	1.0	0.5
5	0.0	0.5	1.0
6	0.0	1.5	1.0





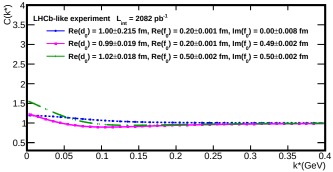


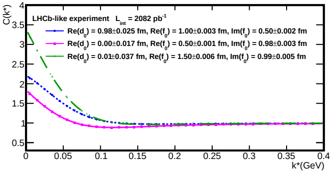
- Simulated sample with Pythia 8.2 configured within parameters of LHCb experiments(LHCb 8TeV and L_{int} 2082pb^{-1}) and STAR experiments (STAR 500GeV, L_{int} 2200 pb^{-1}).



- Non-femtoscopic background: resonances which can decay to J/ψ + hadron such as B mesons

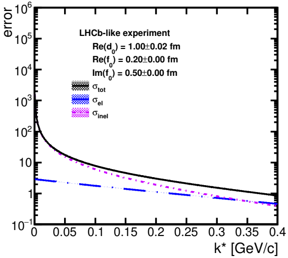
The psuedoexperimental femtoscopic correlation functions and J/ψ breakup cross section

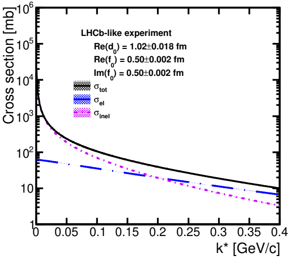




$\chi^2/\mathrm{NDF}=$ (29.63/36), (37.7/36), (24.23/36)

$\chi^2/\mathrm{NDF}=$ (26.41/36), (40.12/36), (46.42/36)





Parameter of interaction

Interaction parameters extracted with fit of the Lednicky-Lyuboshitz model to femtoscopic correlation functions simulated for LHCb-like. The parameters r_0 and $\text{Im}(d_0^S)$ are fixed to 1.25 and 0 fm respectively.

LHCb-like, $\sqrt{s} = 8$ TeV, $L_{int} = 2028\ pb^{-1}$				
Parameter set No.	$\text{Re}(d_0^S)$ [fm]	$\text{Re}(f_0^S)$ [fm]	$\text{Im}(f_0^S)$[fm]	χ^2/NDF
1	1.00±0.215	0.20±0.001	0.00±0.008	29.62/36
2	0.99±0.019	0.20±0.001	0.49±0.002	37.17/36
3	1.02±0.018	0.50±0.002	0.50±0.002	24.23/36
4	0.98±0.025	1.00±0.003	0.50±0.002	26.41/36
5	0.00±0.017	0.50±0.001	0.98±0.003	40.12/36
6	0.01±0.037	1.50±0.006	0.99±0.005	46.42/36

The result for the STAR-like experiments in the backup slides and the result of this study is already available at arXiv:2012.11250.

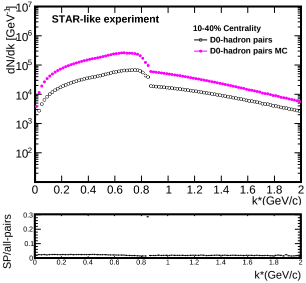
Femtoscopic correlations of D0-hadron

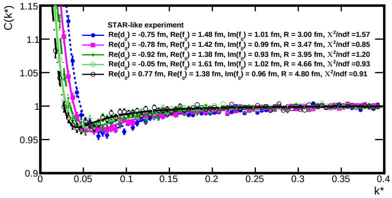
- The goal is to model D^0-$\overline{D^0}$ femtoscopic correlations in heavy ion collisions, Since the possibility of producing the D meson in experiment with high multiplicity is low, It is suggested to also study the D^0-hadron correlation as well and model the source size.
- However in order to perform these studies we need MC generator which produce charm meson femtoscopic correlation in heavy ion collisions, and such generator is not yet published.
- Instead, we can study the D^0-$\overline{D^0}$ and D^0-hadron femtoscopic correlations in pp samples, however in this case we shall use the source size already measured by experiment as an input parameter and model the correlation function.
- Studies (PoS(INPC2016)334) shows that for non-identical particle the source size has such relation:

$$R_{p_1,p_2} = \sqrt{R_{p_1}^2 + R_{p_2}^2} \tag{6}$$

- by using this equation one can access the source size obtained by D^0-hadron correlation to find the source size by D^0-$\overline{D^0}$ correlation

- Simulated sample with Pythia 8.2 configured within parameters of STAR experiments (STAR 200GeV).





- Number of hadron from charge hadron multiplicity distribution and D^0 yield from arXiv:1812.10224.
- Estimated number of D^0-hadron pairs $\simeq$ 60 M
- The CF plot is for set 6 of parameters.

Summary and Conclusion

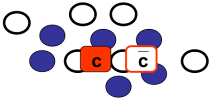
- We proposed an experimental method to study elastic and inelastic interaction of charmonium and bottomonium with hadrons
- The proposed approach is straightforward and experiments employed similar strategy to study final-state interactions with success.
- We used the femtoscopic correlation function and the Lednicky-Lyuboshitz analytical model to extract the scattering length and the effective range of the quarkonium-hadron interaction at low relative momenta.
- Our feasibility study showed that LHCb can already measure both elastic and inelastic(break up) cross sections in a hadronic matter as a function of relative momentum k^* and STAR future run in 2023 can provide enough statistics for this study. Result of this study is already available at arXiv:2012.11250.
- Ongoing work on feasibility study on mesurement of the source size for D^0-hadron pairs using femtoscopic correlation.

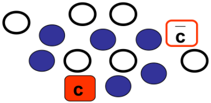
THANK YOU FOR YOUR ATTENTION!

Backup

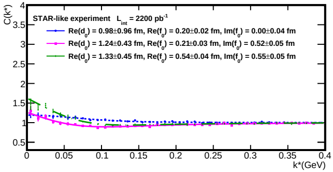
J/ψ-hadron interaction model in heavy ion collision

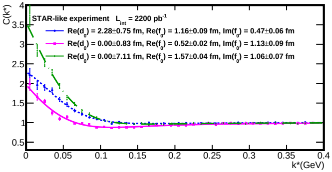
- J/ψ suppresion in the QGP due to the color Debye screening.
- J/ψ yield can also be decreased by interaction with hadron produced in the collision
- The probability of such interaction increases as hadron density increases (stronger in central collision)
- Such scenario is considered in the comover interaction model(however the model also includes the regeneration of J/ψ)
- J/ψ cross section in interactions with hadrons is a crucial parameter of the model
- There are some calculation based on different models for J/ψ breakup cross section for J/ψ-hadron center of mass energy in order of few GeV.
- Directly measuring it using femtoscopic correlation will provide a good opportunity to test and improve those models.





STAR-like experiment results





$\chi^2/\mathrm{NDF}=$ (37.36/36), (35.09/36), (41.37/36)　　$\chi^2/\mathrm{NDF}=$ (37.56/36), (27.91/36), (49.10/36)

STAR-like, $\sqrt{s} = 500$ GeV, $L_{int} = 2.2\, fb^{-1}$

Parameter set No.	$\mathrm{Re}(d_0^S)$ [fm]	$\mathrm{Re}(f_0^S)$ [fm]	$\mathrm{Im}(f_0^S)$[fm]	χ^2/NDF
1	1.02±5.05	0.21±0.02	0.01± 0.07	37.36/36
2	1.06±0.50	0.16±0.03	0.52±0.06	35.09/36
3	1.13±0.49	0.49±0.04	0.51±0.05	41.37/36
4	0.80±0.58	1.01±0.07	0.55±0.05	37.56/36
5	0.00±1.97	0.52±0.02	1.04±0.08	27.91/36
6	0.55±0.79	1.56±0.14	0.87±0.10	49.10/36

STAR-like, $\sqrt{s} = 500$ GeV, $L_{int} = 400\, pb^{-1}$				
Parameter set No.	$\mathrm{Re}(d_0^S)$ [fm]	$\mathrm{Re}(f_0^S)$ [fm]	$\mathrm{Im}(f_0^S)$[fm]	χ^2/NDF
1	0.00±1.45	0.21±0.04	0.00±0.05	37.70/36
2	0.44±1.33	0.24±0.07	0.59±0.13	50.53/36
3	2.39±1.09	0.70±0.13	0.71±0.15	43.32/36
4	1.38±1.15	1.07±0.14	0.47±0.11	32.26/36
5	0.44±0.84	0.54±0.10	1.30±0.24	40.89/36
6	0.00±1.34	1.61±0.10	1.20±0.18	34.04/36