HEFTY Status

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Figure 1: This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344, the LLNL-LDRD Program under Projects 21-LW-034 and 23-LW-036 and the HEFTY Collaboration.

HEFTY Topical Collaboration Has Been Formed to Study Heavy Flavor Probes

US Department of Energy Topical Collaboration, funded for 5 years starting in 2023

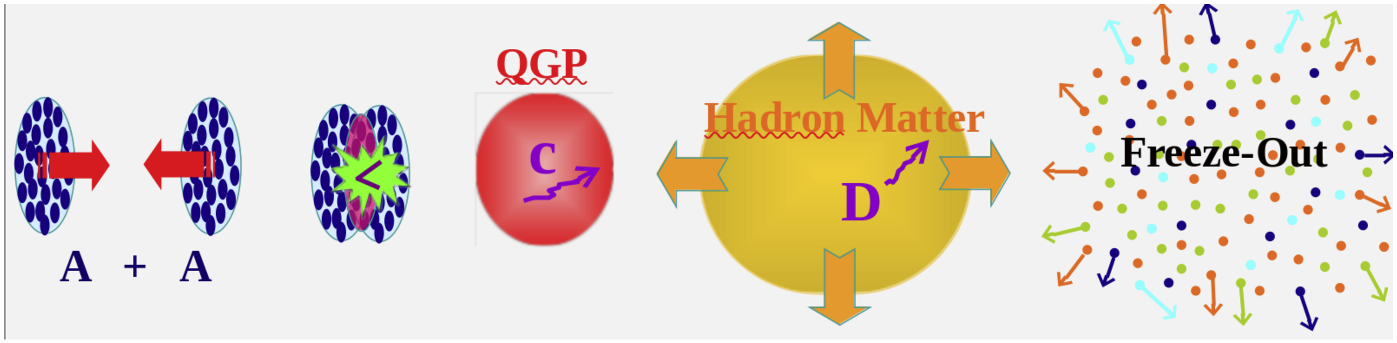
Designed to answer some of the open questions in QCD matter by studying heavy flavor probes:

- **Transport properties and their emergence from the underlying interaction**
- **Spectral functions and the degrees of freedom**
- **Mechanisms for converting quarks and gluons into hadrons**
- **Role of quantum effects in the strongly-coupled quark-gluon plasma**

To understand QCD matter, one has to also understand the underlying cold nuclear matter effects

Connections to experiment through sPHENIX at RHIC; the ongoing LHC experiments; and the upcoming Electron-Ion Collider at Brookhaven National Lab

Heavy Flavors are Important Probes of QCD



Large mass, $m_Q >> \Lambda_{\rm QCD}$, T, T_c, means heavy quarks produced at early times

Heavy quarks diffuse through the QCD medium and do not thermalize right away, providing a gauge of the interaction strength

Allows the study of mass hierarchy in radiative energy loss plus the transition from diffusion to radiation

Hadronization effects probe the medium and study hadron production mechanism, recombination vs. fragmentation through $c \to D$ and $c\bar{c} \to J/\psi$

Many connections to lattice QCD: heavy-quark free energy, heavy flavor fluctuations and correlation functions, dissociation temperature, real and imaginary parts of the quarkonium potential

Study $p+p$, $p+A$ and $A+A$ collisions to differentiate hot and cold matter effects

This talk will focus on quarkonium results and will not discuss open heavy flavor results from the collaboration

HEFTY Collaboration Members

Principal Investigator: Ralf Rapp (Texas A&M) Co-spokespersons: Peter Petreczky (BNL) and RV (LLNL and UC Davis)

Other Co-Investigators:

- **Steffen Bass and Tom Mehen (Duke)**
- **Xin Dong* (LBNL)**
- **Tony Frawley* (Florida State)**
- **Yen-Jie Lee (MIT)**
- **Swagato Mukherjee (BNL)**
- **Jian-wei Qiu (Jefferson Lab)**
- **Mike Strickland (Kent State)**
- **Ivan Vitev (LANL)**

Members with a * by their names are experimentalists

Kent State is in the process of hiring a new faculty member through a "Bridge" position; applications have closed and interviews will begin soon

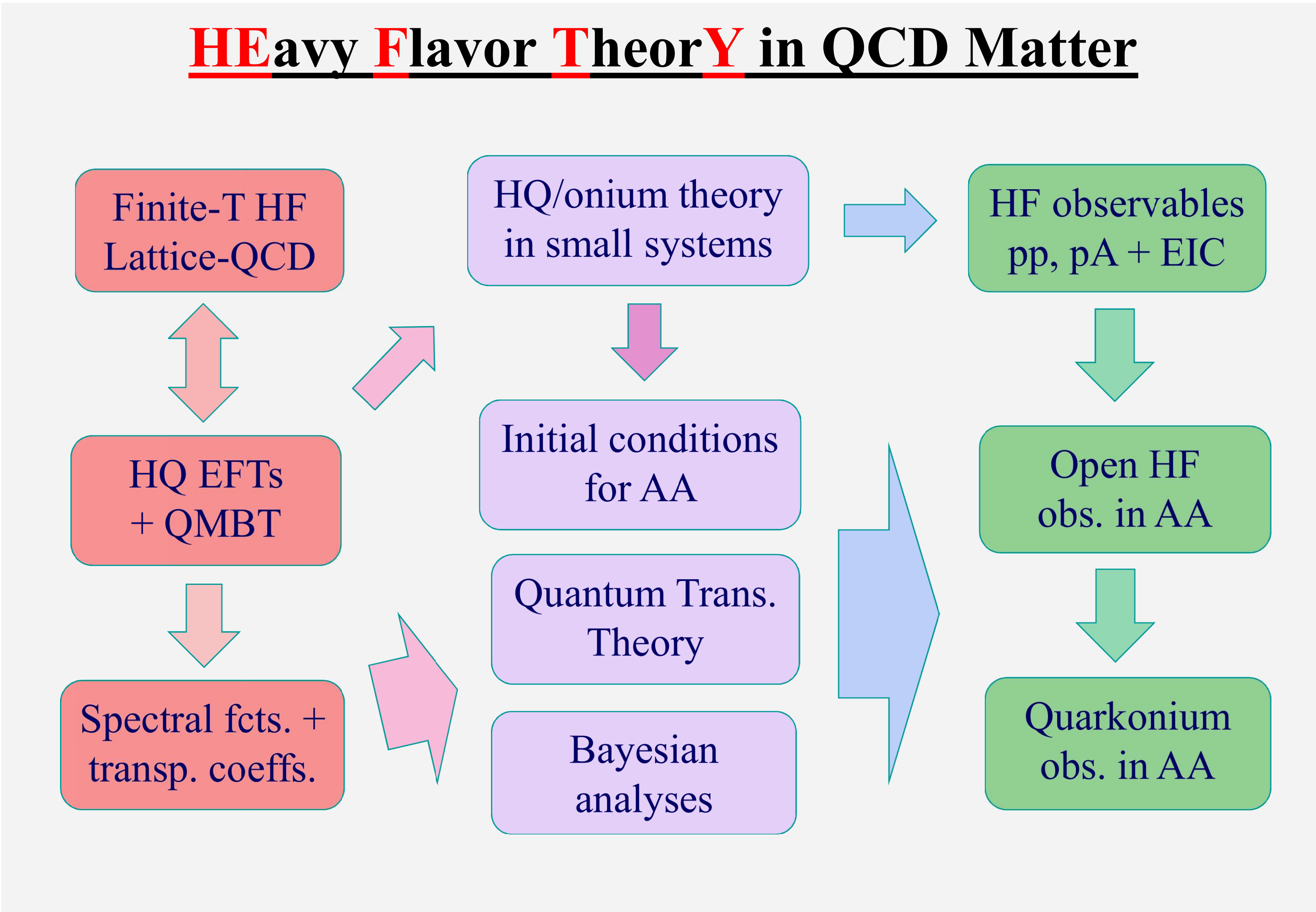
Junior collaboration members include students and postdocs

Four Working Groups

- **WG1: In-medium properties of heavy flavor hadrons and quarks using lattice QCD, T-matrix approaches and effective field theories (in-medium quarkonium masses and widths; complex potential at $T > 0$; transport coefficients and charm quark susceptibilities)**
- **WG2: Heavy flavor production in $p + p$, $p + A$, $e + p$, $e + A$ collisions; push the boundaries of heavy flavor theory in small systems, provide baseline cross sections and cold nuclear matter effects for other working groups**
- **WG3: open heavy flavor transport in heavy-ion collisions; develop and deploy framework for heavy quark transport and hadronization in $A+A$ collisions using lattice QCD based transport coefficients and rigorous statistical analysis**
- **WG4: Quarkonium transport in heavy-ion collisions; develop and deploy an integrated quantum transport approach for quarkonia in heavy-ion collisions**

All working groups interact with each other and depend on each other's results to be successful

Results shown in this talk are from Working Groups 1, 2 and 4


HEavy Flavor TheorY in QCD Matter
Finite-T HF Lattice-QCD
HQ EFTs + QMBT
Spectral fcts. + transp. coeffs.
HQ/onium theory in small systems
Initial conditions for AA
Quantum Trans. Theory
Bayesian analyses
HF observables pp, pA + EIC
Open HF obs. in AA
Quarkonium obs. in AA

Intrinsic Charm Production with SMOG at LHCb

RV, Phys. Rev. C 108 (2023) 015201, arXiv:2304.09356 [hep-ph]

J/ψ **production with SMOG (fixed target** $p + \mathrm{Ne}$, $p + \mathrm{He}$ **and** $p + \mathrm{Ar}$ **collisions at** $\sqrt{s_{NN}} = 69$, **87.7, and 110.4 GeV respectively)**

Production was assumed to be a combination of perturbative production in the Color Evaporation Model at NLO with cold matter effects of modification of the parton densities, intrinsic transverse momentum broadening, and nuclear absorption with intrinsic charm production of J/ψ

Intrinsic charm (IC) probability distribution:

$$dP_{\mathrm{ic}\,5} = P^0_{\mathrm{ic}\,5} N_5 \int dx_1 \cdots dx_5 \int dk_{x\,1} \cdots dk_{x\,5} \int dk_{y\,1} \cdots dk_{y\,5} \frac{\delta(1 - \sum_{i=1}^5 x_i)\delta(\sum_{i=1}^5 k_{x\,i})\delta(\sum_{i=1}^5 k_{y\,i})}{(m_p^2 - \sum_{i=1}^5 (\widehat{m}_i^2/x_i))^2}$$

$i = 1, 2, 3$ **are** u, u, d **light quarks, 4 and 5 are** c **and** $\overline{c}$, N_t **normalizes the probability to unity and** P^0_{ic} **scales the probability to the assumed intrinsic charm content: 1%**

The IC J/ψ **cross section is**

$$\sigma_{\mathrm{ic}}^{J/\psi}(pp) = F_C \sigma_{\mathrm{ic}}(pp) = P_{\mathrm{ic}\,5} \sigma_{pN}^{\mathrm{in}} \frac{\mu^2}{4\widehat{m}_c^2}$$

The A **dependence is (with** $\beta = 0.71$ **from NA3)**

$$\sigma_{\mathrm{ic}}(pA) = \sigma_{\mathrm{ic}}(pp)\, A^\beta$$

SMOG J/ψ Results Compared to Calculations

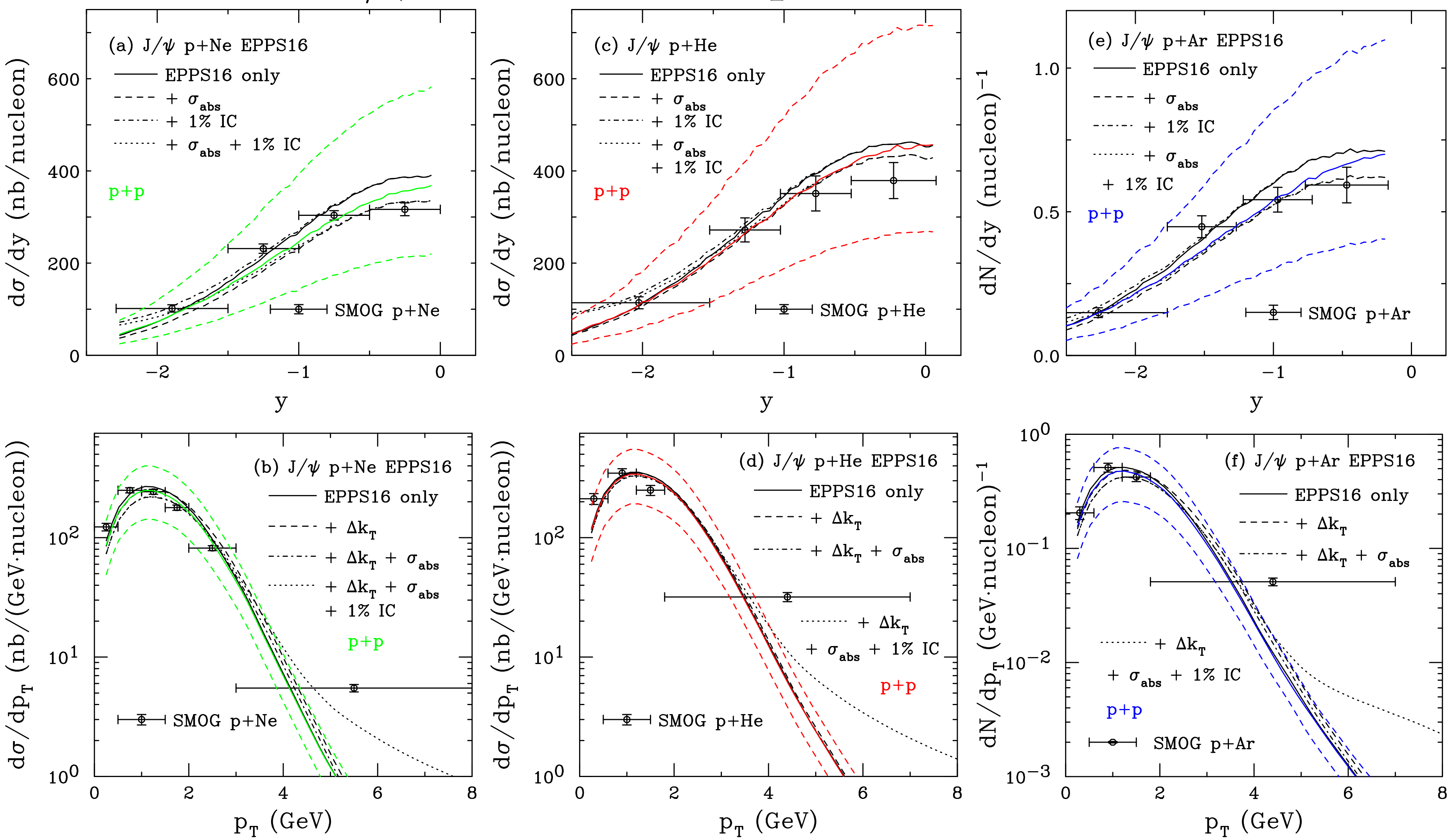


Figure 2: The J/ψ cross section as a function of y in (a), (c), (e) and p_T in (b), (d), (f) for $p+$Ne ($\sqrt{s_{NN}} = 68.5$ GeV) in (a) and (b); $p+$He ($\sqrt{s_{NN}} = 86.6$ GeV) in (c) and (d); and $p+$Ar ($\sqrt{s_{NN}} = 110.4$ GeV) in (e) and (f). The black curves are the $p+A$ calculations. The colored curves (solid and dashed) show the CEM $p+p$ calculations (no IC). The $p+A$ rapidity distributions are shown for EPPS16 only (solid); EPPS16 with absorption (dashed); EPPS16 and $P^0_{\rm ic\,5} = 1\%$ (dot-dashed); and EPPS16, absorption, and $P^0_{\rm ic\,5} = 1\%$ (dotted). The p_T distributions show EPPS16 only (solid); EPPS16 with k_T kick (dashed); EPPS16, absorption, and k_T kick (dot-dashed); and EPPS16, absorption, k_T kick and $P^0_{\rm ic\,5} = 1\%$ (dotted). The $p+$Ne data are from arXiv:2211.11645; the $p+$He and $p+$Ar data are from PRL **122**, 132002 (2019).

Bottomonium feed down at $\sqrt{s_{NN}} = 5.02$ TeV

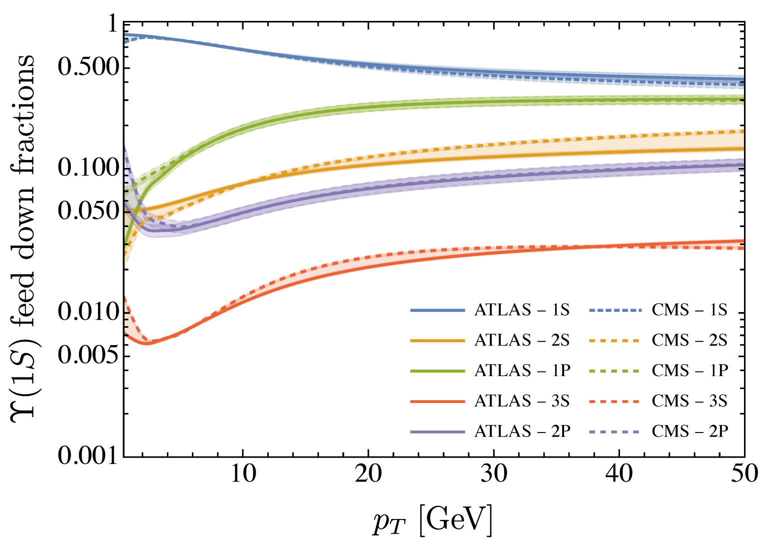
- **J. Boyd, M. Strickland, and S. Thapa, Phys. Rev. D 108, 094024 (2023), performed a data-driven analysis of the p_T dependence of bottomonium feed down.**
- **ATLAS/CMS/LHCb data indicate strong momentum dependence below $p_T = 10$ GeV (see figures).**
- **Direct production at $\langle p_T \rangle$ accounts for $\sim 76\%$ of both $\Upsilon(1S)$ and $\Upsilon(2S)$ production (see tables).**
- **This rules out the possibility that $\Upsilon(1S)$ suppression in $\sqrt{s_{NN}} = 5.02$ TeV AA collisions ($R_{AA} \sim 35\%$) is solely due to the suppression of excited states.**

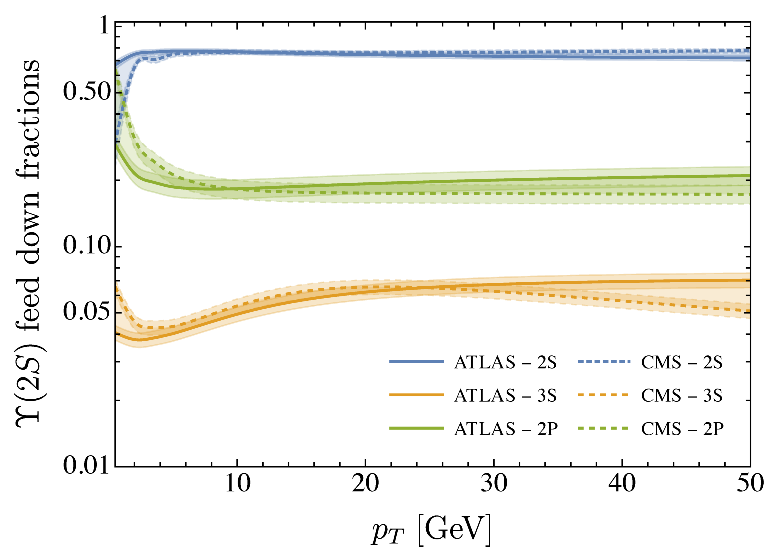
ATLAS + LHCb - 1S	
State	**$\langle p_T \rangle$ feed-down fraction**
$\Upsilon(1S)$	0.763 ± 0.010
$\Upsilon(2S)$	0.0625 ± 0.0019
$\chi_b(1P)$	0.127 ± 0.009
$\Upsilon(3S)$	0.00786 ± 0.00018
$\chi_b(2P)$	0.039 ± 0.004

ATLAS + LHCb - 2S	
State	**$\langle p_T \rangle$ feed-down fraction**
$\Upsilon(2S)$	0.774 ± 0.018
$\Upsilon(3S)$	0.0429 ± 0.0032
$\chi_b(2P)$	0.183 ± 0.018

CMS + LHCb - 1S	
State	**$\langle p_T \rangle$ feed-down fraction**
$\Upsilon(1S)$	0.767 ± 0.010
$\Upsilon(2S)$	0.0561 ± 0.0018
$\chi_b(1P)$	0.129 ± 0.009
$\Upsilon(3S)$	0.00778 ± 0.00018
$\chi_b(2P)$	0.040 ± 0.004

CMS + LHCb - 2S	
State	**$\langle p_T \rangle$ feed-down fraction**
$\Upsilon(2S)$	0.758 ± 0.019
$\Upsilon(3S)$	0.0464 ± 0.0035
$\chi_b(2P)$	0.195 ± 0.019





Bottomonium suppression in 5.02 and 8.16 TeV $p + \mathrm{Pb}$ collisions

Mike Strickland, Sabin Thapa and RV, arXiv:2401.16704[hep-ph], submitted to Phys. Rev. D

Comprehensive look at Υ suppression in cold (+ hot) matter

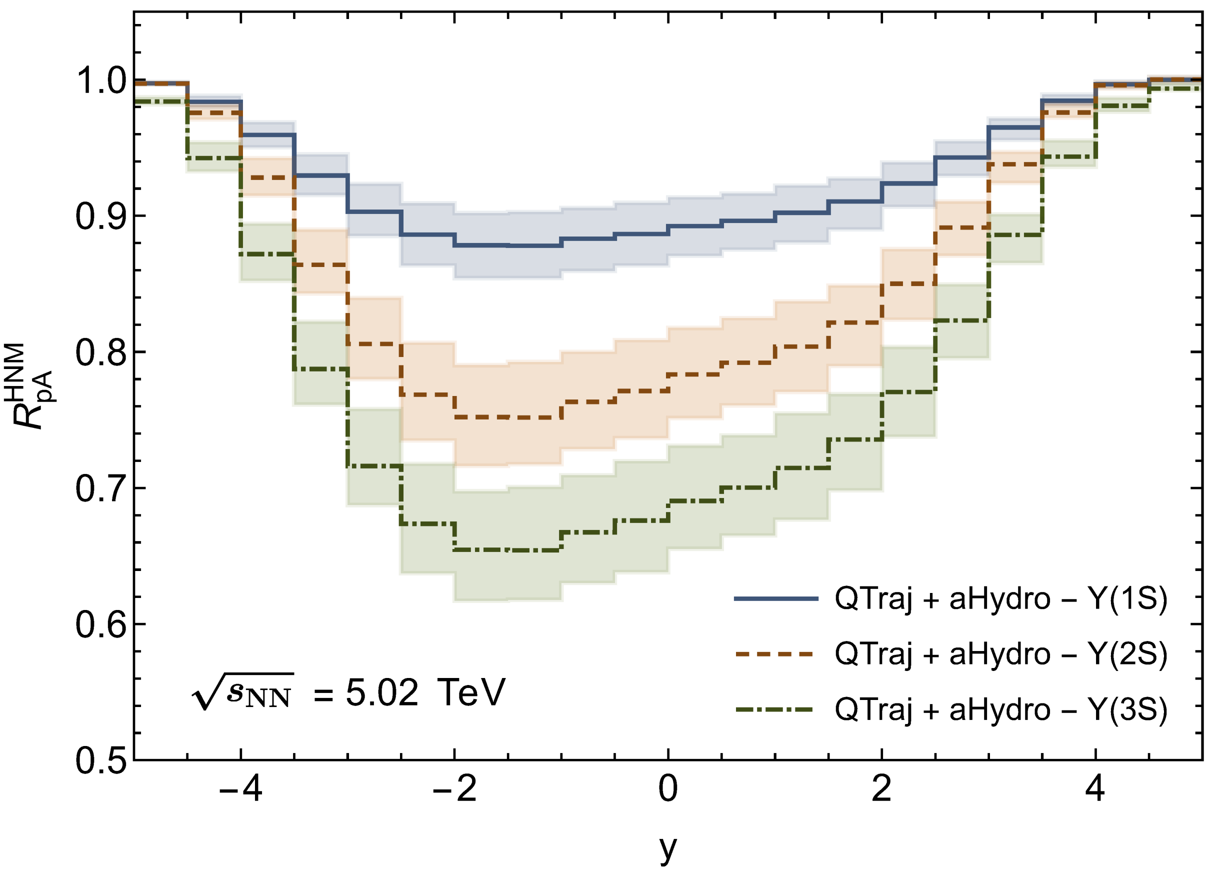
- **nPDF effects included with EPPS21, calculated in the color evaporation model with intrinsic k_T broadening in $p+p$ collisions**
- **Energy loss and momentum broadening in media include a la Arleo and Peigne**
  - **Coherent energy loss with quenching parameter $\hat{q}$**
  - **Transverse momentum broadening in medium, $\delta p_T = (\ell_A^2 - \ell_p^2)^{1/2}$ with $\ell_A^2 = \hat{q} L_A$**
- **NLO pNRQCD + Open Quantum Systems (hot matter)**
  - **Lindblad equation including singlet-octet, octet-singlet and octet-octet transitions**
  - **3+1D anisotropic hydrodynamic background**
  - **Temperature dependence of hydro enables differences in suppression between $\Upsilon(n\mathrm{S})$ states**
- **Excited state feed down as in PRD 108, 094024 (2023)**

$$R_{pA}^{\Upsilon} = R_{pA}^{\mathrm{EPPS21}} \times R_{pA}^{\mathrm{eloss},\delta p_T} \times R_{pA}^{\mathrm{HNM}}$$

Hot Matter R_{pA} as a Function of Rapidity

Higher T in the Pb-going direction

Strongest suppression on Υ(3S) state

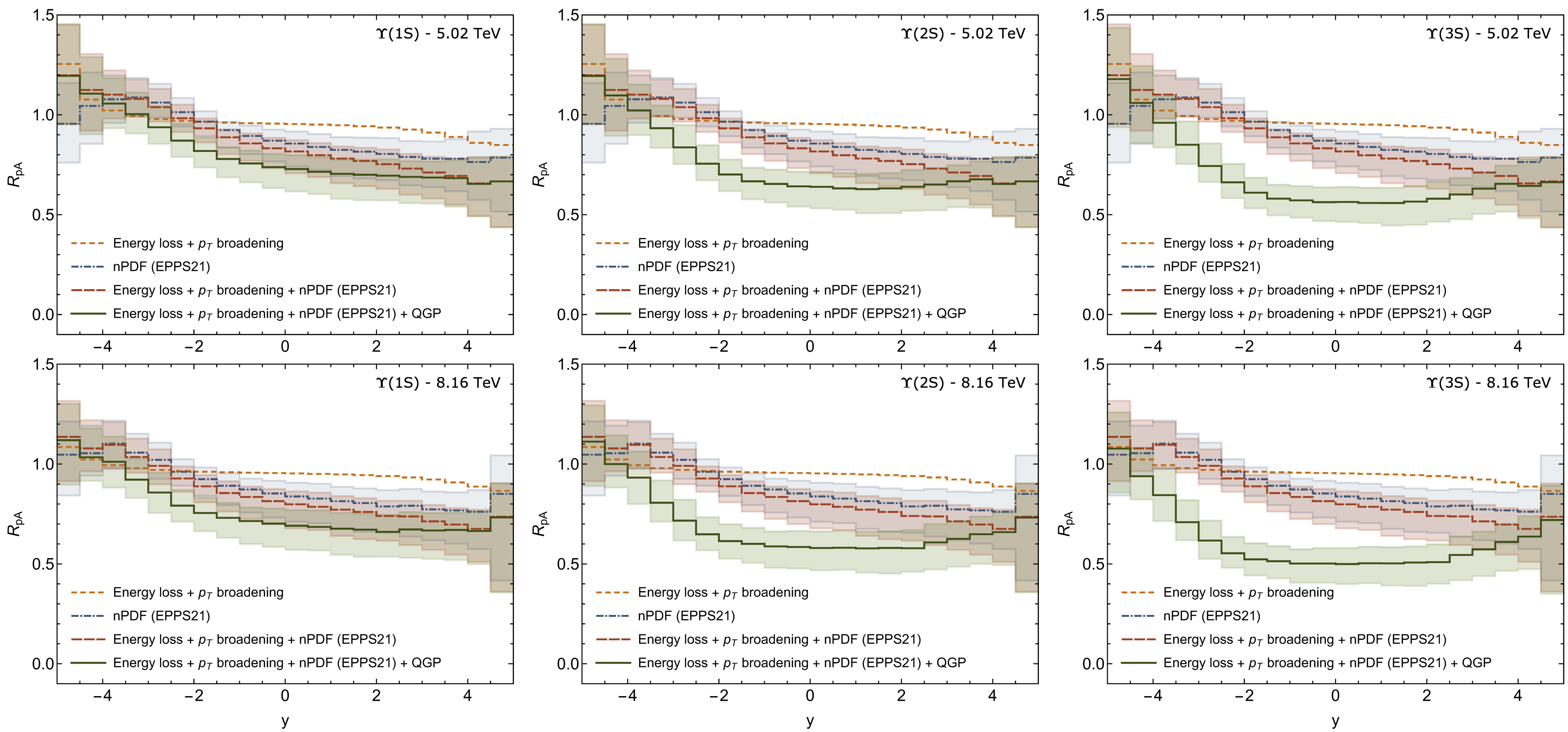


Individual Contributions as Function of Rapidity

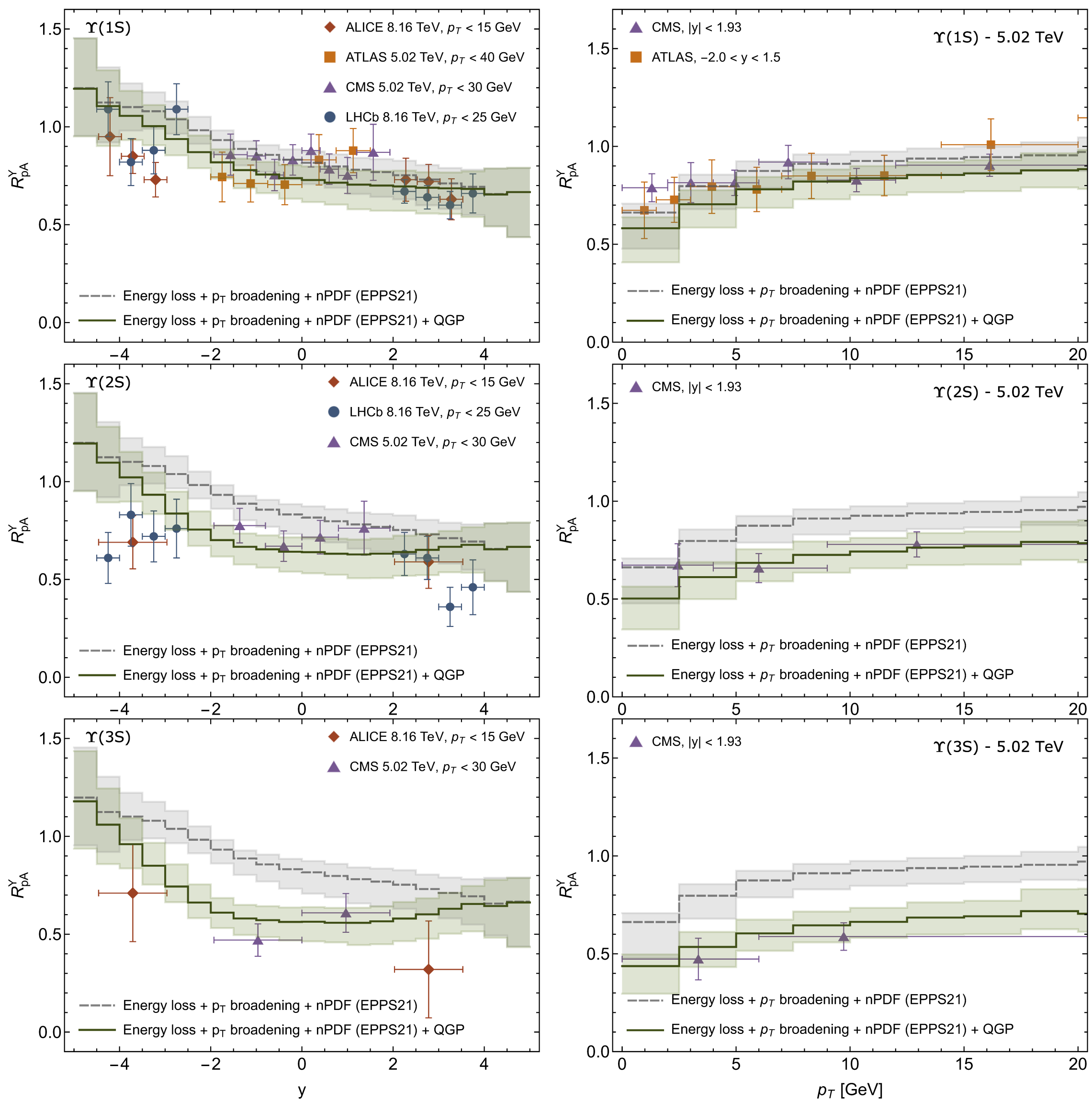
Little difference in energy dependence ($\sqrt{s_{NN}} = 5.02$ TeV (top) and 8.16 TeV (bottom))

Only difference between states is due to the hot matter contribution

Note that at high and low y, the hot matter effects disappear and green band (with QGP) and brown band (including only cold matter effects) merge



Comparison to Data



J/ψ Photoproduction in the ICEM

Vincent Cheung and RV, in preparation

Photoproduction cross section

$$\sigma_{\gamma p\to J/\psi+X} = \frac{\int dy dQ^2 f_\gamma^e(y,Q^2)\sigma_{\gamma p\to J/\psi+X}(y,Q^2)}{\int dy dQ^2 f_\gamma^e(y,Q^2)} = \frac{\sigma_{ep\to J/\psi+X}}{\Phi_T}$$

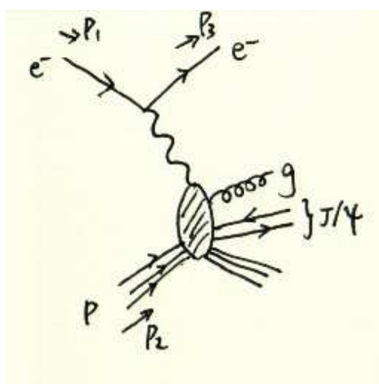
$$\Phi_T = \int dy dQ^2 f_\gamma^e(y,Q^2) = \int dy dQ^2 \frac{\alpha}{2\pi y Q^2}\left[1+(1-y)^2 - \frac{2M_e^2 y^2}{Q^2}\right]$$

We performed calculations at low Q^2 and compared our calculations to HERA photoproduction data [Eur. Phys. J. C 68, 401 (2010)]

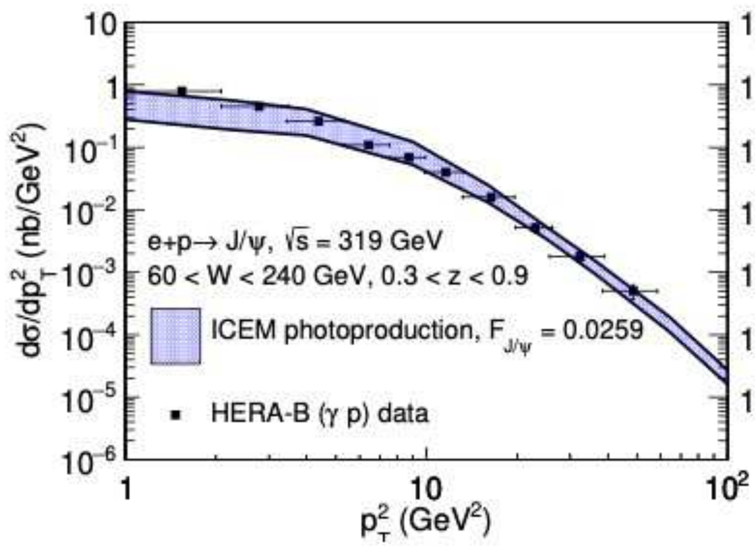
We include only spin triplet combinations in the calculation of the magnitude

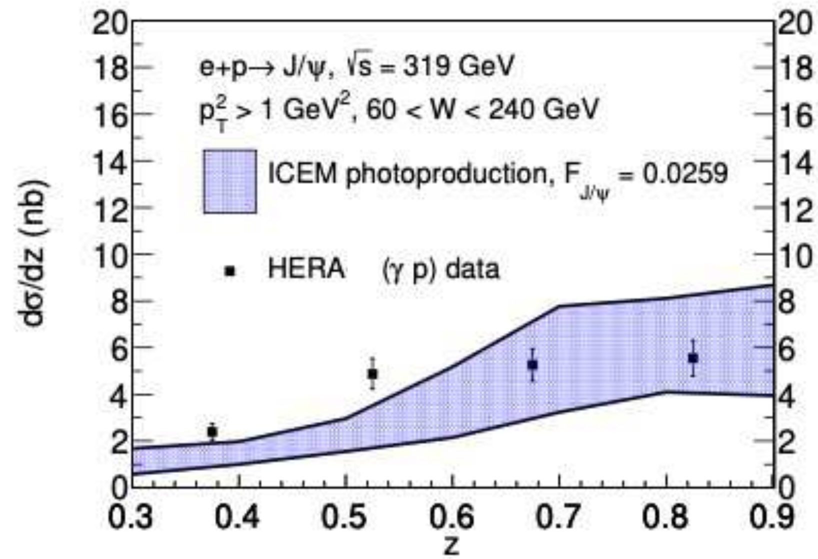
The orbital angular momentum dependent magnitude is obtained the $k=(p_c - p_{\overline{c}})/2$ dependence of the amplitude onto the polarization coordinate system using spherical harmonics, $\mathcal{M}_{i_z} = \int d\Omega_k Y_{l=0,m=i_z}\mathcal{M}$

The polarized cross section matrix, $\sigma_{i_z,j_z} = \int(...)\mathcal{M}_{i_z}\mathcal{M}^*_{j_z}$, can then be formed



Unpolarized Results



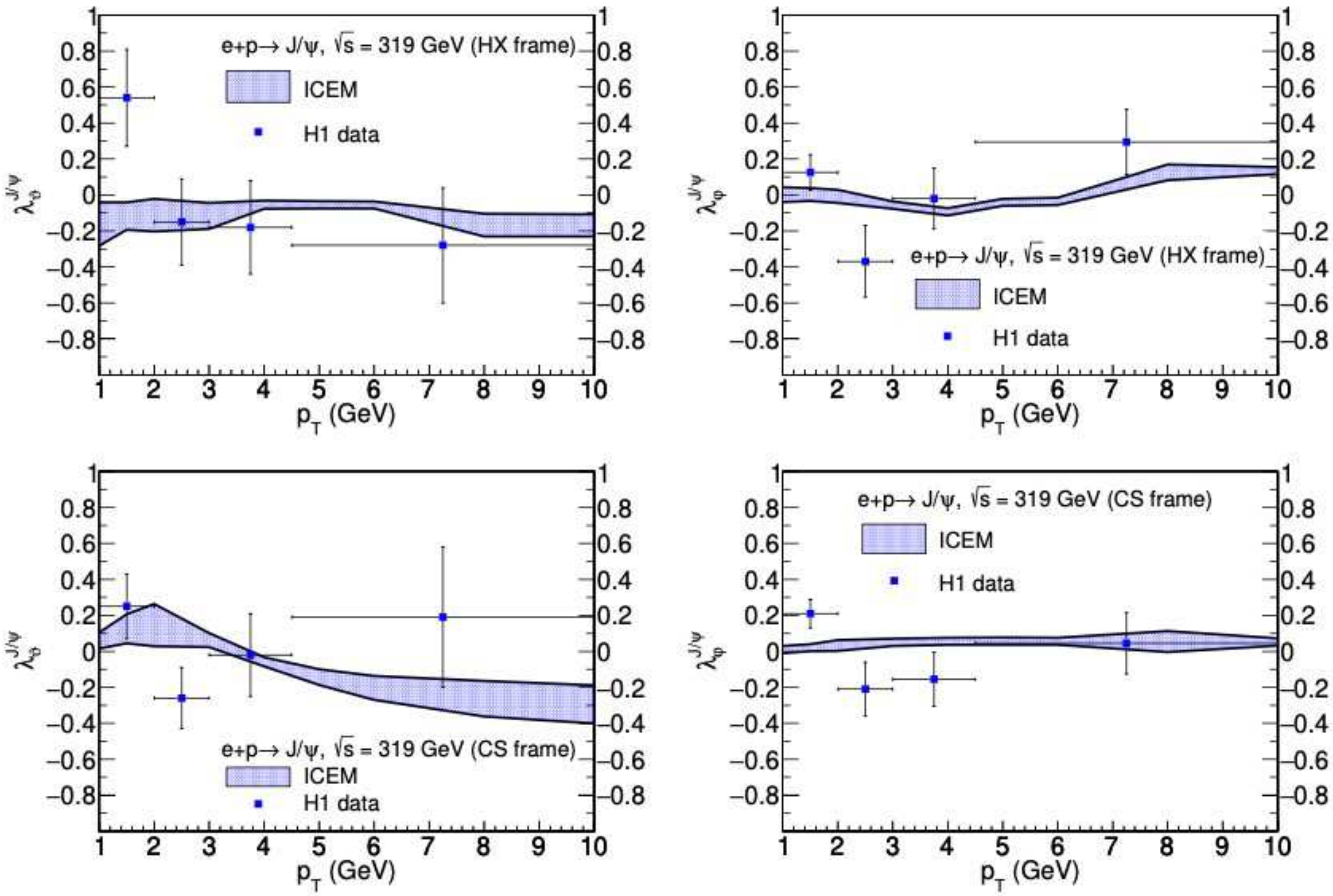


$$\sigma_{\rm unpol} = \sum_{i_z} \sigma_{i_z,i_z} = \sigma_{-1,-1} + \sigma_{0,0} + \sigma_{1,1}$$

Polarized Results

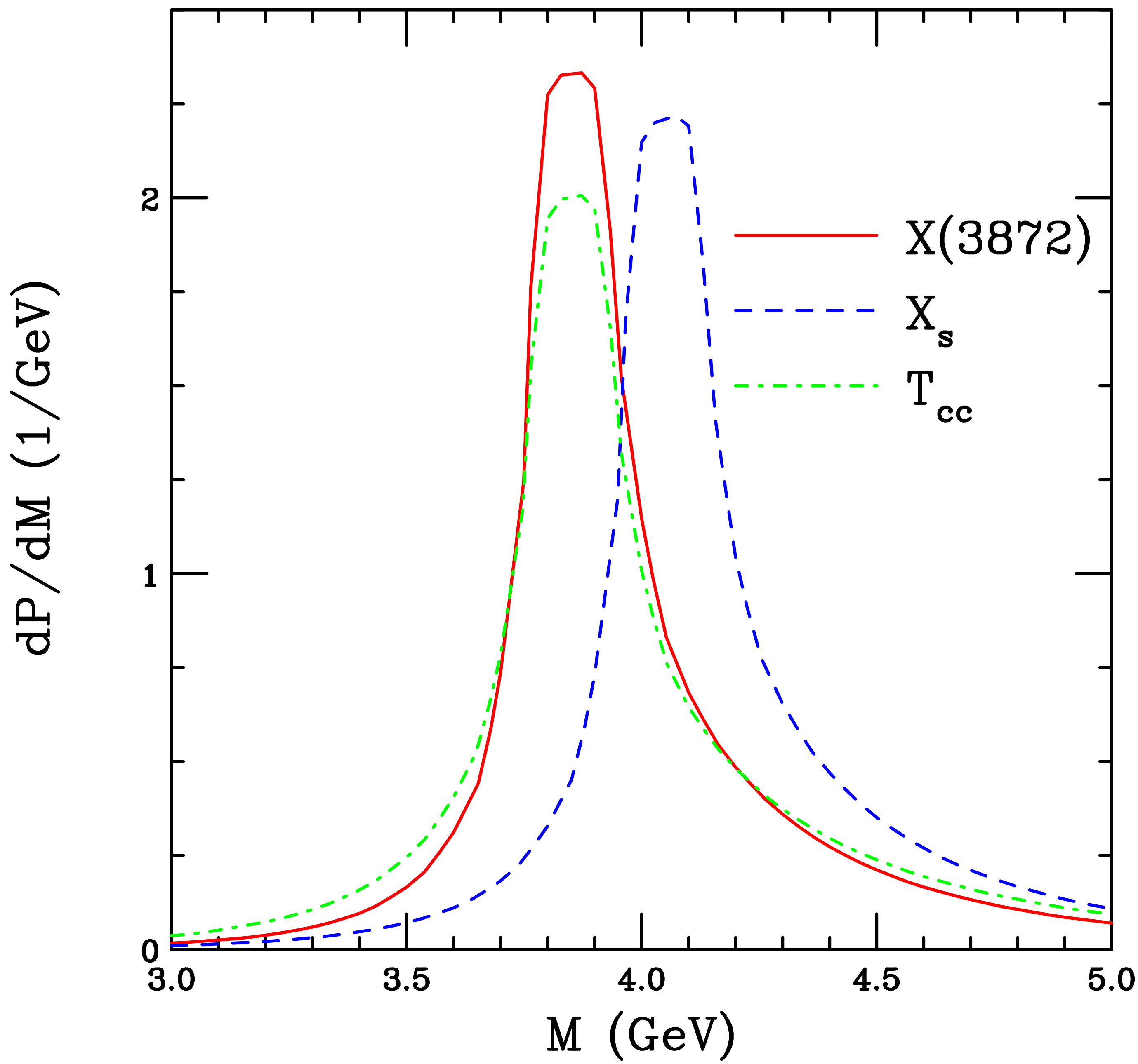
Left side: polar anisotropy $\lambda_\vartheta = \frac{\sigma_{+1,+1} - \sigma_{0,0}}{\sigma_{+1,+1} + \sigma_{0,0}}$

Right side: azimuthal anisotropy $\lambda_\varphi = \frac{Re[\sigma_{+1,-1}]}{\sigma_{+1,+1} + \sigma_{0,0}}$



Tetraquark Production with Intrinsic Charm

RV, in preparation



TAMU Transport Approach: B_c Production

- **Rate equation:**

$$-\frac{dN_{B_c}}{d\tau} = -\Gamma(T)\left[N_{B_c} - N^{eq}_{B_c}(E_B, T, \gamma_b, \gamma_c)\right]$$

- **Transport parameters:**

  (previously used for charmonia and bottomonia)

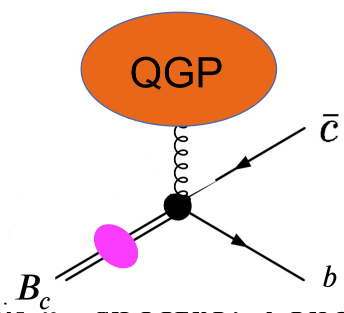
  – **Equilibrium limit:**

  $$N^{eq}_{B_c} = dV_{\rm FB}\gamma_b\gamma_c \int \frac{d^3p}{(2\pi)^3} e^{-\sqrt{m^2_{B_c}+p^2}/T}$$

  – **Reaction rate:** $\Gamma(T)$

  - In-medium E_B from T-matrix approach

  - Perturbative coupling to QGP medium



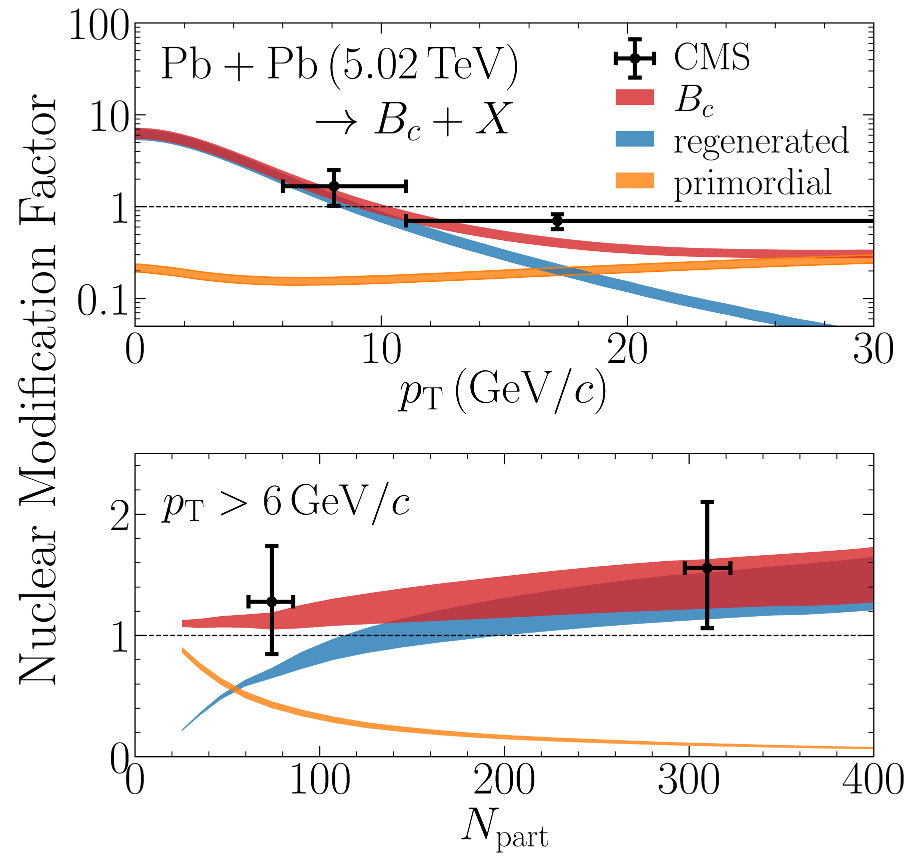
- b **and** c **quark** p_T **spectra: Langevin-transported**

[Grandchamp + Rapp (PRL92), X. Zhao + Rapp (PRC82)]

[Du + He + Rapp(PRC96), He + Rapp (PRL124)]

- **Nuclear modification factor:**

$$R_{\rm AA}(N_{\rm part}, p_T) = \frac{N_{AA}(N_{\rm part}, p_T)}{N_{\rm coll}(N_{\rm part}, p_T)N_{pp}(p_T)}$$



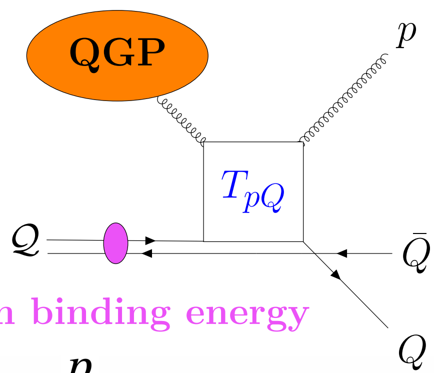
- **Large enhancement from regeneration at low** p_T

[Wu et. al (PRC109)]

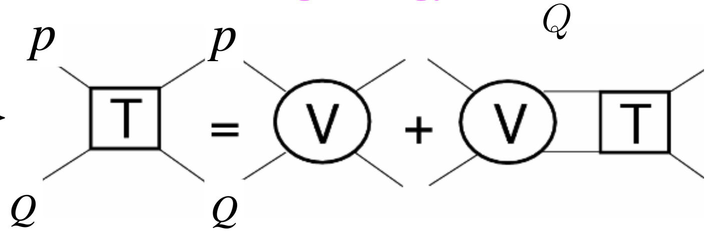
Quarkonia Reaction Rates in Strongly Coupled QGP

$$\Gamma_{\mathcal{Q}}(p_{\mathcal{Q}};T)=\frac{2d_p(2\pi)^4}{2E_Q}\sum_{p=q,\bar{q},g}\int \mathrm{d}^4p_i\mathrm{d}^4p_f\mathrm{d}^4p_{Q,f}\,\rho_i\rho_f\rho_Q\left|\overline{\mathcal{M}_{p\tilde{Q}\to pQ}}\right|^2\delta^{(4)}(P-P')f_p(E_i)\left[1\pm f_p(E_f)\right]\left[1-e^{i\mathbf{q}\cdot\mathbf{r}}\right]$$

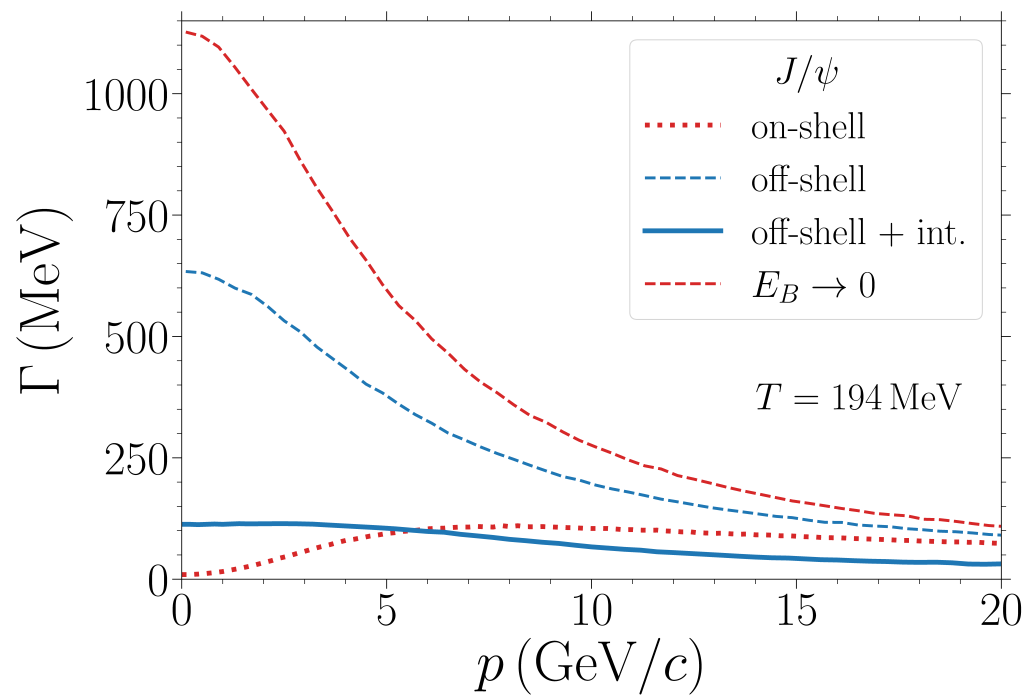
- **Parton spectral functions:** ρ
- **Non-perturbative heavy-light scattering amplitude:** $\mathcal{M}_{pQ\to pQ}\sim T_{pQ}$



In-medium binding energy

$\Rightarrow$ 

- **Interference:** $\left[1-e^{i\mathbf{q}\cdot\mathbf{r}}\right]$
  - **3-body interaction,** r: **radius**



- **Large enhancement from spectral functions**
- **Strong suppression by interference**

[Riek+Rapp (PRC82), Liu+Rapp (PRC97)]

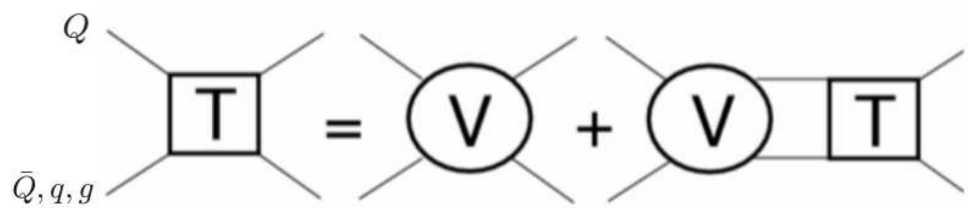
[Wu et. al in preparation]

T-matrix Approach to Strongly Coupled QGP and Lattice QCD

- **Quantum many-body theory**

  (Self-consistent Dyson-Schwinger eqs.):

  [Riek+Rapp '10, Liu+Rapp '18]



- **Input potential:** $V = -\frac{4}{3}\alpha_s \left(\frac{e^{-m_d r}}{r} + m_d\right) - \frac{\sigma}{m_s}\left(e^{-m_s r - (c_b m_s r)^2} - 1\right)$
  - **Constrained by lattice QCD data ($Q\bar{Q}$ free energy, EoS,...)**
  - **Here: static quark-antiquark Wilson line correlators**

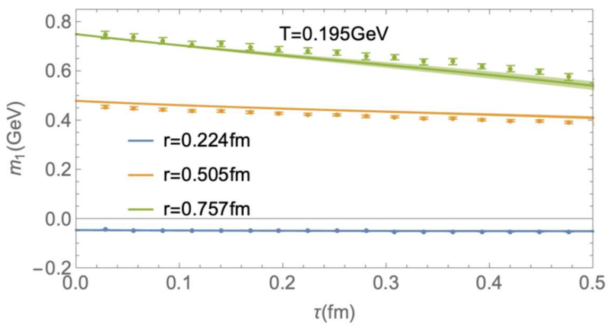
$$W(r,\tau,T) = \frac{1}{3}\left\langle \mathrm{Tr}\left(L(0,\tau)L^\dagger(r,\tau)\right)\right\rangle_T \text{ with } L(r,\tau) = \exp\left(i\int_0^\tau A_4(r,\tau')\,d\tau'\right)$$
$$= \int_{-\infty}^{\infty} d\omega e^{-\omega\tau}\rho_{Q\bar{Q}}(\omega,r,T)$$

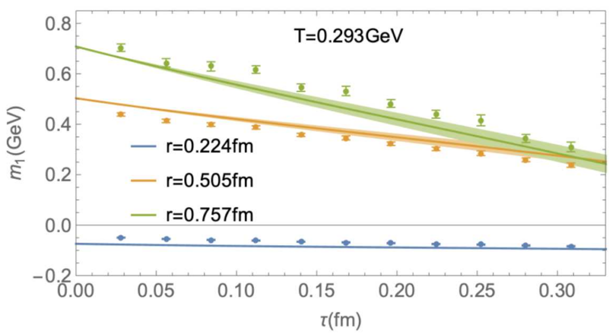
spectral function from T-matrix: $\rho_{Q\bar{Q}}(\omega,r,T) = \frac{-1}{\pi}\,\mathrm{Im}\left[\frac{1}{\omega - V(r,T) - \Phi(r,T)\Sigma_{Q\bar{Q}}(\omega,T)}\right]$

[Z.Tang et al. '23, arXiv:2310.18864]

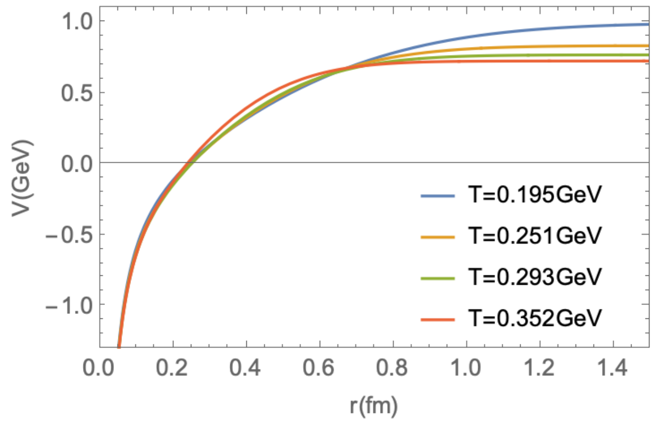
- **Results:** [Z.Tang et al. '23, arXiv:2310.18864]

Fit to Wilson line correlators



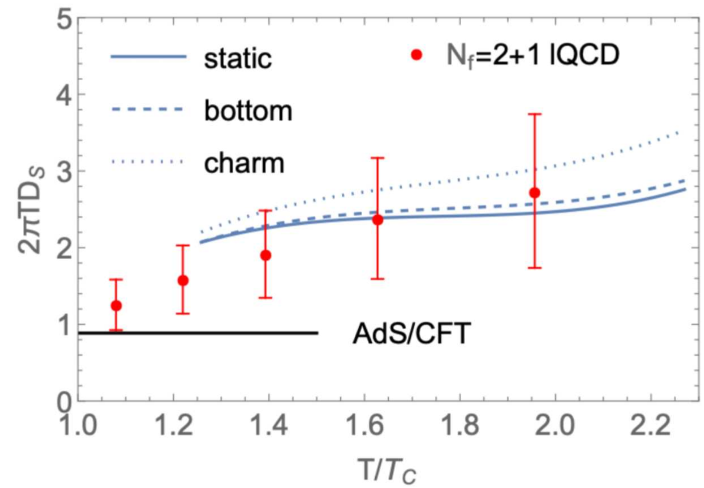


Underlying in-medium potentials



– Less screening at high temperature than previously

Predicted diffusion coefficient



– $2\pi T D_s$ consistent with recent lattice data

[HotQCD Collaboration, PRL 130, 231902 (2023)]

– Fair agreement with lattice data

(challenging for HTL perturbation theory)

[HotQCD Collaboration, PRD 105, 054513 (2022)]

2024 HEFTY Collaboration Summer School

The HEFTY Collaboration will host a summer school in Santa Fe, New Mexico, 24-26 June 2024

The school is limited to 40 students

Ivan Vitev and John Terry of LANL are the school organizers

Lectures will be given by HEFTY Collaboration members

Apply by 1 March 2024 by emailing hefty-school2024@lanl.gov

There will be an excursion to Los Alamos, NM where the movie Oppenheimer was filmed

For more information, see the meeting website at https://cvent.me/lMLl0g

Thank You!

HEFTY Journal Publications To Date

- **Heavy Quark Diffusion from 2+1 Flavor Lattice QCD with 320 MeV Pion Mass, L. Altenkort *et al.*, Phys. Rev. Lett. 130, 231902 (2023), arXiv:2302.08501.**
- **Recombination of B_c Mesons in Ultra-Relativistic Heavy-Ion Collisions, B. Wu *et al.*, Phys. Rev. C 109, 014906 (2023), arXiv:2302.11511.**
- **Spin-Dependent Interactions and Heavy-Quark Transport in the QGP, Z. Tang and R. Rapp, arXiv:2304.02060.**
- **Contribution from Intrinsic Charm Production to Fixed-Target Interactions with the SMOG Device at LHCb, R. Vogt, Phys. Rev. C 108, 015201 (2023), arXiv:2304.09356.**
- **Transverse momentum dependent feed-down fractions for bottomonium production, J. Boyd, S. Thapa and M. Strickland, Phys. Rev. D 108,094024 (2023), arXiv:2307.03841.**
- **Polarized TMD fragmentation functions for J/ψ production, M. Copeland *et al.*, accepted for Phys. Rev. D, arXiv:2308.08605.**
- **Un-screened forces in Quark-Gluon Plasma? A. Bazavov *et al.*, arXiv:2308.16587.**
- **Polarized J/ψ production in semi-inclusive DIS at large Q^2: Comparing quark fragmentation and photon-gluon fusion, M. Copeland *et al.*, arXiv:2310.13737.**
- **T-matrix Analysis of Static Wilson Line Correlators from Lattice QCD at Finite Temperature, Z. Tang *et al.*, arXiv:2310.18864.**
- **Quark Mass Dependence of Heavy Quark Diffusion Coefficient from Lattice QCD, L. Altenkort *et al.*, Phys Rev. Lett. 132, 051902 (2024), arXiv:2311.01525.**
- **Hadronization of Heavy Quarks, J. Zhao *et al.*, arXiv:2311.10621.**
- **Charm degrees of freedom in hot matter from lattice QCD, A. Bazavov *et al.*, Phys. Lett. B 850, 138520 (2024), arXiv:2312.12857.**
- **Bottomonium suppression in 5.02 and 8.16 TeV p-Pb collisions, M. Strickland, S. Thapa and R. Vogt, arXiv:2401.16704.**