Heavy Flavor Theory (HEFTY) for QCD Matter

HEFTY COLLABORATION

Develop comprehensive heavy-quark theory to unravel properties of quark-gluon

Lead institution:
Texas A&M University

PI: Ralf Rapp

A Nuclear Theory Topical Collaboration

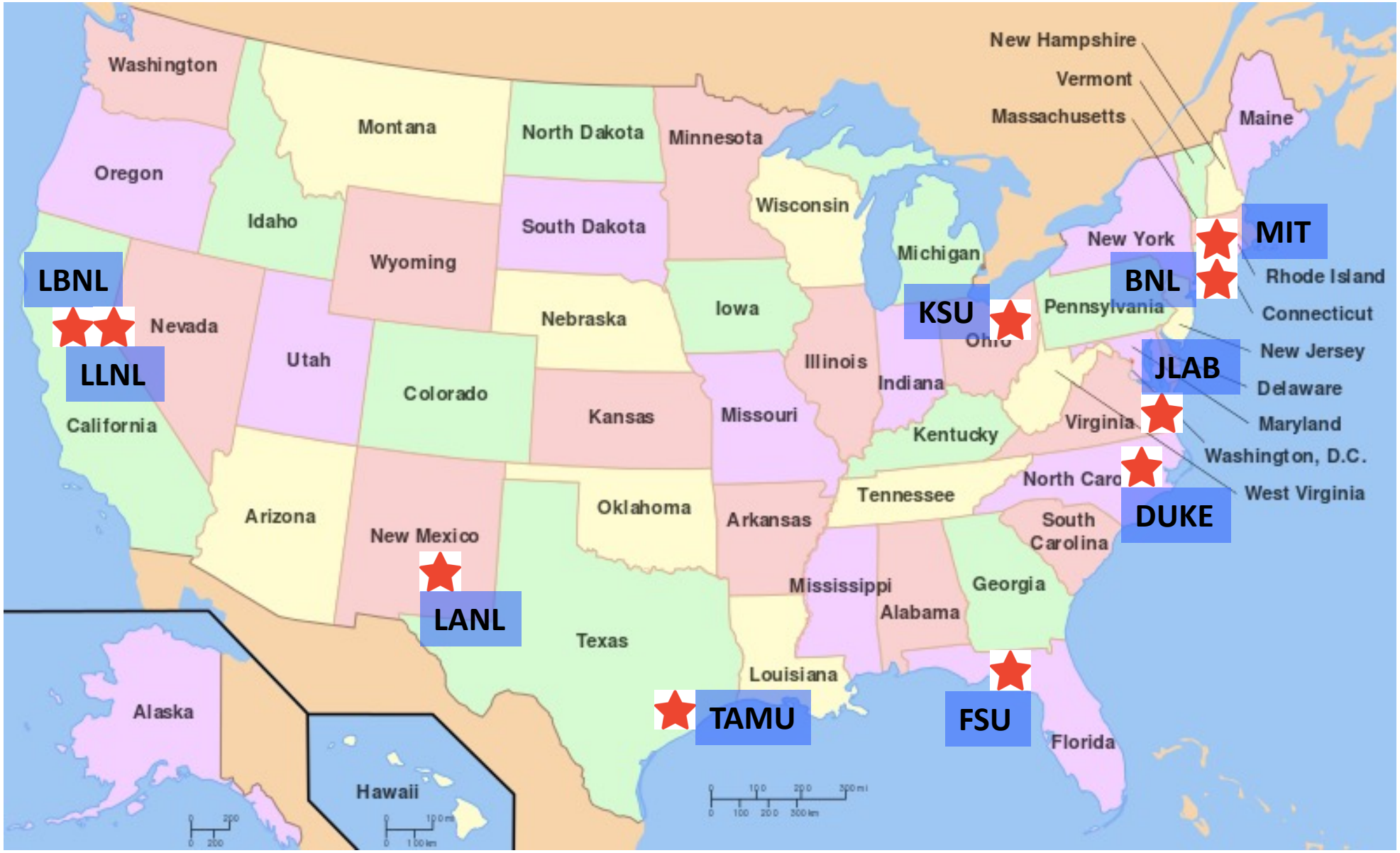
Goal/approach:

Developing framework for studying heavy quarks and quarkonia in QCD by employing Lattice QCD computation, QCD factorization and effective field theory, and rigorous statistical data analysis

5 National Labs
5 Universities

Jianwei Qiu
Jefferson Lab, Theory Center

HEFTY Collaboration – The Team & Member Institutions



10 Institutions
9 States

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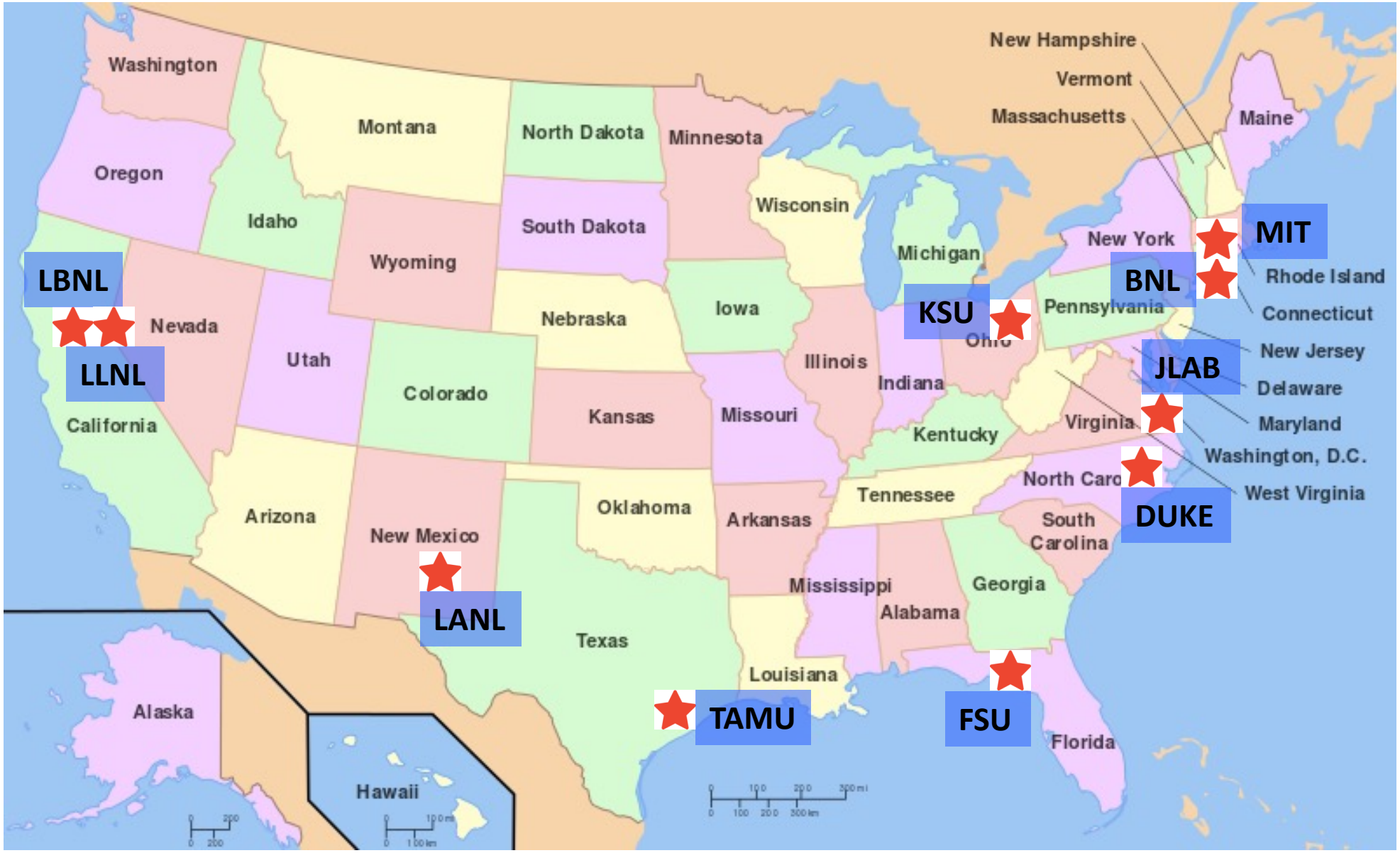

Organization:

PI: R. Rapp

Co-Spokespersons:

P. Petreczky

R. Vogt

Ombuds person:

R. Vogt

WG1:
Heavy flavor in equilibrium QCD matter

WG2:
Heavy flavor in small systems

WG3:
Open HF transport

WG4:
Quarkonium transport

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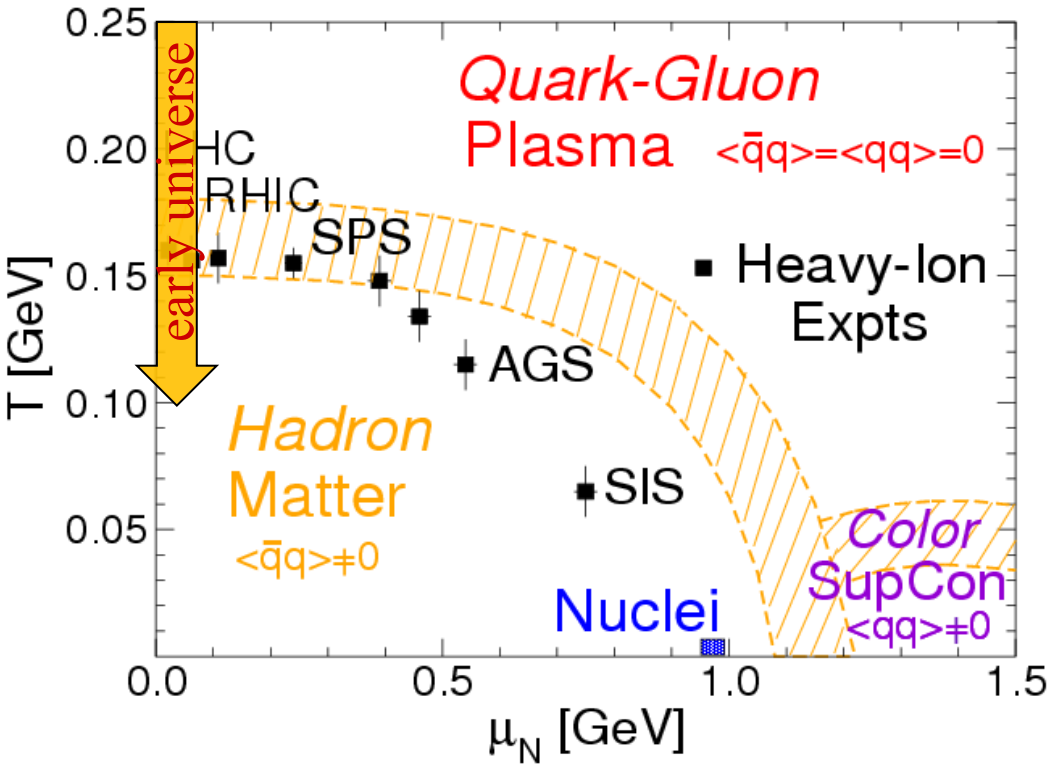
QCD Matter: Open Questions

- **QCD phase diagram:**



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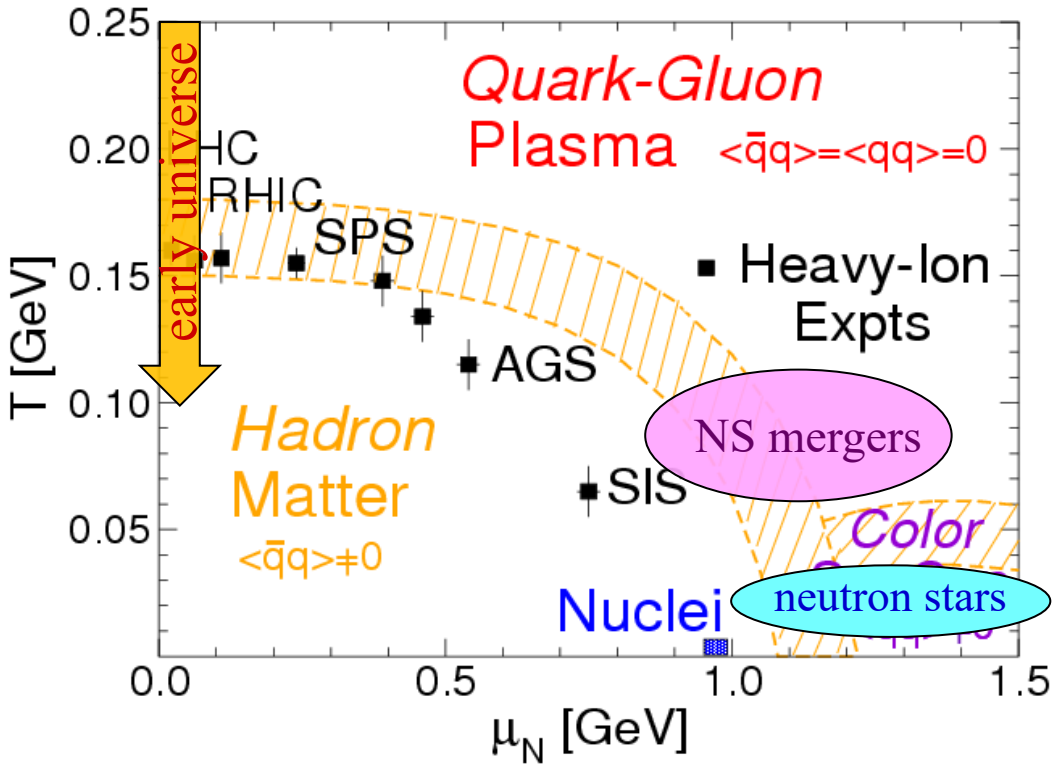
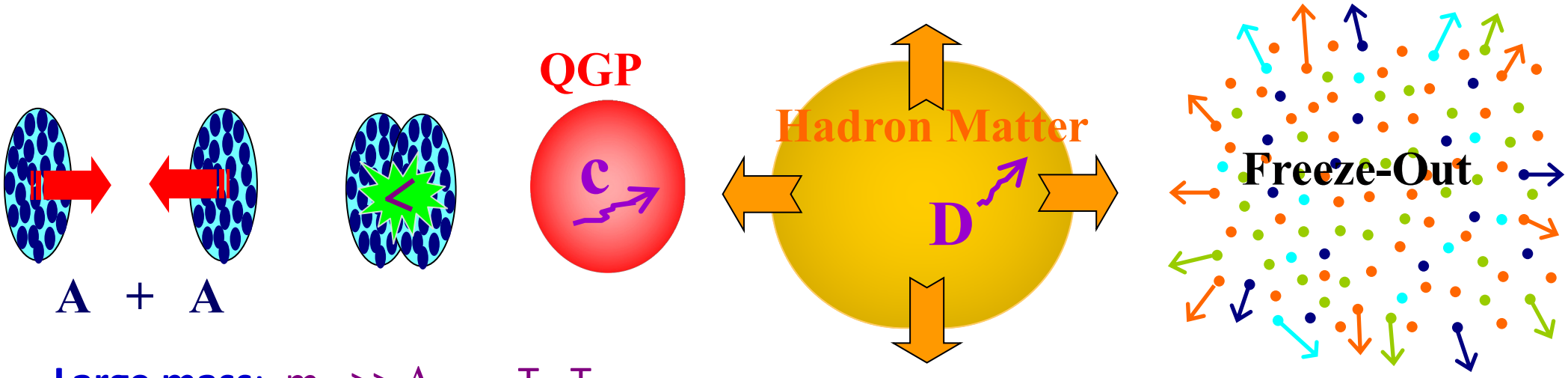


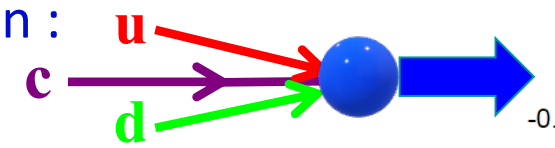
- **Transport properties** + their emergence from the underlying interaction
- **Spectral functions** + degrees of freedom
- Mechanisms for **converting** quarks + gluons into hadrons
- Role of **quantum effects** in the strongly-coupled QGP

Why Heavy-Flavor Probes?

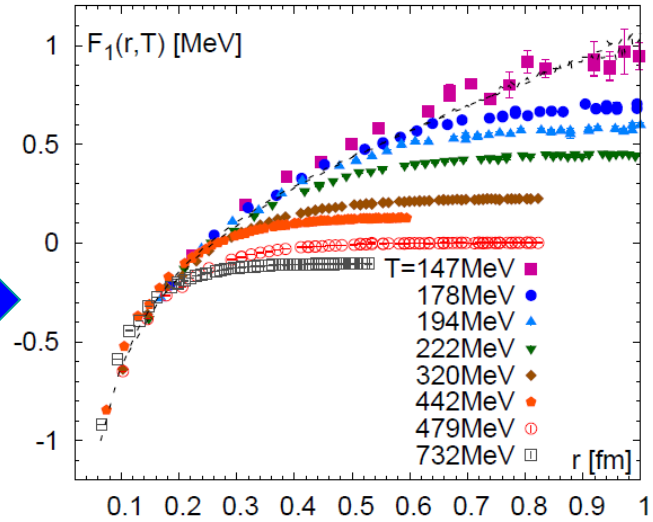


- **Large mass**: $m_Q >> \Lambda_{QCD}$, T , T_c
- Produced early, **diffuse** through QCD medium
- Delayed thermalization: gauge of **interaction strength**
- Ample connections to thermal lattice QCD
- **Hadronization**: recombination vs fragmentation :

  $c \rightarrow D, D_s, \Lambda_c, J/\psi, \ldots$
- Discernible **transition** from diffusion to radiation
- Mass effects in radiation
- **Hot vs. cold** matter effects



Heavy-Quark Free Energy



Integrated approach needed!

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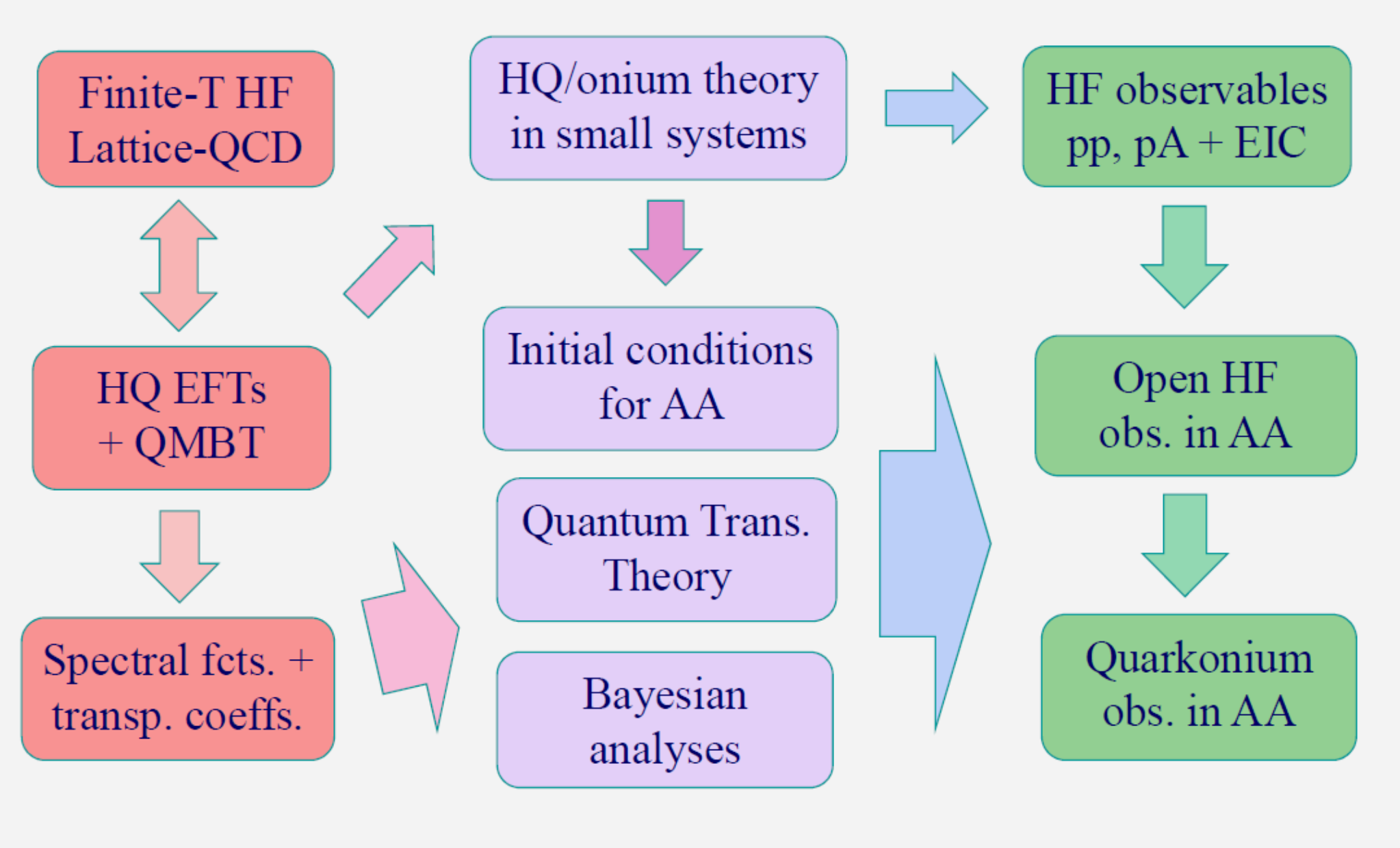
HEFTY Collaboration – Flow Chart + PI Expertise



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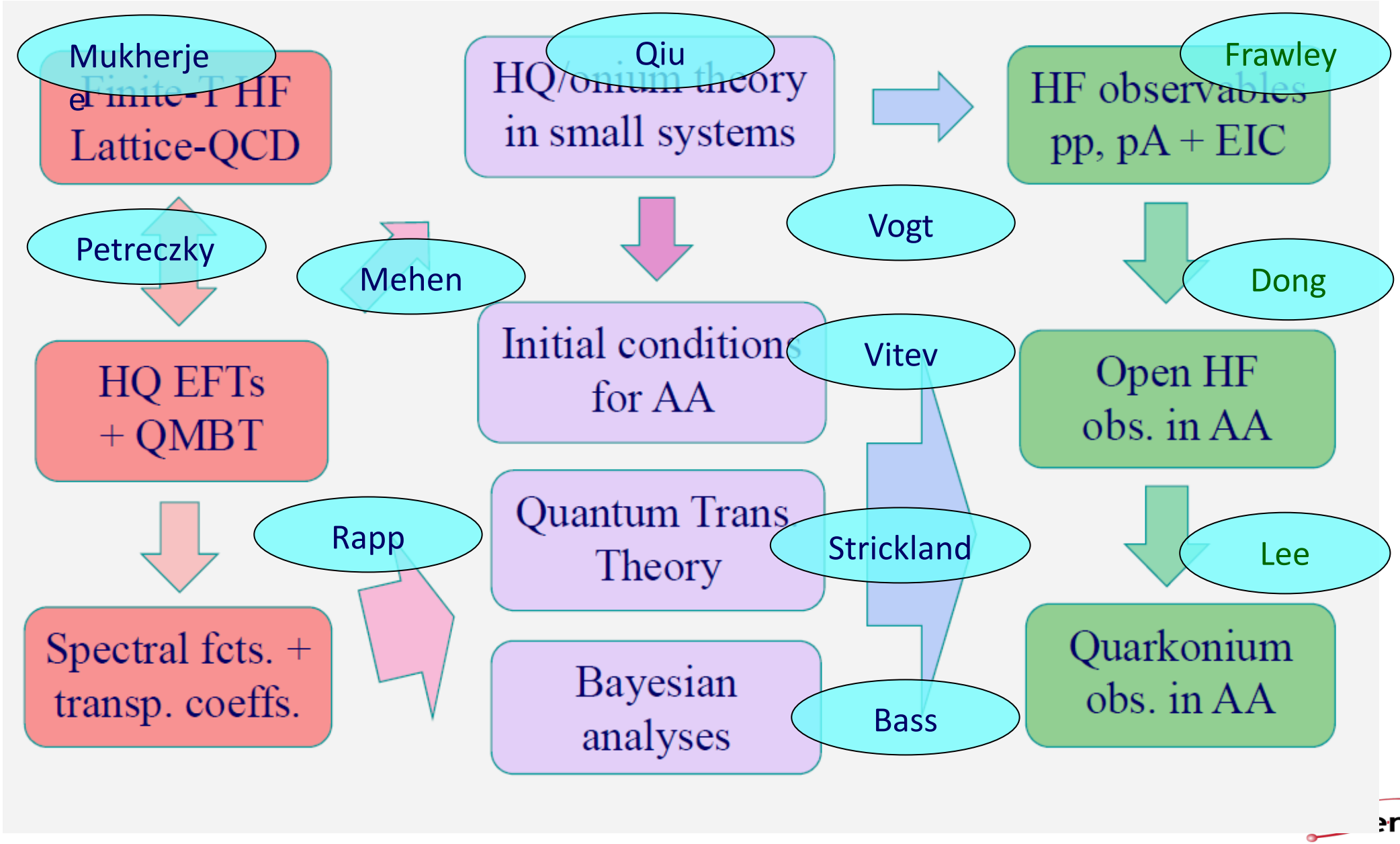
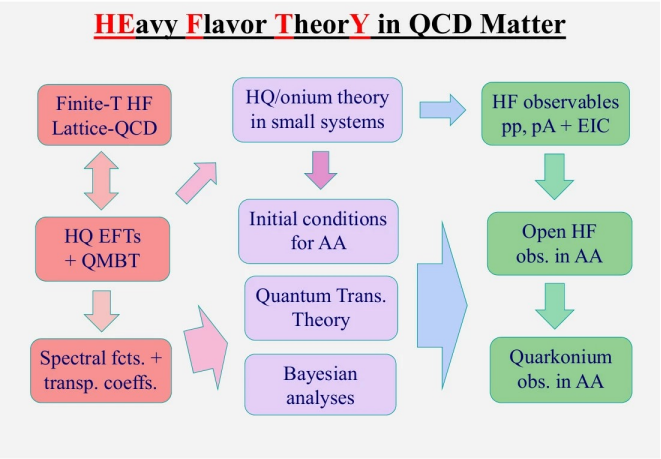


WG1: In-medium properties of heavy flavor hadrons and quarks

Co-PIs: Swagato Mukherjee, Peter Petreczky (convener)

Ralf Rapp (also convener of WG3 and WG4),

Hai-Tao Shu (PD, BNL, starting May 2023), Zhanduo Tang (GS, TAMU)



Tasks and Milestones:

1) In–medium quarkonium masses and widths from lattice and T-matrix approach
2) Complex potential at *T>0* from lattice => input into T-matrix approach

MS-1: Complete set of bottomonium spectral functions in sQGP with Uncertainties ➔ WG4

3) Heavy quark and quarkonium transport coefficients using EFT and lattice QCD
4) Charm quark susceptibilities : in-medium charm quark mass

Determination of temperature and momentum dependence of the heavy quark diffusion coefficient from T-matrix approach

MS-4: Over-constrained extraction of T - and p-dependent HF transport coefficients ➔ WG3

MS-7: Complete set of nonperturbative quarkonium transport coefficients ➔ WG4

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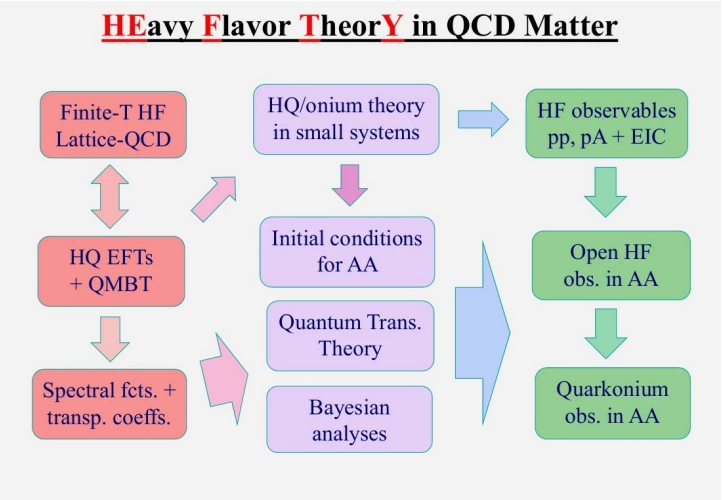
WG2: Heavy-Flavor Production in pp, pA, ep and eA Collisions

Co-PIs: Xin Dong, Anthony Frawley, Thomas Mehen, Jianwei Qiu, Ivan Vitev (convener), Ramona Vogt

- Affiliates: Vincent Cheung, Weiyao Ke, Haitao Li, Frederick Olness



- Close collaboration within the WG2
- We push the boundaries of HF theory in small systems
- We provide baseline cross sections and CNM effects for other WGs

Tasks and Milestones

Perform resummed NLO calculations for HQ production and analyze HF jet observables in ep and pp reactions to obtain novel constraints on parton fragmentation and intrinsic charm in the proton (LLNL-PD+JLab-PD)

MS-2: Comprehensive theory of open HF production + hadronization in pp and ep

Analyze quarkonium and open HF production in pA and eA, combining EFTs, nuclear PDFs, and inelastic break-up reactions (LANL-PD+Duke-GS)

MS-8: Microscopic theory of quarkonia and open HF production on nuclear targets

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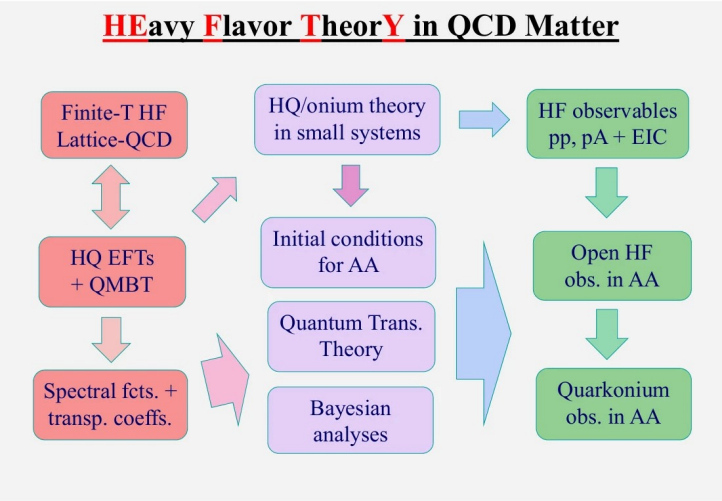
WG3: Open Heavy-Flavor Transport in Heavy-Ion Collisions

Co-PIs: Steffen A. Bass, Xin Dong, Yen-Jie Lee, Ralf Rapp (convener), Ivan Vitev, Ramona Vogt

- Affiliates: Yu Fu, Weiyao Ke, GS (tbd)



- Microscopic interactions for transport coeffs. from **WG1**
- Initial conditions from **WG2**
- HQ distributions input to quarkonium regen. in **WG4**

Tasks and Milestones

Develop + deploy framework for heavy-quark transport + hadronization in URHICs: Lattice-QCD based transport coefficients + rigorous statistical data analysis.

- HQ hadronization model with in-medium spectral functions + transport coefficients from lQCD-based T-matrix + Bayesian data analysis with Langevin simulations at low p_T

$\Rightarrow$ **MS-4: Over-constrained extraction of T - and p-dependent HF transport coefficients**

- Analyze high-p_T data with newly developed SCETM + hadronization using ML techniques

$\Rightarrow$ **MS-5: Quantified extraction of HF jet-transport coefficients.**

- Match transition from low-p_T diffusion to high-p_T energy loss in Bayesian analysis

$\Rightarrow$ **MS-9: Novel assessment of transport + hadronization in transition regime**

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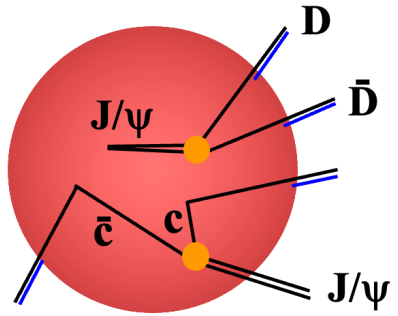
WG4: Quarkonium Transport Heavy-Ion Collisions



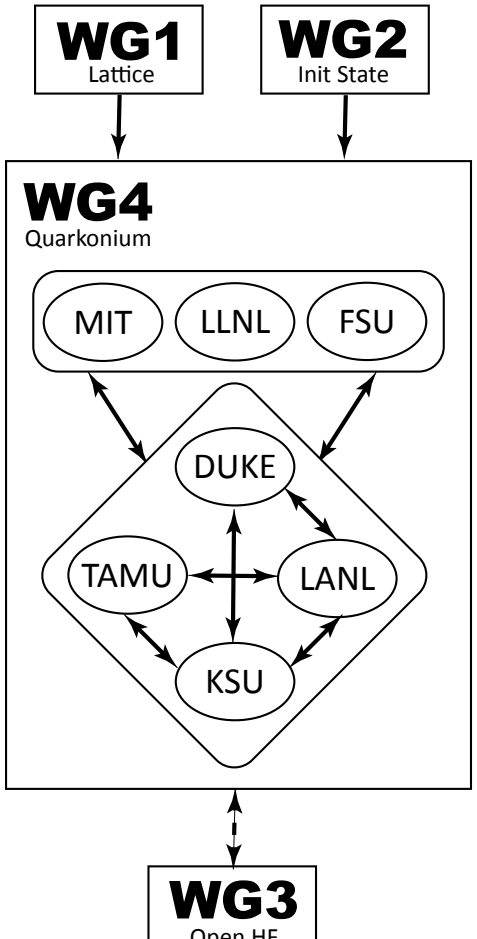
Co-PIs: Anthony Frawley, Yen-Jie Lee, Thomas Mehen, Ivan Vitev, Ralf Rapp (convener), Michael Strickland, and Ramona Vogt

Affiliates: Jacob Boyd (KSU) and Biaogang Wu (TAMU)

Develop and deploy an integrated quantum transport approach for quarkonia in heavy ion collisions (HICS).

Tasks and milestones

- Implement nonperturbative bottomonia reaction rates within Boltzmann transport. **(KSU+TAMU)**
- Compare semiclassical vs. quantum transport. **(KSU+TAMU)**
- Match semiclassical to quantum transport. **(KSU+TAMU) [Milestone 6]**
- Combine HQET, T-matrix, and lattice-QCD to obtain complete set of HQ diffusion coefficients. **(TAMU+KSU) [Milestone 7]**
- Analyze quarkonium and open HF production in pA and eA. **(LANL+Duke) [Milestone 8]**
- Combine HQ diffusion, quarkonium ICs, and quantum transport. **(KSU+TAMU) [Milestone 10]**



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NRQCD factorization and the "lack" of universality of LDMEs

Bodwin, Braaten, Lepage, PRD, 1995

❑ NRQCD factorization:

Expansion in powers of both α_s and v !

$$d\sigma_{A+B\to H+X} = \sum_n d\sigma_{A+B\to Q\bar{Q}(n)+X} \langle \mathcal{O}^H(n)\rangle$$

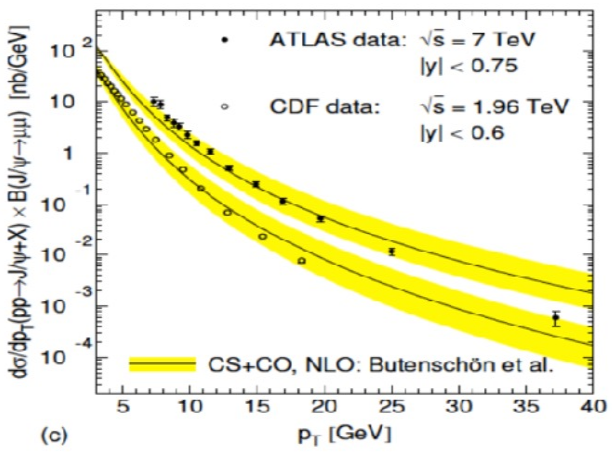
Hadronization

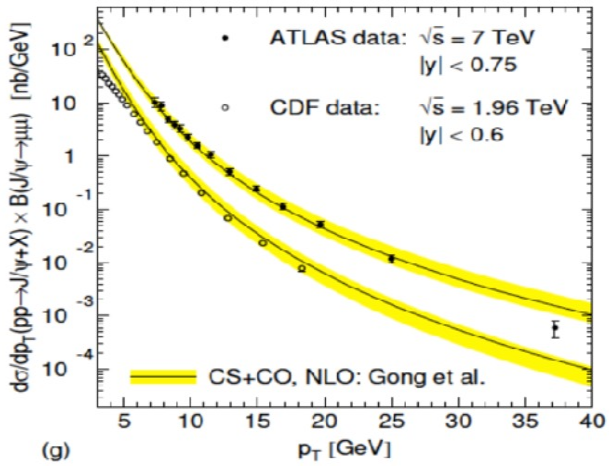
- **4 leading channels in v:**

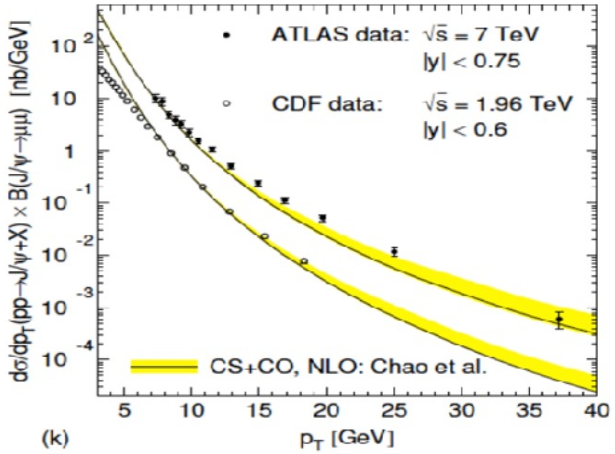
$$^3S_1^{[1]},\ ^1S_0^{[8]},\ ^3S_1^{[8]},\ ^3P_J^{[8]}$$

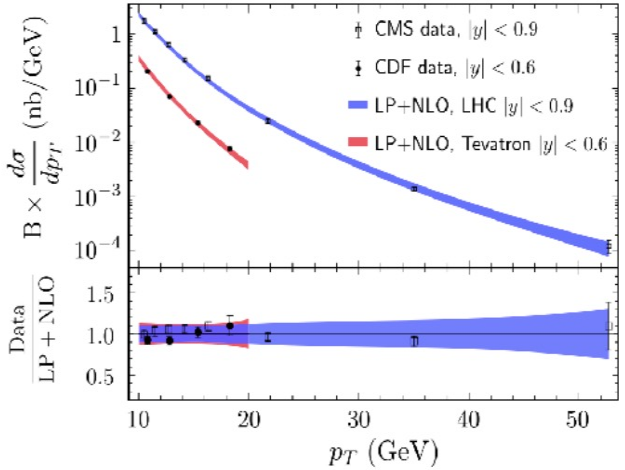
	$\langle\mathcal{O}(^3S_1^{[1]})\rangle$ GeV^3	$\langle\mathcal{O}(^1S_0^{[8]})\rangle$ 10^{-2} GeV^3	$\langle\mathcal{O}(^3S_1^{[8]})\rangle$ 10^{-2} GeV^3	$\langle\mathcal{O}(^3P_0^{[8]})\rangle$ 10^{-2} GeV^5
Set I (Butenschoen *et al.*)	1.32	3.04	0.16	−0.91
Set II (Chao *et al.*)	1.16	8.9	0.30	1.26
Set III (Gong *et al.*)	1.16	9.7	−0.46	−2.14
Set IV (Bodwin *et al.*)	-	9.9	1.1	1.1

❑ Phenomenology – full NLO in α_s:









LDMEs should be universal, however:

- **Numbers are not the same.**
- **Not even the sign.**

More work is needed!

Fits in NRQCD
Butenschoen, Kniehl, PRD84, 051501 (2011).
Chao, Ma, Shao, Wang, Zhang, PRL108, 242004 (2012).
Gong, Wan, Wang, Zhang, PRL110, 042002 (2013).
Bodwin, Chung, Kim, Lee, PRL113, 022001 (2014).
…
Fits in pNRQCD
Brambilla, Chung, Vairo, Wang, PRD105, no.11, L111503 (2022).

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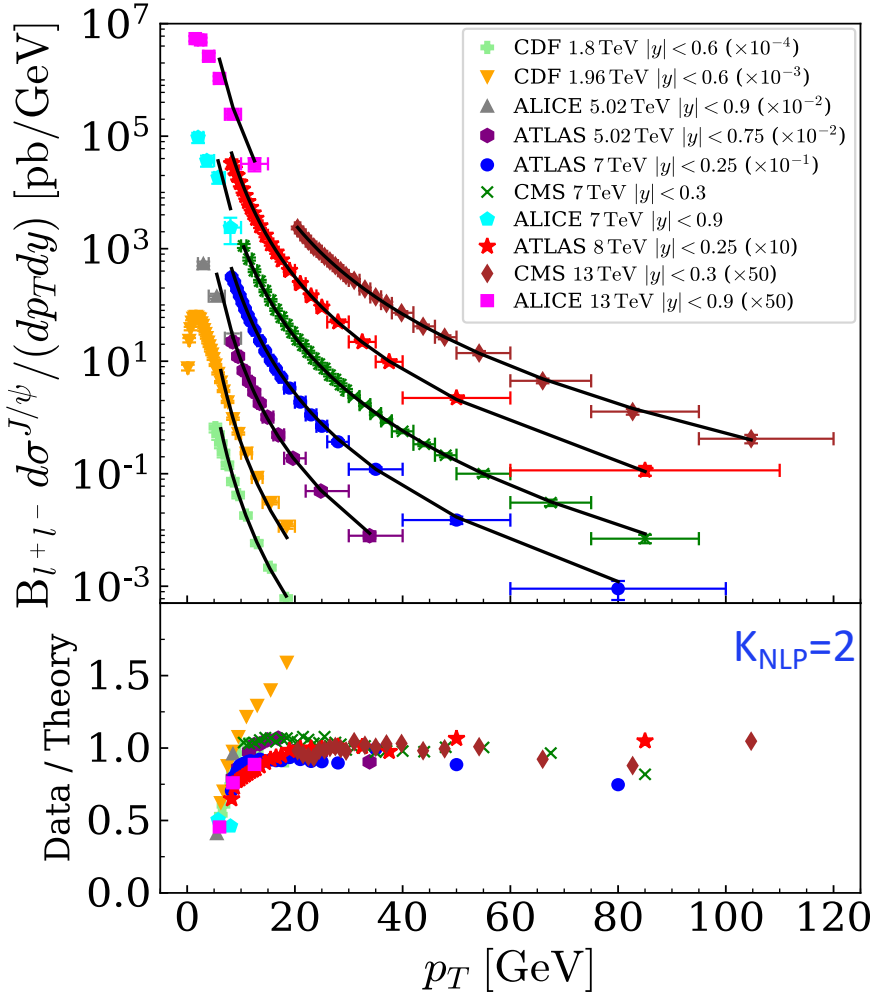
PQCD + NRQCD factorization for J/ψ-production in lepton-hadron/nuclei collisions

Success of QCD factorization at LP + NLP:



Lee, Qiu, Sterman, Watanabe,
2108.00305, 2211.12648, in preparation

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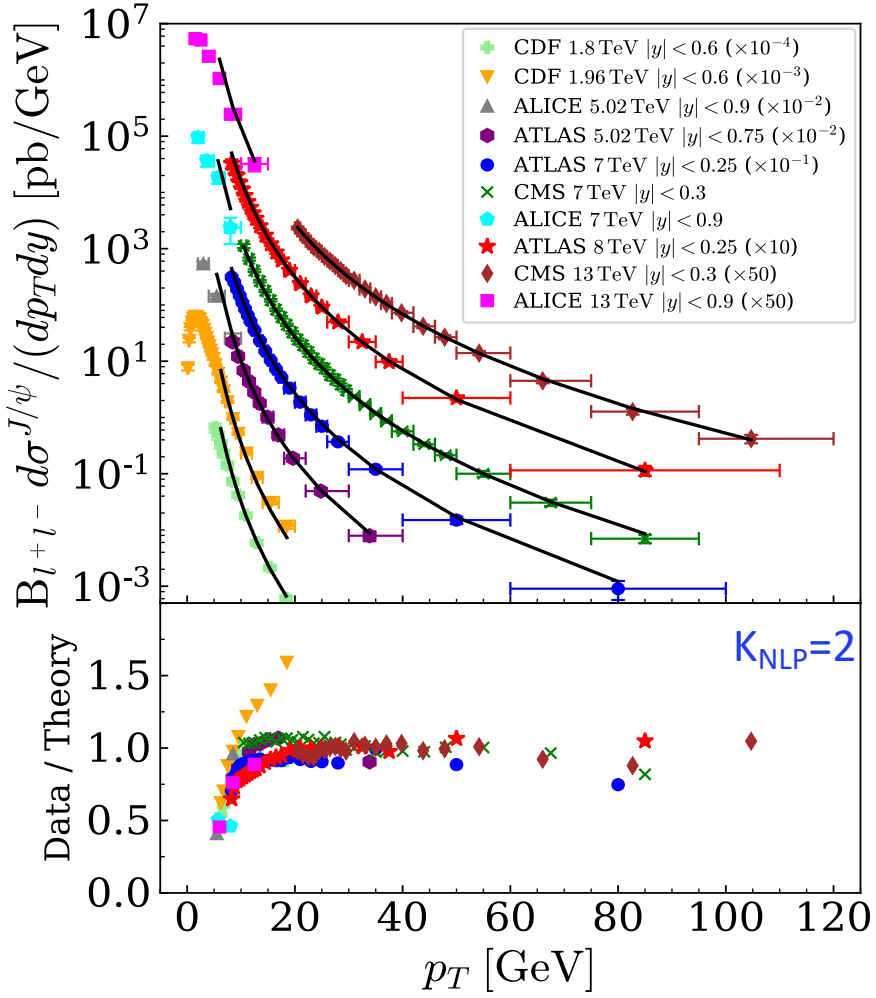
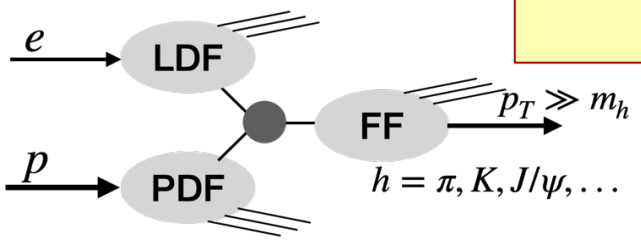


Lee, Qiu, Sterman, Watanabe, 2108.00305, 2211.12648, in preparation

New observable for the EIC:

$$e + p \to h(p_T) + X$$



Not measure the scattered lepton!
Universal lepton distributions

$$\frac{d\sigma^{\rm SIDIS}}{dx_B\, dQ^2\, dy\, dp_T^2} \propto \frac{1}{Q^4} \cdots$$

PDFs, FFs are common blocks in all collisions.

Jefferson Lab

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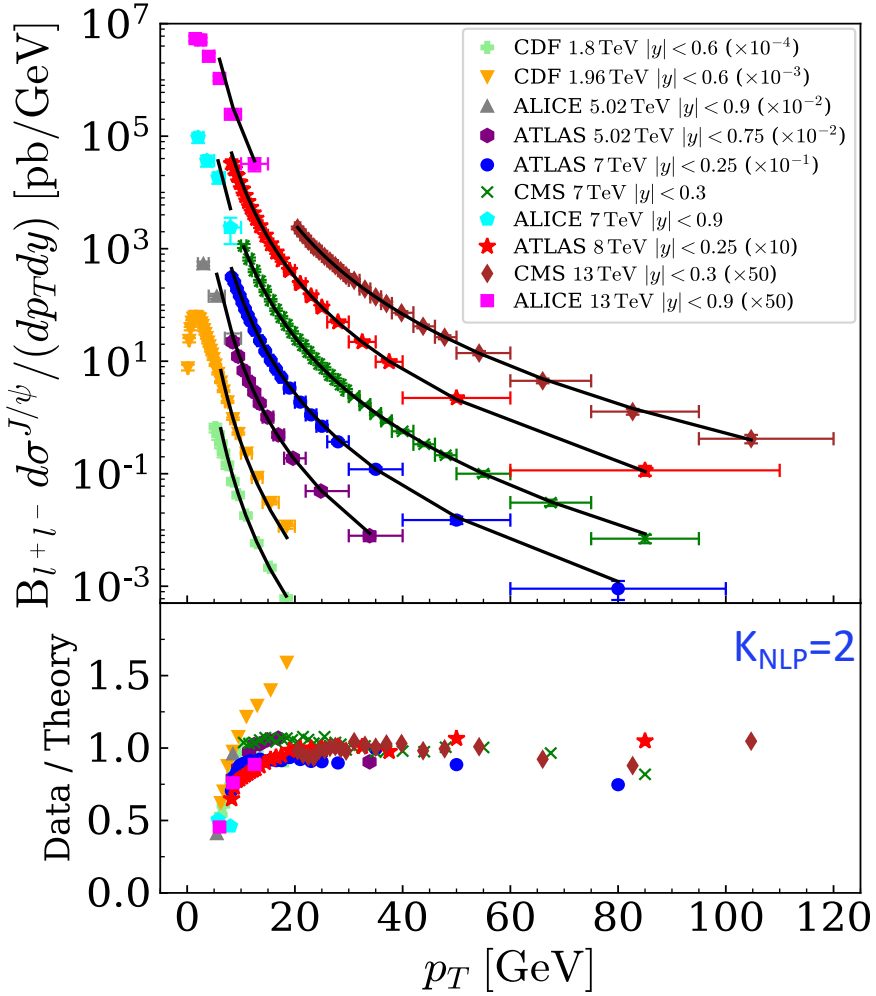

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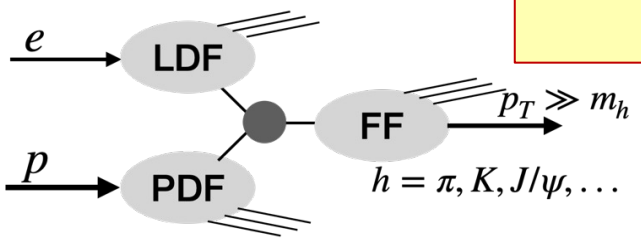

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Theory development

Perturbatively calculable coefficients

$$\frac{d\sigma_{e+p\to J/\psi+X}}{dp_T} \approx f_{i/e} \otimes f_{j/p} \otimes \left[D_k^{J/\psi} \otimes C_{ij\to k} + D_{c\bar{c}}^{J/\psi} \otimes C_{ij\to c\bar{c}} \right]$$

Universal functions: LDFs, PDFs, FFs

Leading power

Next-to-leading power

Kang, Metz, Qiu and Zhou, PRD84, 034046 (2011)
Hinderer, Schlegel, Vogelsang, PRD92, 014001 (2015)
Abelof, Boughezal, Liu, Petriello, PLB763, 52-59 (2016)

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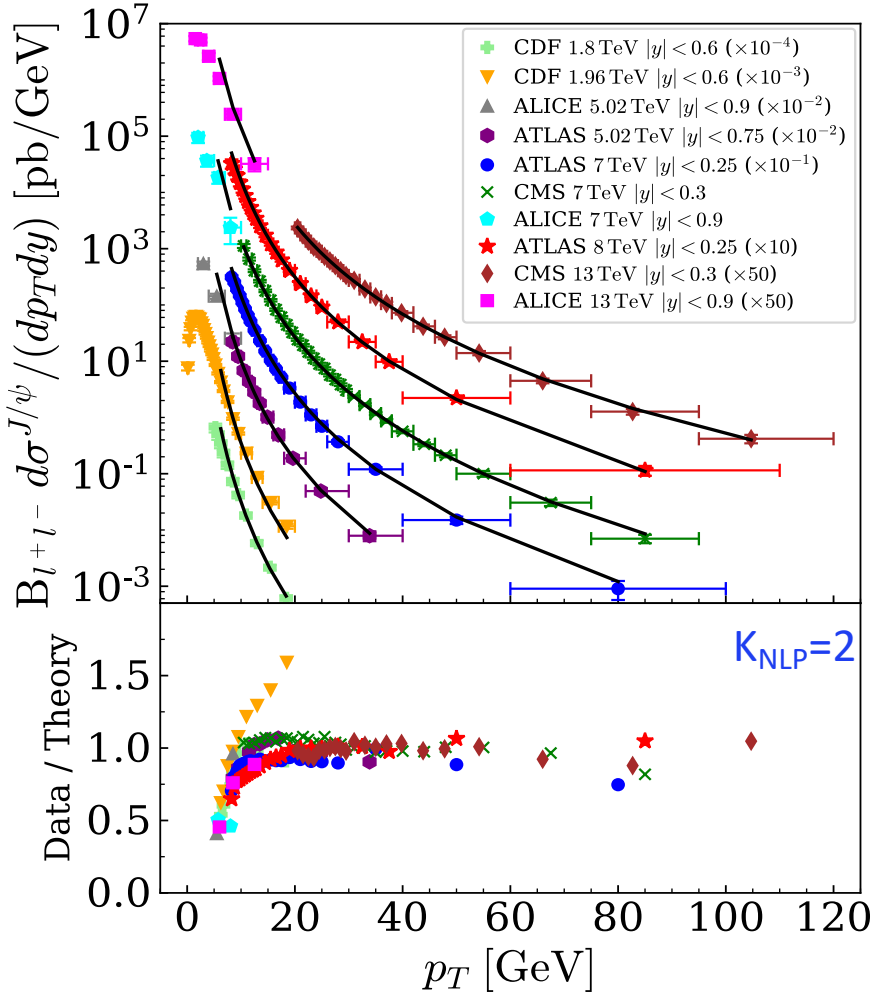

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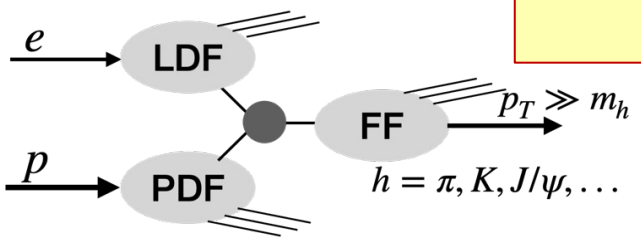

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Predict the J/psi production in ep/eA at the JLab & EIC

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Summary

- HEFTY collaboration functions as a hub of experts with a common focus:

  the production of heavy quarks and quarkonia in hot and cold matter (pA, AA, ep, and eA) to learn and explore the microscopic properties of the dense matter, such as QGP, as well as the hadronization – emergence of hadrons from heavy quarks

  while members have different strengths at different participating institutions to provide a unique environment for sustained interactions and communications, and development of new ideas

- HEFTY collaboration, like other topical collaborations, is
  - creating a network of sustained interactions and communications through summer schools, workshops, and collaboration visits/meetings
  - energizing young people (postdocs and students) and their interests in research, and
  - strengthened our field with a new tenure-track faculty

- Locally, JLab gets a postdoc support to focus on the production of heavy quarkonia, which helps the theory support to heavy quarkonium production at JLab energies and the future EIC