Out of Equilibrium — Duke Approach

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EMMI Rapid Reaction Task Force (RRTF)
Suppression and (re)generation of quarkonium in heavy-ion collisions at the LHC

GSI, Dec. 19, 2019

Overview

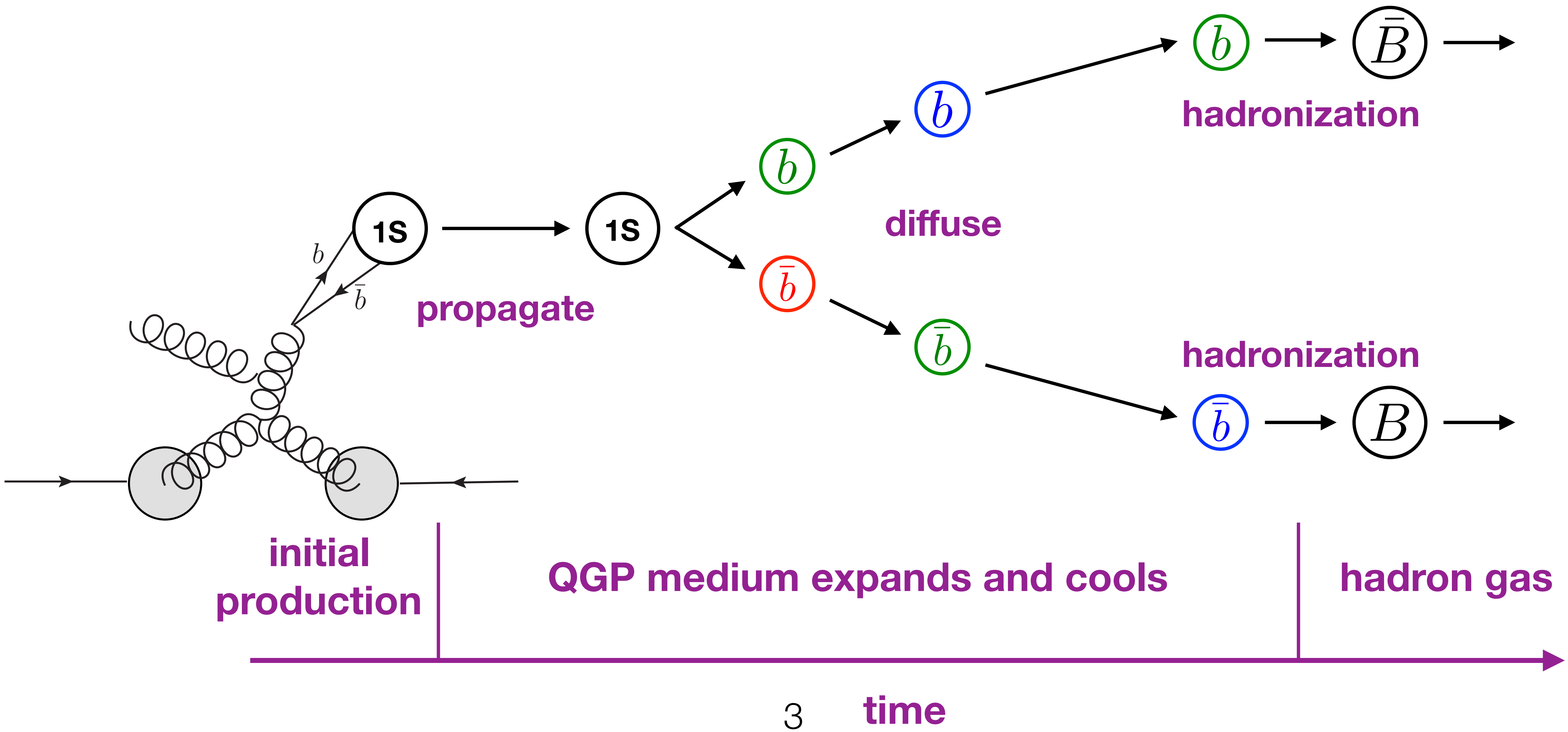
- Coupled transport equations for open and hidden heavy flavors
- Hydro background (calibration)
- Open heavy flavor transport (calibration)

Coupled with Transport of Open Heavy Flavor

heavy quark $$(\frac{\partial}{\partial t} + \dot{\boldsymbol{x}} \cdot \nabla_{\boldsymbol{x}}) f_Q(\boldsymbol{x}, \boldsymbol{p}, t) = \mathcal{C}_Q - \mathcal{C}_Q^+ + \mathcal{C}_Q^-$$

anti-heavy quark $$(\frac{\partial}{\partial t} + \dot{\boldsymbol{x}} \cdot \nabla_{\boldsymbol{x}}) f_{\bar{Q}}(\boldsymbol{x}, \boldsymbol{p}, t) = \mathcal{C}_{\bar{Q}} - \mathcal{C}_{\bar{Q}}^+ + \mathcal{C}_{\bar{Q}}^-$$

each quarkonium state
nl = 1S, 2S,1P etc. $$(\frac{\partial}{\partial t} + \dot{\boldsymbol{x}} \cdot \nabla_{\boldsymbol{x}}) f_{nls}(\boldsymbol{x}, \boldsymbol{p}, t) = \mathcal{C}_{nls}^+ - \mathcal{C}_{nls}^-$$



Coupled with Transport of Open Heavy Flavor

heavy quark $$(\frac{\partial}{\partial t}+\dot{\boldsymbol{x}}\cdot\nabla_{\boldsymbol{x}})f_Q(\boldsymbol{x},\boldsymbol{p},t)=\mathcal{C}_Q-\mathcal{C}_Q^{+}+\mathcal{C}_Q^{-}$$

anti-heavy quark $$(\frac{\partial}{\partial t}+\dot{\boldsymbol{x}}\cdot\nabla_{\boldsymbol{x}})f_{\bar{Q}}(\boldsymbol{x},\boldsymbol{p},t)=\mathcal{C}_{\bar{Q}}-\mathcal{C}_{\bar{Q}}^{+}+\mathcal{C}_{\bar{Q}}^{-}$$

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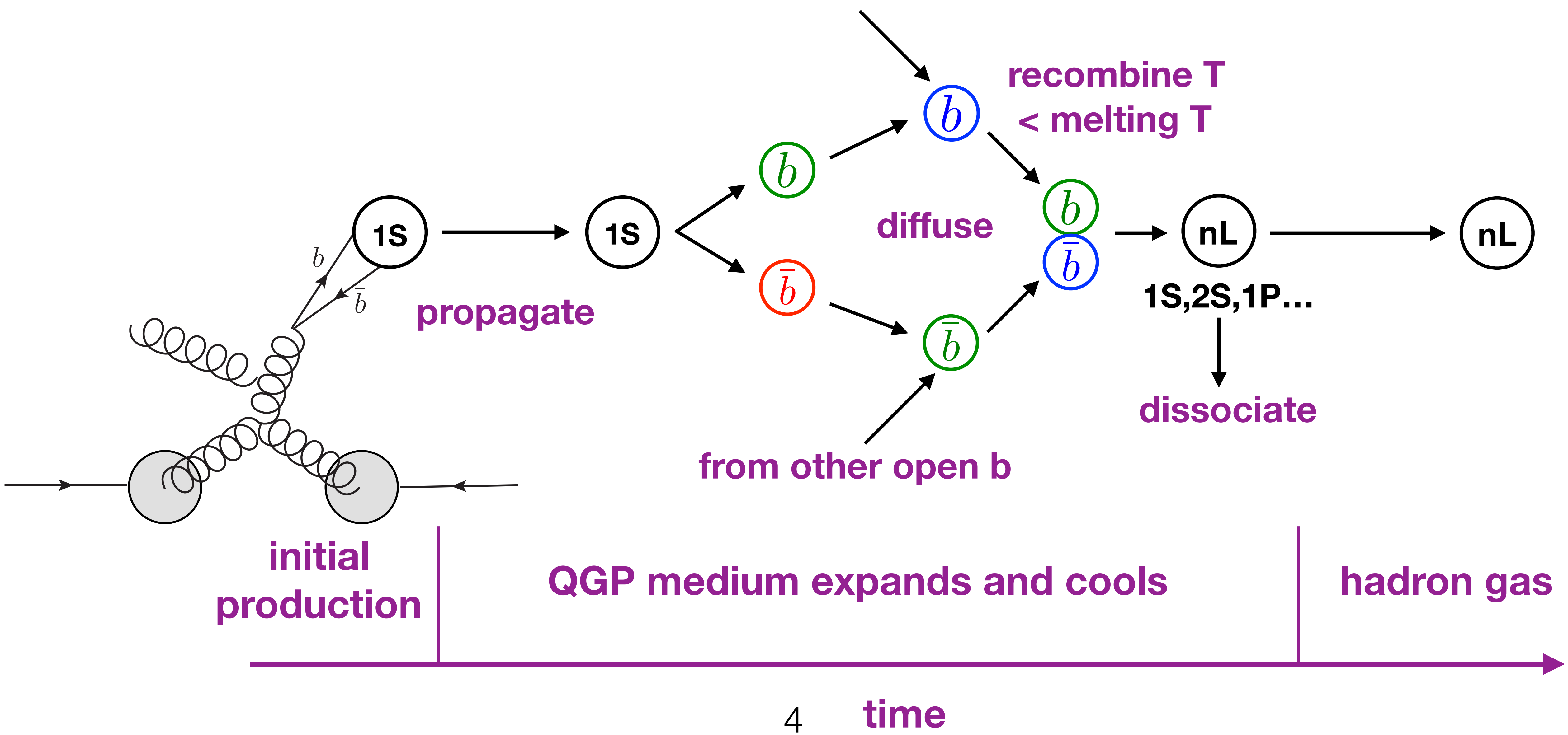


Collision Event Simulation

- **Initial production:** for bottomonium pT < 20 GeV, assume production at tau = 0, free streaming before hydro starts at tau = 0.6 fm/c

PYTHIA 8.2: NRQCD factorization (LDME: singlet and octet)

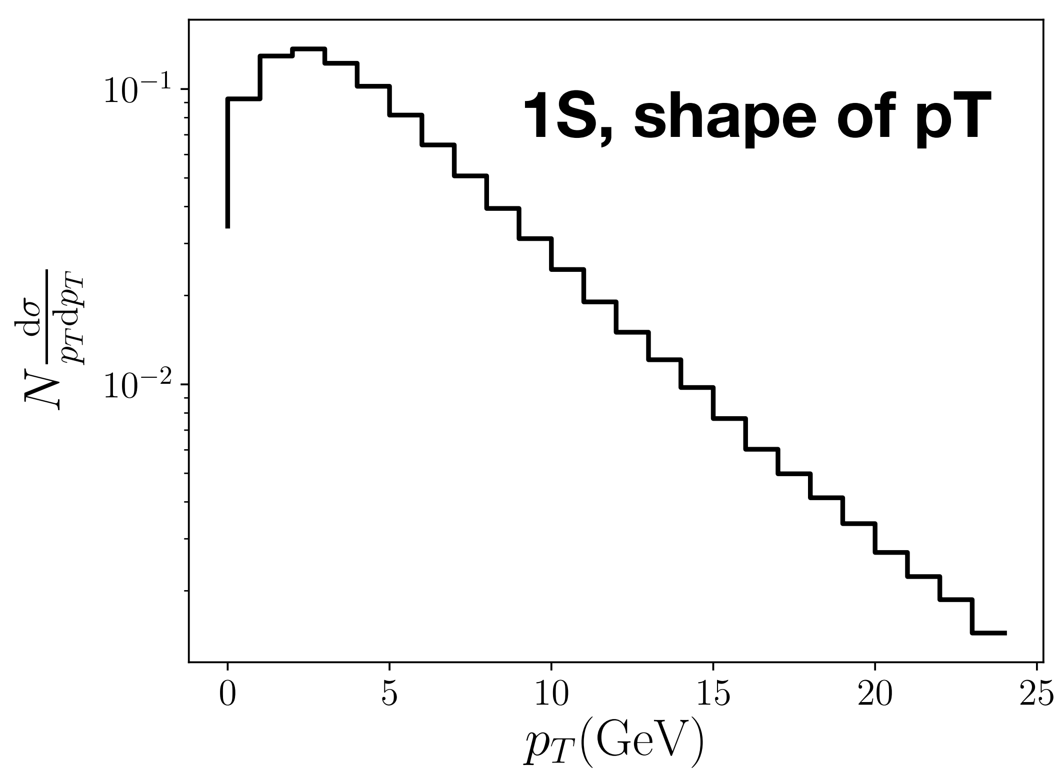
Sjostrand, et al, Comput. Phys.Commun.191 (2015) 159
Bodwin, Braaten, Lepage Phys. Rev. D 51, 1125 (1995)

Nuclear PDF: EPS09 (cold nuclear matter effect)

Eskola, Paukkunen, Salgado, JHEP 0904 (2009) 065

Trento, sample position, production probability proportional to N_bin

Moreland, Bernhard, Bass, Phys. Rev. C 92, no. 1, 011901 (2015)



2S has similar shape

Assume CNM effect is constant in pT

Initial cross section ratio 1S:2S roughly 4:1

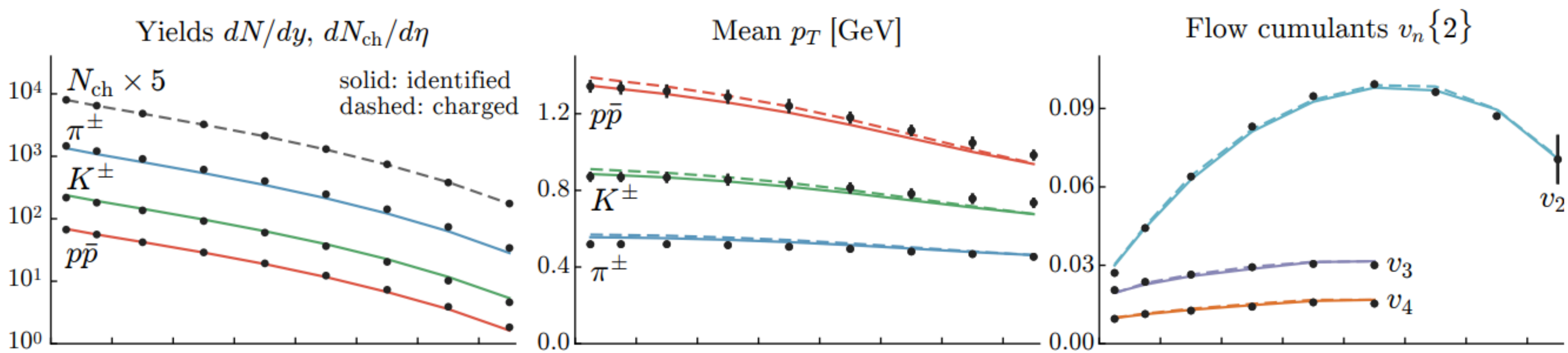
Hydro Background: Trento + VISHNEW

- **VISHNEW**: 2+1D viscous hydro; **Trento**: initial condition model

$$T_{A,B}(x,y) = w_{A,B} \int dz\, \rho_{A,B}(x,y,z) \qquad T_R(p;T_A,T_B) \equiv \left(\frac{T_A^p + T_B^p}{2}\right)^{1/p}$$

$$dS/dy\,|_{\tau=\tau_0} \propto T_R(p;T_A,T_B) \qquad (\eta/s)(T) = \begin{cases} (\eta/s)_{\min} + (\eta/s)_{\text{slope}}(T-T_c) & T > T_c \\ (\eta/s)_{\text{hrg}} & T \leq T_c \end{cases}$$

- Use machine learning (Bayesian analysis) to fit parameters with light particle observables



Song, Heinz, Phys.Rev.C77,064901(2008)
Shen, Qiu, Song, Bernhard, Bass, Heinz, Comput. Phys. Commun.199,61 (2016)
Bernhard, Moreland, Bass, Liu, Heinz, Phys. Rev. C 94,no.2,024907(2016)

Open Heavy Flavor Transport: Lido

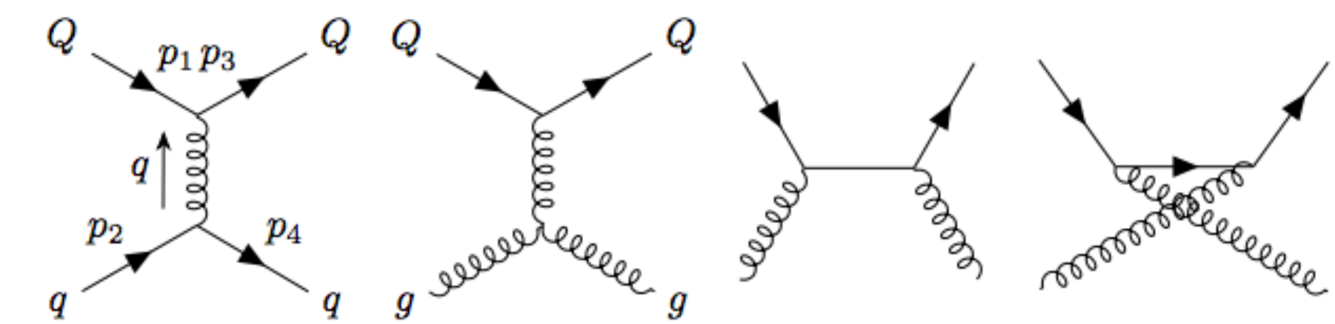
- **Lido**: linearized Boltzmann + Langevin

Ke, Xu, Bass, Phys.Rev. C98 (2018) no.6, 064901

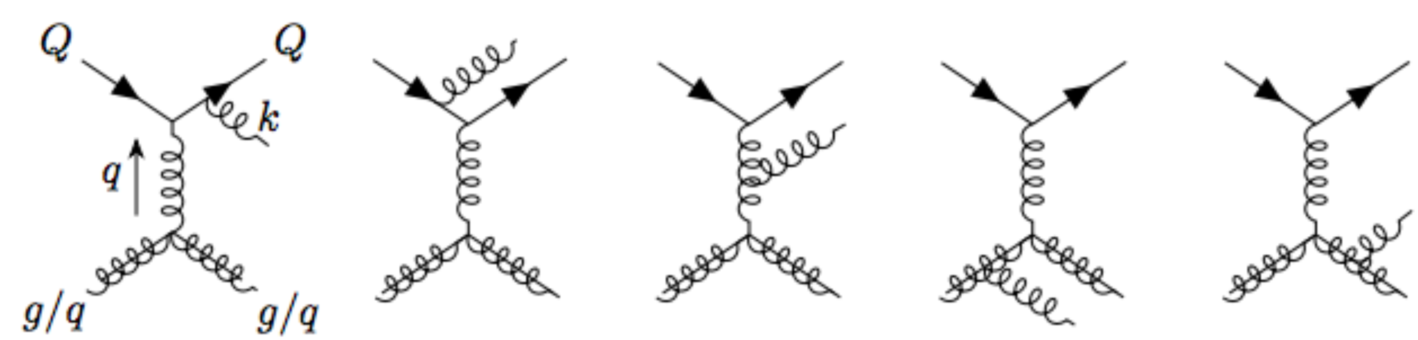
- We only use linearized Boltzmann part for quarkonium phenomenology

$$\frac{p\cdot\partial f_Q}{E} = \mathcal{C}[f_Q]$$

2—>2



2—>3 and 3—>2



LPM effect:

$$dk^3/2k \to 2\left(1-\cos\left((t-t_0)/\tau_f\right)\right) dk^3/2k,$$

$$\tau_f = \frac{2x(1-x)E}{k_\perp^2 + x^2M^2 + (1-x)m_D^2/2}, x = \frac{k+k_z}{E+p_z}$$

Open Heavy Flavor Transport: Lido

- Use Bayesian analysis, Calibration with RAA and v2 of open heavy mesons (Boltzmann + Langevin)

Ke, Xu, Bass, Phys.Rev. C98 (2018) no.6, 064901

- Should redo calibration with only Boltzmann part

When to start HQ energy loss

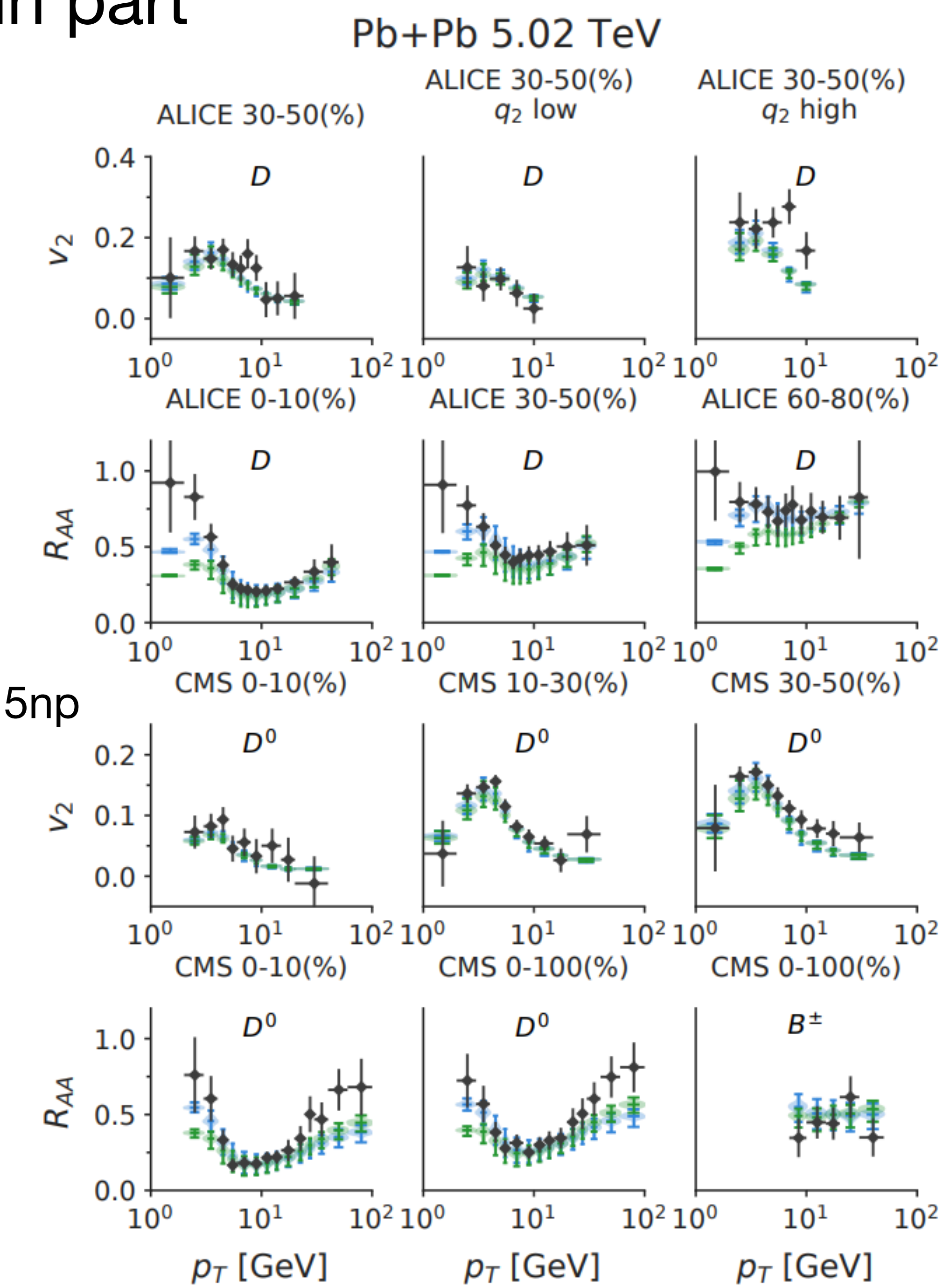
Parameters	τ_0 [fm/c]	μ	κ_D	x_D
Values	0.9	0.6	0.4	0.5

$$\alpha_s[\max(Q, \mu\pi T)]$$

HQ diffusion coefficient

$$\frac{\kappa}{T^3} = \kappa_D \left(x_D + (1 - x_D) \frac{\mathrm{GeV}^2}{ET} \right)$$

blue: EPPS
green: nCTEQ15np



Numerical Implementation

- **Test particle Monte Carlo** $f(\boldsymbol{x}, \boldsymbol{p}, t) = \sum_i \delta^3(\boldsymbol{x} - \boldsymbol{y}_i(t))\delta^3(\boldsymbol{p} - \boldsymbol{k}_i(t))$

- Each time step: read in hydro-cell velocity, temperature; consider open HQ scattering, dissociation, recombination in particle's rest frame, boost back

- If specific process occurs, sample incoming medium particles and outgoing particles from differential rates, conserving energy momentum

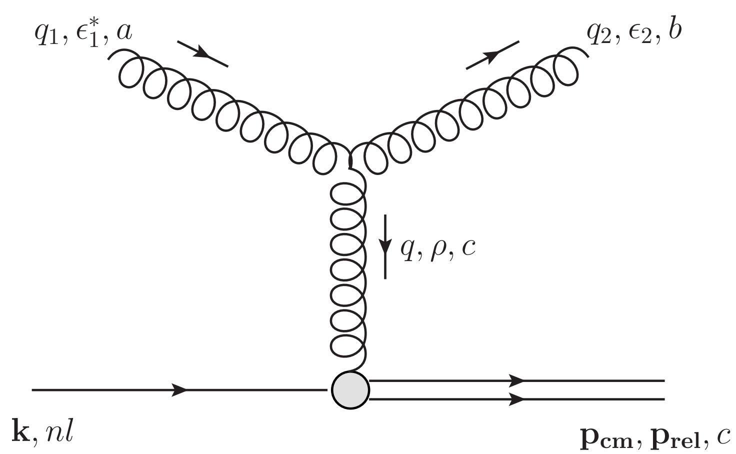
- Recombination term contains $f_Q(\boldsymbol{x}_1, \boldsymbol{p}_1, t) f_{\bar{Q}}(\boldsymbol{x}_2, \boldsymbol{p}_2, t)$

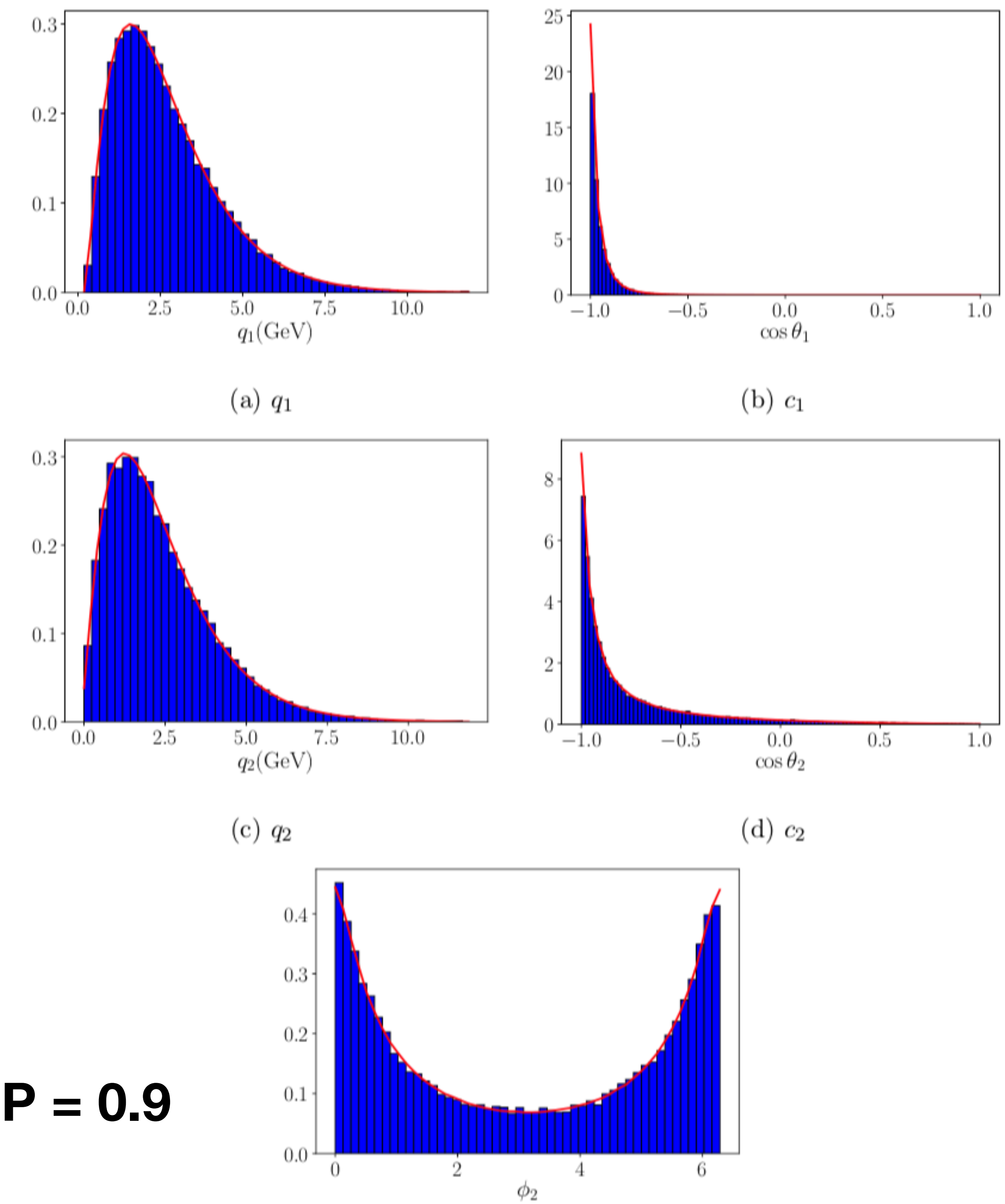
For each HQ, search anti-HQ within a radius, weighted sum

$$f_Q(\boldsymbol{x}_1, \boldsymbol{p}_1, t) f_{\bar{Q}}(\boldsymbol{x}_2, \boldsymbol{p}_2, t) = \sum_{i,j} \frac{e^{-(\boldsymbol{y}_i - \bar{\boldsymbol{y}}_j)^2/2a_B^2}}{(2\pi a_B)^{3/2}} \delta^3\left(\frac{\boldsymbol{x}_1 + \boldsymbol{x}_2}{2} - \frac{\boldsymbol{y}_i + \bar{\boldsymbol{y}}_j}{2}\right) \delta^3(\boldsymbol{p}_1 - \boldsymbol{k}_i) \delta^3(\boldsymbol{p}_2 - \bar{\boldsymbol{k}}_j)$$

Sampling Reaction Momentum

Sampling v.s. marginal distribution from differential rates





(a) q_1 (b) c_1

(c) q_2 (d) c_2

(e) ϕ_2

relative velocity between Y(1S) and QGP = 0.9

Conclusions

- Coupled transport equations of open and hidden heavy flavors
- Open heavy flavor transport: Lido (calibrate to open heavy meson observables)
- Hydro background: Trento + VISHNEW (calibrate to light particle observables)