Electromagnetic field and QGP induced yield enhancement of vector mesons in HIC

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Motivation

Nuclei are accelerated to nearly speed of light, $v > 0.9999c$ in heavy ion collisions at RHIC and LHC energies. AA collisions can generate both

an extremely hot medium (QGP)
and strong electromagnetic fields (EB).

1) electromagnetic fields → change particle evolution
2) electromagnetic fields → directly produce mesons (or dileptons)

EB-induced particle productions are usually studied in *Ultra-peripheral Collisions*, absent of hadronic collisions and QGP. Why now considering photoproduction EVEN in $b < 2R_A$?

- Experiments already observed NEW enhancement of J/ψ yield in extremely low p_T region in semi-central collisions, calling for new production mechanisms.
- Dileption yield beyond the expection of QGP contribution
- Photoproductions of vector mesons and dileptons are $\propto B^2$ and $\propto B^4$ respectively, and more sensitive to B-field compared with CME. This can give additional constraints on the *magnitudes* and *fluctuations* of EB fields at the very beginning of heavy ion collisions.

We give a fully consistent study about vector meson production from both QGP and EB fields, and also find an interesting behavior of $\psi'/J/\psi$ which reveals the importance of BOTH QGP and EB fields in vector meson production.

Photoproduction

Fast moving nucleus carrying electric charges
→ Lorentz-contracted electromagnetic fields ($\mathbf{E} \to \mathbf{E}_T$)
→ treated as "quasi-real" photons.

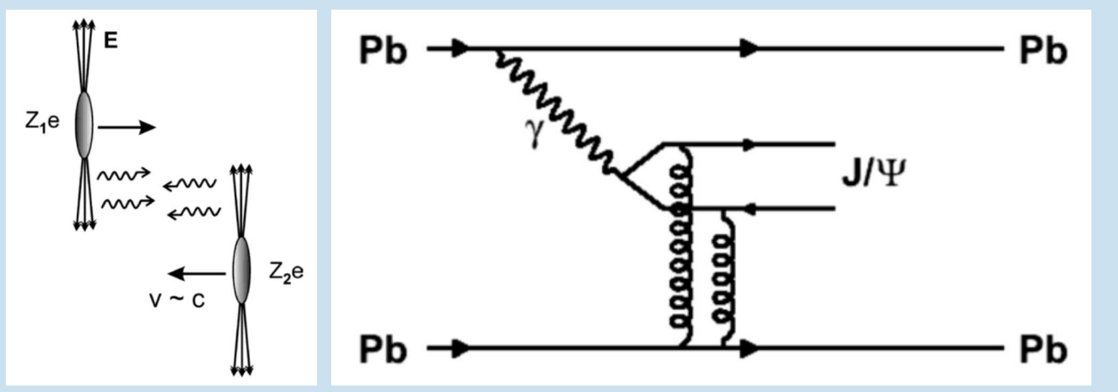

Figure 1: Schematic figures for interactions between electromagnetic fields and target nucleus.

Then, interactions between EB fields and target nucleus, can be approximated as $\gamma - A$ scatterings. Easier !

1) photon density $n(w)$:

In particle production, electromagnetic fields are treated as *longitudinally moving quasi-real photons*, proposed by "Equivalent-Photon-Approximation (EPA)"

$$\int_{-\infty}^{\infty} d\tau \int d\mathbf{x}_T \cdot (\mathbf{E}_T \times \mathbf{B}_T) = \int_0^{\infty} dw\, wn(w) \qquad (1)$$

Here $n(w) \equiv dN_\gamma/dw$, and w is the photon energy.

2) photoproduced Ψ with QGP modifications

Coherent photoproduction: photons scatter with *entire* nucleus and fluctuate into vector mesons (such as ρ^0, ϕ, J/ψ, ψ'), see Fig.1.

$$\frac{dN_\Psi}{dy} = \int d\mathbf{x}_T\, w\tilde{n}_\gamma(w,b)\sigma_{\gamma A\to\Psi A} f^{\rm norm}(\mathbf{x}_T)\Gamma_{\rm QGP}(\mathbf{x}_T) + (y \to -y \text{ term}) \qquad (2)$$

$\tilde{n}_\gamma(w,b)$ is the averaged value of *photon spatial density* $dN_\gamma/dwd\mathbf{x}_T$ in the area of target nucleus, depending on impact parameter $\mathbf{b}$.

$f^{\rm norm}(\mathbf{x}_T)\Gamma_{\rm QGP}(\mathbf{x}_T)$ considers QGP dissociations on the photoproduced Ψ in AA semi-central collisions. Charmonium Ψ rapidity is connected with photon energy by $y = \ln[2w/m_\Psi]$ in the lab frame (m_Ψ is the mass of Ψ). For more details, please see [1][2]

Hadroproduction

Charmonium final yields consists of *initial production* and *recombination of* $c - \bar{c}$ in QGP dynamical expansions. Charmonium suffers parton inelastic scatterings and color screening in QGP, $g + \Psi \leftrightarrow c + \bar{c}$. New charmonium can also be regenerated by the unbound charms inside QGP (the inverse reaction). Charmonium phase space densities are evolved by our transport model,

$$\frac{\partial f_\Psi}{\partial t} + \frac{\mathbf{p}_\Psi}{E_\Psi}\cdot\nabla f_\Psi = -\alpha_{g\Psi\to c\bar{c}} f_\Psi + \beta_{c\bar{c}\to g\Psi} \qquad (3)$$

$\alpha_{g\Psi\to c\bar{c}}$ is the decay rate of J/ψ due to gluon inelastic scatterings with color screened binding energy. The typical value of J/ψ decay rate in QGP is ~ 30 MeV (T_c) and ~ 80 MeV ($1.5T_c$). Excited states suffer much larger decay rate.
$\beta_{c\bar{c}\to g\Psi}$ is the charmonium regenerated rate, depends on both dynamical evolutions of ρ_c and $\rho_{\bar{c}}$ inside QGP and also their recombination cross section.

Hydro in LHC $\sqrt{s_{NN}}$=2.76 TeV Pb-Pb, $2.5 < y < 4$			
b(fm)	N_p	$T_0^{\rm QGP}/T_c$	$\tau_f^{\rm QGP}$ (fm/c)
0	406	2.6	7.3
9	124	2.1	4.2
10.2	83	1.95	3.5
12	35	1.5	2.3

Figure 2: QGP information in our hydrodynamic model at different centralities

Results

- J/ψ nuclear modification factor in LOW $p_T < 0.3$ GeV/c:

1) $R_{AA}^{J/\psi} \sim 1.0$ at $N_p \sim 100$, around 40% of them are from photoproduction
2) $R_{AA}^{J/\psi} \gg 1$ and $\to \infty$ at $N_p \to 0$

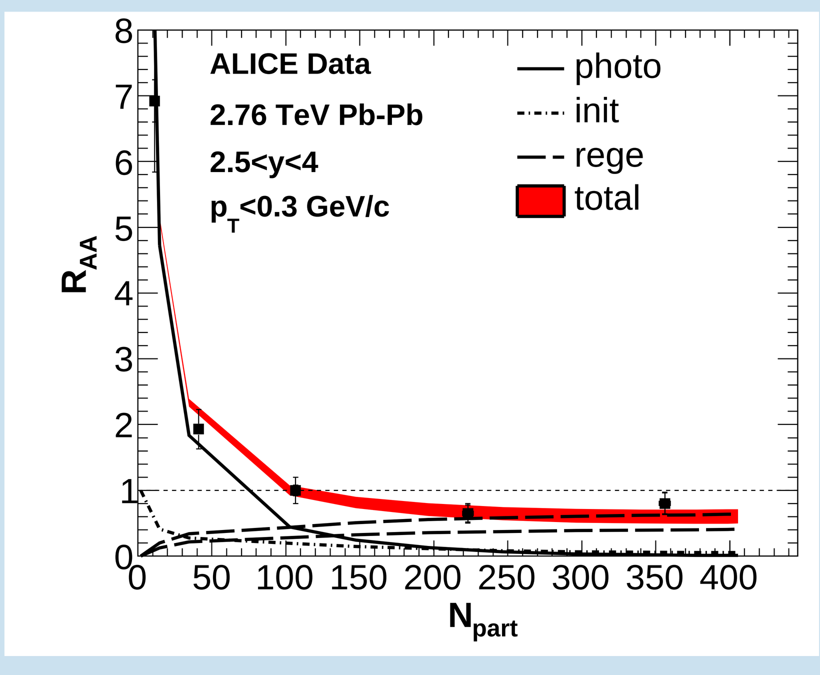

Figure 3: Dotted line: initial production, dashed lines: recombination of $c + \bar{c} \to J/\psi + g$ with two different $\sigma_{pp}^{c\bar{c}}$, solid line: production from EB-field, color band: total.

J/ψs from different sources dominate in the different p_T in semi-central AA collisions, see Fig.4

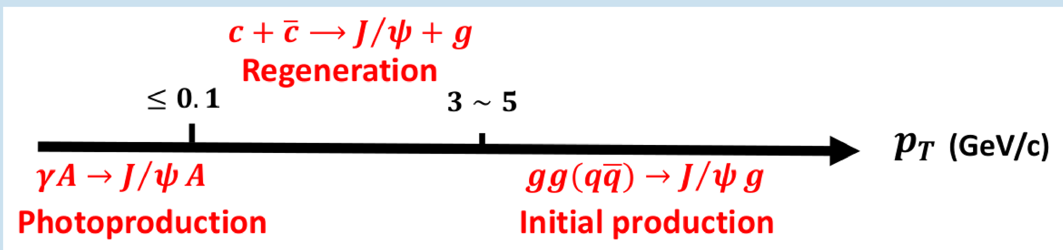

Figure 4: p_T dependence of charmonium yields from different sources in AA collisions with impact parameter $b < 2R_A$

In figure of $R_{AA}(p_T)$, photoproduction can make $R_{AA} \sim 1.6$ at $p_T \to 0$ with a sudden "jump", far above hadronic contribution $R_{AA}^{\rm hadronic} \sim 0.6$.

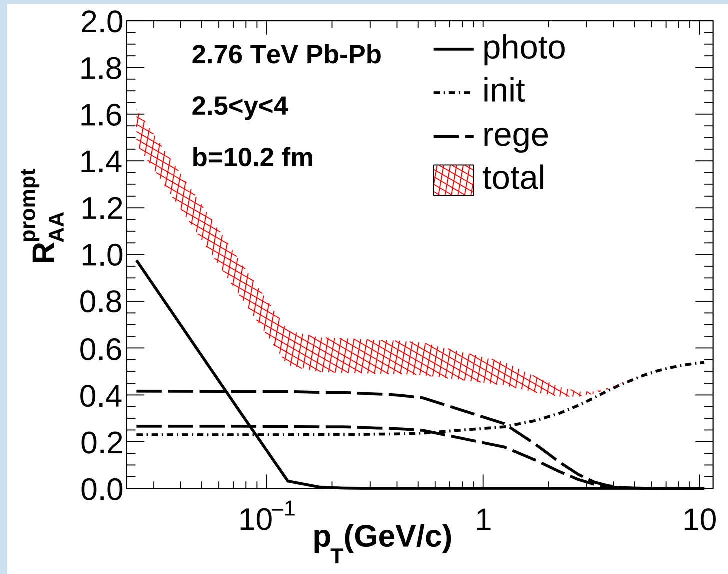

Figure 5: Dotted line: initial production, dashed lines: regeneration, solid line: photoproduction $\gamma A \to J/\psi A$, color band: total.

- **Combined Effects of EB Fields + QGP Effects on $\psi'/J/\psi$ Yield Ratio:**

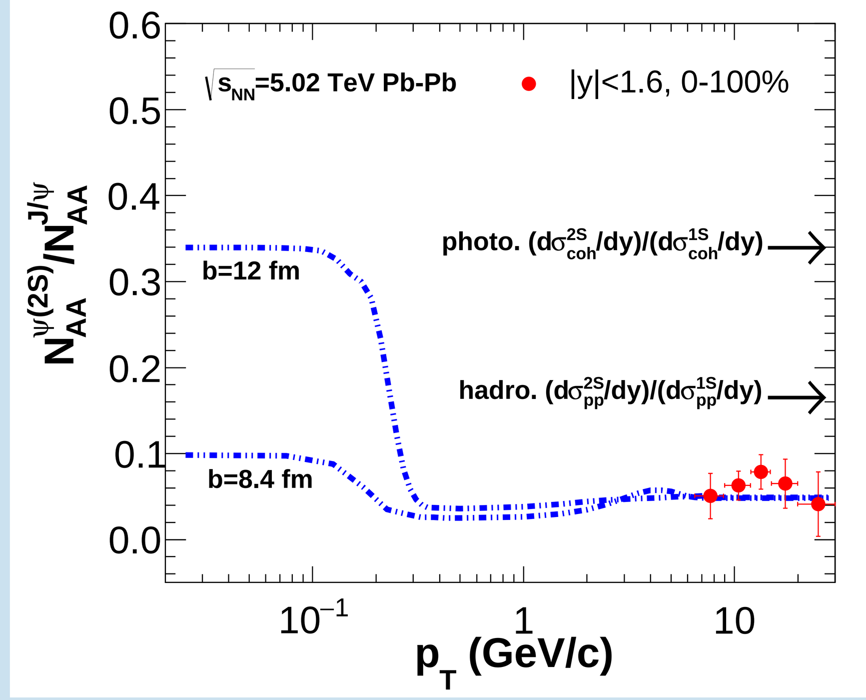

Figure 6: Yield ratio $N_{AA}^{\psi'}/N_{AA}^{J/\psi}$ in AA collisions.

1) At high p_T: Ratio < pp value, ← QGP stronger suppression on the excited state ψ' than J/ψ
2) At low p_T: Ratio enhanced, ← photoproduction
Advantage: This ratio does not depend on *shadowing effect*, etc. A clean probe to study EB fields and QGP effects.

- **RHIC Energy (or Isobar Collisions):**

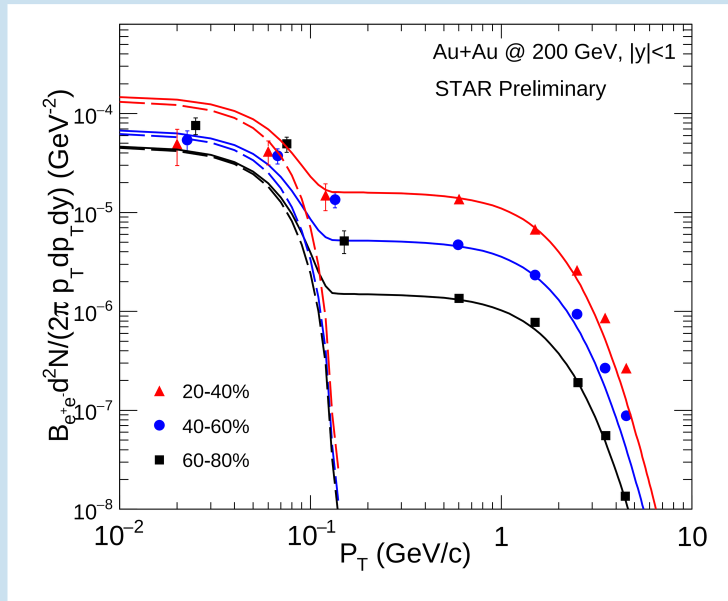

Figure 7: Our preliminary calculations. Dashed lines: Only photoproduction, solid lines: photo. + hadro. This is in collaboration with Jiaxing Zhao.

Conclusions

Even in the semi-central collisions with QGP existence, photoproduction still becomes important for charmonium (and ϕ) but only in extremely low p_T bin. With the competition between EB fields and QGP suppression, we propose an interesting behavior of $\psi'/J/\psi$.
Outlook: *Is photoproduction also important in most central collisions ? As it is sensitive to EB fields ($\propto B^2$ or B^4), give more constraint on initial EB fields ? Photoproduced particle polarization to probe EB-fluctuations ?*

References

[1] B. Chen, C. Greiner, W. Shi, W. Zha, and P. Zhuang, (2018), 1801.01677.
[2] W. Shi, W. Zha, and B. Chen, Phys. Lett. **B777**, 399 (2018), 1710.00332.

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