Duke QCD Group:
Progress and Plans

- **Heavy Quark Dynamics:**
  - **Langevin with Radiation**
  - **HQ Correlations**
- **Bulk Evolution Models**
- **Model to Data Comparison**

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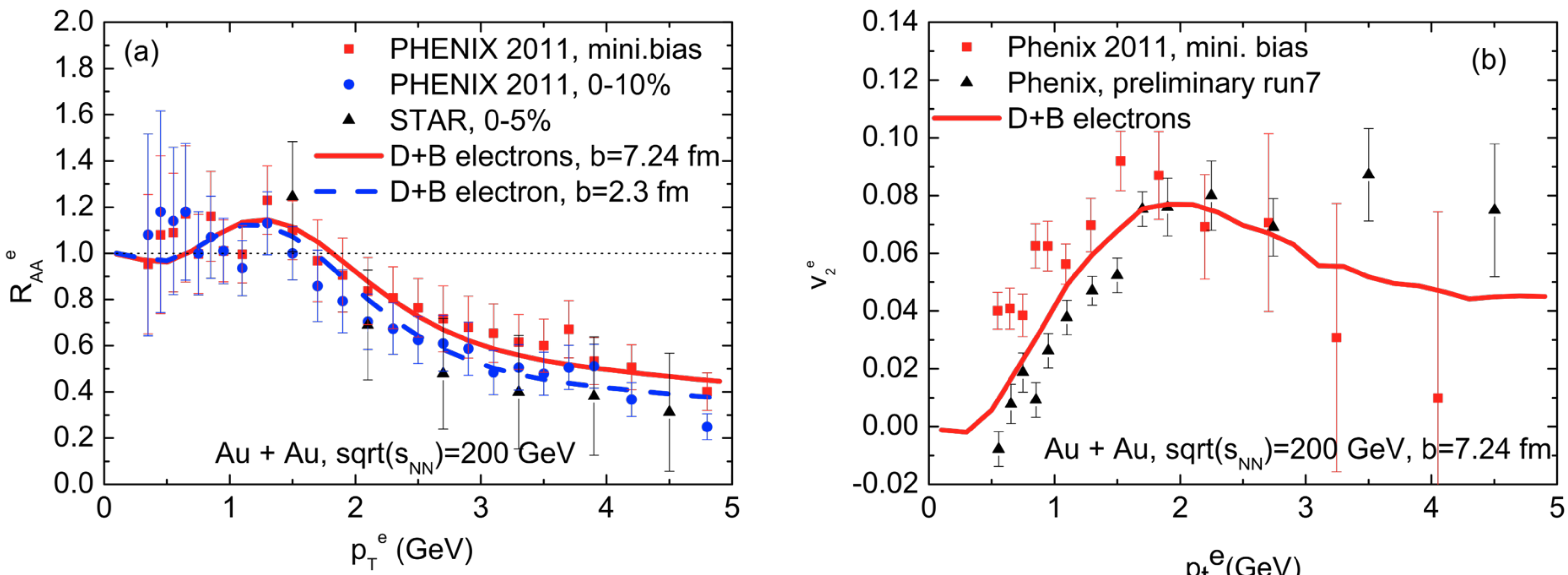
Heavy Quarks in a RFD Medium: Langevin+Radiation

From RHIC to LHC

Current State-of-the-Art:

- Langevin for HQ + coalescence & fragmentation for hadronization + heavy meson diffusion in a hadron gas



He, Fries, Rapp, *Phys. Rev* ***C86****: 014903*, *arXiv:1208.0256*, and private communication with He

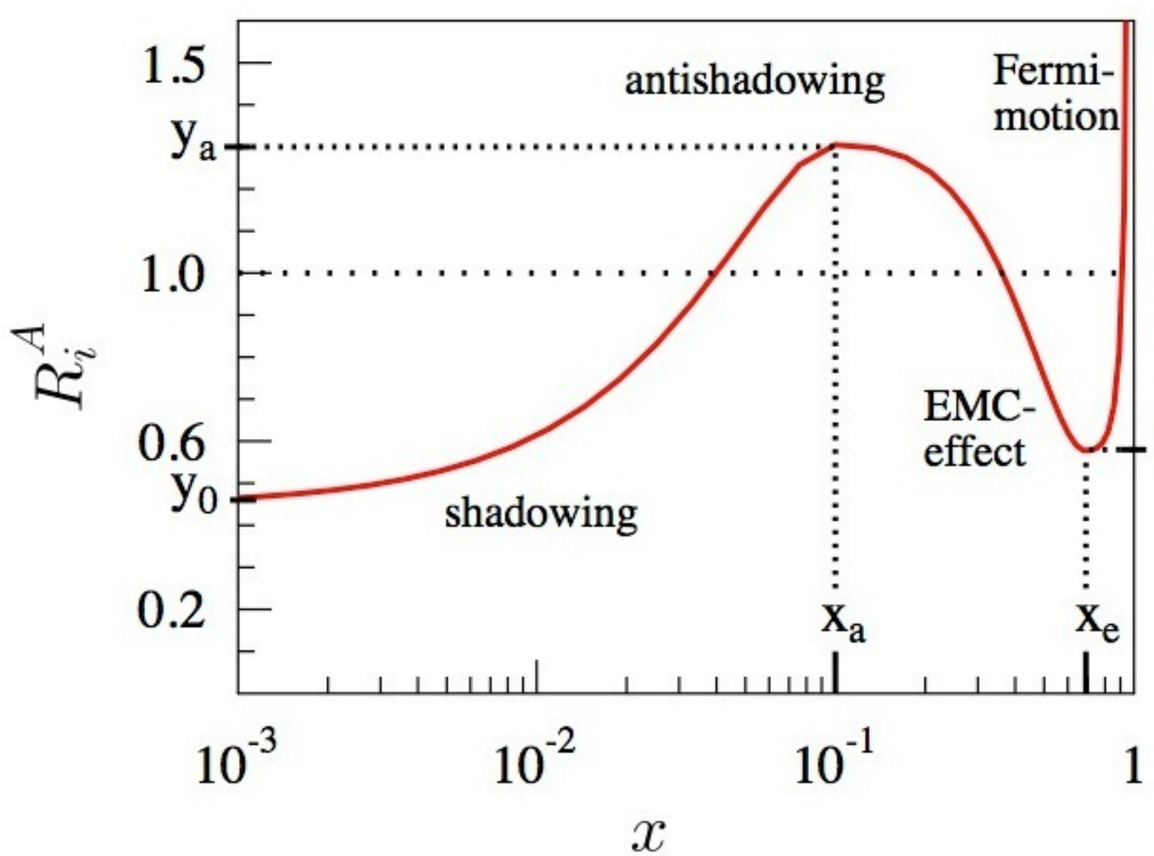
From RHIC to LHC:

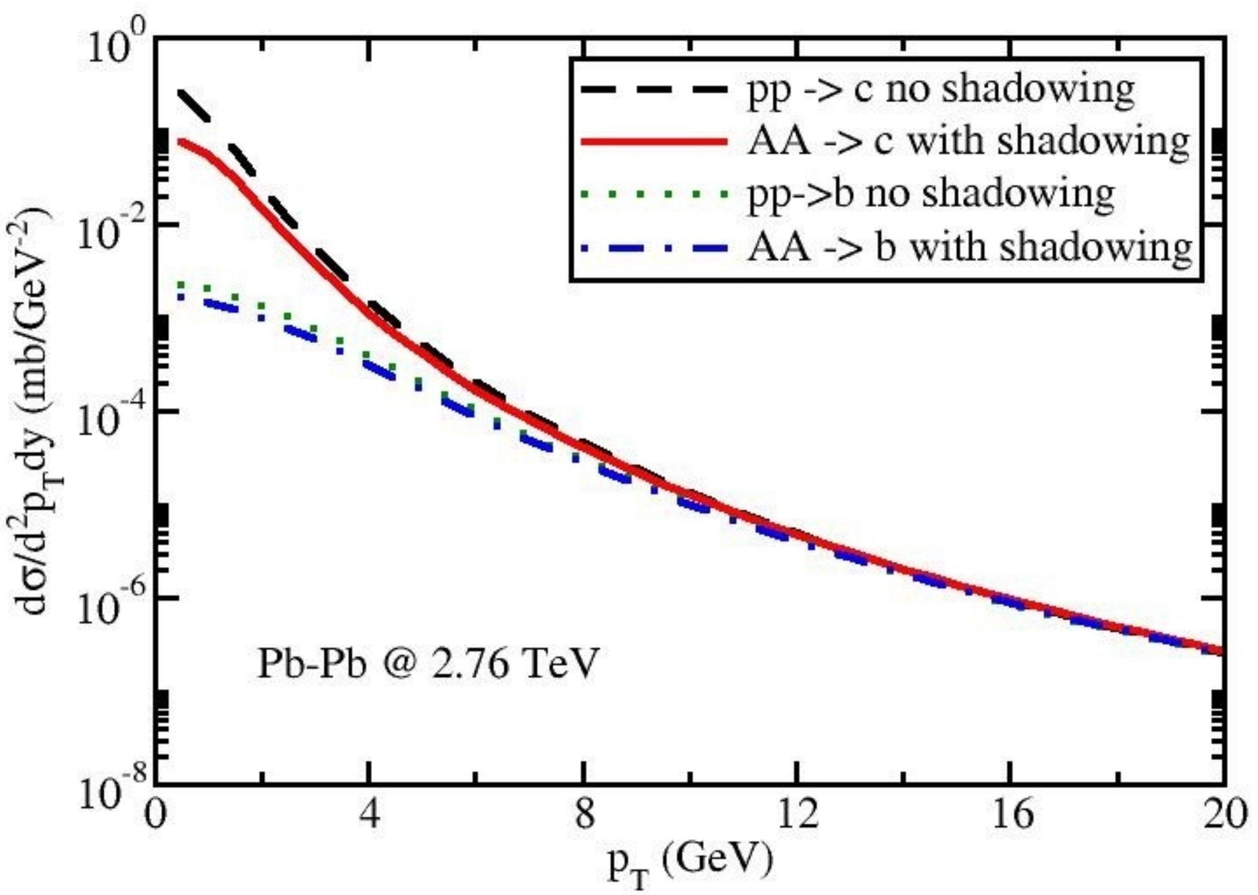
- Heavy Quarks now (partially) ultra-relativistic:
  - radiative energy-loss
  - fragmentation as dominant hadronization mechanism

HQ Initial Conditions

- Initial production: MC-Glauber for the position space and LO pQCD calculation (Combridge,1979) for the momentum space
- Parton distribution functions: CTEQ5 (Lai, 2000)
- Nuclear shadowing effect: EPS09 (Eskola, 2009)

(Taken from Eskola 2009)





Significant shadowing effect for heavy quark production at low p_T (especially at the LHC energy) → impact on R_{AA}

Langevin with Radiative Processes

modify Langevin Eqn. with force term due to gluon radiation:

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

radiation force defined through rate of radiated gluon momenta:

$$\vec{f}_g = \frac{d\vec{p}}{dt}$$

- same noise correlator and fluctuation-dissipation relation still hold:

$$\eta_D(p) = \frac{\kappa}{2TE} \quad \text{and} \quad \langle \xi^i(t)\,\xi^j(t')\rangle = \kappa\,\delta^{ij}\,\delta(t-t')$$

- gluon radiation calculated in Higher Twist formalism:

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

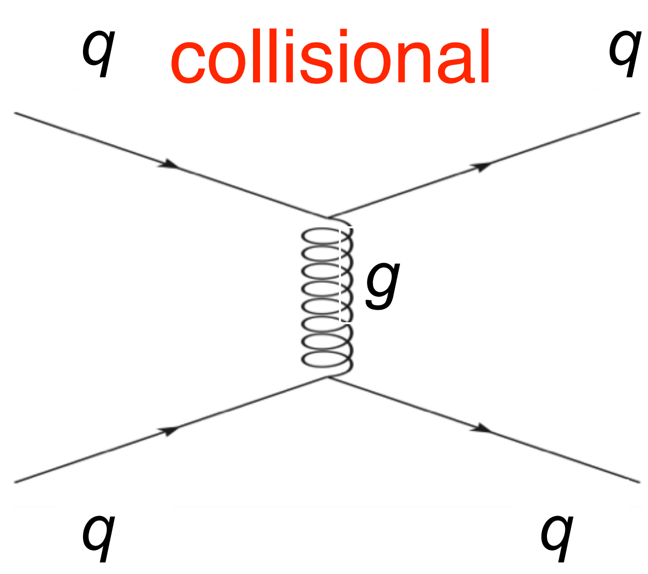
Guo & Wang: *PRL 85, 3591*
Majumder: *PRD 85, 014023*
Zhang, Wang & Wang: *PRL 93, 072301*

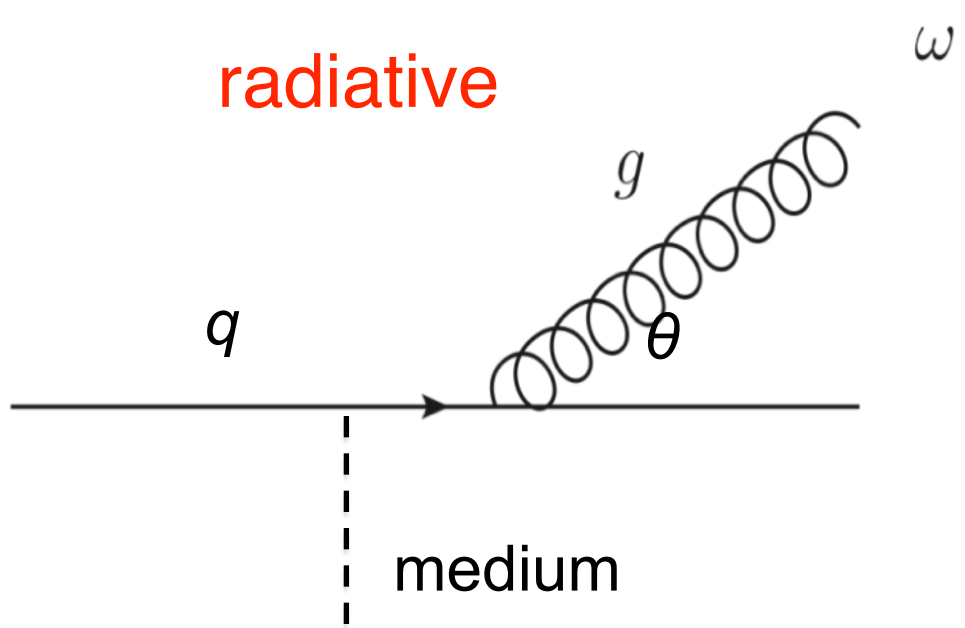
- relevant transport coefficients are now:

$$D = \frac{t}{M\eta_D(0)} = \frac{2T^2}{\kappa} \quad \text{and} \quad \hat{q} = 2\,\kappa\,C_A/C_F$$

Radiative vs. Collisional Energy Loss

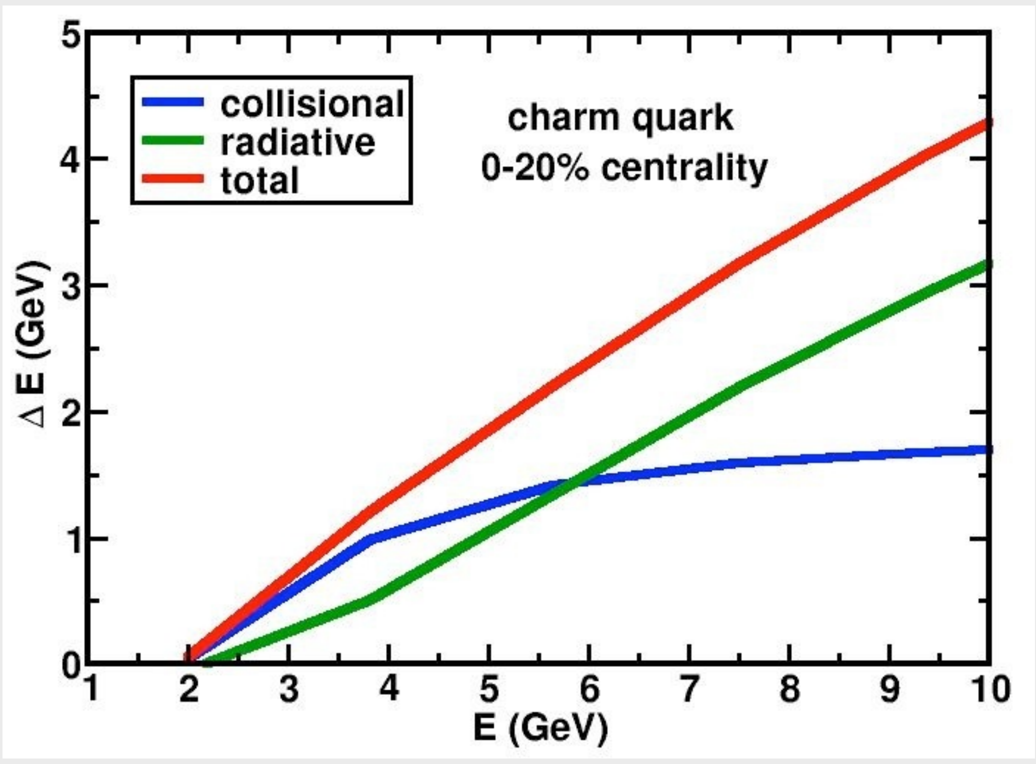
partons propagating through a QGP medium loose energy via two mechanisms:





dominant mechanism depends on parton mass and energy:

- collisional energy-loss: heavy quarks at low momenta
- radiative energy loss: light quarks, gluons & heavy quarks at high momenta
- two-particle correlation observables as discriminators?



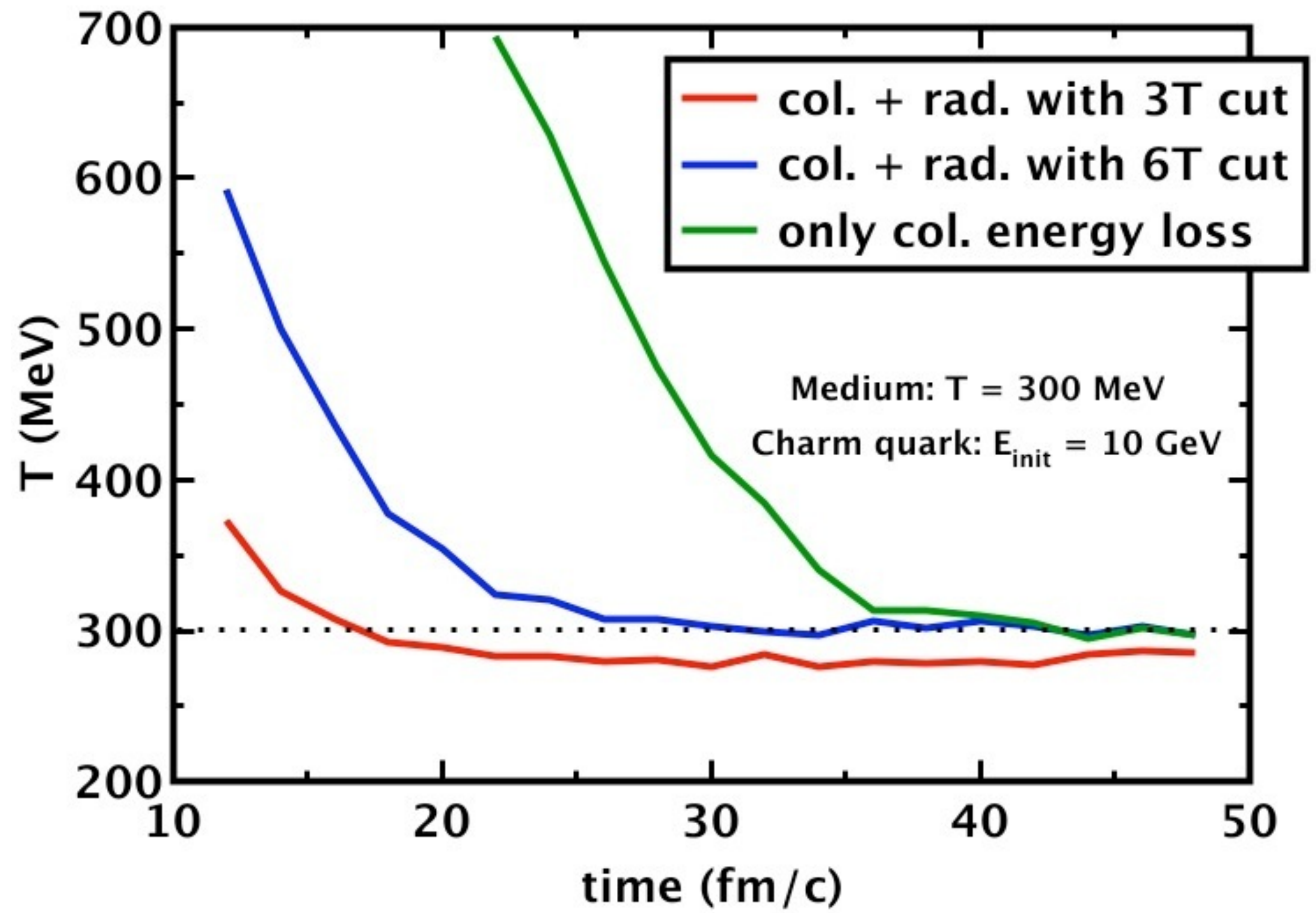
Thermalization in Langevin+Radiation

radiative term in Langevin Equation violates detailed balance:

- radiation should be suppressed for thermal momentum scale
  - introduce low momentum cut-off for gluon radiation: $p_{cut}=\alpha 3T$
- vary parameter α to ensure proper HQ thermalization

thermalization analysis in Langevin+Radiation approach:

- system shows proper thermalization dynamics for α≈2
- note that τ_{therm} may depend on initial HQ momentum distribution
- for this particular set of parameters thermalization time: τ_{therm} is reduced from ≈35 fm/c to ≈25 fm/c (compared to standard Langevin)



HQ Hadronization:

- Recombination + Fragmentation

Hadronization

QGP: Cooper-Frye Freeze-out (OSU iSS)

$$E\frac{dN}{d^3p} = \int_\sigma f(x,p)p^\mu d\sigma_\mu$$

- *f*(*x*,*p*): thermal distribution of soft hadrons
- *σ*: hypersurface of freeze-out

HQ: Fragmentation + Recombination

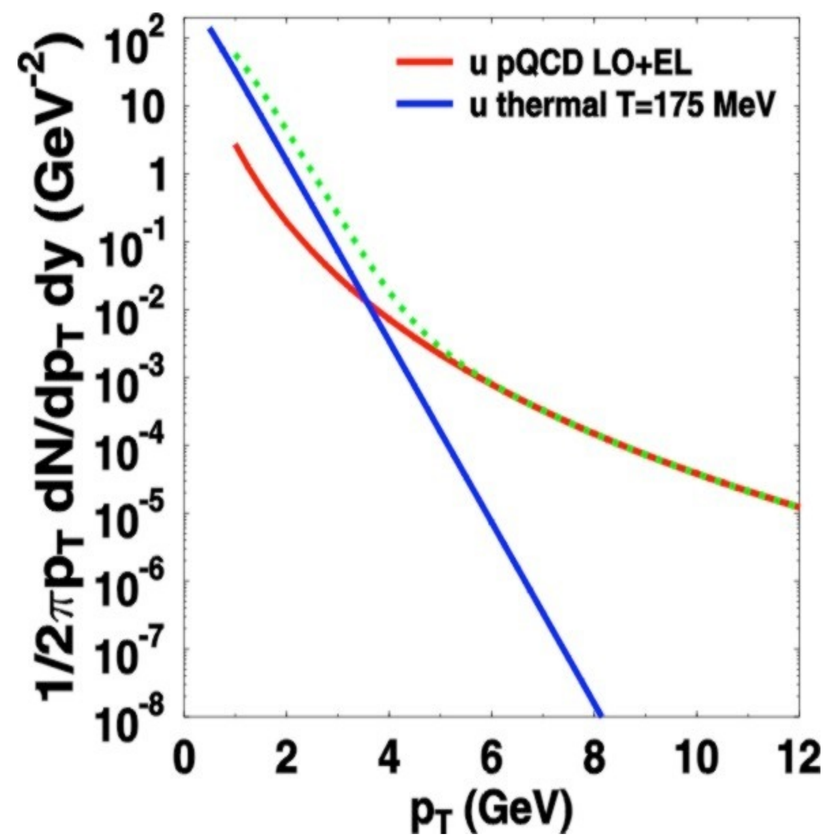
- most high momentum heavy quarks fragment into heavy mesons: use PYTHIA 6.4
- most low momentum heavy quarks hadronize to heavy mesons via recombination (coalescence) mechanism: use the instantaneous coalescence model (Y. Oh, TAMU 2009)

Recombination+Fragmentation Model

basic assumptions:

- at low p_t, the parton spectrum is thermal and HQs recombine with light quarks into hadrons locally "at an instant":

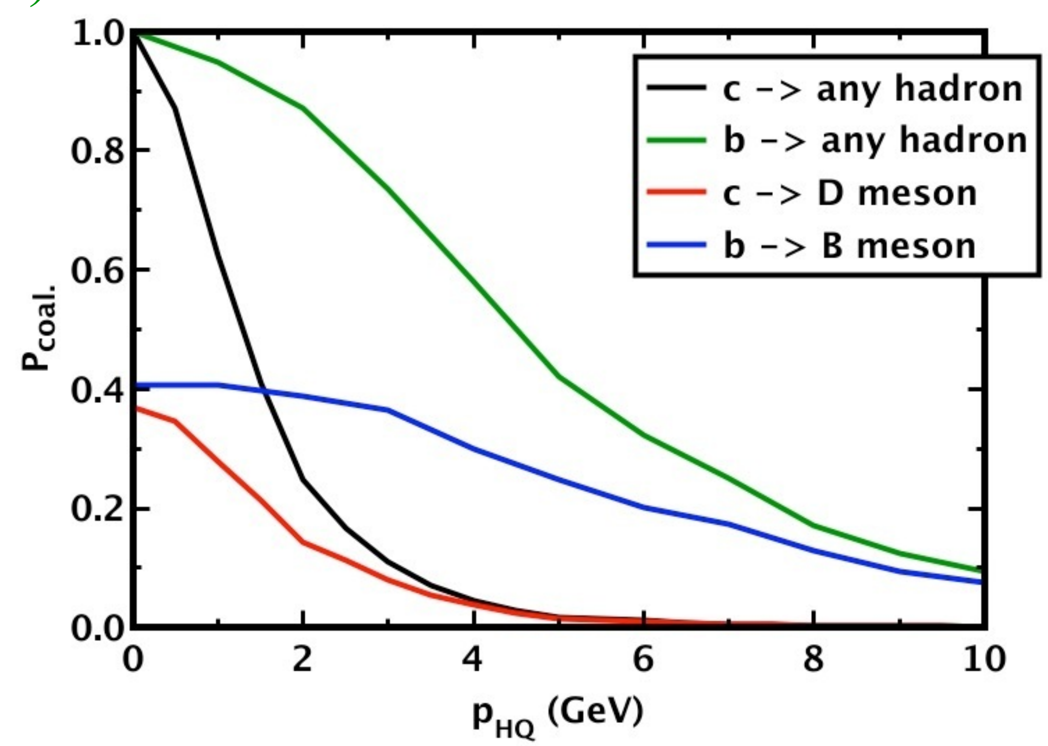
$$\frac{dN_M}{d^3P} = C_M \frac{V}{(2\pi)^3} \int \frac{d^3q}{(2\pi)^3} w\left(\tfrac{1}{2}P - q\right) w\left(\tfrac{1}{2}P + q\right) \left|\hat{\varphi}_M(q)\right|^2$$



- at high p_t, the parton spectrum is given by a pQCD power law, HQs suffer radiative energy loss and hadrons are formed via fragmentation of HQs:

$$E\frac{dN_h}{d^3P} = \int d\Sigma \frac{P\cdot u}{(2\pi)^3} \int_0^1 \frac{dz}{z^2} \sum_\alpha w_\alpha(R, \tfrac{1}{z}P) D_{\alpha\to h}(z)$$

- shape of spectrum determines if reco or fragmentation is more effective:
  - for thermal distribution recombination yield dominates fragmentation yield
  - vice versa for pQCD power law distribution



Hadronic Rescattering

soft hadrons emitted from the QGP

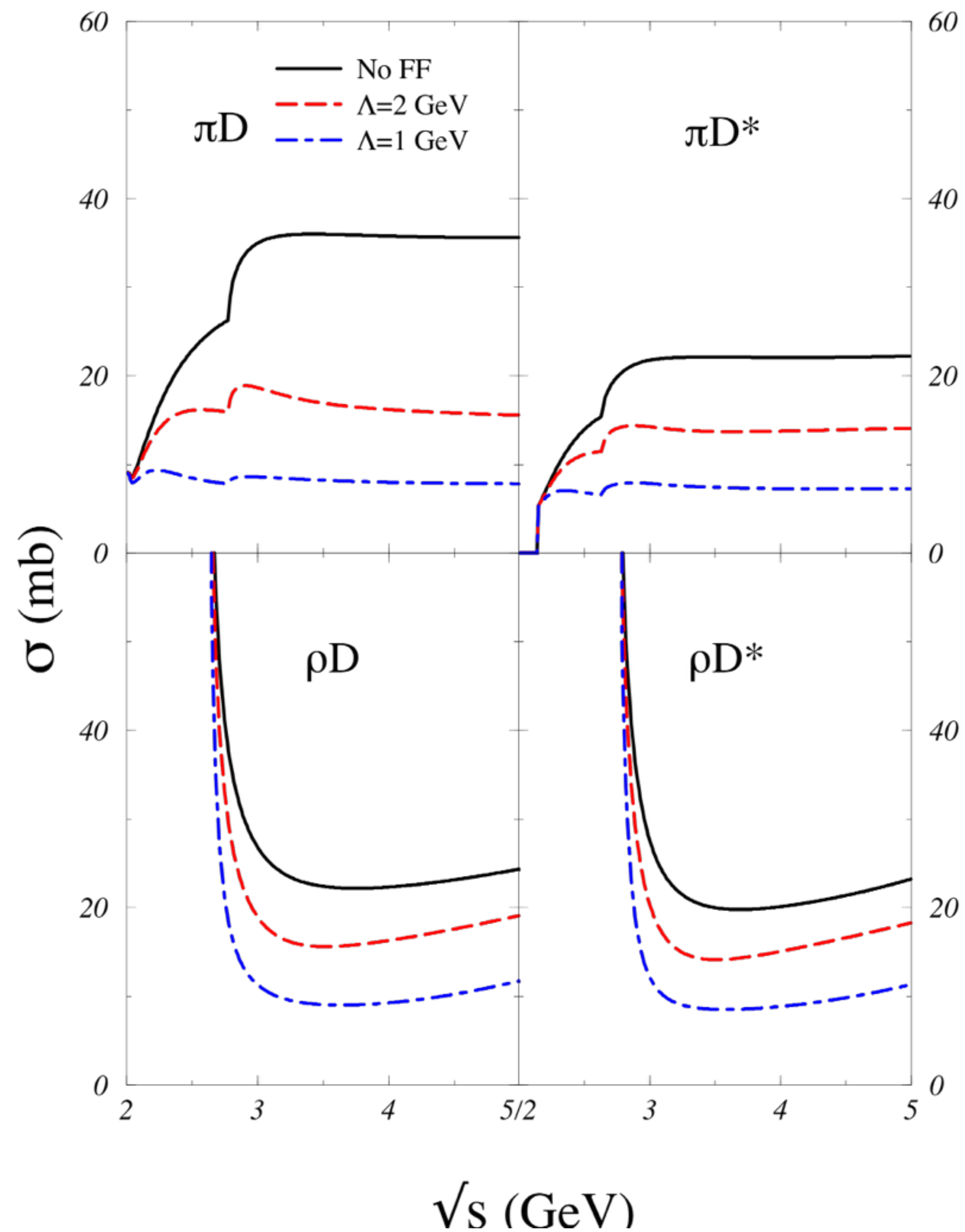
heavy mesons hadronized from heavy quarks

} UrQMD

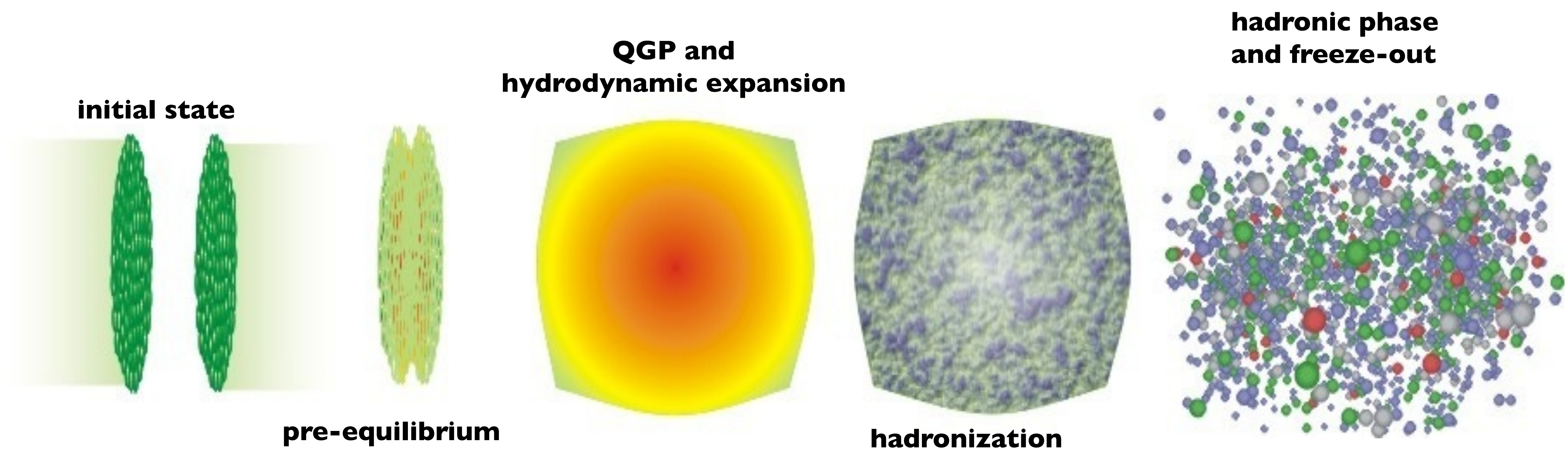
charm meson scattering cross sections:
(Lin and Ko, 2001)

- pion and rho exchange
- Λ: cutoff parameter in hadron form factors

- consider resonance model as alternative (Rapp et al.)



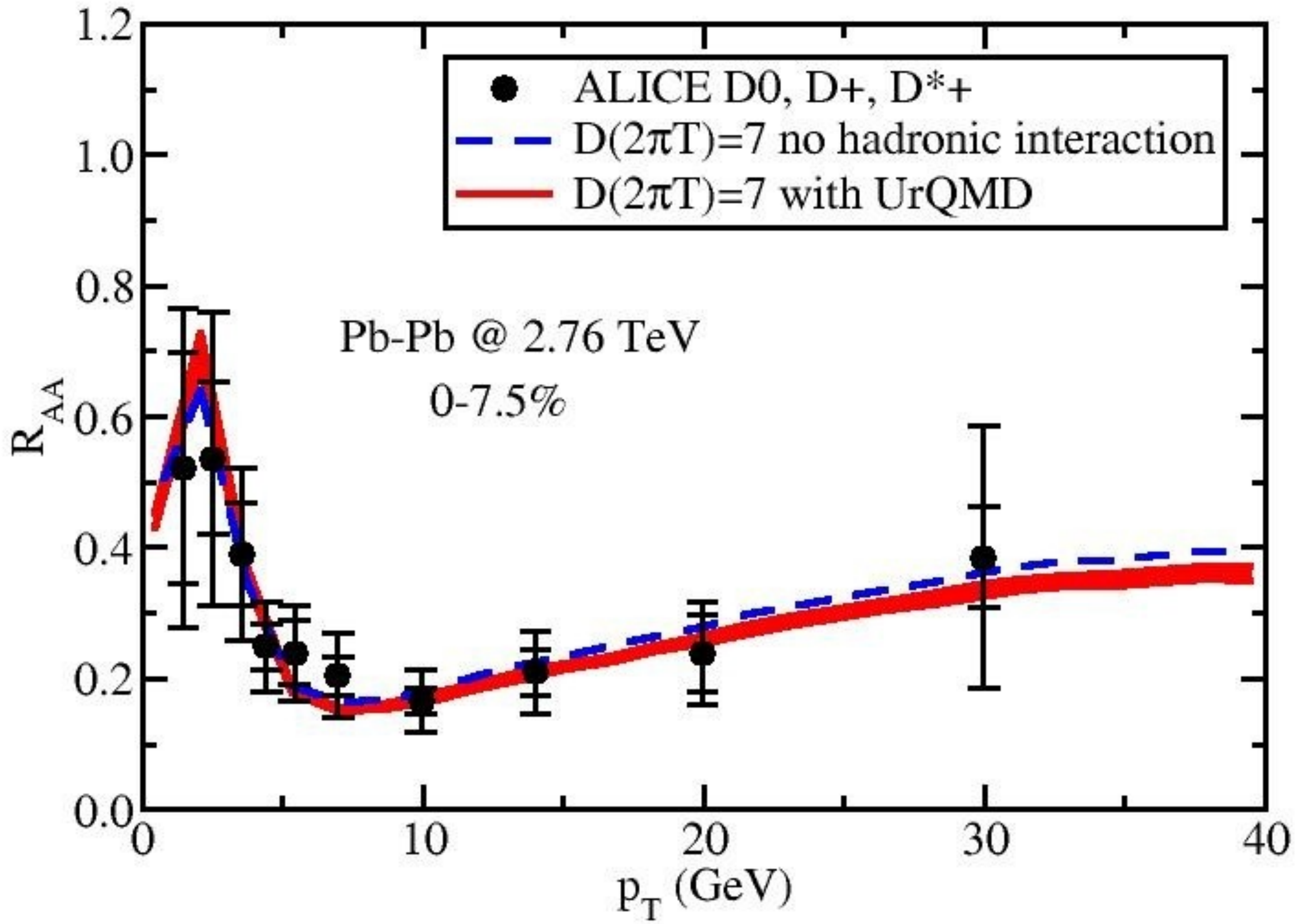
EbE Heavy Quark and Bulk Dynamics



Bulk Matter:	Glb/KLN initial condition	(2+1)-d viscous hydro (OSU)	Cooper-Frye (OSU iSS)	} UrQMD
Heavy Flavor:	Glauber for *x* LOpQCD+CTEQ + EPS09 for *p*	Improved Langevin (col.+rad.)	Hybrid model of frag.+coal.	

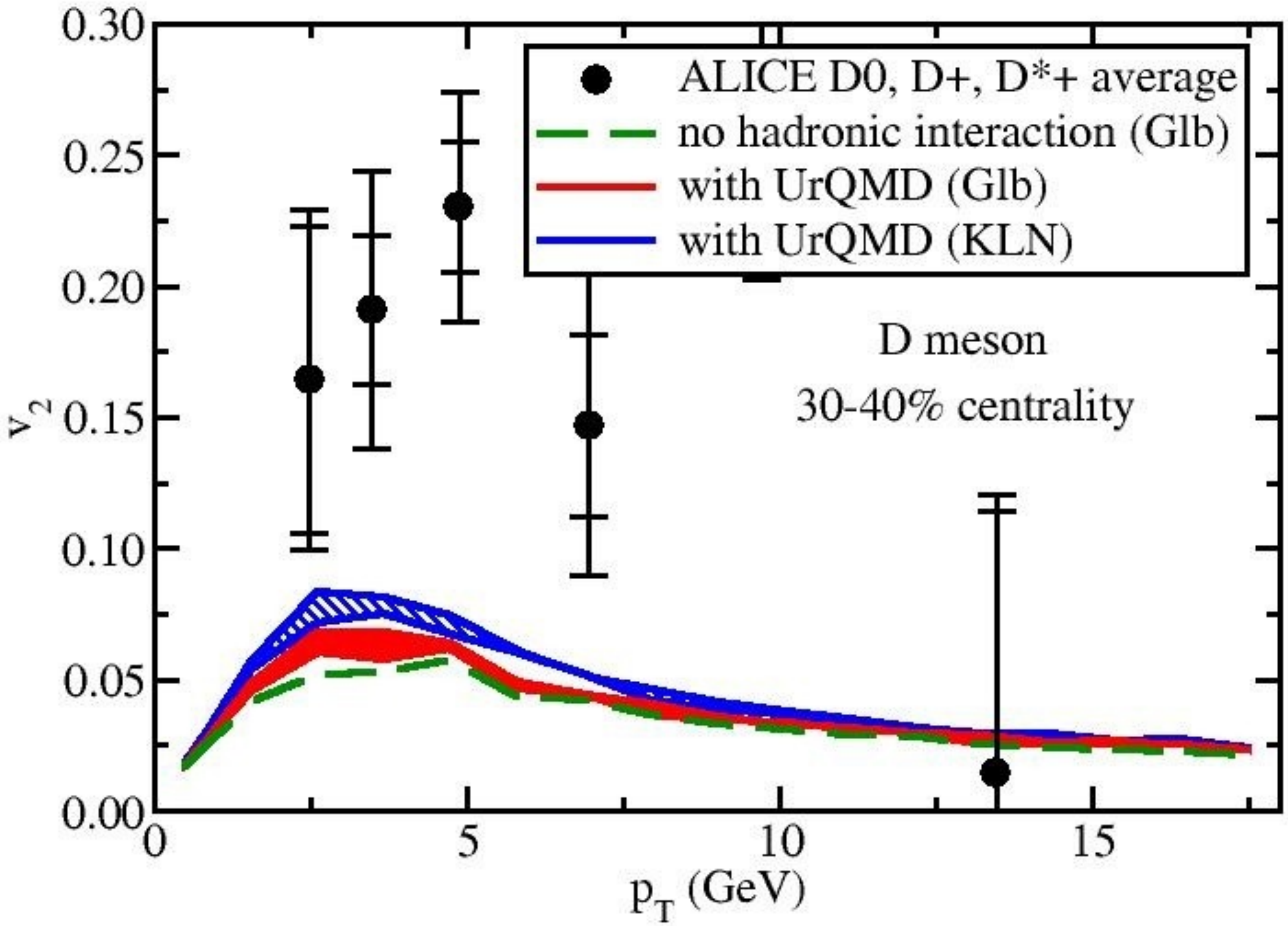
Comparison to Data

Comparison to Data: R_{AA}



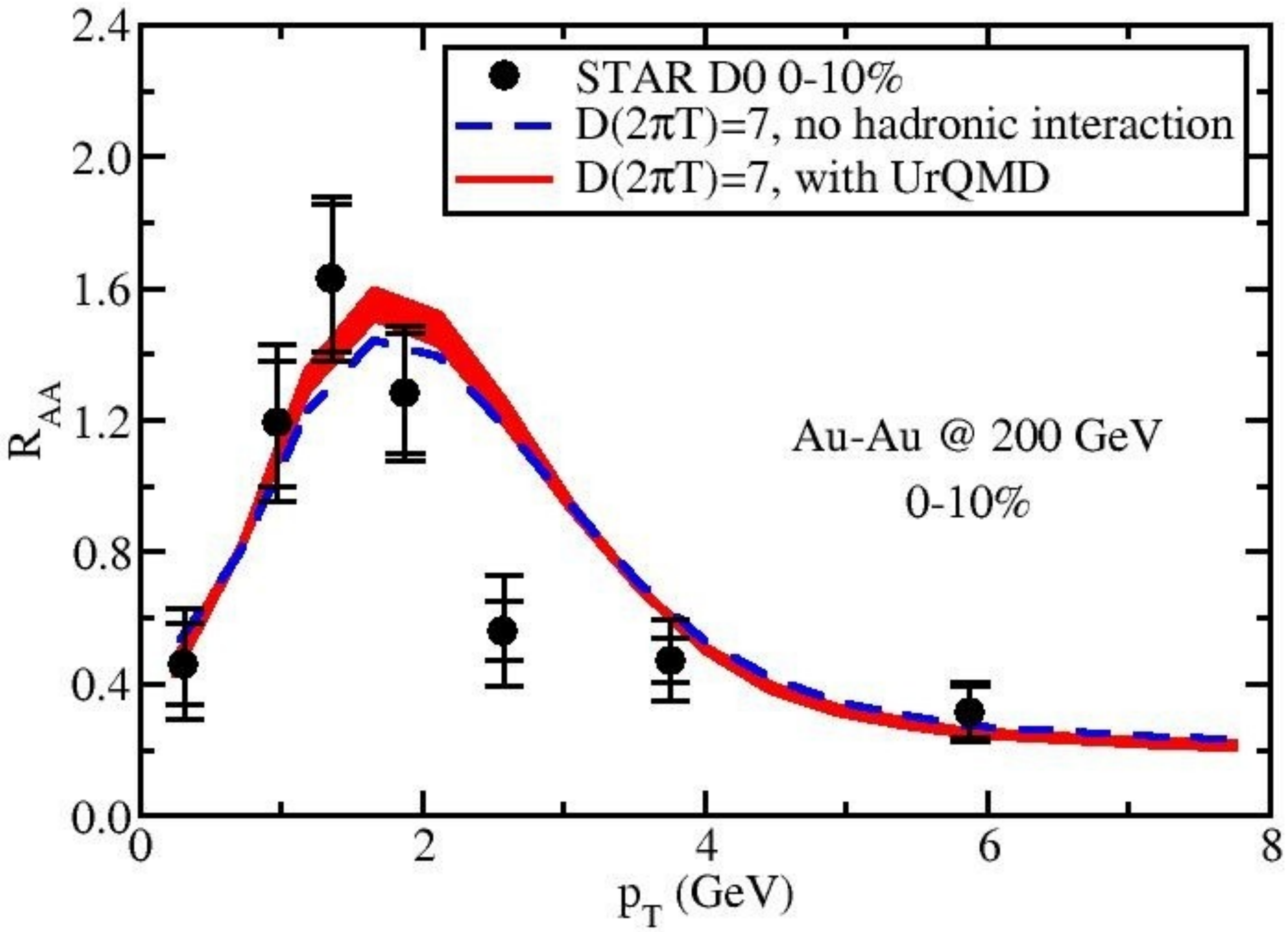
- Hadronic interaction further suppresses R_{AA} at large p_T but slightly enhances it at low p_T
- Good description of the experimental data

Comparison to Data: Elliptic Flow



- hadronic interaction enhances *D* meson v_2 by over 30%
- difference between the Glb to KLN initial condition for hydro leads to another 30% uncertainties in *D* meson v_2
- still under-estimate *D* meson v_2 as measured by ALICE

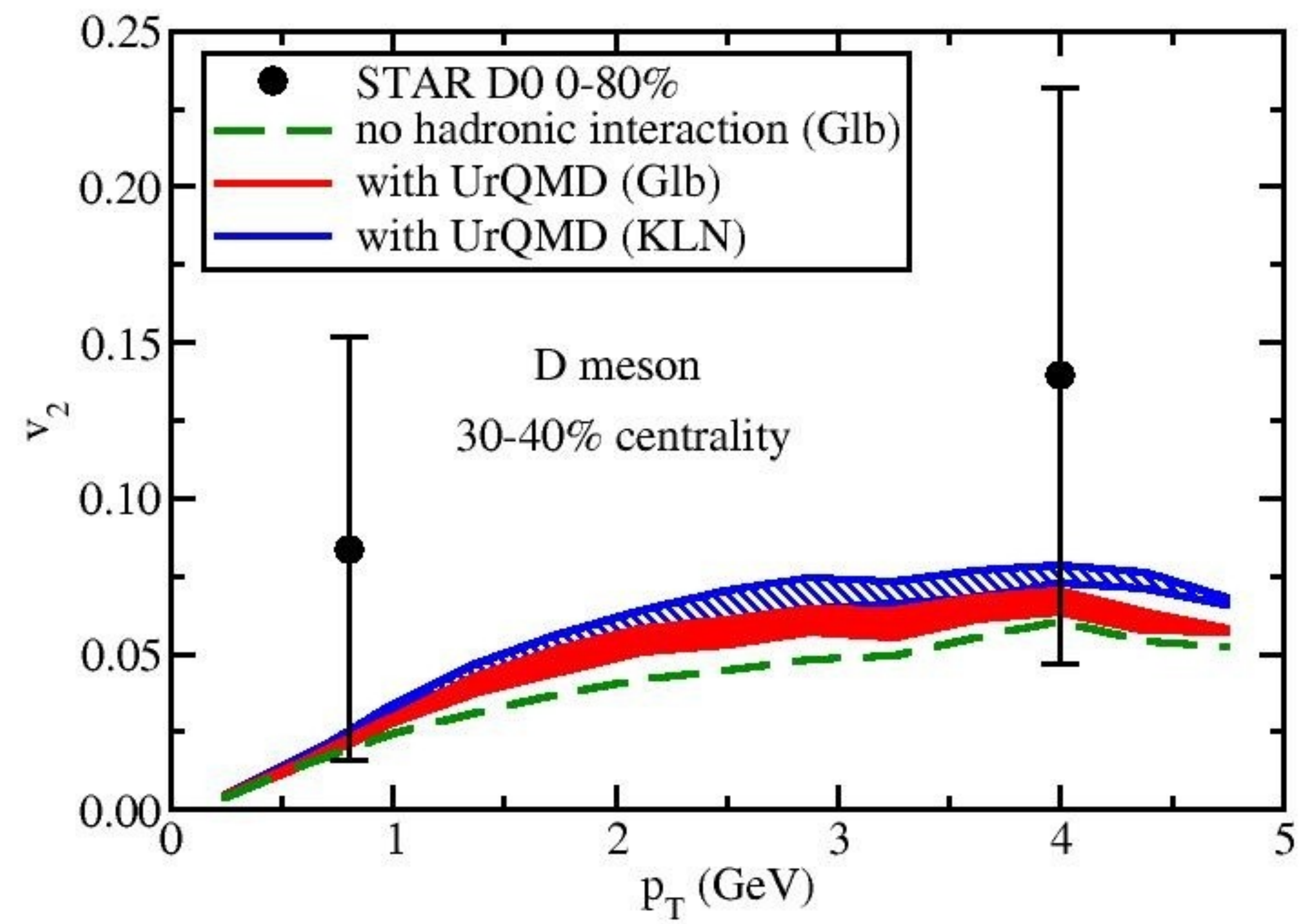
RHIC: D^0 R_{AA} and v_2



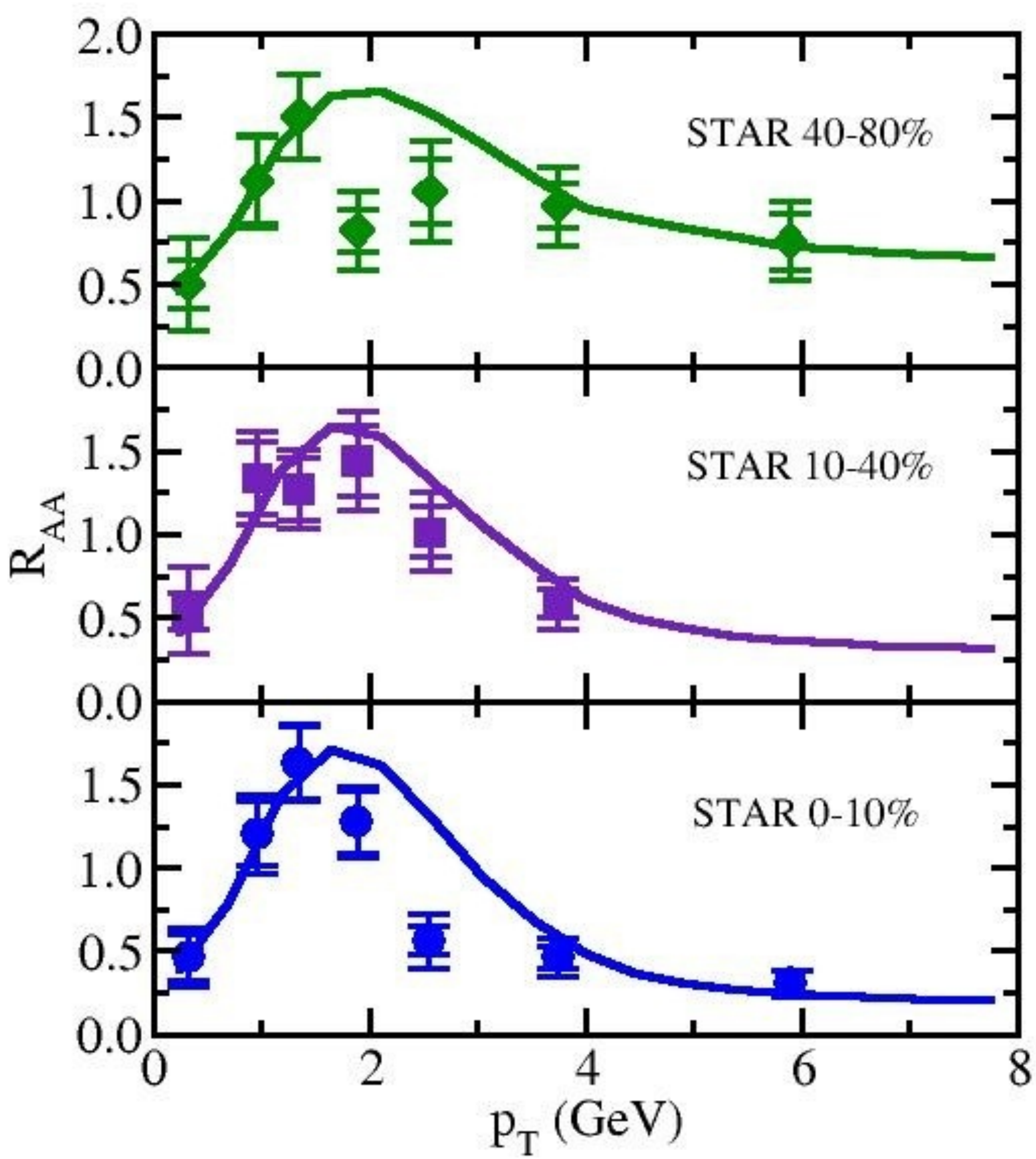
- good agreement with R_{AA} data
- shadowing in PDFs provides a degree of uncertainty

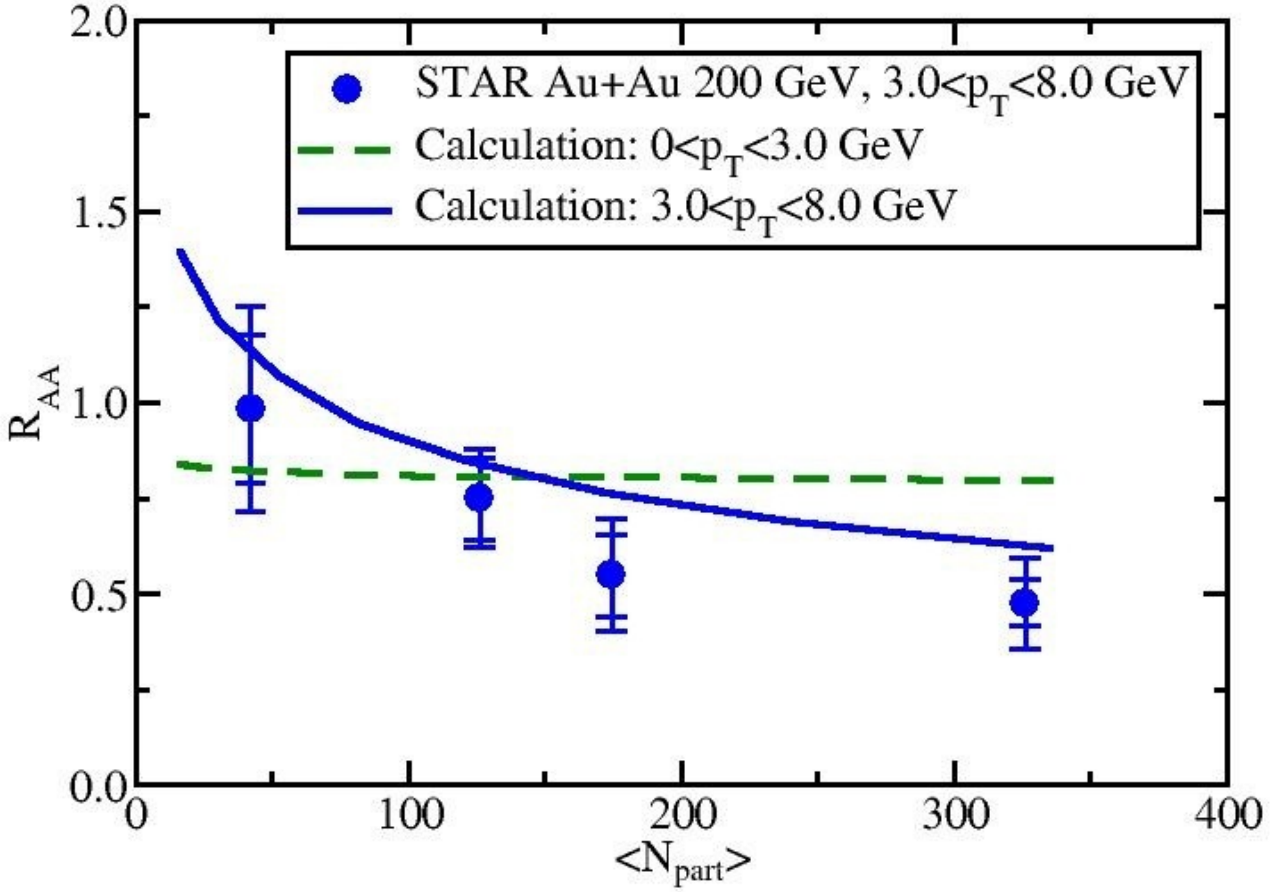
v_2 significantly underpredicted:

- data in p_T domain still dominated by recombination as hadronization mechanism



RHIC: D^0 R_{AA} centrality dependence

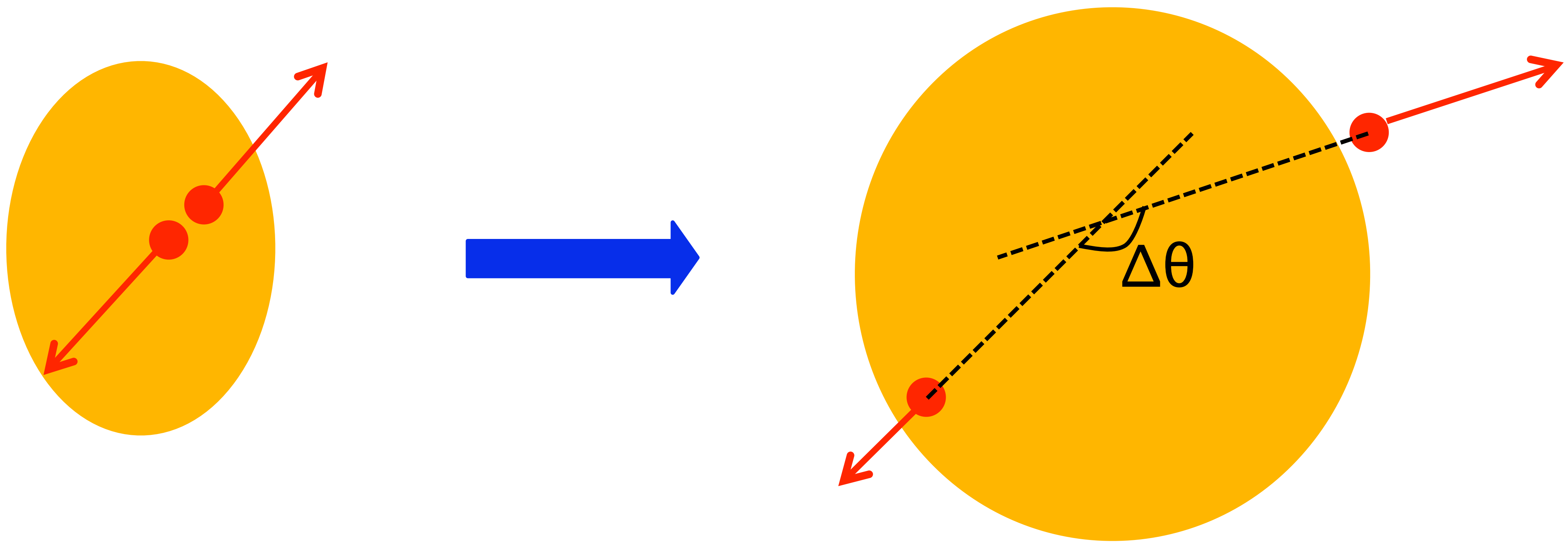




- centrality and participant number dependence consistent with RHIC observations

HQ Correlations

Angular HQ Correlations

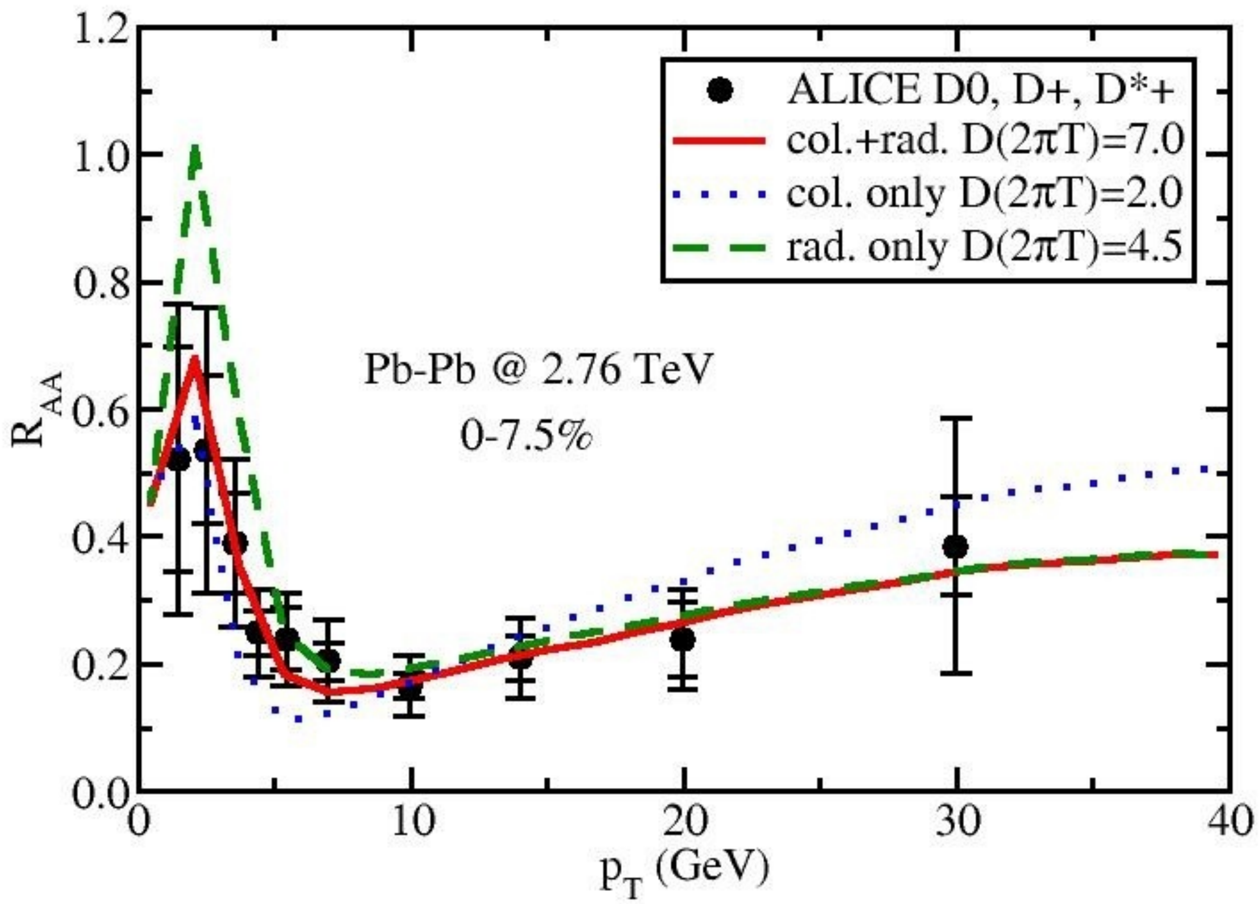


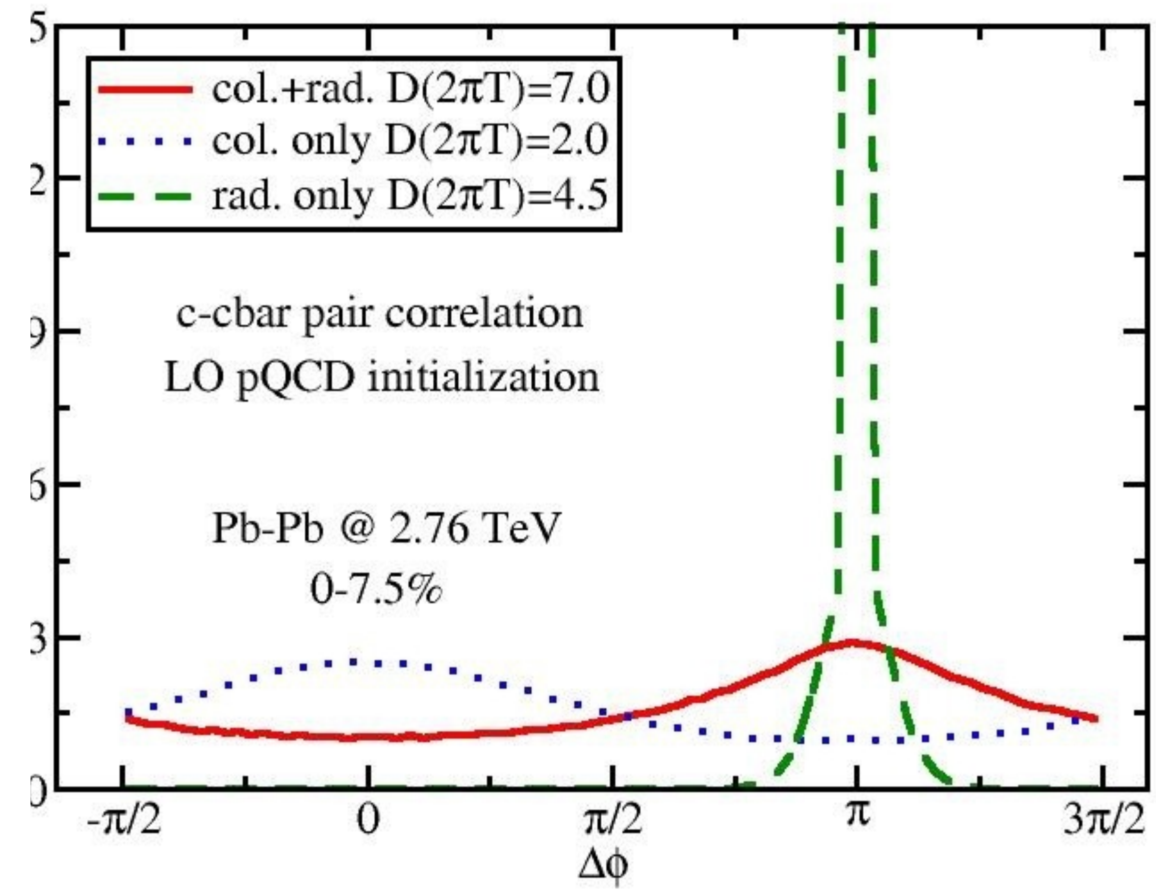
assume back-to-back production of initial Q & Qbar with the same magnitude of momentum

angular correlation of the final state QQbar is sensitive to:

- momentum broadening of heavy quark
- degree of thermalization of heavy quarks
- coupling strength between heavy quarks and the QGP

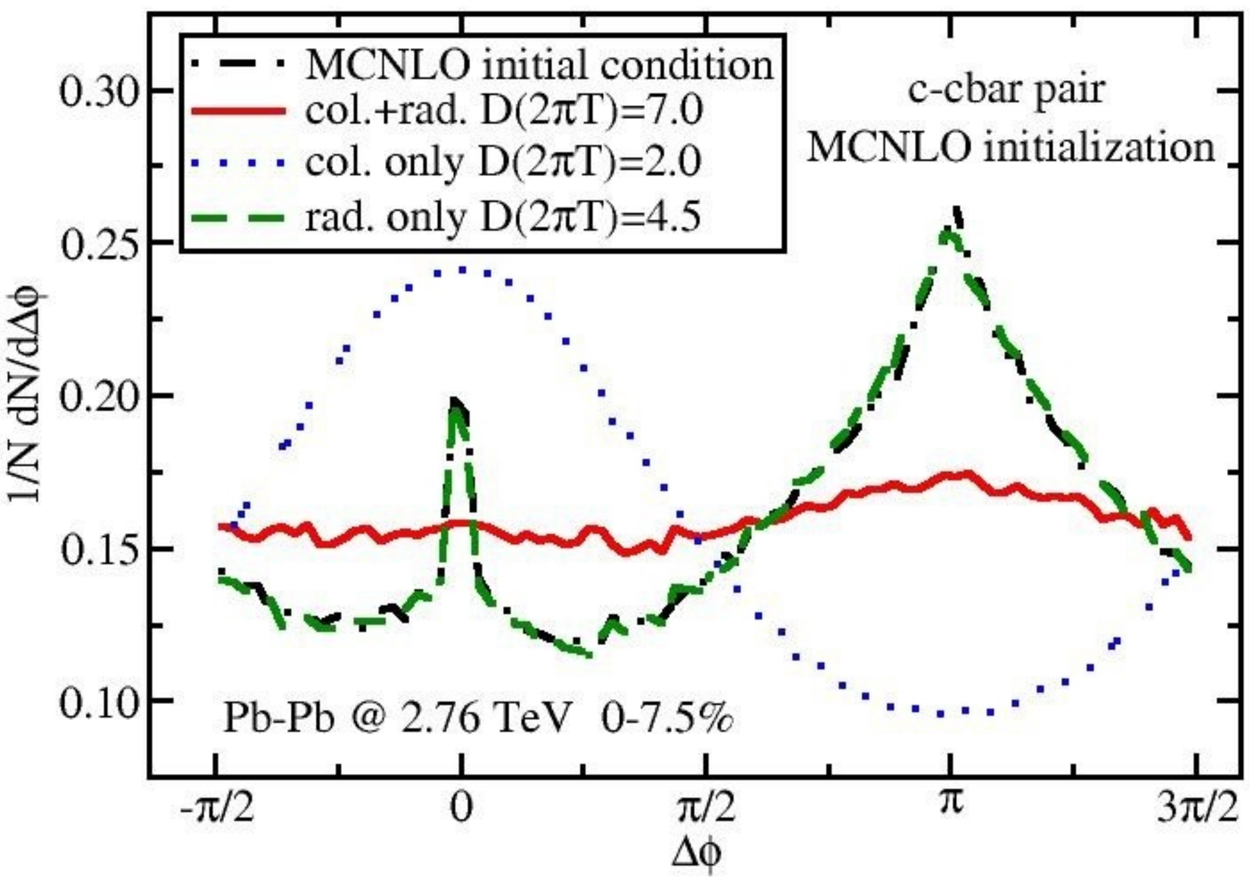
Correlations: Elastic vs. Radiative Processes

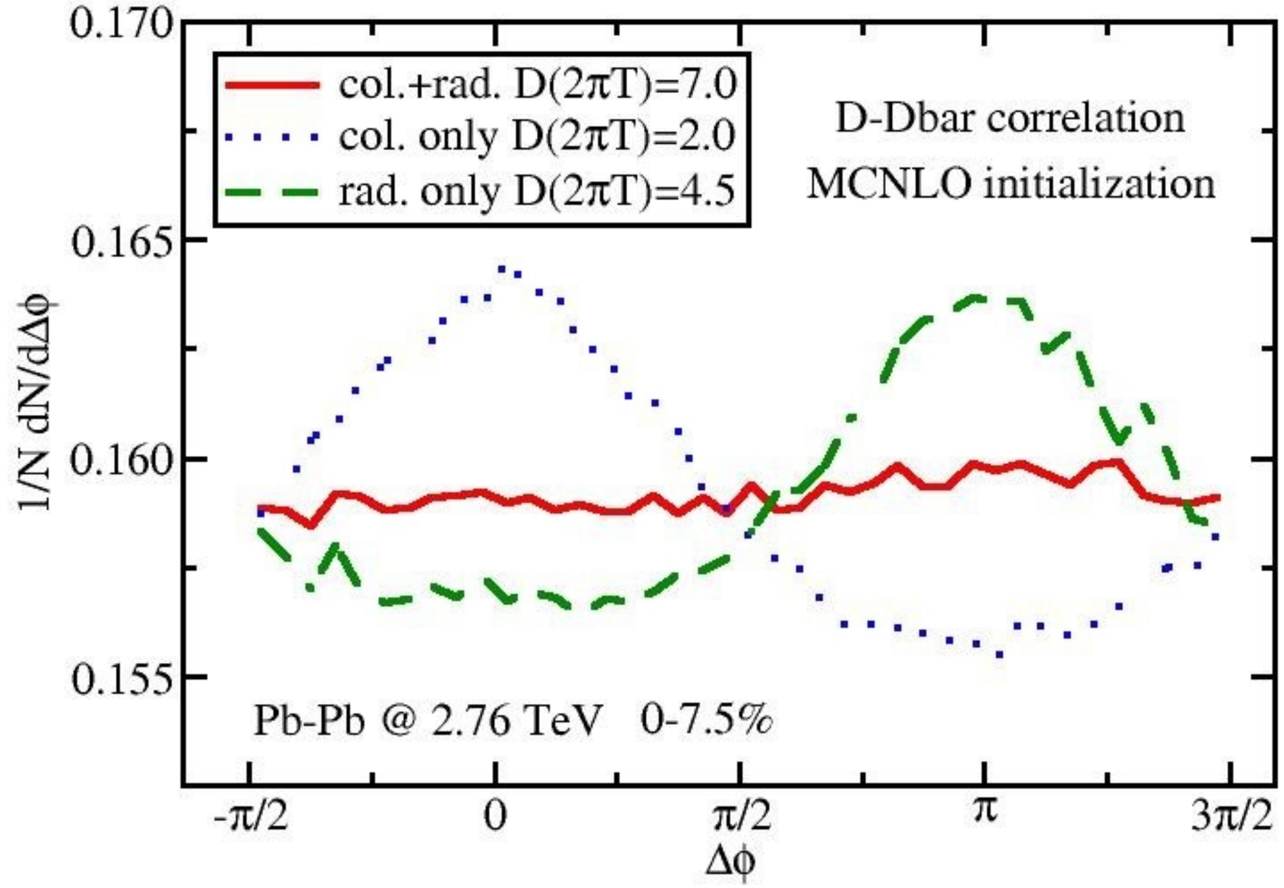




- each energy loss mechanism alone can fit R_{AA} with certain accuracy and choice of diffusion coefficient, yet they display very different behavior in the angular correlation function
- experimental observation may discriminate between the energy loss mechanisms of heavy quarks inside the QGP

Correlations II: D Mesons





- initial HQ production: MCNLO + Herwig
- calculate angular correlation of final state ccbar pairs

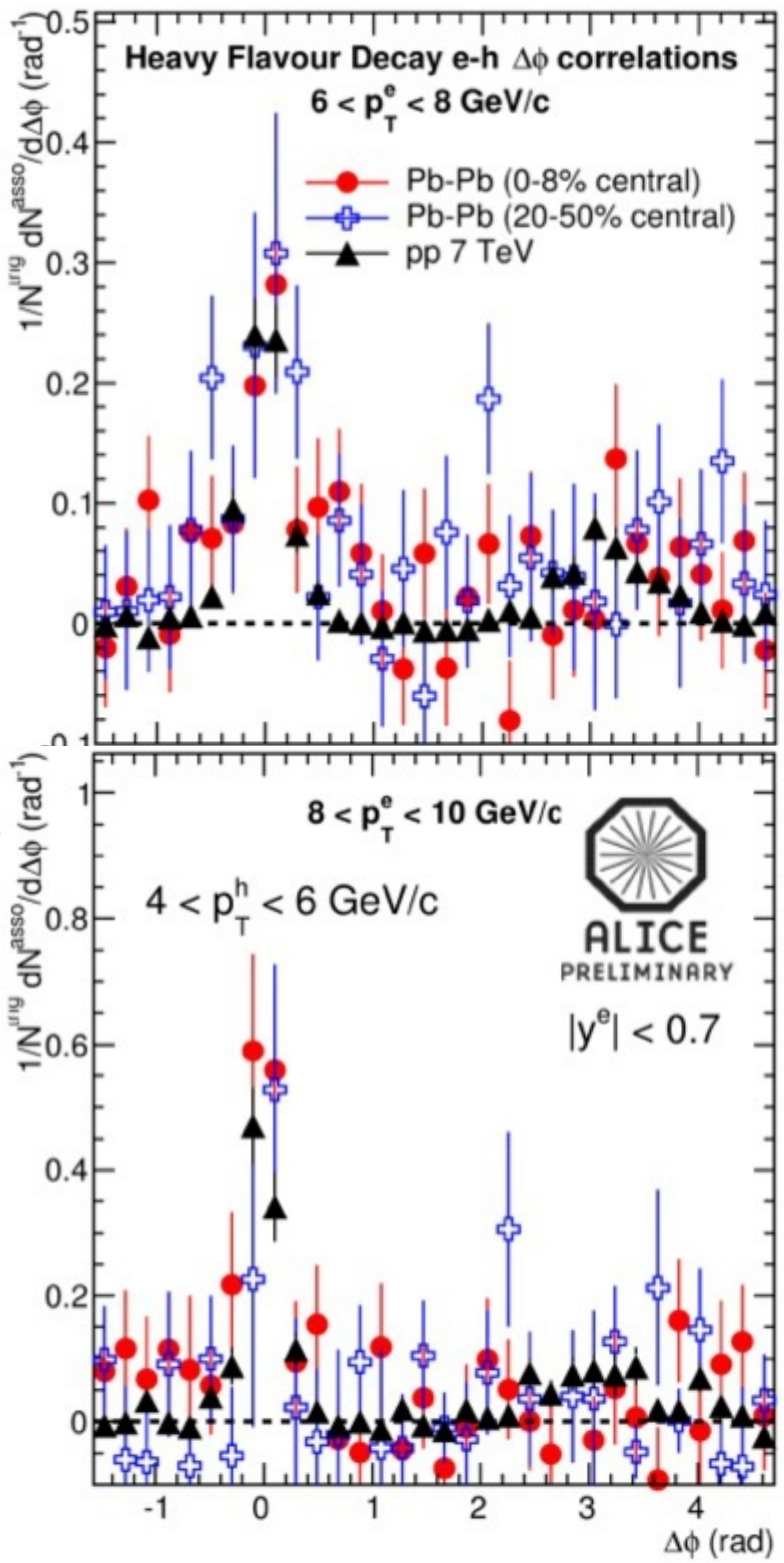
- within each event, correlate each D with all Dbar's
- similar shape as direct ccbar correlation, but on top of a large background

viable signal with good sensitivity to HQ energy loss mechanism if experiments could measure D Dbar angular correlation functions!

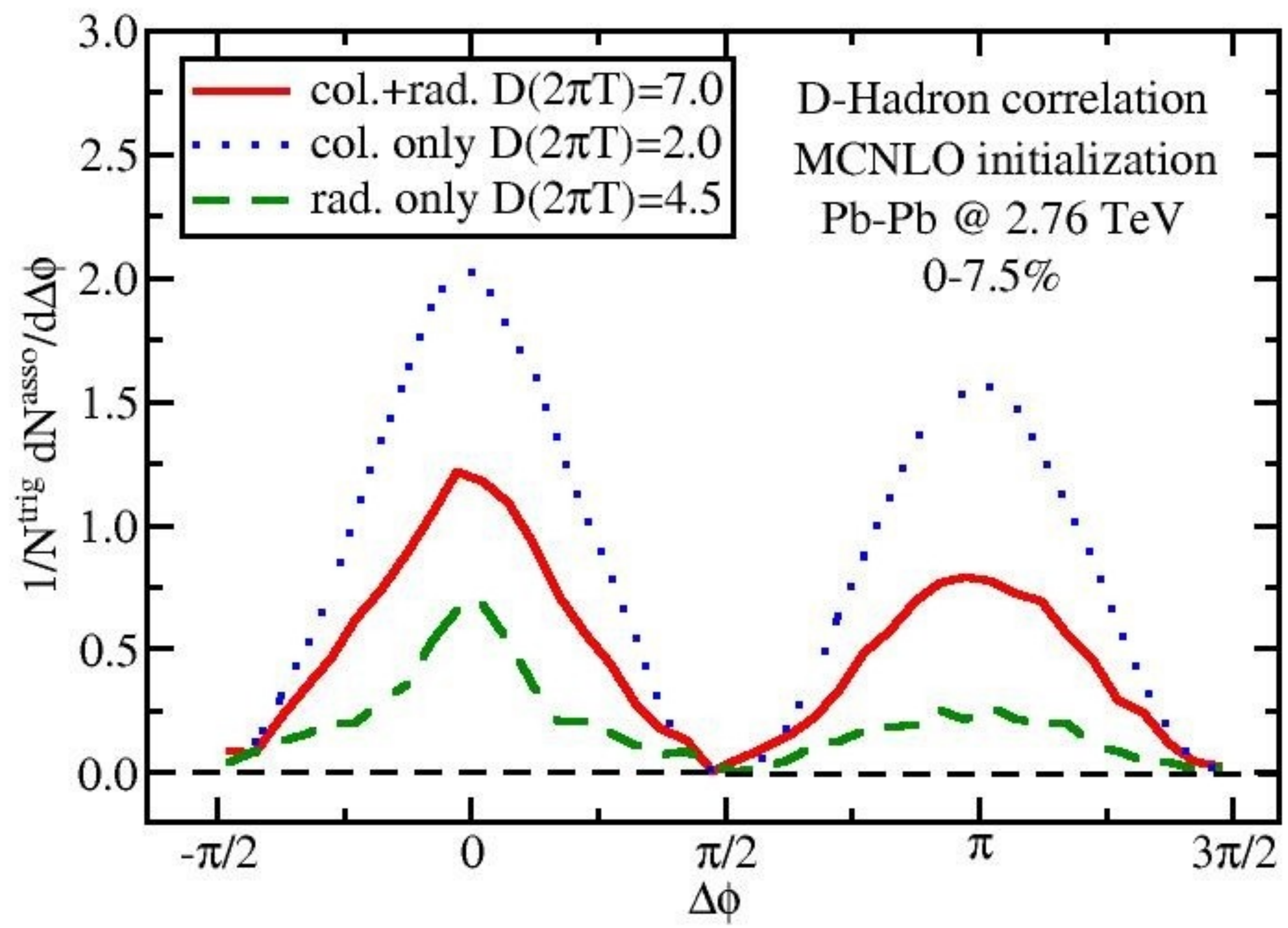
Current Experiments: HF-Hadron Correlations

(e from c, b) - h correlation

(talk by Pereira at HP2013)



Calculation of D-hadron correlation:



- peaks around 0 and π
- complication: collective flow of medium affects correlation function
- differences between various energy loss mechanisms depend on *y* and p_T cut (needs to be further investigated)

Next Steps

Transport Models for HQ in Medium

Choice of transport approach allows for study of HQ-medium interactions:

- Langevin+vRFD: sQGP + strong (non-perturbative) HQ-medium interaction
- linearized Boltzmann+vRFD: sQGP + pQCD driven HQ-medium interaction

(viscous) relativistic fluid dynamics:

- transport of macroscopic degrees of freedom
- based on conservation laws:

$$\partial_\mu T^{\mu\nu} = 0$$

$$\begin{aligned} T_{ik} &= \varepsilon u_i u_k + P\left(\delta_{ik} + u_i u_k\right) \\ &- \eta \left(\nabla_i u_k + \nabla_k u_i - \frac{2}{3}\delta_{ik}\nabla\cdot u\right) \\ &+ \varsigma\, \delta_{ik}\nabla\cdot u \end{aligned}$$

(plus an additional 9 eqns. for dissipative flows)

hybrid transport models:

- combine microscopic & macroscopic degrees of freedom
- current state of the art for RHIC modeling

diffusive transport models based on the **Langevin Equation**:

- transport of a system of microscopic particles in a thermal medium
- interactions contain a drag term related to the properties of the medium and a noise term representing random collisions

$$\vec{p}(t+\Delta t) = \vec{p}(t) - \frac{\kappa}{2T}\vec{v}\cdot\Delta t + \vec{\xi}(t)\Delta t$$

microscopic transport models based on the **Boltzmann Equation**:

- transport of a system of microscopic particles
- all interactions are based on binary scattering

$$\left[\frac{\partial}{\partial t} + \frac{\vec{p}}{E}\times\frac{\partial}{\partial \vec{r}}\right] f_1(\vec{p},\vec{r},t) = \sum_{processes} C(\vec{p},\vec{r},t)$$

HQ Transport w/ Linearized Boltzmann

current implementation:

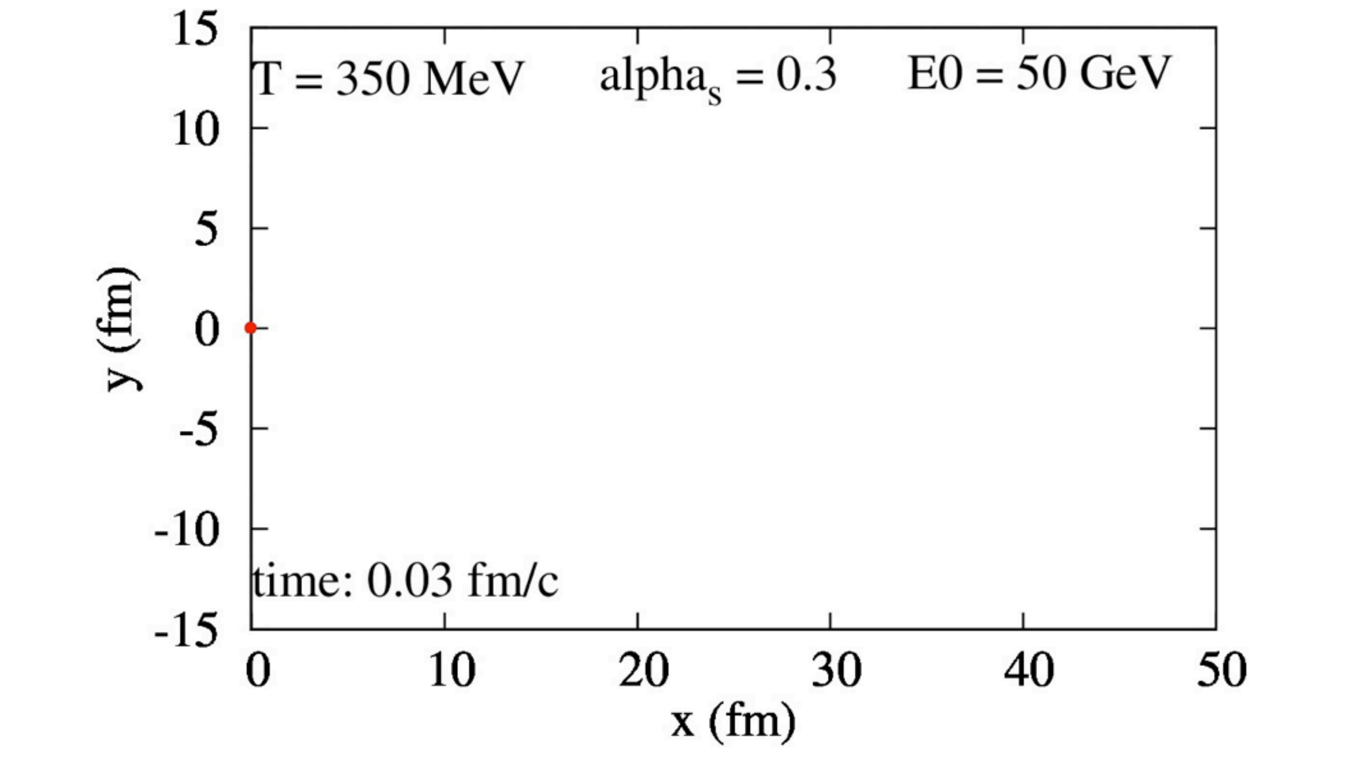
- elastic energy loss: cg➔cg & cq➔cq pQCD matrix elements
- infinite medium at fixed temperature

next steps:

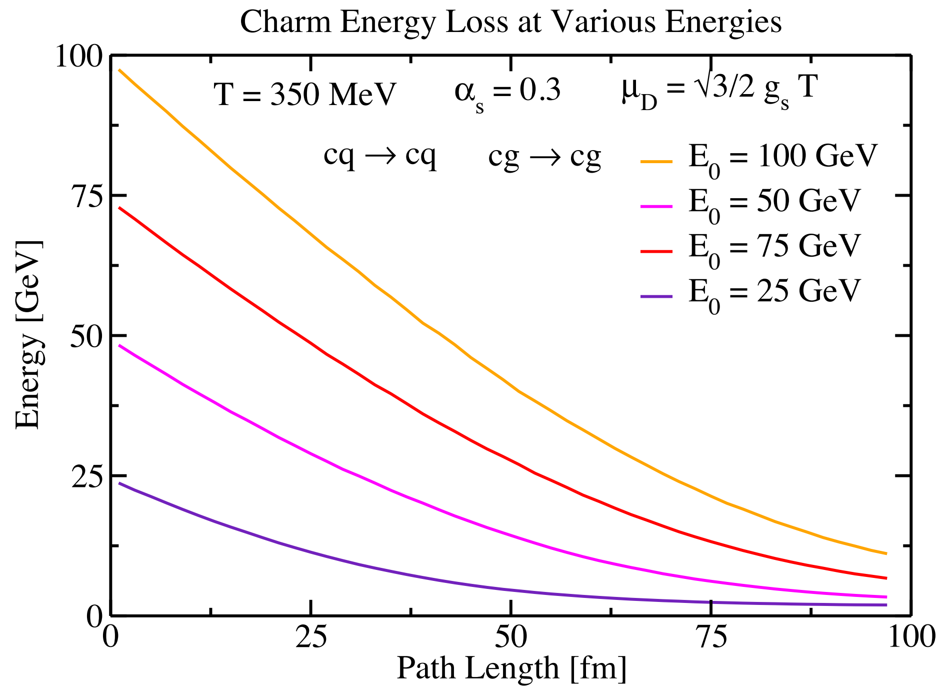
- realistic vRFD medium & initial conditions
- implementation of radiative processes & runn coupling
- comparison to data

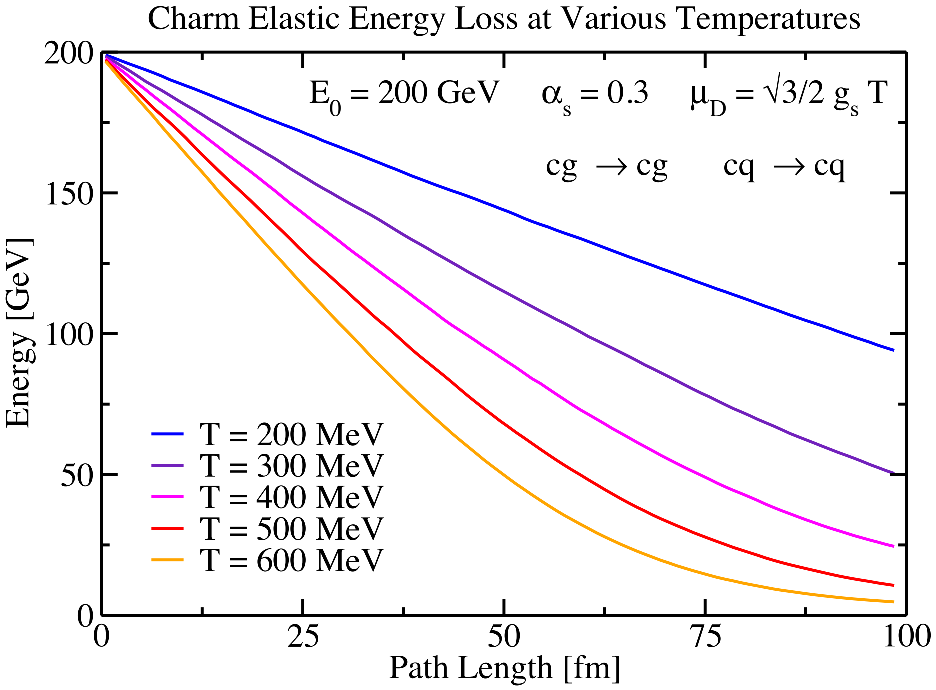
challenges:

- range of applicability



verification & validation: energy loss vs. path length in infinite QGP medium





HQ Transport in the PCM

current implementation:

- pQCD matrix elements: cg➔cg & cq➔cq
- radiation with LPM effect
- infinite medium at fixed temperature
- fixed coupling (for comparison with analytic calculations)

next steps:

- running coupling
- thermal screening masses
- bottom production
- A+A collisions & comparison to data

optional:

- linearized Boltzmann with realistic vRFD medium

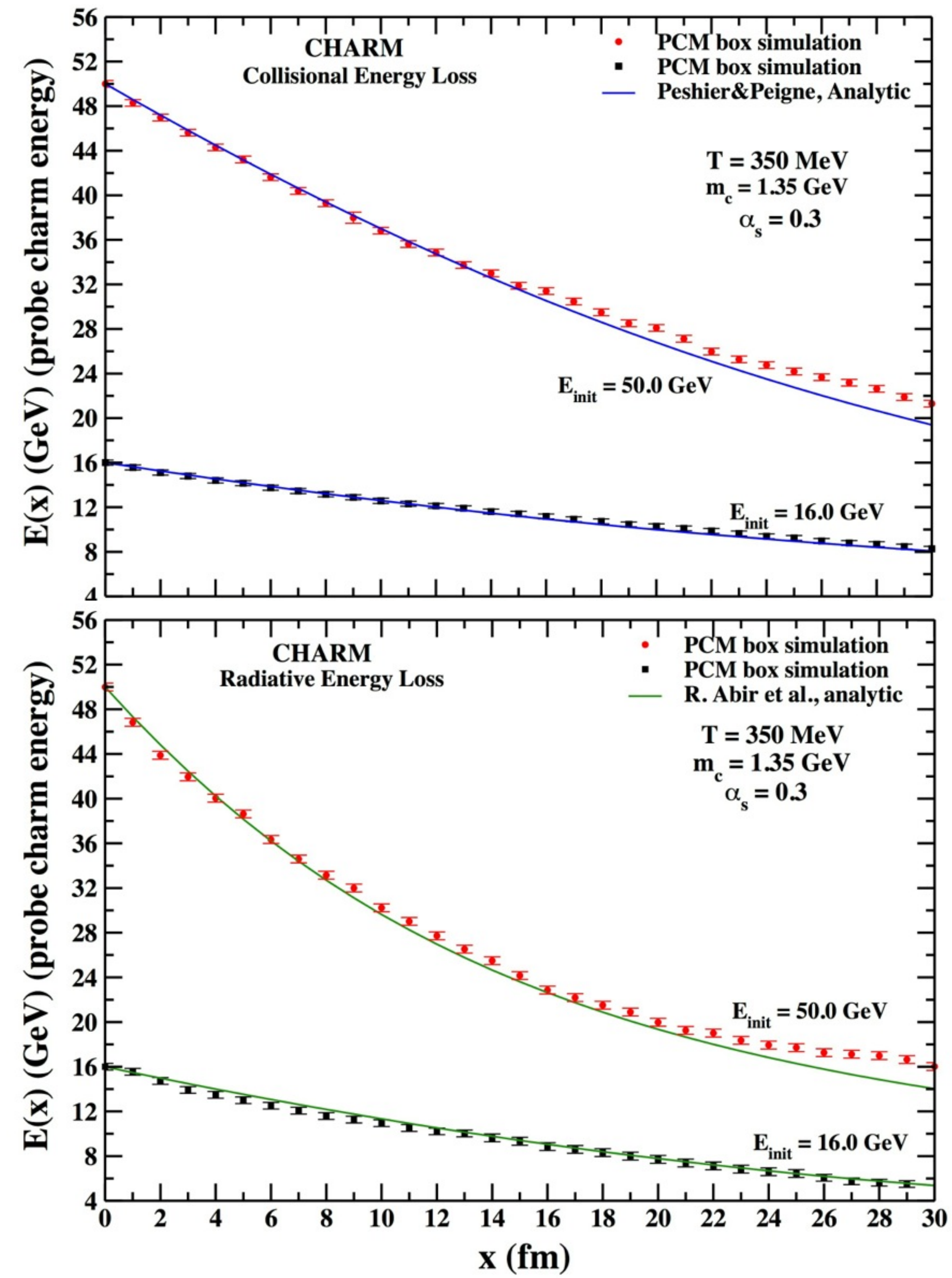
challenges:

- range of applicability for PCM:
  - regularization of cross section: p_T cut-off or Debye screening mass?
  - bulk properties and collective flow

M.D. Younus, C.E. Coleman-Smith, S.A. Bass & D.K. Srivastava arXiv:1309.1276

verification & validation:

energy loss vs. path length in infinite QGP medium



Bulk Evolution Models

Hybrid vRFD+UrQMD Models

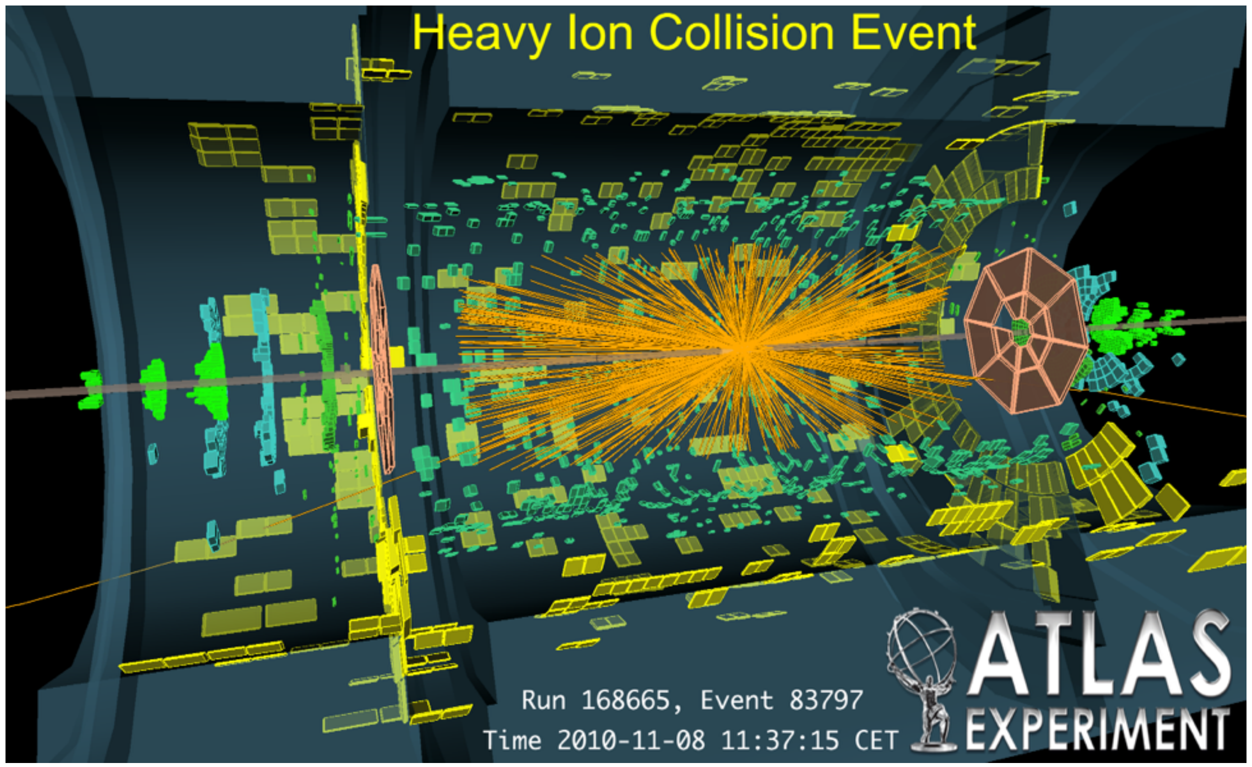
JET relevance: collaboration w/ OSU group on bulk dynamics model

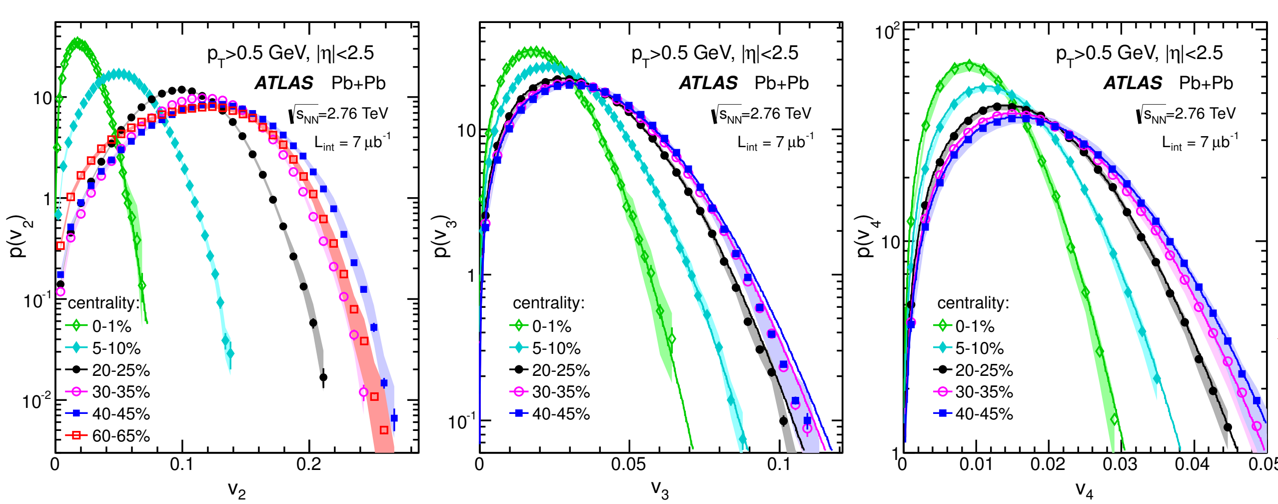
- **Collaboration with OSU group on EbE VISHNU**
  - bulk evolution model for global model to data analysis
  - multi-strange baryon production
  - study of resonances, e.g. Φ meson
- **Collaboration with Nagoya group**
  - initial condition interface
  - particalization hyper-surface sampler
  - hadronic afterburner
- **Collaboration with Frankfurt group**
  - maintenance of UrQMD
  - development of SMASH

Model to Data Comparison

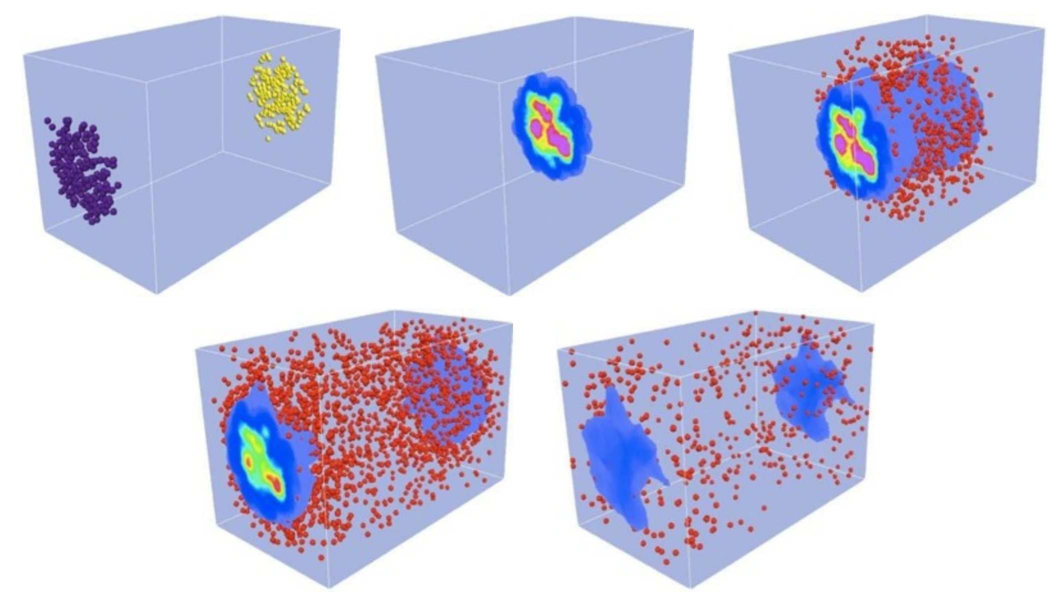
Probing QCD in Heavy-Ion Collisions

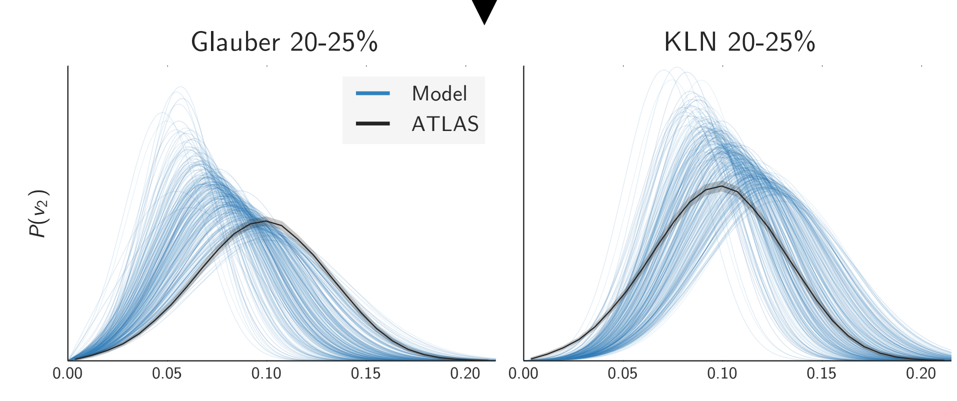
Data:





Model:
initial conditions, τ_0, η/s, ζ/s, ...





Model to Data Comparison Effort @ Duke

Current Scope:

- focus on extraction of QCD bulk properties via model to data comparison of EbE v_n distributions
- funded via NSF CDI award: MADAI Collaboration
- access to OSG resources provides unique capability for very large scale EbE vRFD+UrQMD studies
- first publications using EbE VISHNU later this year

JET Collaboration:

- apply same technique to constrain HQ transport properties simultaneously with bulk QCD properties
- can be extended to jet energy-loss transport coefficients as well
- useful in particular for complex dependencies
- extraction of temperature-dependence of q-hat?

Summary and Outlook

Heavy Quark Dynamics:

- Langevin with Radiation
- HQ Correlations
- different models for bulk evolution and HQ-medium interaction

Bulk Evolution Models:

- continuing development and application of of hybrid vRFD+micro approach

Model to Data Comparison:

- new tools/capabilities that can be applied to quantities of key interest to JET collaboration

new postdoc: **Jussi Auvinen** (starts 9/2014)

- strengthen hard probes expertise and capabilities

The End

The Parton Cascade Model

The PCM is a microscopic transport model based on the Boltzmann Equation:

$$\left[\frac{\partial}{\partial t} + \frac{\vec{p}}{E} \times \frac{\partial}{\partial \vec{r}}\right] f_1(\vec{p}, \vec{r}, t) = \sum_{processes} C(\vec{p}, \vec{r}, t)$$

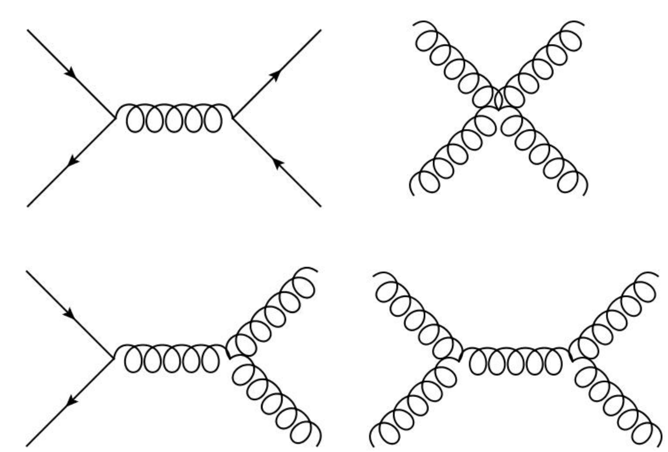
- describes the full time-evolution of a system of quarks and gluons at high density & temperature
- ideally suited for describing the interaction of jet with medium as well as the medium response

- classical trajectories in phase space (with relativistic kinematics)
- interaction criterion based on geometric interpretation of cross section:

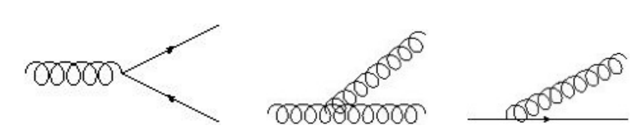
$$d_{\min} \leq \sqrt{\frac{\sigma_{\rm tot}}{\pi}} \qquad \sigma_{\rm tot} = \sum_{p_3, p_4} \int \frac{d\sigma(\sqrt{\hat{s}}; p_1, p_2, p_3, p_4)}{d\hat{t}} d\hat{t}$$

- system evolves through a sequence of binary (2↔2) elastic and inelastic scatterings of partons and initial and final state radiations within a leading-logarithmic approximation (2→N)
- guiding scales:
  - initialization scale Q_0
  - IR divergence regularization: p_T cut-off p_0 or Debye-mass μ_D
  - intrinsic k_T
  - virtuality > μ_0

- binary cross sections are calculated in leading order pQCD:



- radiative processes (full DGLAP evolution):



Medium Dependencies

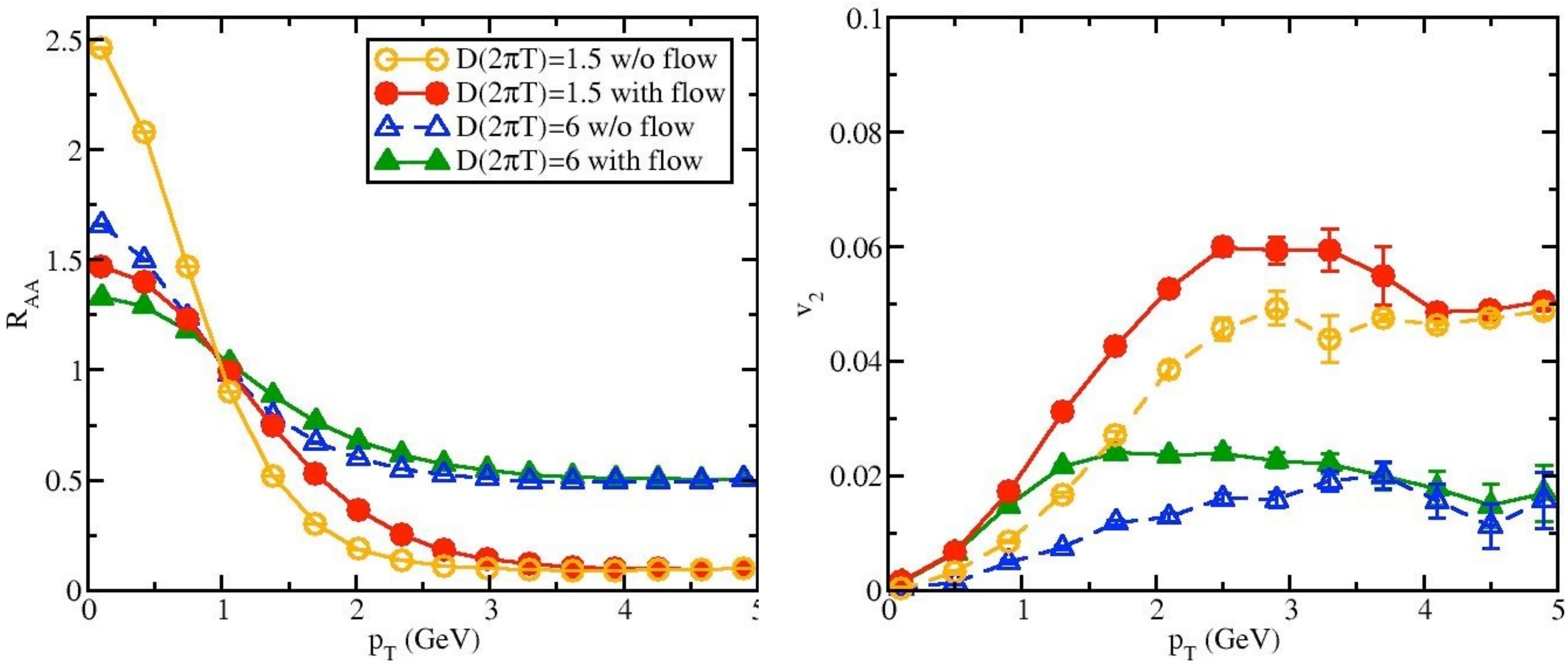
How do HQ observables such as elliptic flow and the nuclear modification factor depend on parameters of the medium and the HQ evolution?

- contributions of medium flow vs. geometry
- RFD initial conditions
- C/B ratio when using non-photonic electrons
- thermalization time of the medium
- ...

Geometry vs. Flow

Both geometric asymmetry and collective flow generate positive v_2:

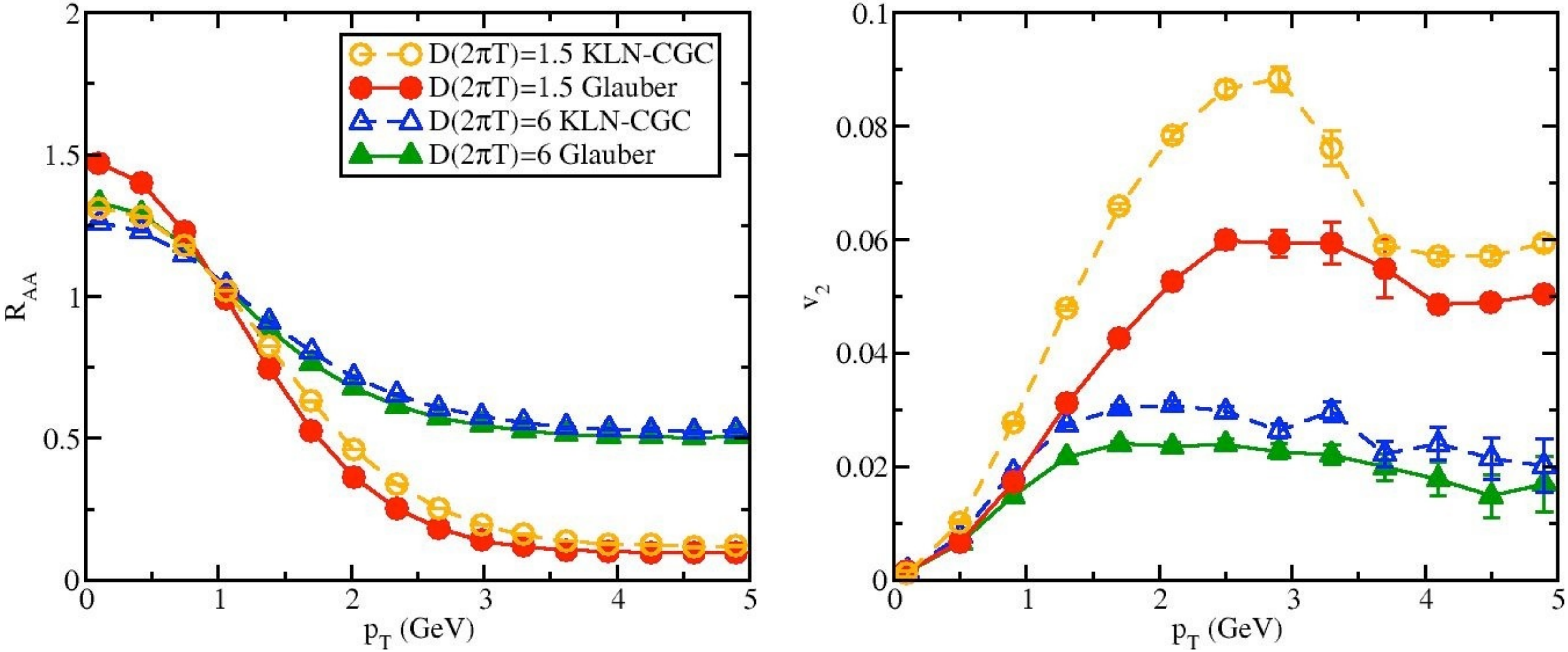
- decouple the influence of QGP collective flow on heavy quark motion by solving Langevin equation in the **global** c.m. frame, instead of the **local** rest-frame
- medium geometry dominates the high p_T region, while the collective flow has a significant impact in the low p_T region



Initial Conditions

KLN-CGC model exhibits a larger eccentricity of the medium:

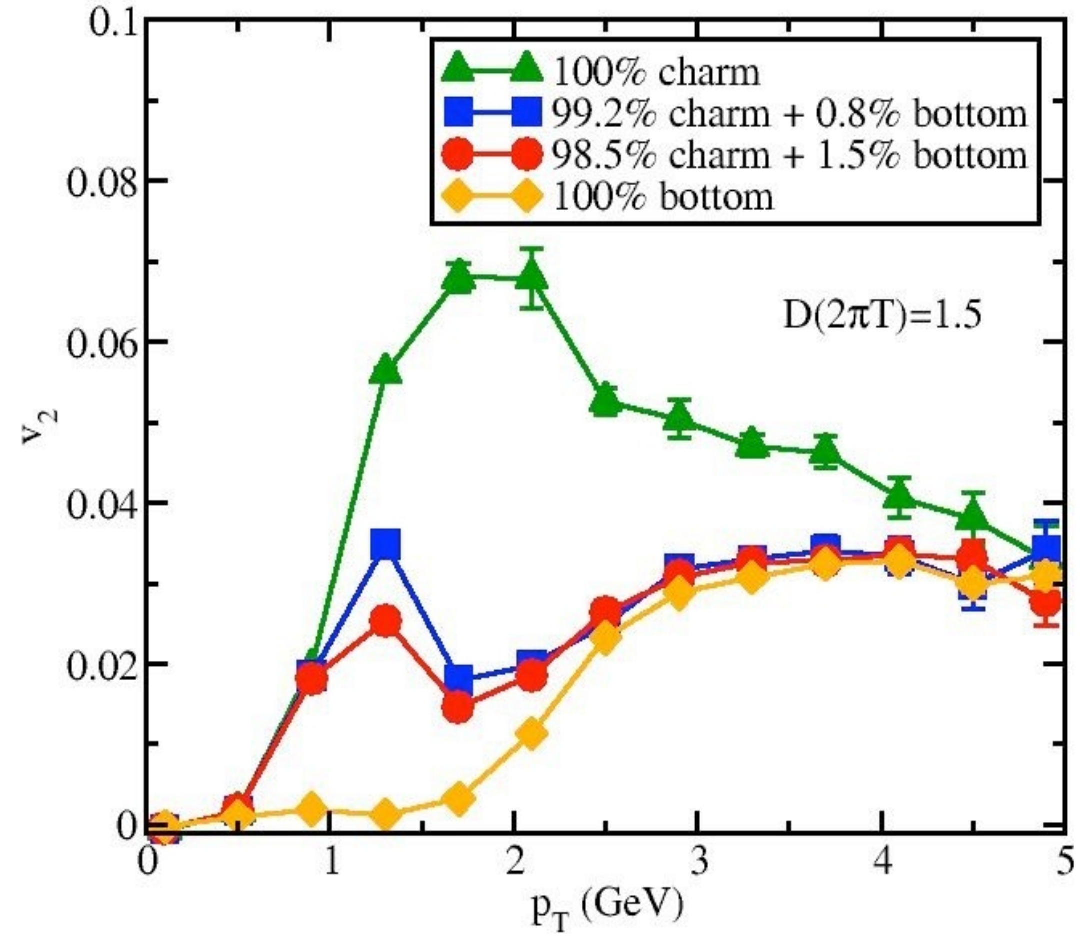
- no apparent difference in R_{AA}, but significant larger v_2 from KLN-CGC initialization

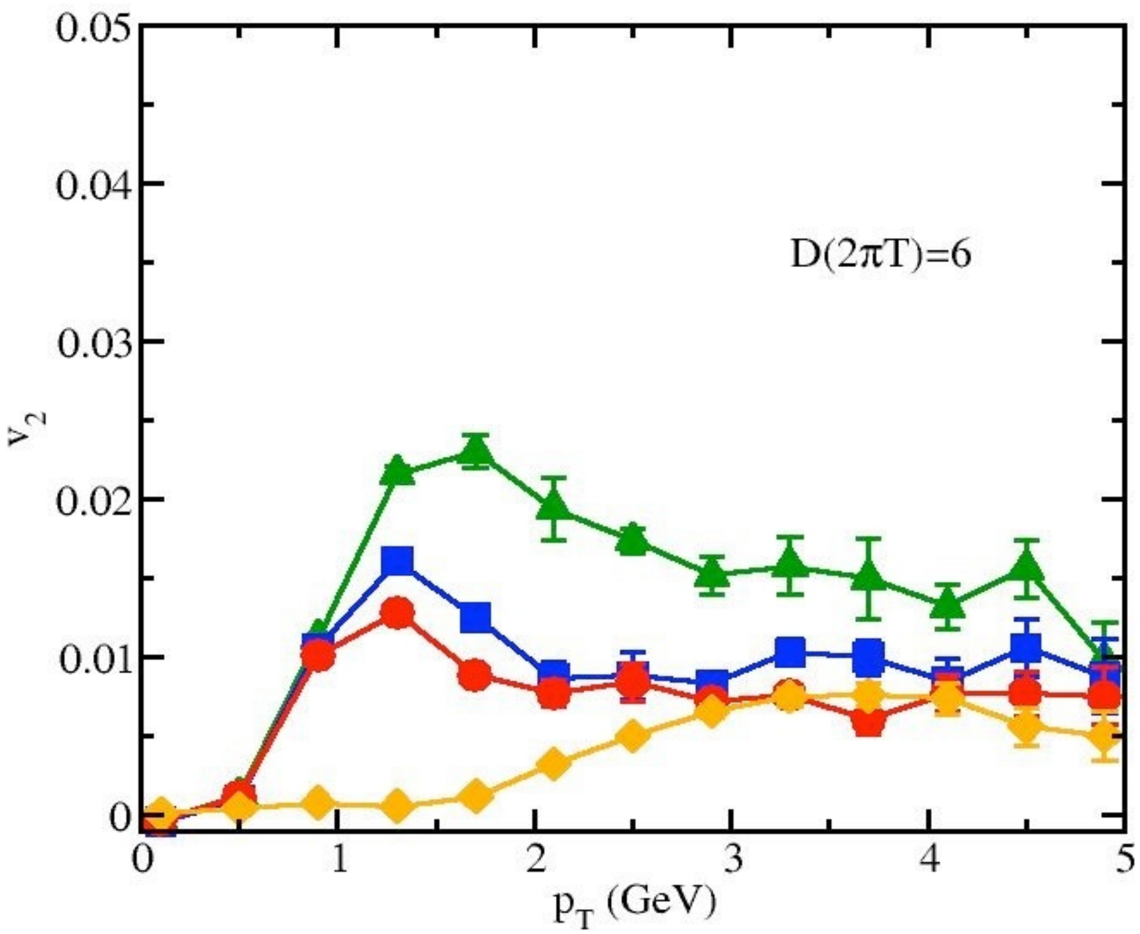


Charm to Bottom Ratio

there still exists an uncertainty in the relative normalization of charm and bottom quark production in pQCD calculations:

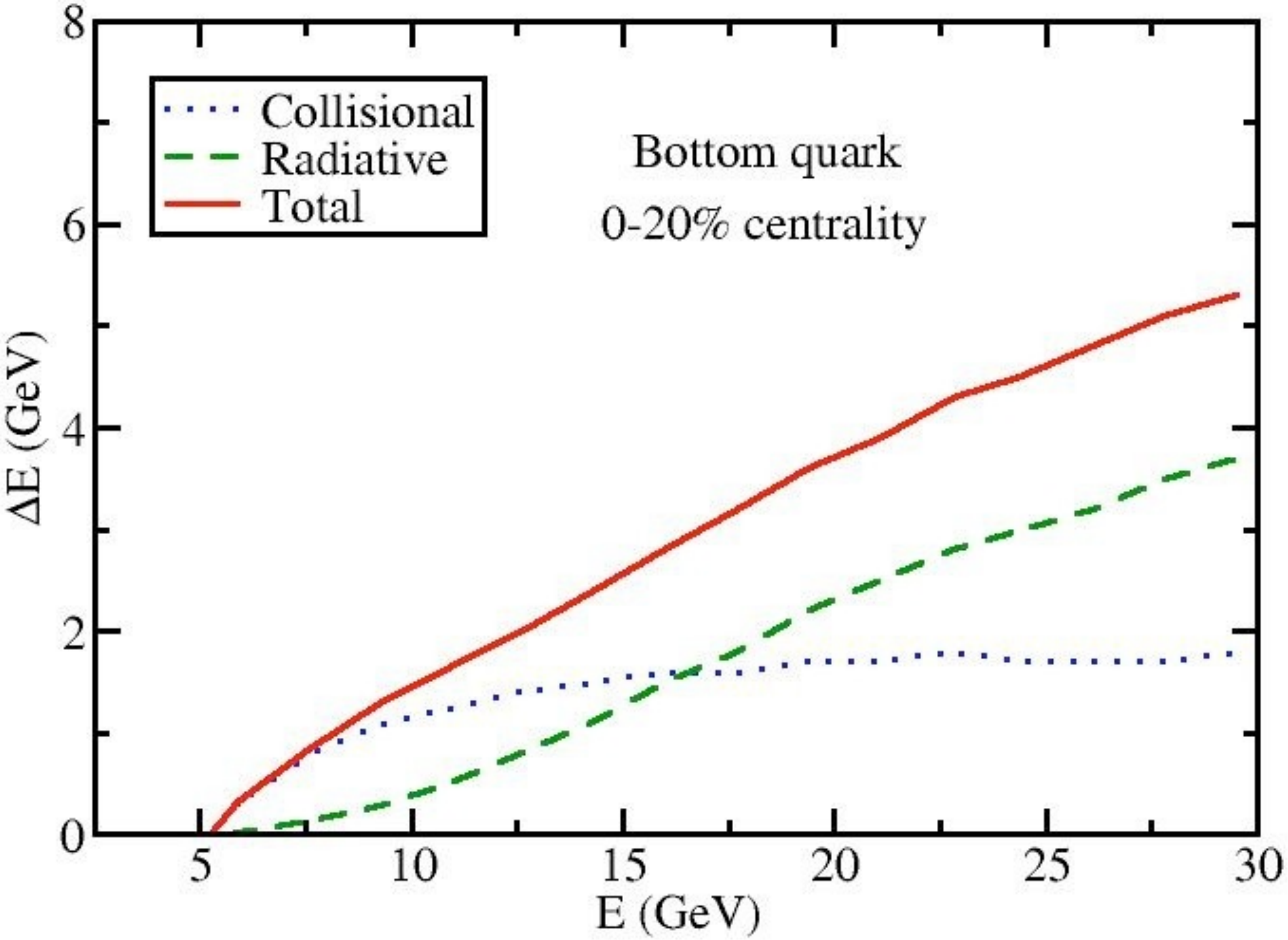
- Choose two mixtures with b/c ratio around 1% in our simulation





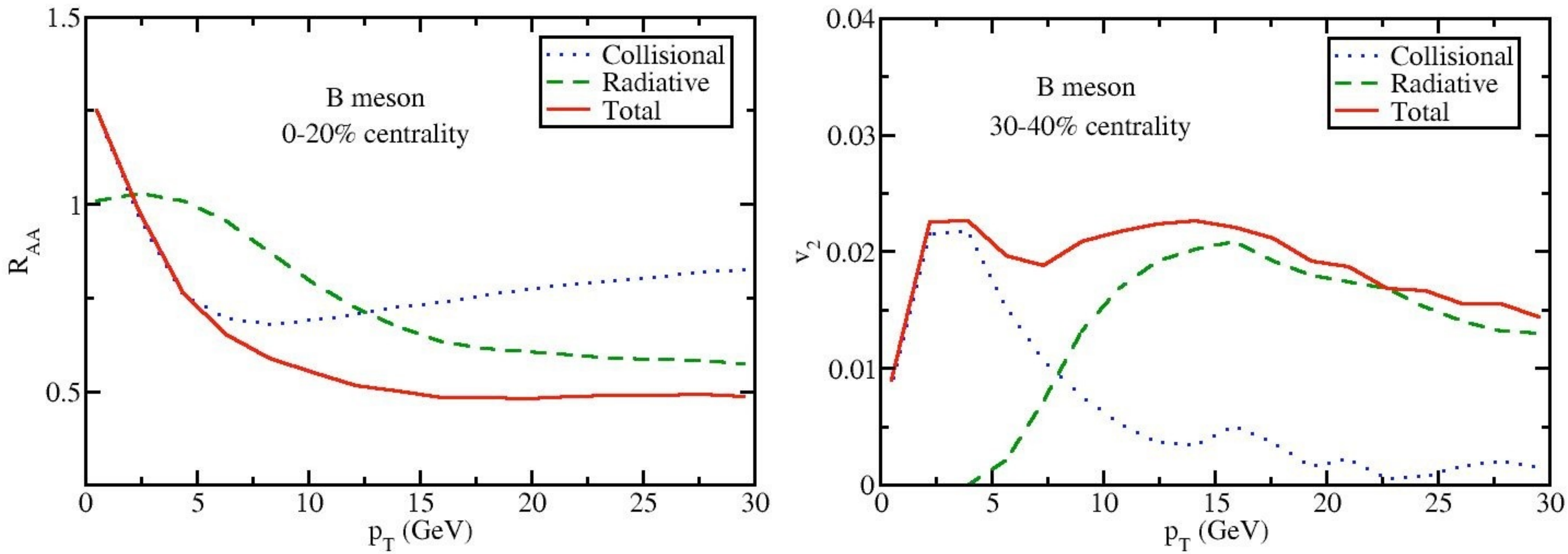
- non-photonic electron spectrum follows c-decay electron behavior at low p_T, but b-decay at high p_T
- v_2 behavior varies with coupling strength and cannot be resolved by current experimental data

Backup: Bottom Quark Energy Loss



- Collisional energy loss dominates low energy region, while radiative dominates high energy region.
- Crossing point: around 17 GeV, much larger than charm quark because of heavier mass.

B-Meson Prediction



- similar behavior as with D mesons: collisional energy loss dominates for the low p_T region, while radiative dominates the high p_T region
- crossing point from collisional to radiative is significantly higher due to the much larger mass of bottom vs. charm quark
- B meson has larger R_{AA} and smaller v_2 than D meson