

# Data-driven analysis of the heavy-quark transport coefficient temperature dependence

Yingru Xu

Duke University

*yx59@phy.duke.edu*

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In collaboration with :

Shanshan Cao

Marlene Nahrgang

Jonah E. Bernhard

Steffen A. Bass

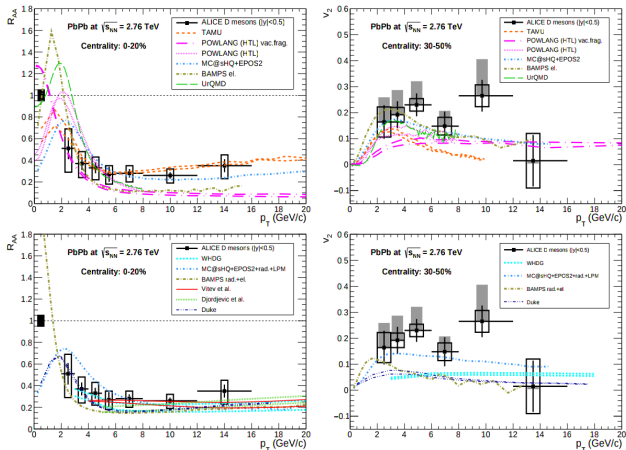
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# HQ in-medium evolution



## Simultaneously describing $D$ -meson $R_{AA}$ and $v_2$ ??

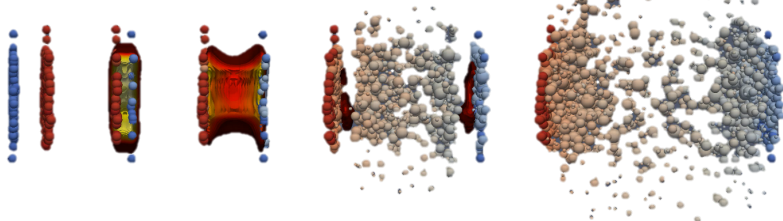


arxiv: 1506.03981

Pb+Pb @ 2.76 TeV: comparison between models and experimental observables

# HQ in-medium evolution

figure credit: Hannah Petersen (Au-Au collisions)



## Initial condition

**Spatial IC:**  $T_{\text{RENTo}}$   
**Momentum IC:** pQCD

## HQ in-medium

**HQ transport:**  
 Langevin (col + rad)  
**Medium:**  
 hydrodynamic

## Hadronization

**Hybrid model:**  
 fragmentation +  
 recombination

# Initial condition

## Position space: T<sub>R</sub>ENTo (A parametric IC model)

- Entropy deposition proportional to eikonal parameterization

$$\left. \frac{ds}{dy} \right|_{\tau=\tau_0} \propto \left( \frac{T_A^p + T_B^p}{2} \right)^{1/p}$$

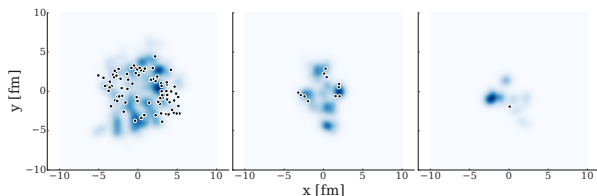
J.S.Moreland, J.Bernhard, and S.A.Bass,  
Phys.Rev.C 92, 011901(2015)

- $p = 0 \Rightarrow ds/dy \propto \sqrt{T_A T_B}$  (mimic the behavior of IP-Glasma)
- Heavy quark initial production probability:  $\left. \frac{dN}{dy} \right|_{\tau=\tau_0} \propto T_A T_B$

## Momentum space: Leading order pQCD

- Parton distribution function: CTEQ5
- Nuclear shadowing effect: EPS09

S.Cao, G.Qin, and S.A.Bass,  
Phys.Rev.C 92, 024907(2015)





# Calibration of the medium

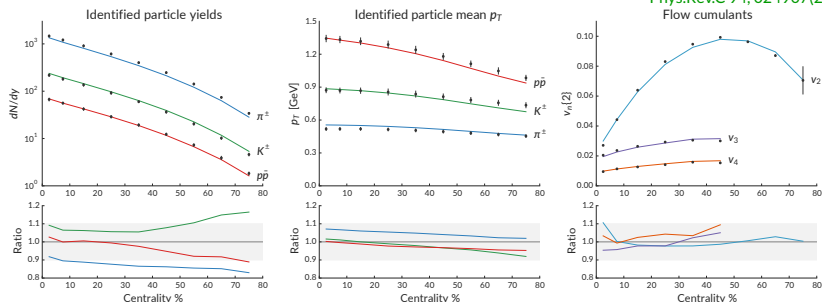


## Medium evolution: hydrodynamics

H.Song and U.W.Heinz,  
Phys.Rev.C 77, 064901(2008)

- (2+1)D viscous hydro: iEeE-VISHNU
- Temperature-dependent shear + bulk vis correction
- $(\eta/s)(T) = (\eta/s)_{\min} + (\eta/s)_{\text{slope}}(T - T_c)$ , for  $T > T_c$
- All the initial/medium related parameters (norm,  $p$ ,  $\eta/s$  etc.) are calibrated by Bayesian analysis with experimental observables ( $\kappa$ ,  $\pi$ , proton: yields, mean  $p_T$ , flow cumulants  $v_n\{2\}$ ,  $v_3$ ,  $v_4$ )

J.Bernhard, J.S.Moreland, S.A.Bass,  
J.Liu, and U.Heinz  
Phys.Rev.C 94, 024907(2015)





# HQ in-medium evolution



S.Cao, G.Qin, and S.A.Bass,  
Phys.Rev.C 92, 024907(2015)

## Improved Langevin transport model

$$\frac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{\xi} + \vec{f}_g \quad (1)$$

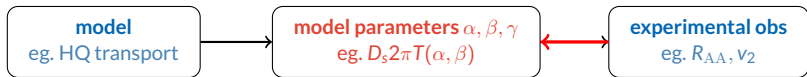
- Drag force:  $\eta_D(p) = \kappa/(2TE)$
- Thermal random force:  $\langle \xi^i(t)\xi^j(t') \rangle = \kappa\delta^{ij}\delta(t-t')$
- Recoil force from gluon radiation:  $\vec{f}_g = -d\vec{p}_g/dt$
- Gluon emission probability:

$$\frac{dN_g}{dxdk_{\perp}^2 dt} = \frac{2\alpha_s P(x)\hat{q}_g}{\pi k_{\perp}^4} \sin^2\left(\frac{t-t_i}{2\tau_f}\right) \left(\frac{k_{\perp}^2}{k_{\perp}^2 + x^2 M^2}\right)^4 \quad (2)$$

- $\hat{q}_g = \hat{q}C_A/C_F = 2\kappa C_A/C_F, D_s = 2T^2/\kappa$
- **Diffusion coefficient  $D_s=?$**

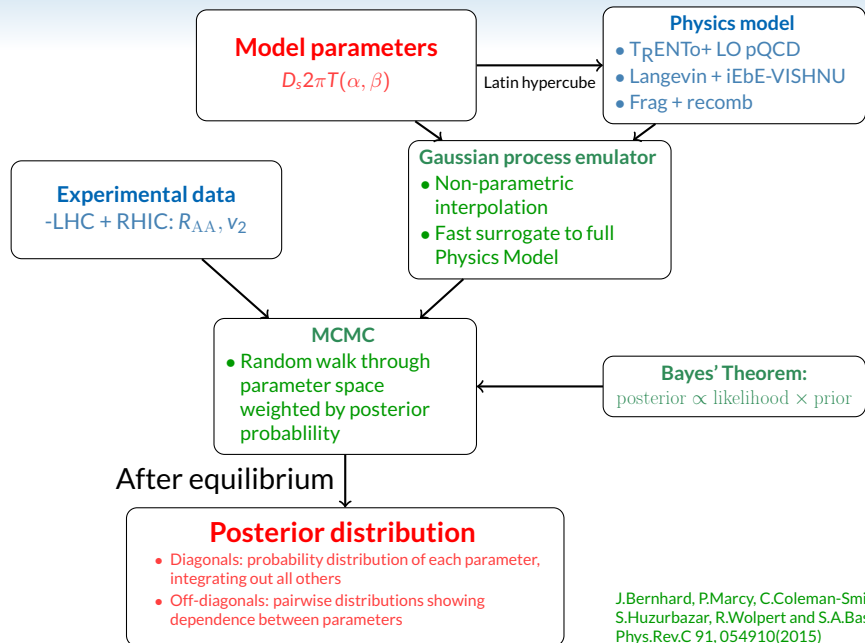


# Bayesian model-to-data analysis



## Bayesian analysis:

- Physical properties of the system encapsulated in parameters of the model
- Bayesian analysis allows us to simultaneously calibrate all model parameters through model-to-data comparison
- Find the optimal parameters such that the model best describes the experimental observables
- Extract the probability distribution of all parameters

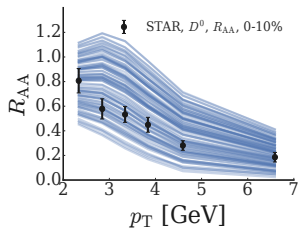
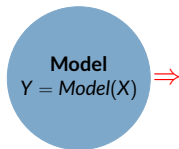
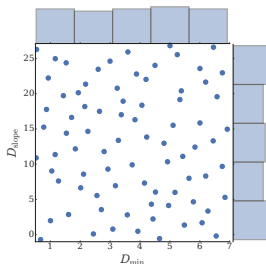




## HQ diffusion coefficient parameterization:

$$D_S 2\pi T = D_{\min} + D_{\text{slope}}(T - T_C) \quad (3)$$

- Parameter space:  $D_{\min} \in (0.5, 7)$ ,  $D_{\text{slope}} \in (-1, 27)$   $\text{GeV}^{-1}$
- Uniformly sample 100 design points throughout parameter space:  $\vec{x}^* = (D_{\min}, D_{\text{slope}})$
- Full Langevin framework calculation at each design point  $\Rightarrow$  100 sets of prior results:  $\vec{y}^* = \text{Model}(\vec{x}^*)$ ,  $\vec{y}^* = (R_{AA}, v_2)$

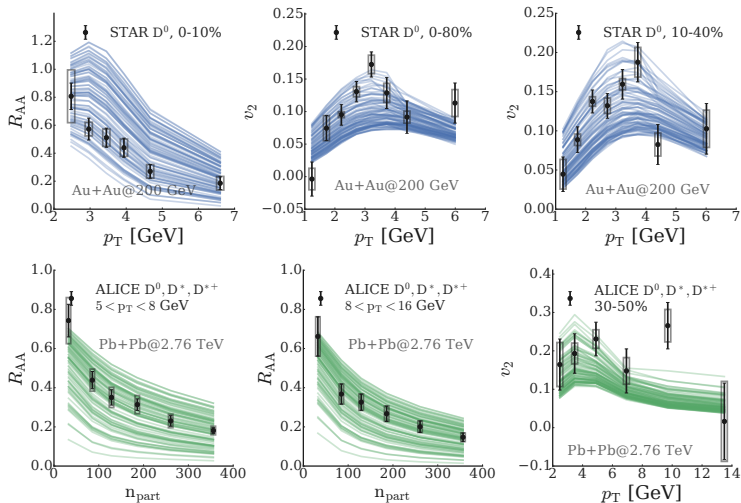




# Prior calibration: training data



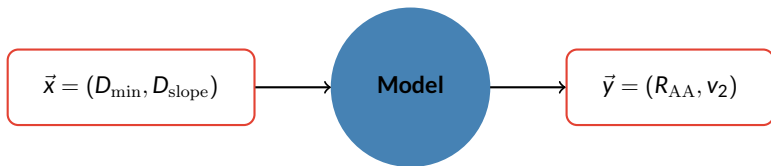
## Model calculation of $(R_{AA}, v_2)$ at 100 design points



[STAR Collaboration] arxiv:1601.00695; arXiv:1701.06060

[ALICE Collaboration] JHEP **1511**, 205 (2015); Phys.Rev.C **90**, no. 3, 034904 (2014)

# Training GP emulator



## Difficulties

Full Langevin framework run  $\propto$  8hrs for 100 events produced



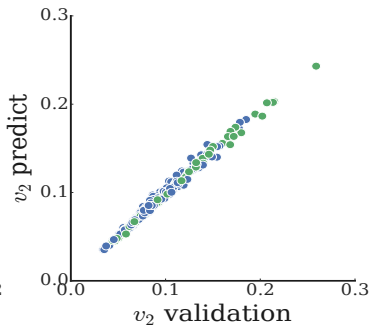
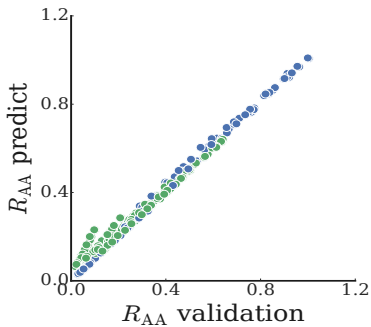
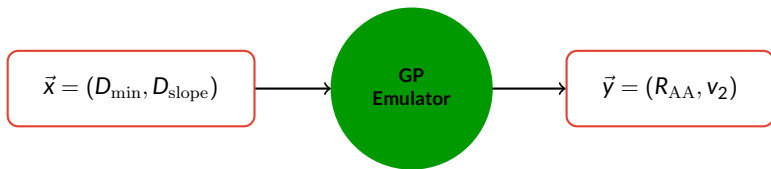
10000 events needed for an event-by-event study



$O(10^3)$  CPU hours to evaluate one design point  $\vec{x}$



# Training GP emulator

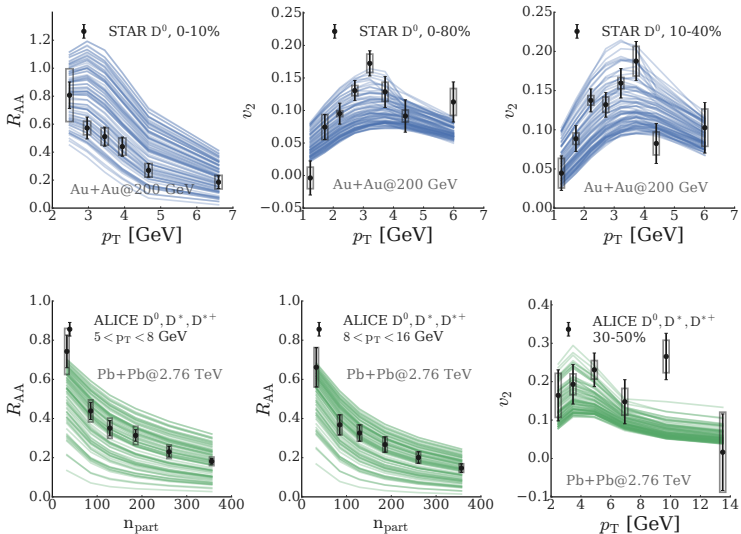




# Prior calibration: training data



## Prior results: 100 sets of $(R_{AA}, v_2)$ from model calculation



Model calculation  
 $\downarrow$   
 training data  $Y = f(X)$

GP emulator  
 $\downarrow$   
 any  $\vec{x}$  predict  $\vec{y}$

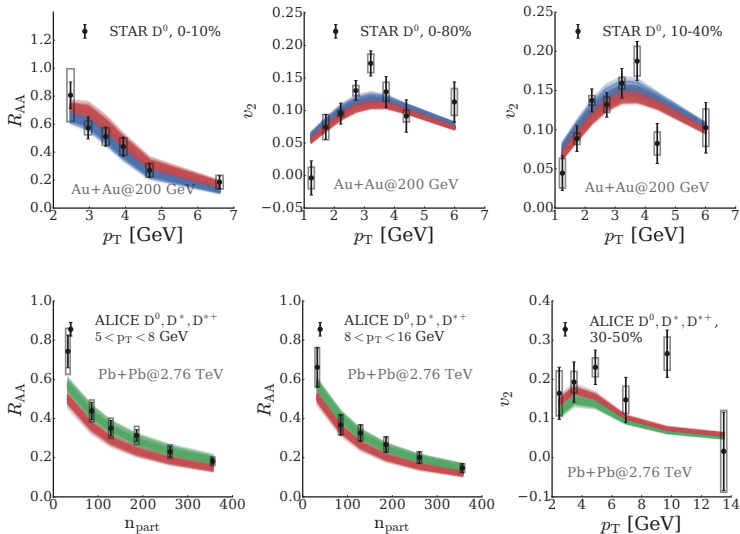
MCMC  
 $\downarrow$   
 $\vec{x}$  posterior distribution



# Posterior calibration



## Posterior results: 200 random sets of $(R_{AA}, v_2)$



Model calculation  
 $\downarrow$   
 training data  $Y = f(X)$

GP emulator  
 $\downarrow$   
 any  $\vec{x}$  predict  $\vec{y}$

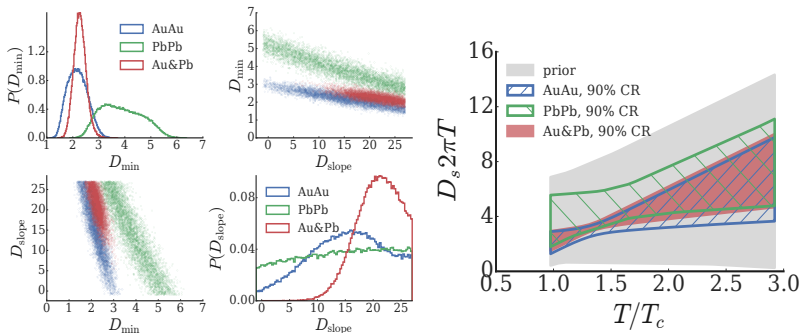
MCMC  
 $\downarrow$   
 $\vec{x}$  posterior distribution



# Posterior calibration



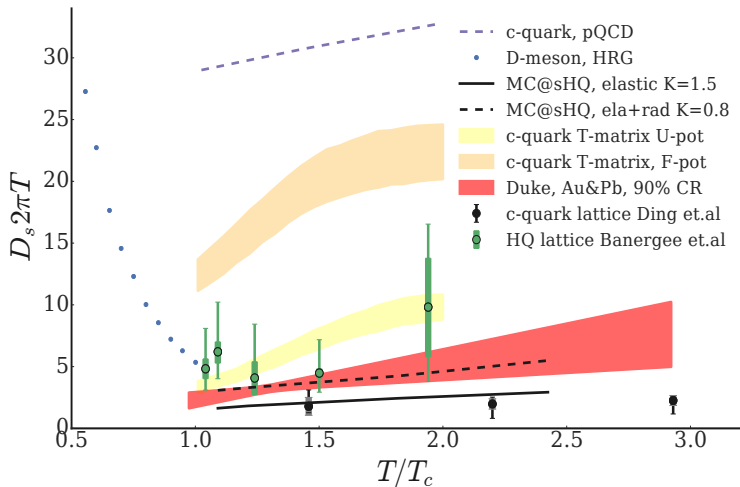
## Posterior distributions of $(D_{\min}, D_{\text{slope}})$



param	prior range	posterior(AuAu)	posterior(PbPb)	posterior(AuAu&PbPb)
$D_{\min}$	(0.5, 7)	(1.60, 2.83)	(2.70, 5.19)	(1.90, 2.67)
$D_{\text{slope}}$	(-1, 27)	(3.47, 25.56)	(0.86, 25.74)	(14.16, 26.23)



# Comparison between different models



F.Riek, and R.Rapp,  
Phys.Rev.C 82,035201(2010)

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Phys.Rev.Lett 11,112301(2013)

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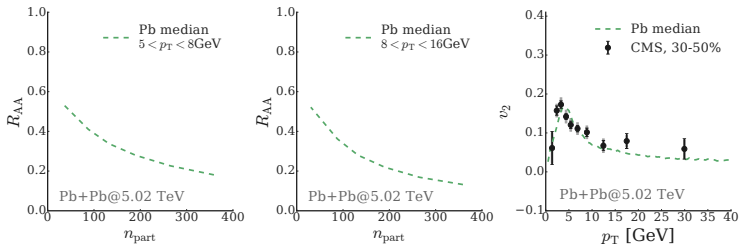




# Pb+Pb @ 5.02 TeV



Langevin calculation taking the favorable value of ( $D_{\min}$ ,  $D_{\text{slope}}$ ) on another system.



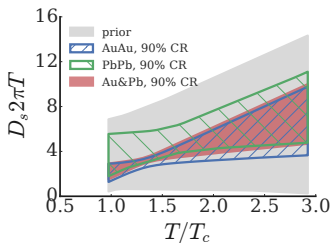
**Not a calibration!**



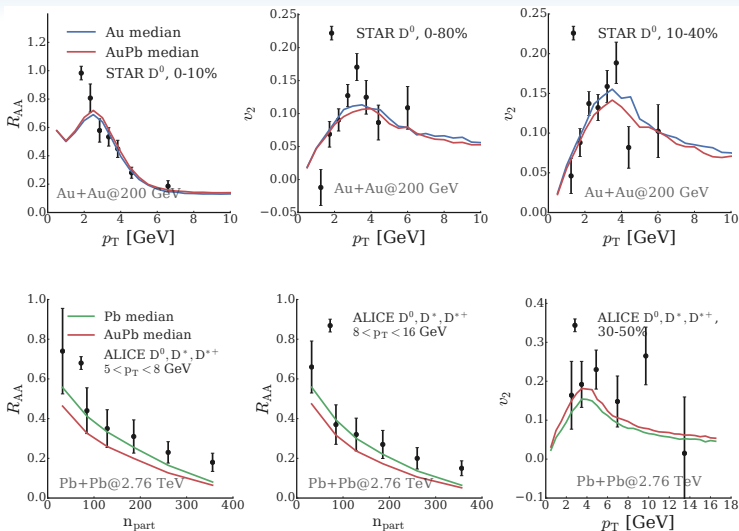
# Summary



- Bayesian model-to-data analysis  $\Rightarrow$  extract the temperature dependence of  $D_s 2\pi T \propto (2 - 10)$



- Simultaneous agreement of  $R_{AA}$  and  $v_2$  compared to data
- A higher precision of experimental data?  $\Rightarrow$ 
  - Better constrain diffusion coefficient
  - Further discriminate between different HQ in-medium transport models
- Extension of calibrating on Pb+Pb @ 5.02 TeV, p+Pb @ 5.02 TeV; improve uncertainty analysis



$(D_{\min}, D_{\text{slope}})$ :

Au median (2.10, 16.44); Pb median (3.60, 14.01); AuPb median (2.26, 18.63)