A data-driven analysis for the heavy quark diffusion coefficients

Wenkai Fan, Yingru Xu, Steffen A. Bass

Duke University

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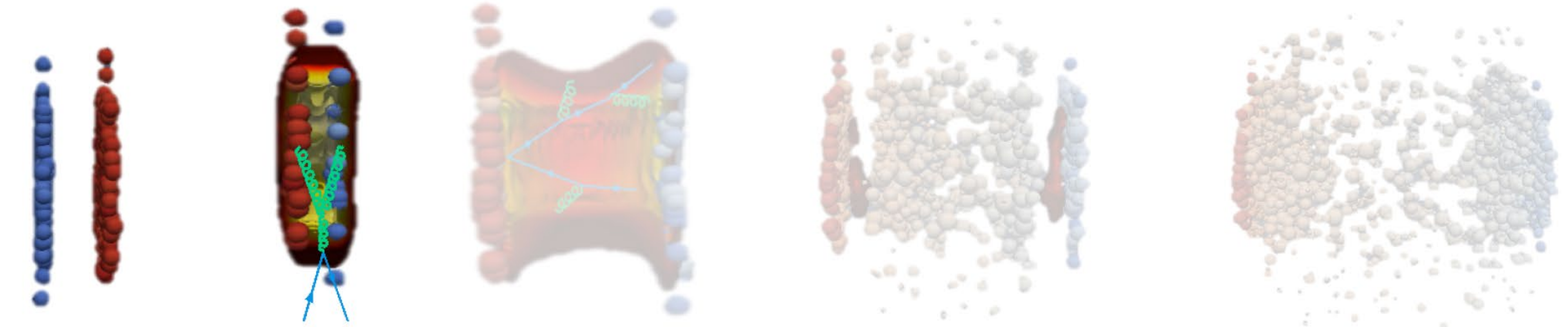
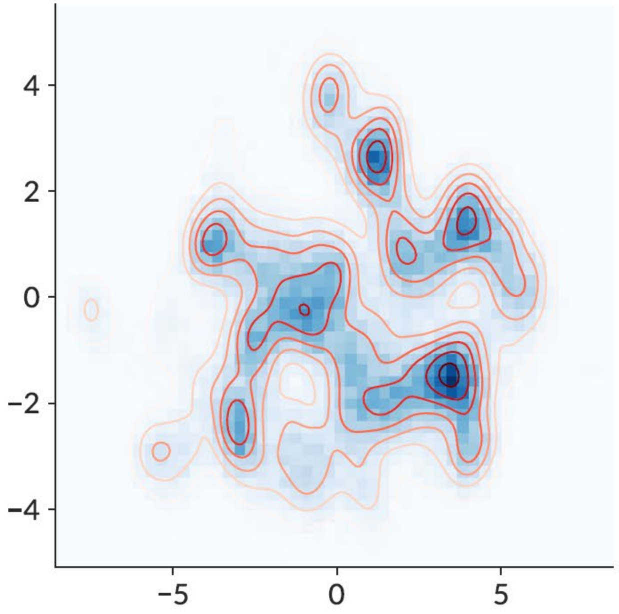
PART 1 **Simulation Pipeline**



Initial conditions

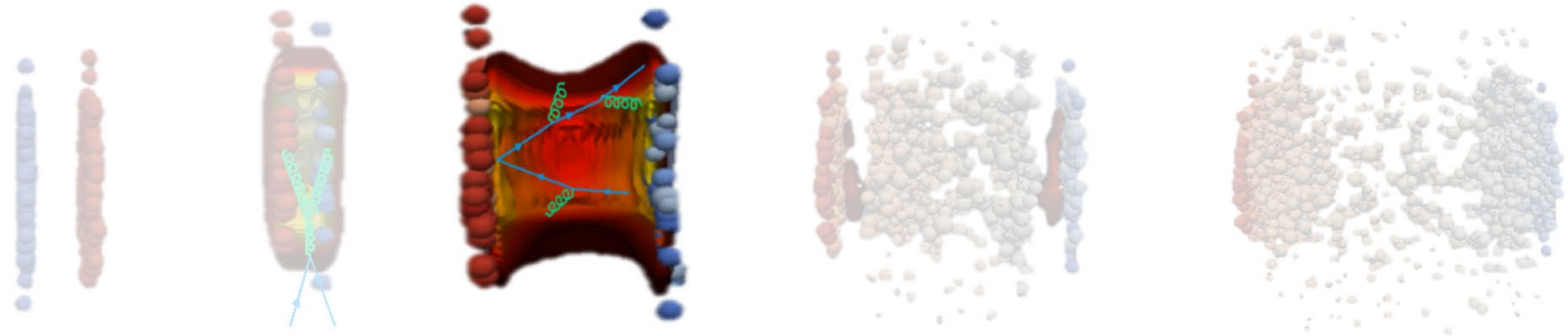
- Soft matter: T$_\mathrm{R}$ENTo
  - Entropy deposition proportional to empirical parametrization: $\frac{ds}{dy}|_{\tau=\tau_0} \propto \sqrt{T_A T_B}$, T_A (nucleon thickness function)
- Heavy quarks
  - Position space: binary collision density
  - Momentum space: (initial hard scattering) Fixed-Order + Next-to-Leading Log (FONLL)



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

PART 1

Simulation Pipeline



Soft medium evolution

- Event-by-event (2+1)D viscous hydrodynamic model: `iEbE-VISHNU`
  - Shear and bulk viscosities: $\eta/s(T), \zeta/s(T)$
  - All the soft medium related parameters are calibrated on soft hadronic observables by Bayesian analysis

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

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

Heavy quark in-medium transport

- Model A: improved Langevin model
- Model B: `Lido` - linearized Boltzmann + diffusion model

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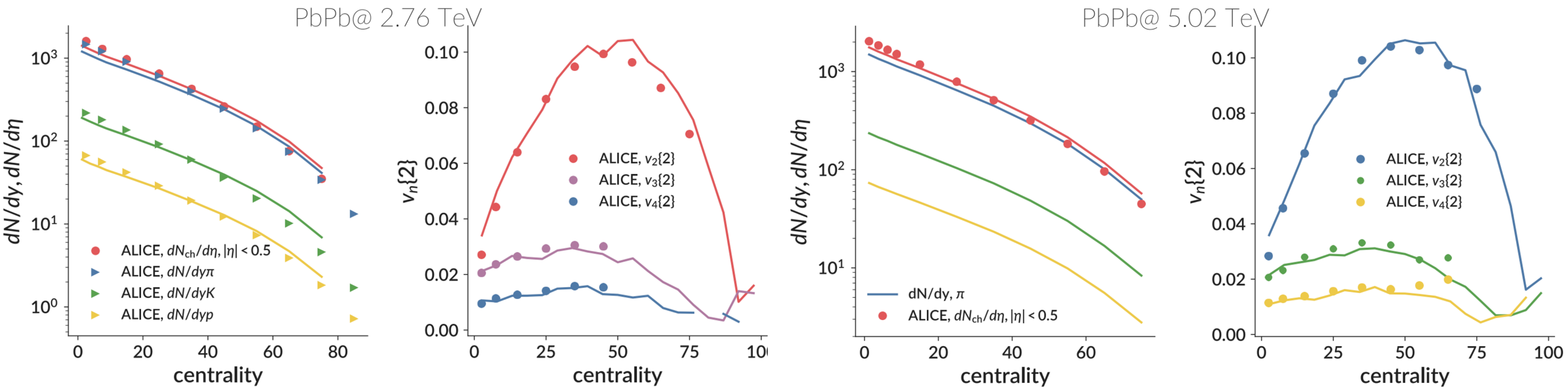
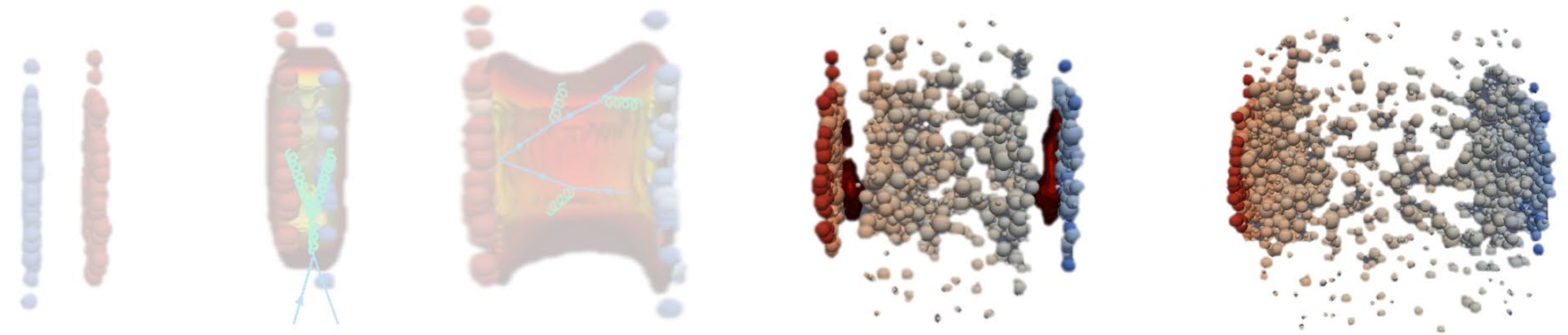


Best fit of bulk medium observables

Simulation Pipeline



Hadronization/particalization

- Soft medium: particlization (hydrodynamic model $\rightarrow$ hadron gas) at T_{switch}
- $c \rightarrow D$-meson, charmed baryons at $T_c = 154$ MeV:
  combined model of recombination and fragmentation

S. A. Bass et al., Prog. Part. Nucl. Phys. 41 (1998)

Hadronic re-scattering

M. Bleicher et al. J. Phys. G: Nucl. Part. Phys. 25 (1999)

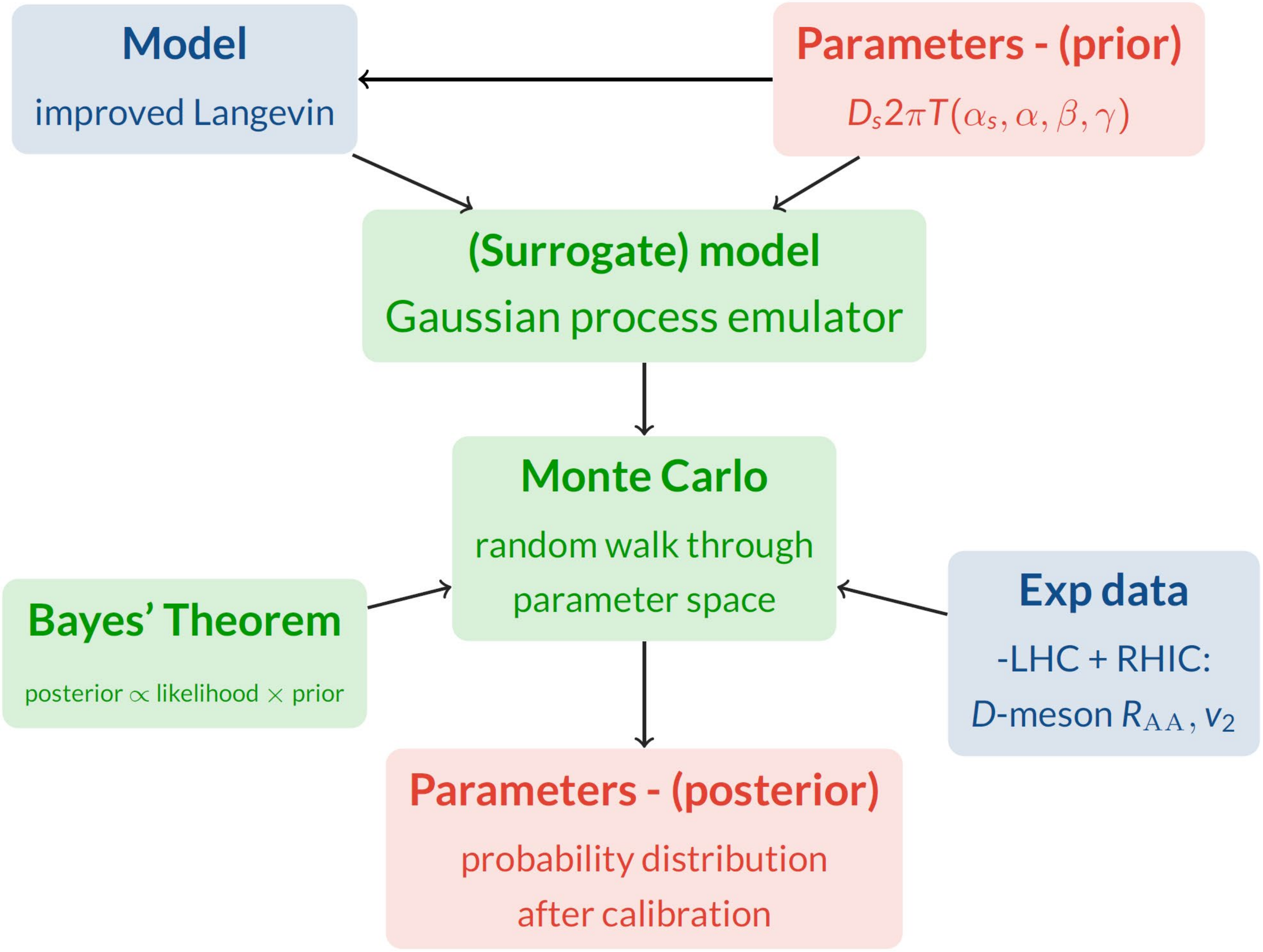
- UrQMD: solving the Boltzmann equation of hadron scattering
- D-mesons scatter with π, ρ:
  $\pi D \rightarrow \pi D$, $\pi D^* \rightarrow \pi D^*$, $\pi D \leftrightarrow \rho D^*$
  $\rho D \rightarrow \rho D$, $\rho D^* \rightarrow \rho D^*$, $\rho D \leftrightarrow \pi D^*$

Z.-W. Lin, T. Di, and C. Ko, Nucl. Phys. A689, 965 (2001)

PART 1 **Bayesian Analysis**

Answer the following question:

Given the model and the experimental data, can we constrain the model parameters?



Bayesian Analysis

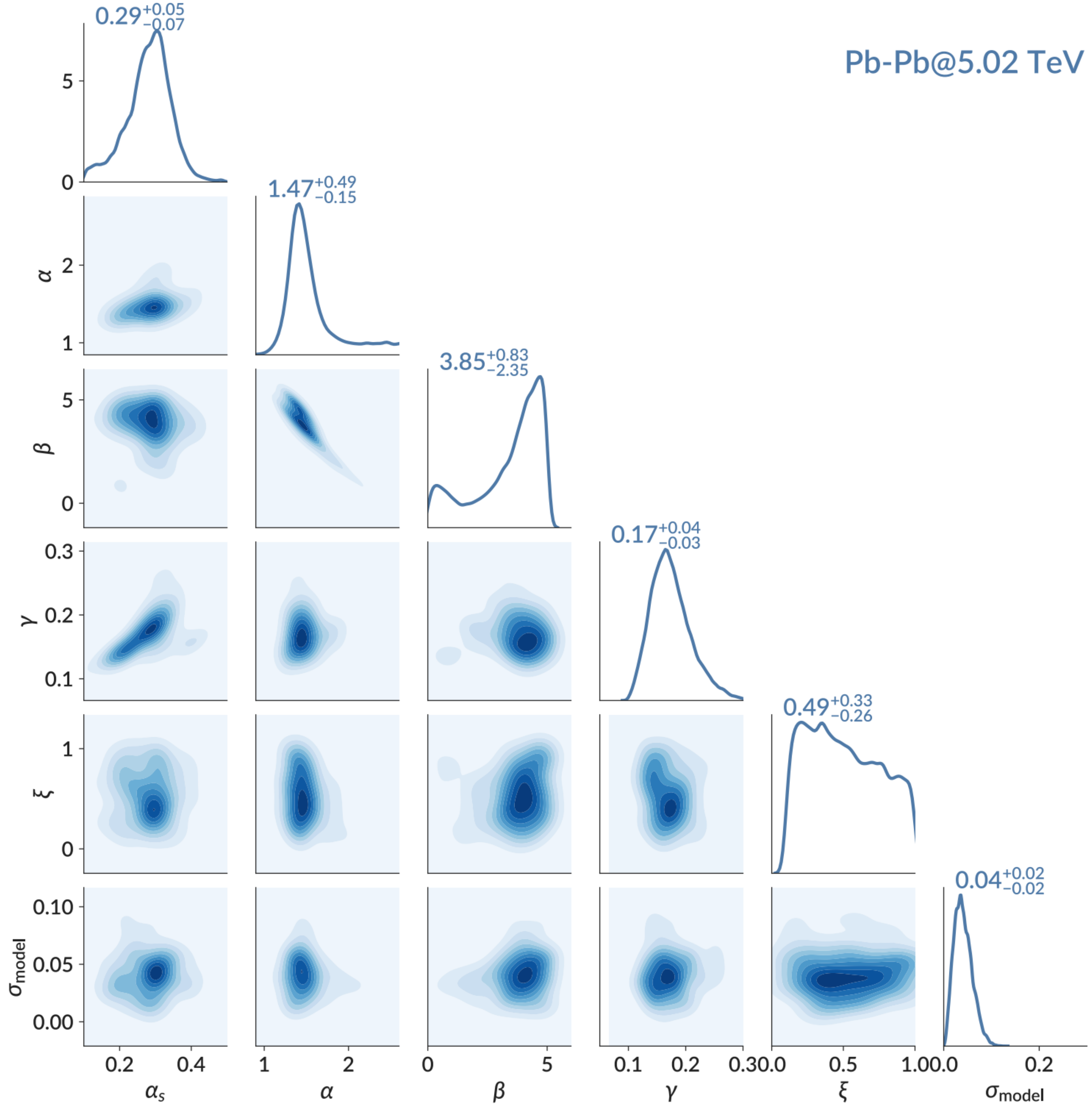
$$D_s 2\pi T = 8\pi/(\hat{q}/T^3)$$

$$D_s 2\pi T = \frac{1}{1+(\gamma^2 p)^2}(D_s 2\pi T)^{soft} + \frac{(\gamma^2 p)^2}{1+(\gamma^2 p)^2}(D_s 2\pi T)^{pQCD}$$

$$(D_s 2\pi T)^{soft} = \alpha(1+\beta(\frac{T}{T_c}-1))$$

Generate $\frac{dN}{d^3p}$ of heavy quarks up to hadronization.

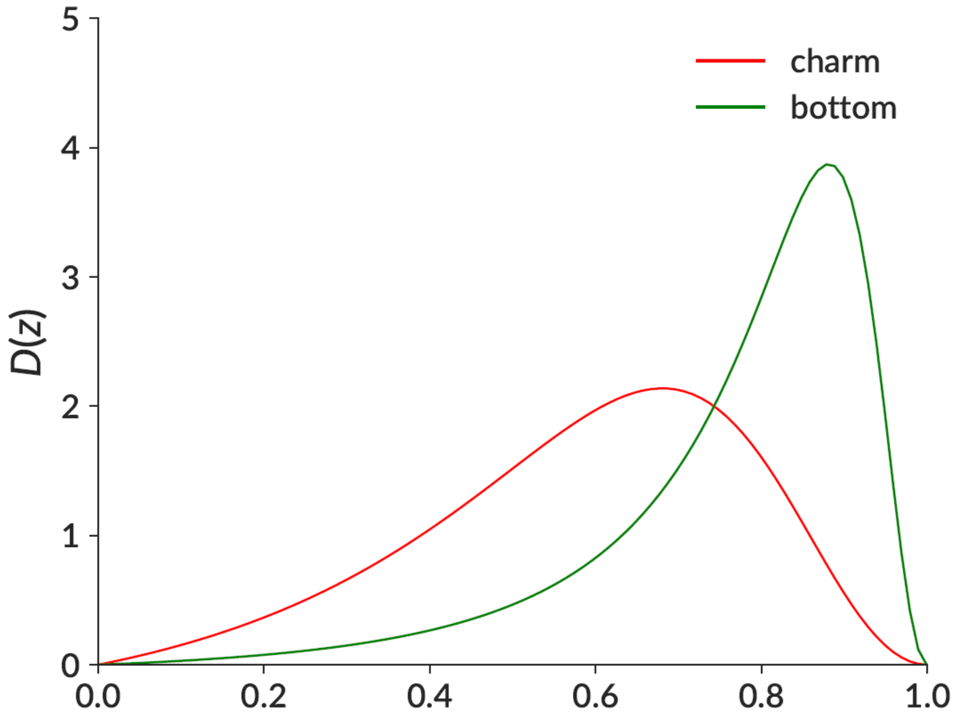
Posterior distribution of model parameters



PART 2 **Heavy quark hadronization and hadronic re-scattering**

Heavy quark hadronization in A+A: fragmentation (Pythia) + recombination/coalescence

Heavy quark hadronization in p+p: fragmentation (Pythia)



$$D(z) \propto \frac{1}{z}\left(1 - \frac{1}{z} - \frac{\epsilon}{1-z}\right)^{-2}$$

PART 2 **Heavy quark hadronization and hadronic re-scattering**

Sudden coalescence approximation. Similar to what Shanshan has presented.

$$\frac{dN_M}{d^3p_M} = \int d^3p_1 d^3p_2 \frac{dN_1}{d^3p_1}\frac{dN_2}{d^3p_2} f_M^W(\vec{p}_1,\vec{p}_2)\delta(\vec{p}_M - \vec{p}_1 - \vec{p}_2)$$

$$\frac{dN_B}{d^3p_B} = \int d^3p_1 d^3p_2 d^3p_3 \frac{dN_1}{d^3p_1}\frac{dN_2}{d^3p_2}\frac{dN_3}{d^33} f_B^W(\vec{p}_1,\vec{p}_2,\vec{p}_3)\delta(\vec{p}_M - \vec{p}_1 - \vec{p}_2 - \vec{p}_3)$$

where

$$f_M^W(q^2) = \frac{g_M\left(2\sqrt{\pi}\sigma\right)^3}{V} e^{-q^2\sigma^2}$$

$$f_B^W(q_1^2, q_2^2) = \frac{g_B\left(2\sqrt{\pi}\sigma_1\right)^3\left(2\sqrt{\pi}\sigma_2\right)^3}{V^2} e^{-q_1^2\sigma_1^2 - q_2^2\sigma_2^2}$$

[Phys. Rev. C88 (2013) 044907]

PART 2 Heavy quark hadronization and hadronic re-scattering

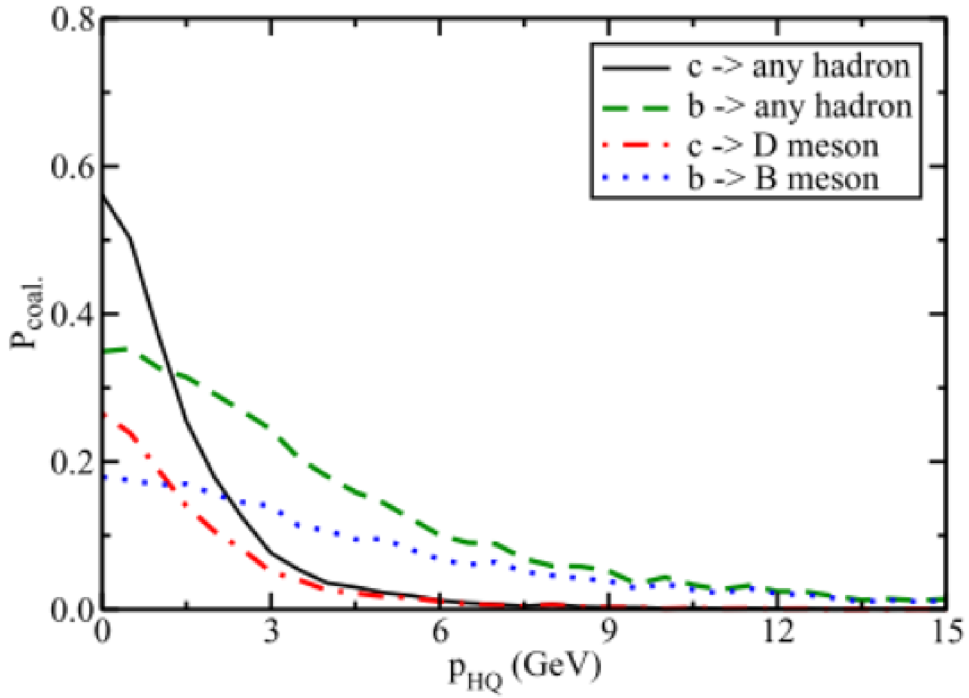
$$f_M^W(q^2) = \frac{g_M\left(2\sqrt{\pi}\sigma\right)^3}{V} e^{-q^2\sigma^2}$$

$$q = |\vec{p}_1 - \vec{p}_2|\sigma = \frac{1}{\sqrt{\mu\omega}}, \mu = \frac{m_1 m_2}{m_1 + m_2}$$

ω determined by comparing to the charge radii:

$$\langle r_M^2 \rangle_{\rm ch} = \frac{3}{2\omega}\frac{1}{(m_1+m_2)(Q_1+Q_2)}\left(\frac{m_2}{m_1}Q_1 + \frac{m_1}{m_2}Q_2\right),$$

$$\langle r_B^2 \rangle_{\rm ch} = \frac{3}{2\omega}\frac{1}{(m_1+m_2+m_3)(Q_1+Q_2+Q_3)}\left(\frac{m_2+m_3}{m_1}Q_1 + \frac{m_3+m_1}{m_2}Q_2 + \frac{m_1+m_2}{m_3}Q_3\right),$$



ω = 0.33 GeV for charm and beauty mesons, 0.43 GeV for charm baryons and 0.41 GeV for beauty baryons.

[Phys. Rev. C88 (2013) 044907]

PART 2 **Heavy quark hadronization and hadronic re-scattering**

The Ultra-relativistic Quantum Molecule Dynamics (UrQMD) model:

$$\frac{df_i(x,p)}{dt} = \mathcal{C}_i(x,p)$$

collision terms (C), including binary collisions, 2 → n inelastic process, annihilation, resonance formation and decays.

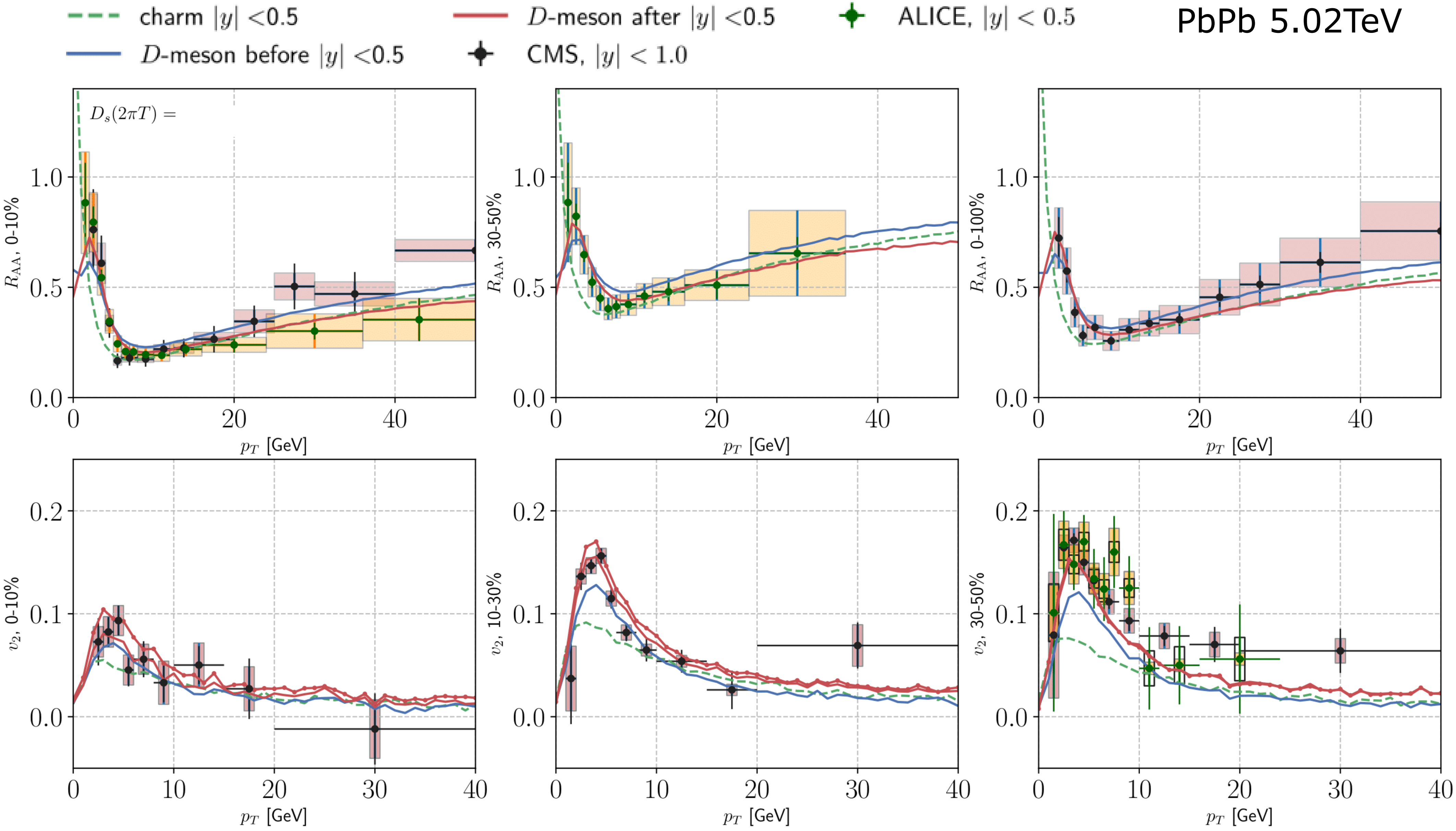
In the semi-classical criterion, the cross section between a pair of particles is approximated as $\sigma_{tot}(\sqrt{s}) = \pi d_0^2$, which means that if the relative distance between the two particles $d_{trans} < d_0$, the collision would happen.

[Physical Review C 93.1 (2016): 014911]

PART 2

Heavy quark hadronization and hadronic re-scattering

PbPb 5.02TeV

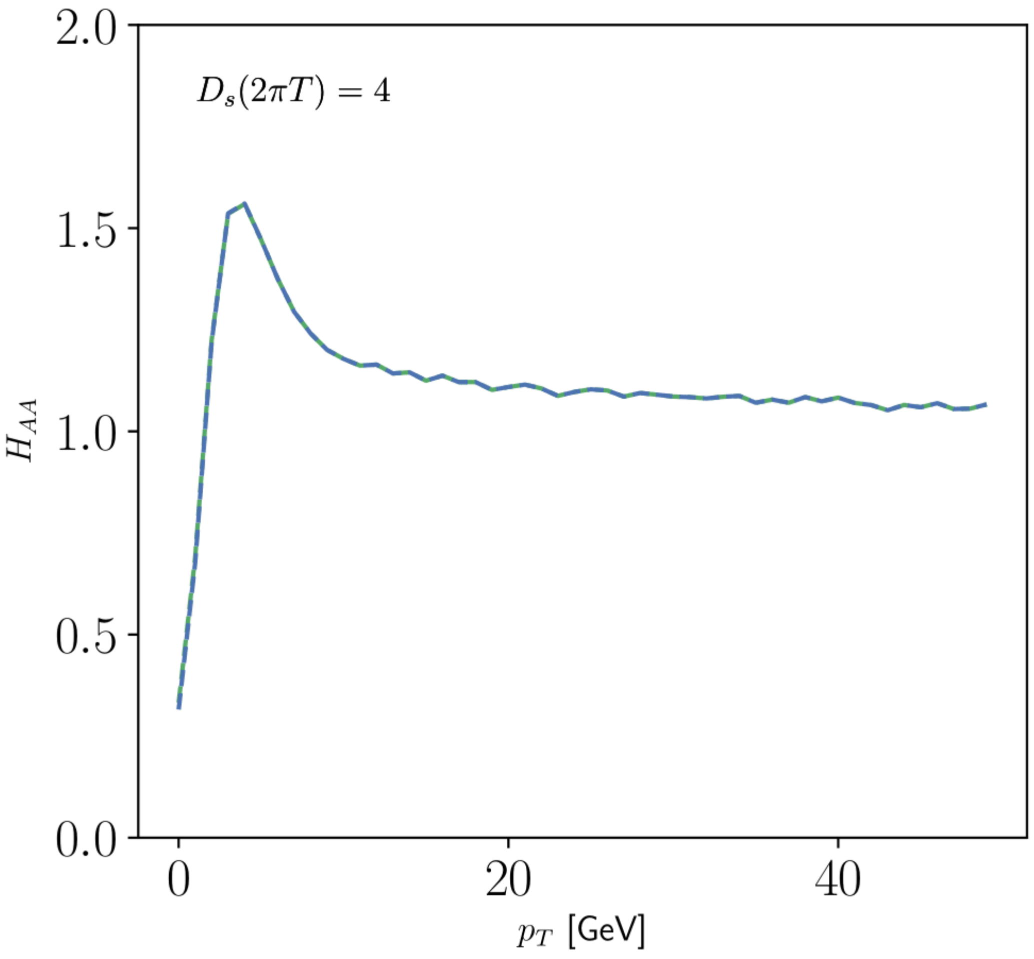


$\alpha_s = 0.32,$
$\alpha = 1.74,$
$\beta = 2.43,$
$\gamma = 0.18$

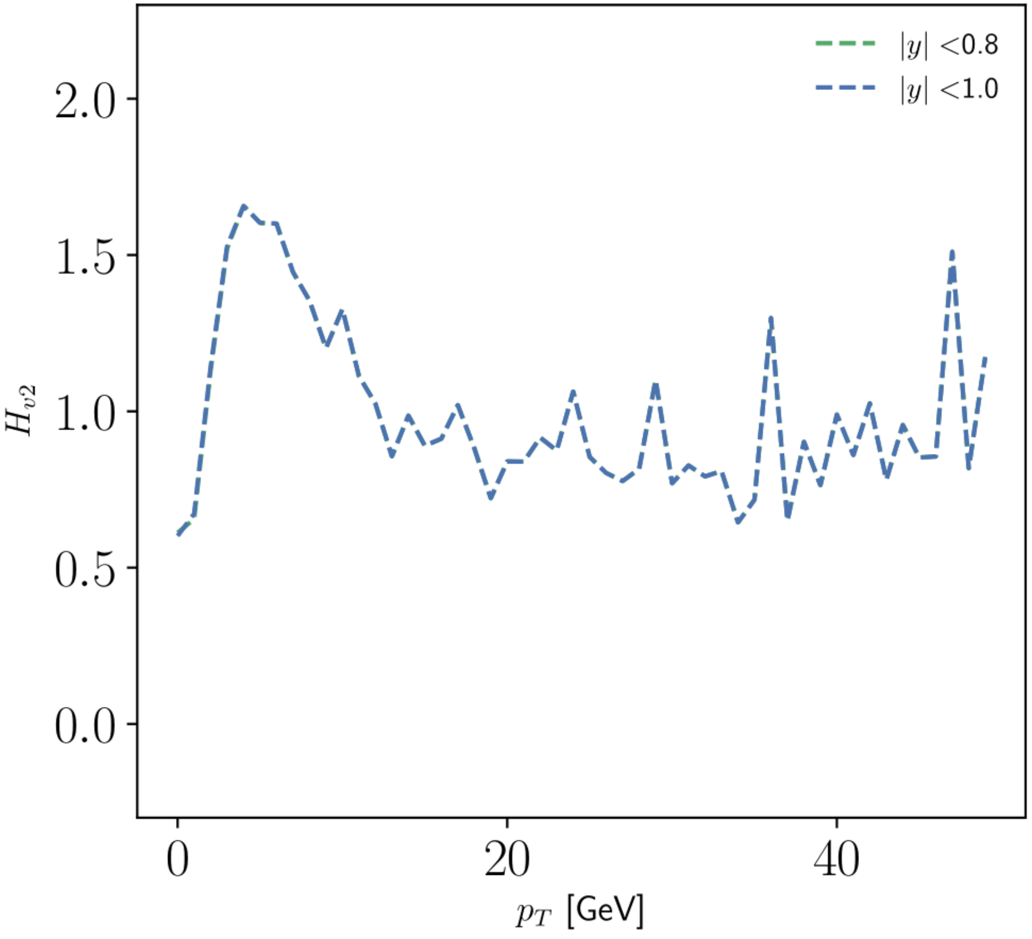
PART 2

Heavy quark hadronization and hadronic re-scattering

$$H_{AA} = R_{AA}^{D}/R_{AA}^{c}$$



$$H_{v_2} = v_2^{D}/v_2^{c}$$



Conclusion

- Use Bayesian analysis to “fix” other ingredients of the simulation. The effects of hadronization and re-scattering are singled out.
- Hadronization brings up R_{AA} and v_2 at low p_T.
- Hadronic re-scattering further enhances the v_2, enhance R_{AA} at low p_T but reduce R_{AA} at low p_T.

Thank you!