Nonperturbative Computation of Open Heavy Flavor Transport in Medium

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Work done in collaboration with Ralf Rapp & Rainer Fries of TAMU

Non-Perturbative HQ Transport Approach

1. Introduction:
- Heavy quark probe of hot & dense matter

2. HQ probe: a strongly coupled framework
- Transport coefficient
- HQ diffusion in QGP: Langevin + hydro simulation
- Hadronization: coalescence vs fragmentation
- D-meson diffusion in hadronic phase

3. Heavy ion phenomenology
- RHIC: Non-photonic electrons, Ds vs D mesons
- LHC: D,B mesons, non-photonic electrons
- A new potential & its phenomenological consequences

4. Summary

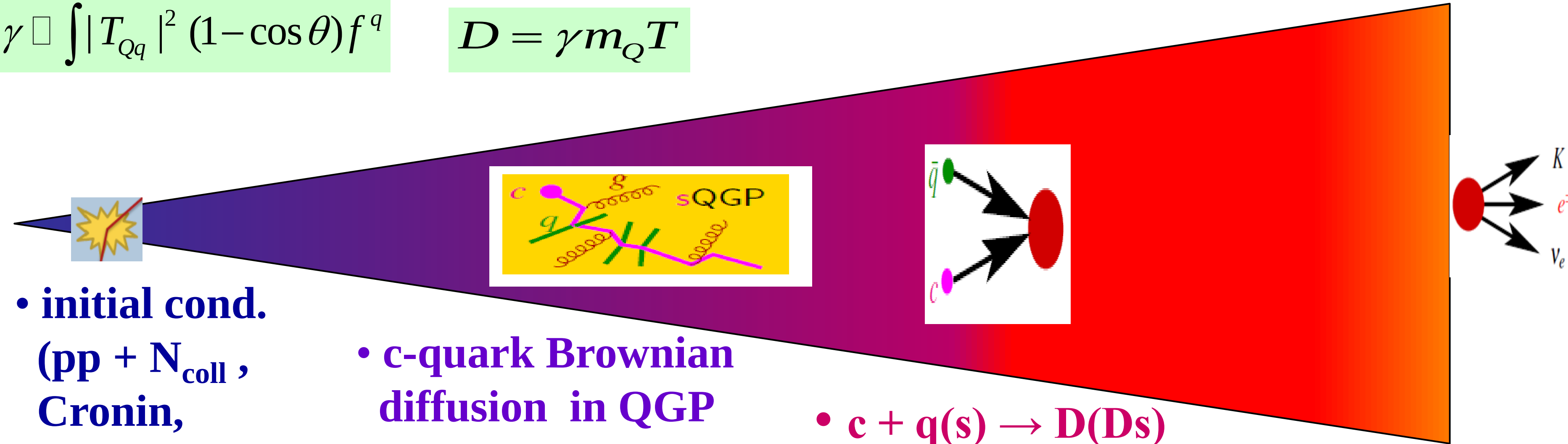
HQ evolution in HIC

$$\frac{\partial f}{\partial t} = \gamma \frac{\partial (pf)}{\partial p} + D \frac{\partial^2 f}{\partial p^2}$$

thermalization rate   diffusion coefficient

$$\gamma \propto \int |T_{Qq}|^2 (1-\cos\theta) f^q$$

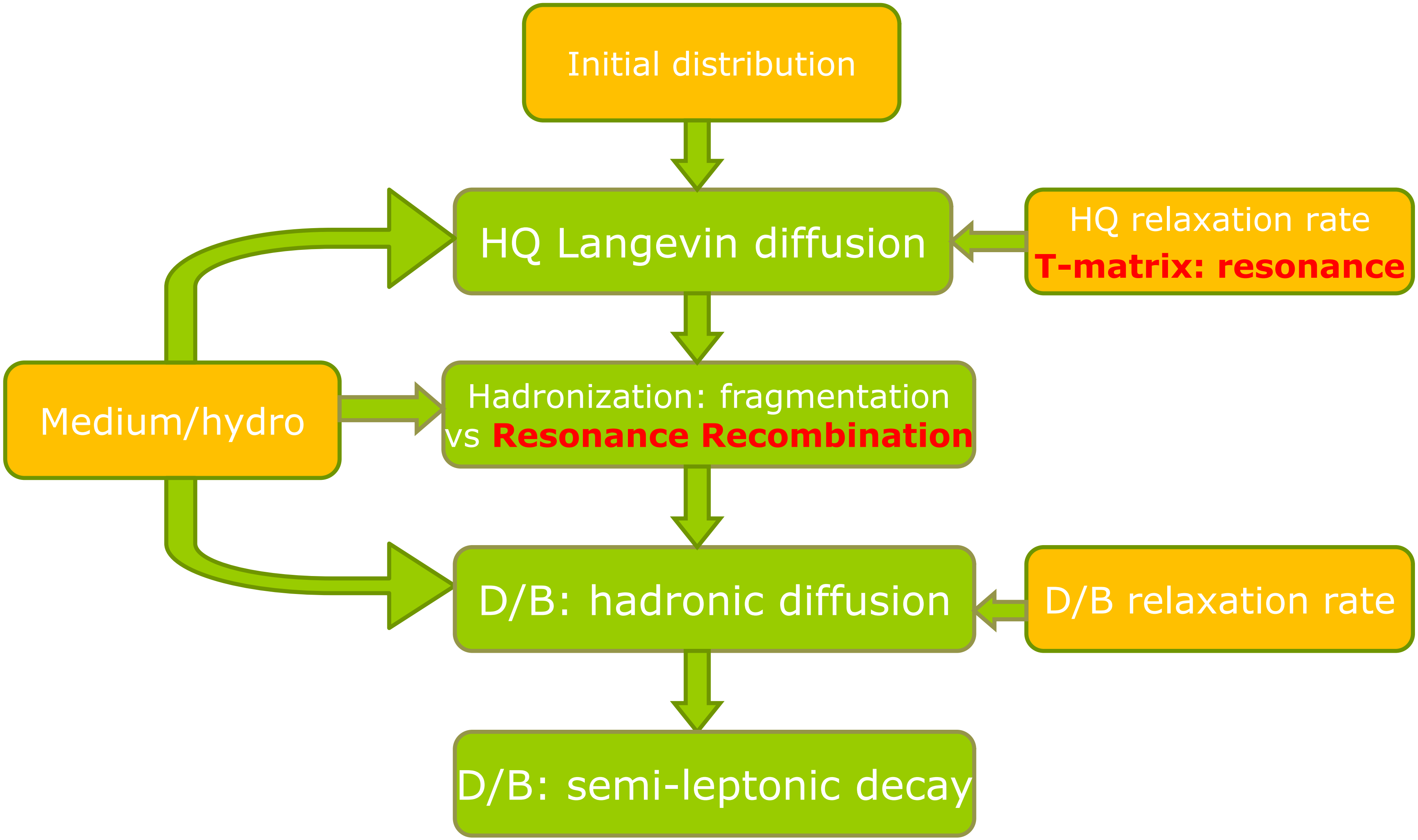
$$D = \gamma m_Q T$$



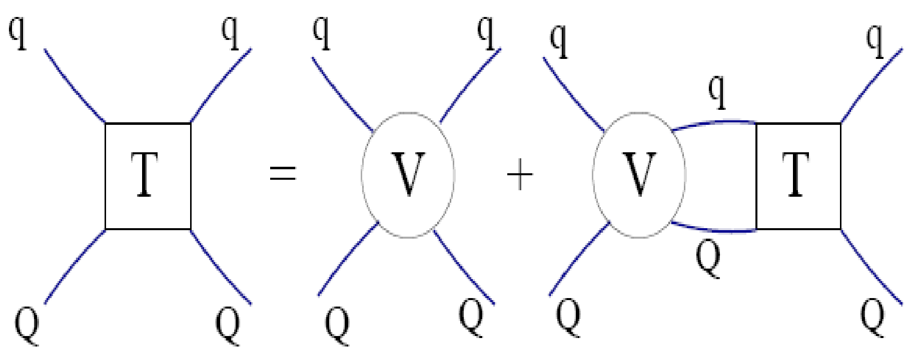
- **initial cond. (pp + N_{coll}, Cronin, shadowing)**
- **c-quark Brownian diffusion in QGP liquid (T-matrix resonant correlation, *No K-factor*)**
- **c + q(s) → D(Ds) resonance recombination; Ds freezeout**
- **D-meson diffusion in hadron liquid**

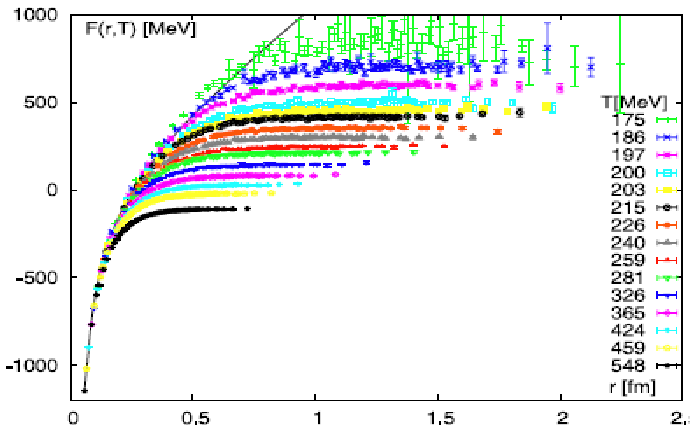
--- primordial hard production, pQCD (FONLL/PYTHIA)
m_Q >> T, Lambda_QCD ➔number conserved

Non-Perturbative HQ Transport: flow chart



HQ thermal relaxation rate: T-matrix



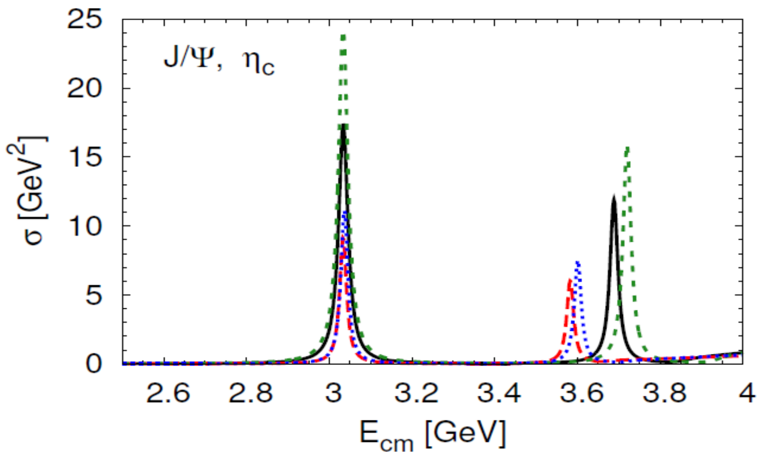


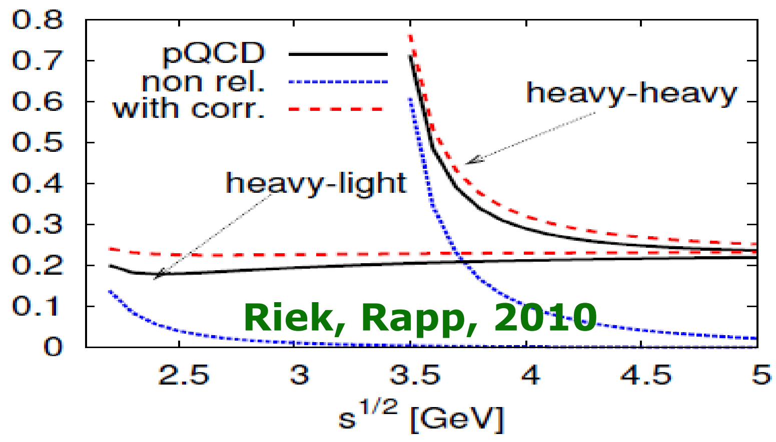
◆**lattice potential:** Kaczmarek,2008

$$U = F - T\frac{\partial F}{\partial T}$$

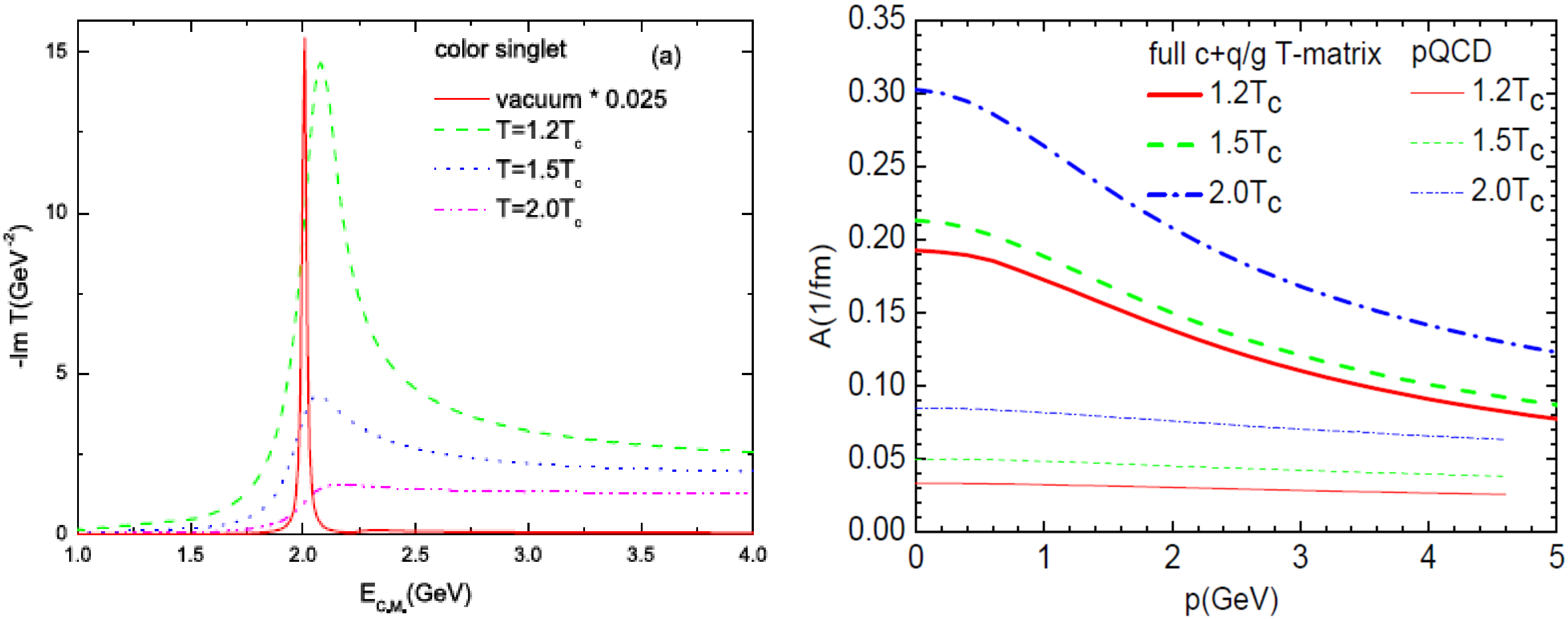
➔ **Resummation & Unitarization**

◆**Open/hidden HF: vacuum spectroscopy reproduced; high energy pQCD recovered**





Charm quark relaxation rate: QGP

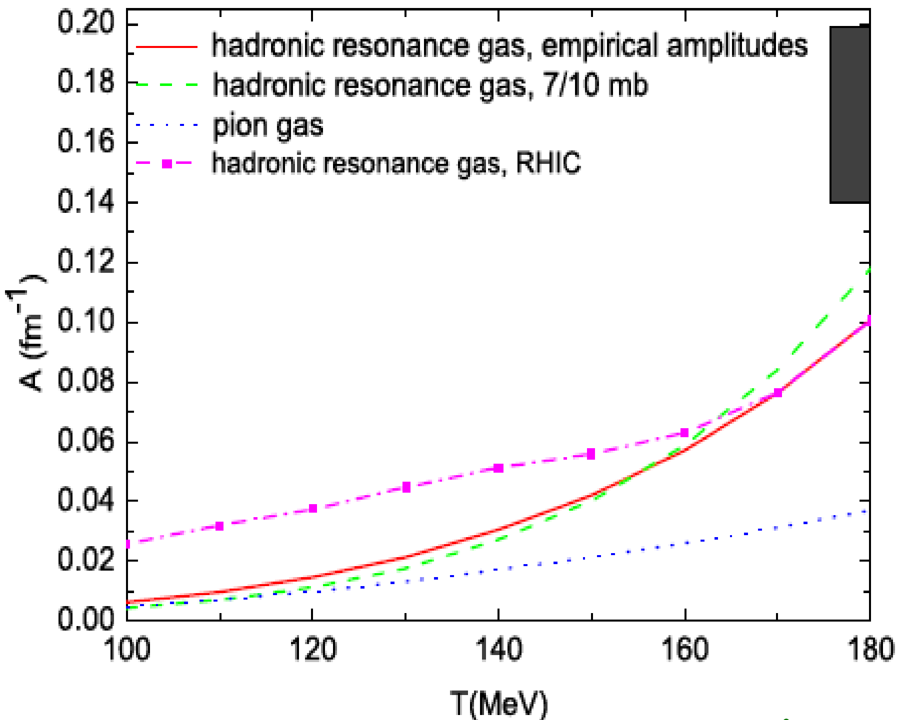


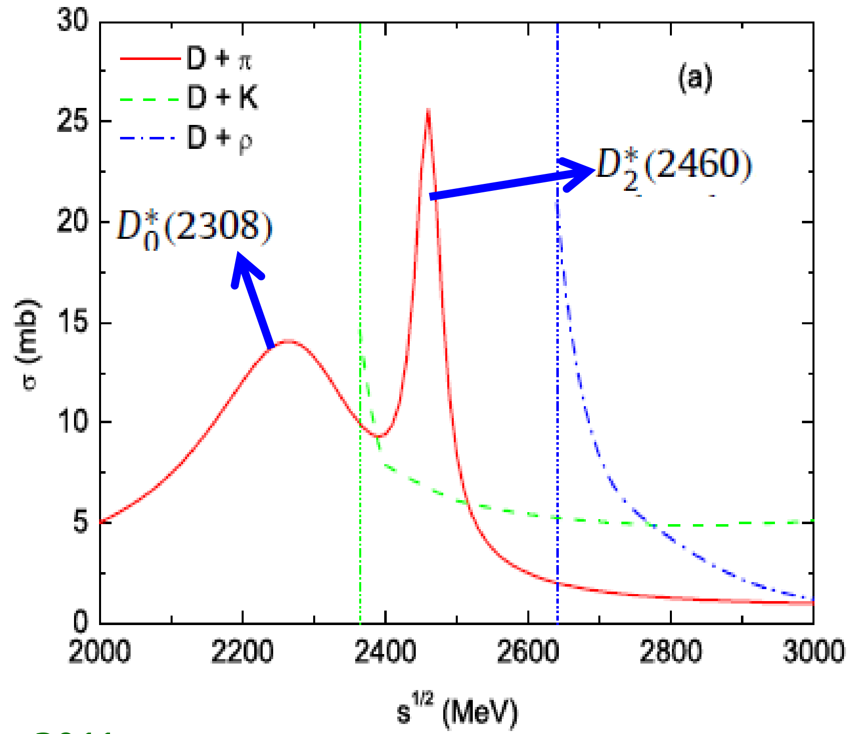
Riek, Huggnis, Rapp, 2010, 2012

- ◆ **T-matrix resummation ➔ color singlet and anti-triplet broad Feshbach resonances up to ~1.5 T_C**
- ◆ **this resonance correlation ➔ resonance recombination**
- ◆ **T-matrix relaxation rate: a factor ~4-5 larger than LO pQCD at T=1.2 T_c**
- ◆ **T-dependence: screening potential; p-dependence: less contribution from Feshbach resonance as p increases**

D-meson thermal relaxation rate : HRG

◆ **D + pion, K,eta,rho,omega,K*,N,Delta, empirical s-wave cross sections from effective hadronic theory:** Lutz et al., 2004; E.Oset et al. 2007

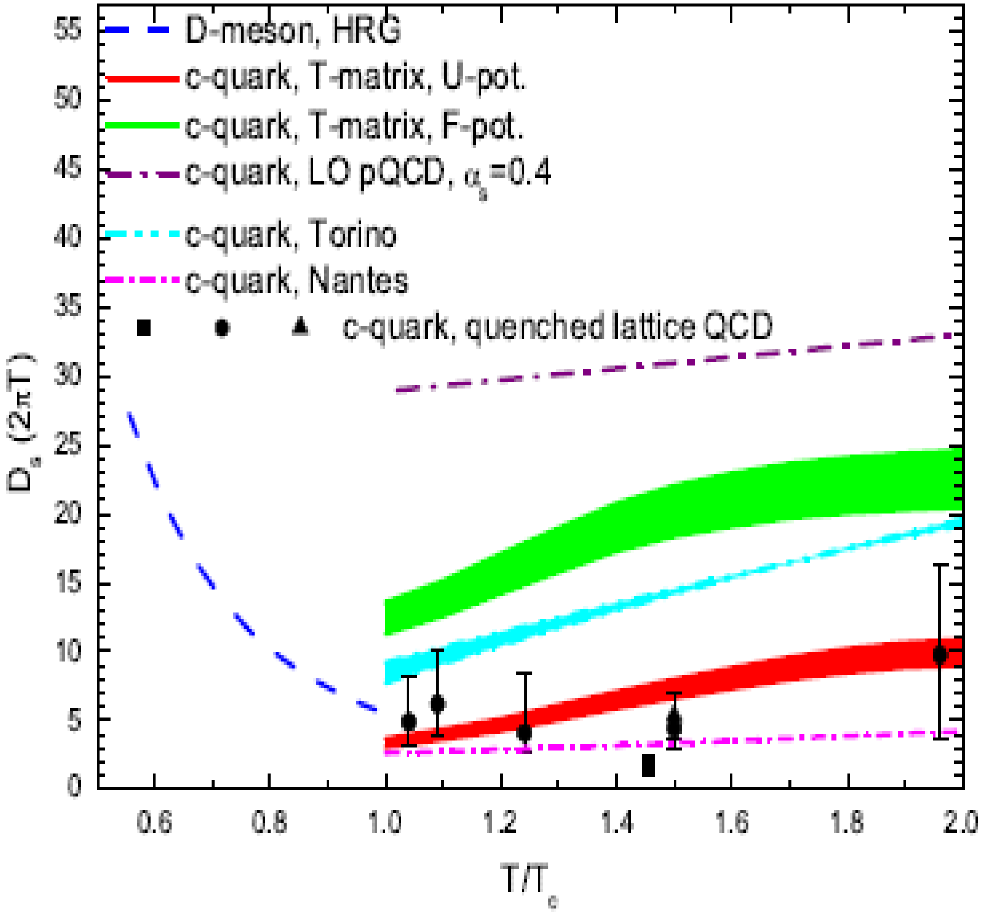




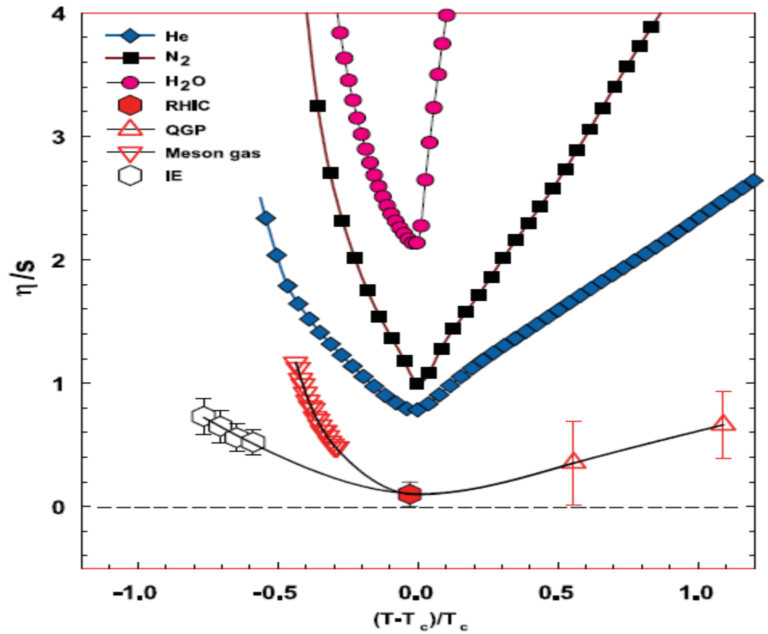
He,Fries,Rapp 2011

◆ **A~0.1 /fm at T=180 MeV, comparable to the non-perturbative T-matrix calculation of charm quark thermal relaxation rate in QGP**

Summarizing charm diffusion coeffi.

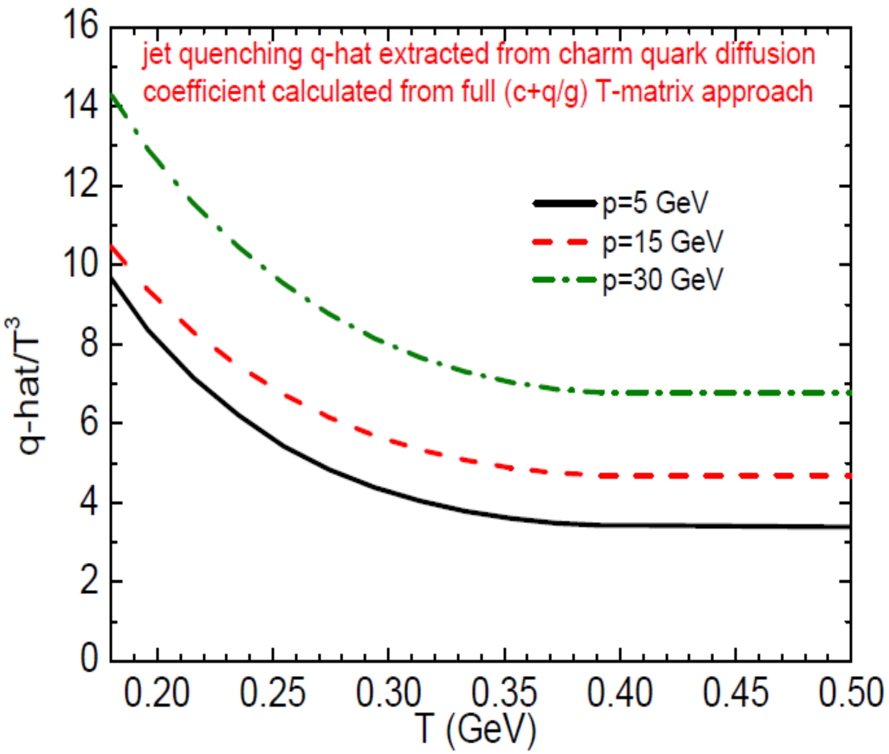


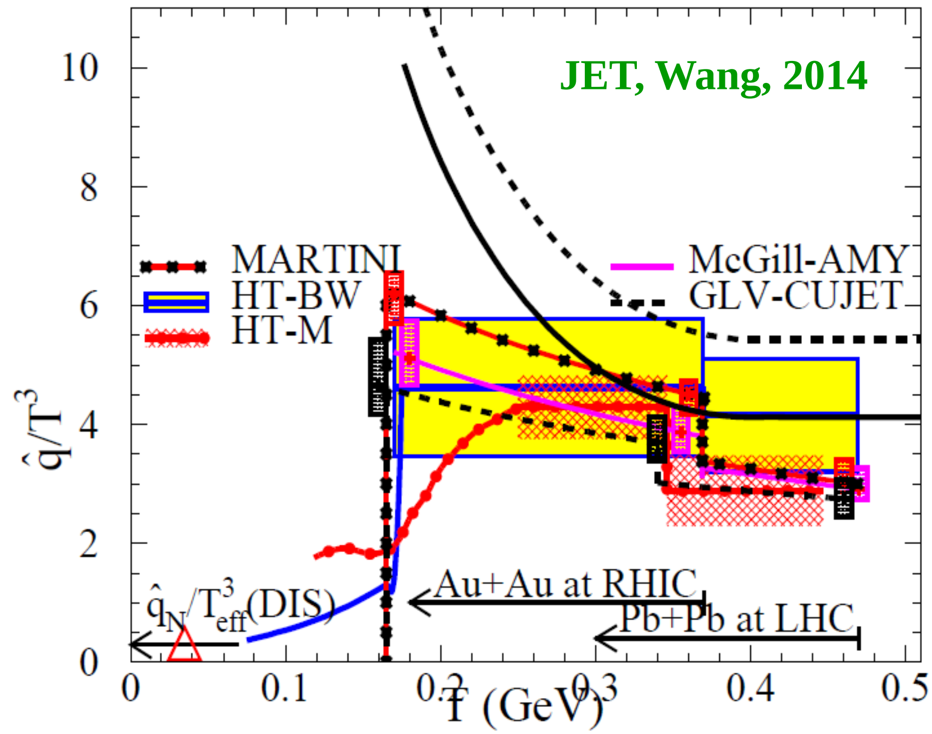
- ◆ **viscosity.**: **eta/s = (1/5 ~ 1/2)D_sT;** Danielewicz&Gyulassy, 1985
- ◆ **D_s translates into eta/s = (2-5)/4pi at T=180 MeV**



- ◆ **Ds=T/(mA): T-matrix vs lattice; Minimum around Tc + Quark-hadron duality?!**
- ◆**The charm diffusion: another perspective of looking into the transport properties of sQGP/dense matter**

Jet quenching q-hat from charm diffusion



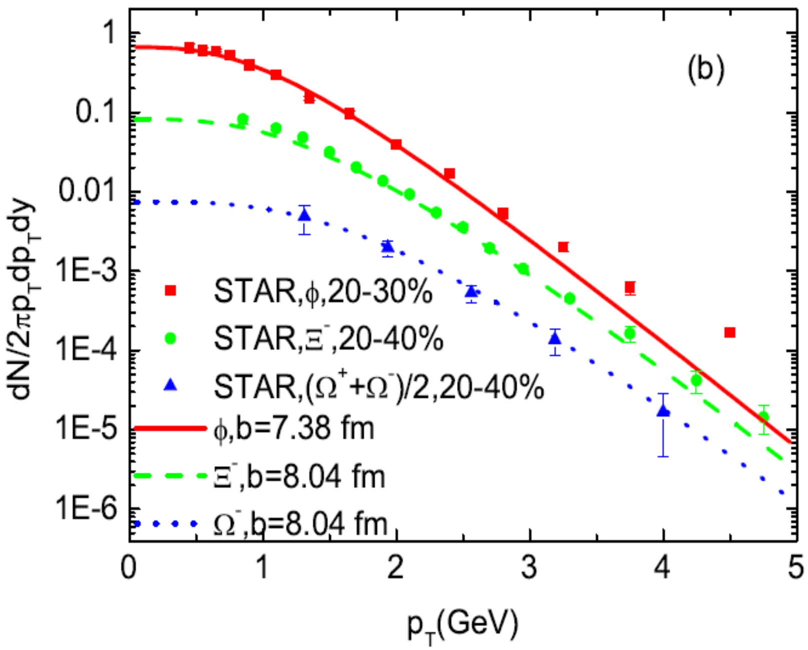


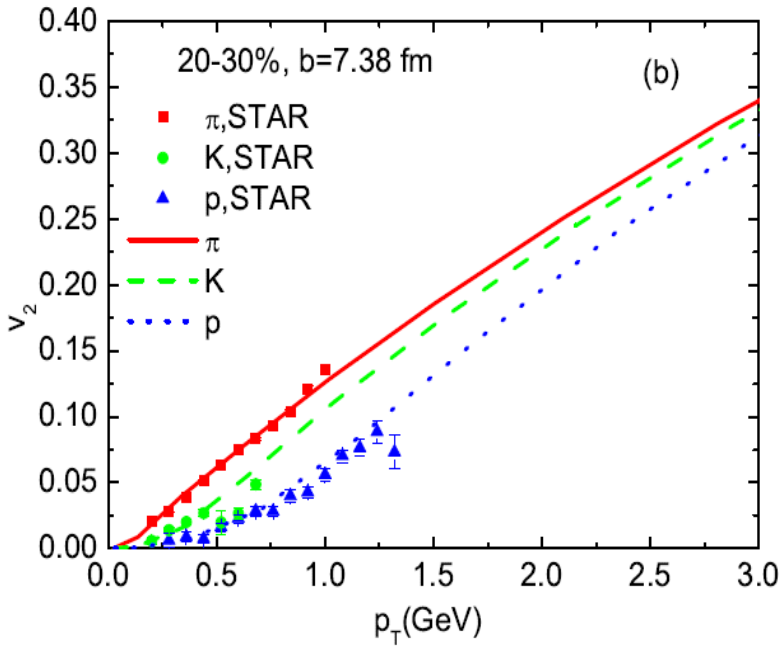
- **At high T, consistent with emperical values used in Jet models**
- **At T~T_c, enhanced due to non-perturbative charm diffusion, similar to CUTJET3.0 accounting for non-perturbative chromo-EM quasiparticles**

Xu, Liao, Gyulassy, 2015

Medium evolution: hydro RHIC

- updated ideal 2+1 D hydro based on AZHYDRO Kolb + Heinz, 2003
- lattice/HRG-PCE EoS + pre-equilibrium flow + compact initial density s(x,y)~ nBC (x,y)➔ fast build-up of radial flow + essential saturation of bulk v_2 around Tc





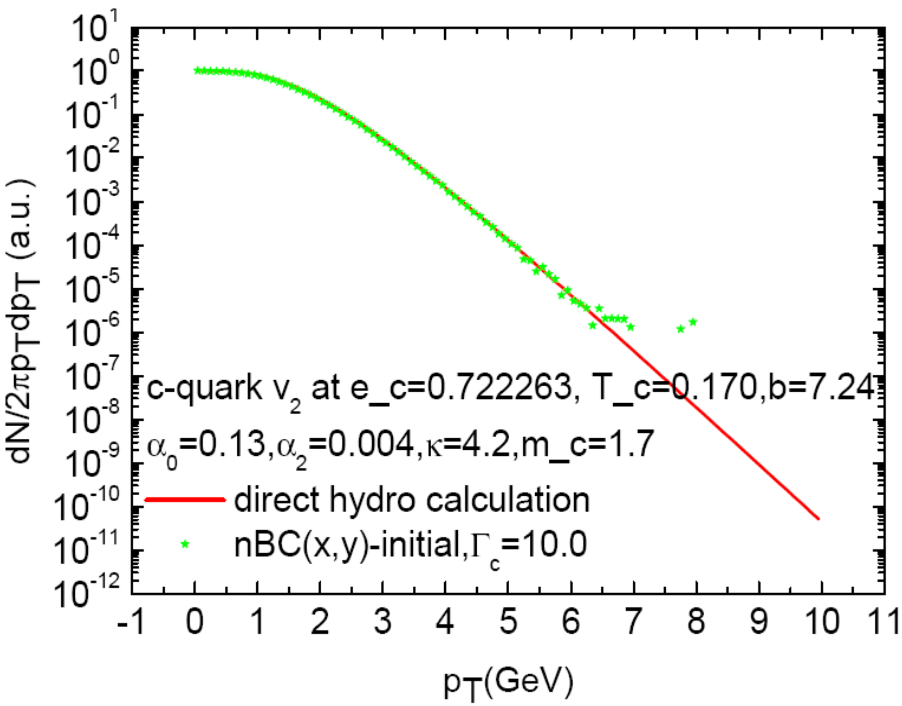
- multistrange hadrons ϕ, Ξ, Ω probably freeze out earlier STAR, PRC79,2009
- multi-strange particles' spectra and v_2 fitted at T_{ch} =160 MeV
  bulk particles' spectra and v_2 fitted at T_{kin}=110 MeV He, Fries,Rapp,2012

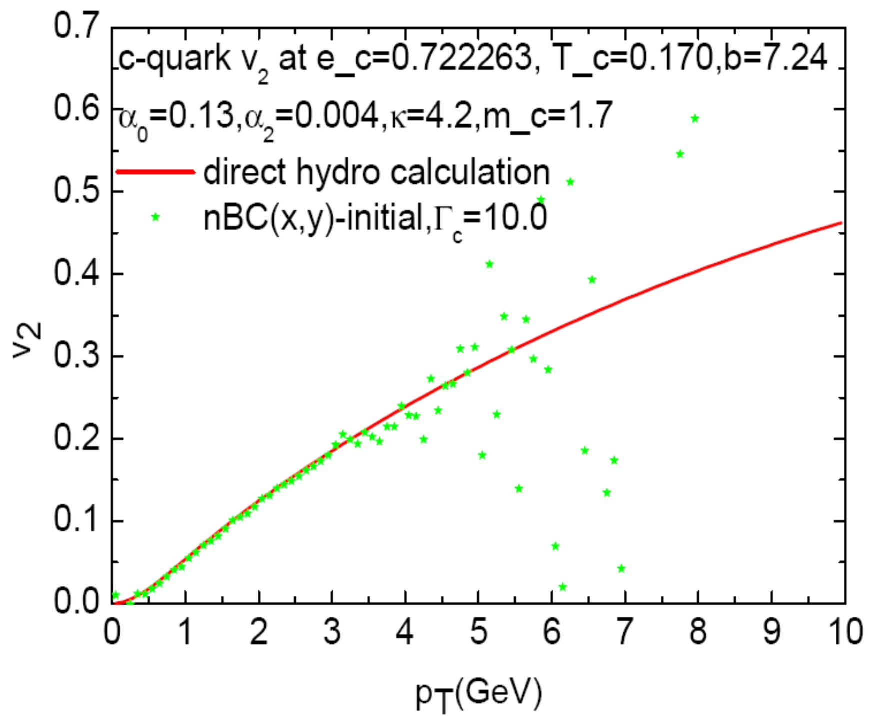
HQ diffusion: Langevin equilibrium limit check

- **Using an arbitrarily large relaxation rate**

$$dx_j = \frac{p_j}{E}dt,$$

$$dp_j = -\Gamma(p)p_j dt + \sqrt{2dt\, D(|\mathbf{p} + \xi d\,\mathbf{p}|)}\rho_j.$$





- **Fluctuation-Dissipation theorem: pre- vs post-point scheme** **He et al. 2013**

$$\Gamma(p) = \frac{1}{E(p)}\left(\frac{D[E(p)]}{T} - \frac{\partial D[E(p)]}{\partial E}\right) = A(p)$$

$$D[E(p)] = \Gamma(p)E(p)T,$$

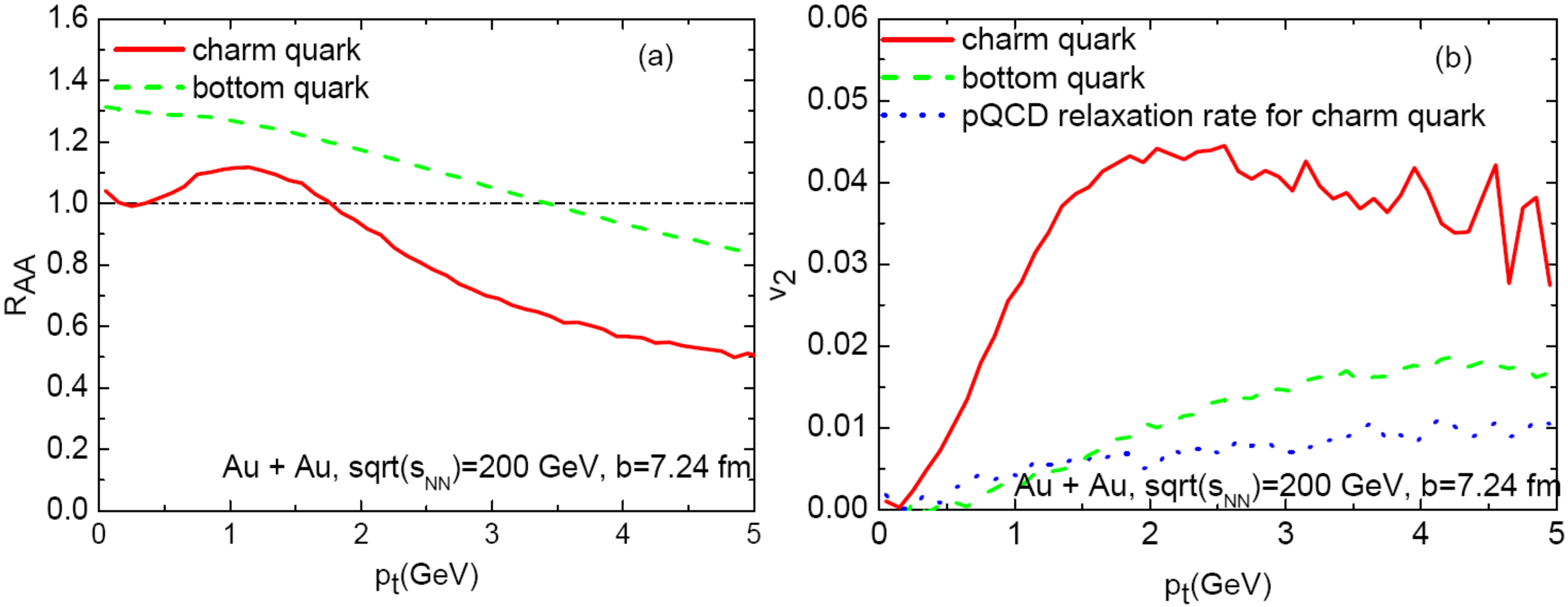
$$\Gamma(p) = A(p) + \frac{1}{E(p)}\frac{\partial D[E(p)]}{\partial E}.$$

HQ diffusion: Langevin simulation

Langevin + hydro simulation down to Tc=170 MeV
fluid rest frame updates → boost to lab frame

$$dx_j = \frac{p_j}{E}dt,$$

$$dp_j = -\Gamma(p)p_j dt + \sqrt{2dt\, D(|\mathbf{p}+\xi d\,\mathbf{p}|)}\rho_j.$$



- **initial HQ distribution: PYTHIA/FONLL + Glauber nBC**
- **quenching: early stage when medium particles' density is high**
- **v_2 : develops at later stage when the medium particles' v_2 is large**

Hadronization: Resonance Recombination

- **Hadronization = Resonance formation** $c\bar{q} \rightarrow D$

  → ***consistent with T-matrix findings of resonance correlations towards T_c***

- **Realized by Boltzmann equation** **Ravagli & Rapp,2007**

$$p^{\mu}\partial_{\mu} f_M(t,\vec{x},\vec{p}) = -m\Gamma f_M(t,\vec{x},\vec{p}) + p^0\beta(\vec{x},\vec{p})$$

gain term

$$\beta(\vec{x},\vec{p}) = \int \frac{d^3p_1 d^3p_2}{(2\pi)^6} f_q(\vec{x},\vec{p}_1) f_{\bar{q}}(\vec{x},\vec{p}_2) \times \sigma(s) v_{\rm rel}(\vec{p}_1,\vec{p}_2)\delta^3(\vec{p}-\vec{p}_1-\vec{p}_2)$$

Breit-Wigner

$$\sigma(s) = g_\sigma \frac{4\pi}{k^2} \frac{(\Gamma m)^2}{(s-m^2)+(\Gamma m)^2}$$

- **Equilibrium limit** $$f_M^{\rm eq}(\vec{p}) = \frac{E_M(\vec{p})}{m\Gamma} \int d^3x \beta(\vec{x},\vec{p})$$

- **Energy conservation** + **detailed balance**

→

equilibrium mapping between quark & meson distributions

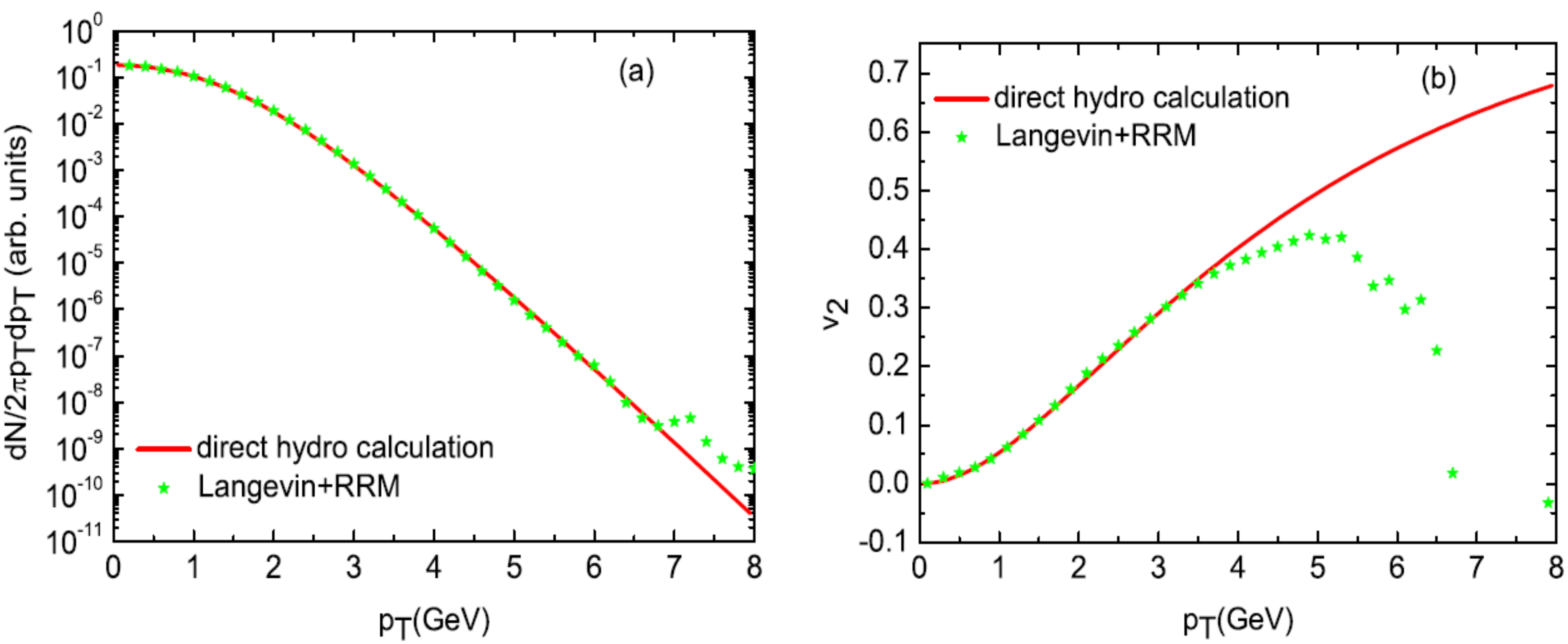
Hadronization: Coalescence(RRM)

- **RRM coalescence:**

--- 4-mom. conservation, correct thermal equilibrium limit

--- implemented on hydro freezeout hypersurface with full space-mom. correl.

--- taking care of the inhomogeneities of the hypersurface: d\tau/dx,y \=0

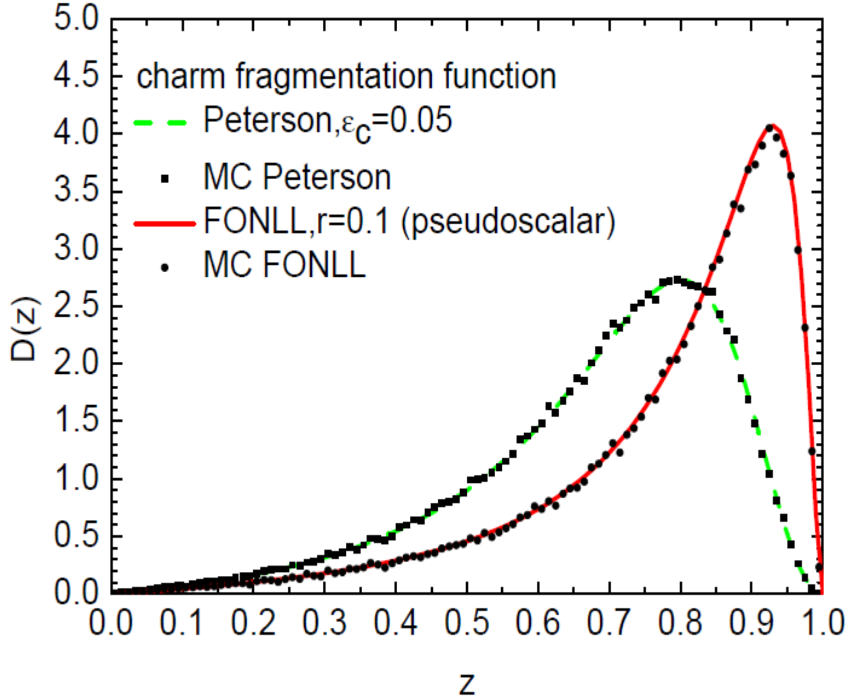


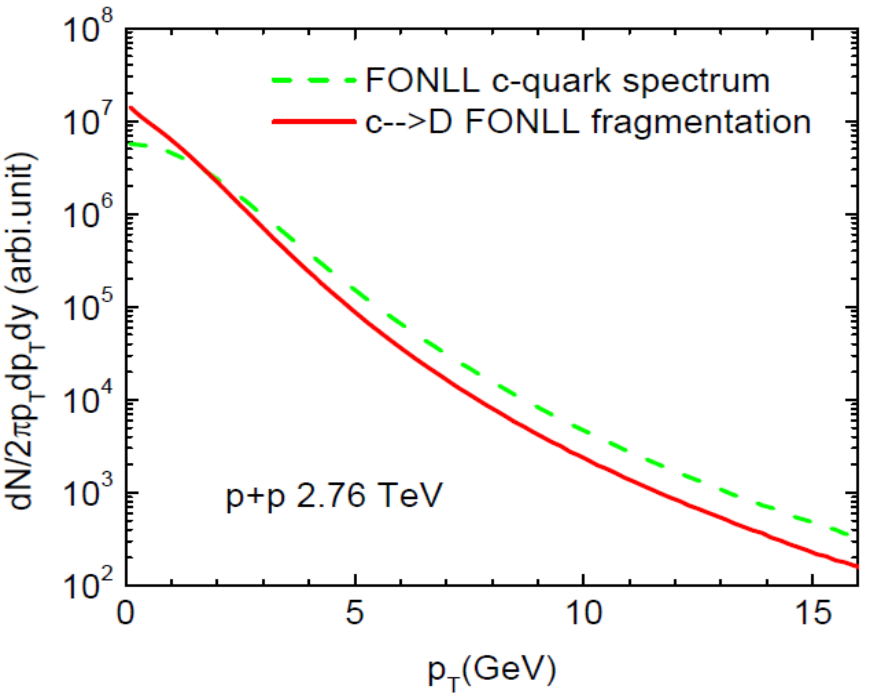
- **Diffusion vs coalescence**: **conceptually consistent**

--- same interaction (T-matrix) underlying diffusion + hadronization

Hadronization: Fragmentation (FONLL)

- **Fragmentation: incompatible with thermalization**





- **Coalescence vs fragmentation:**

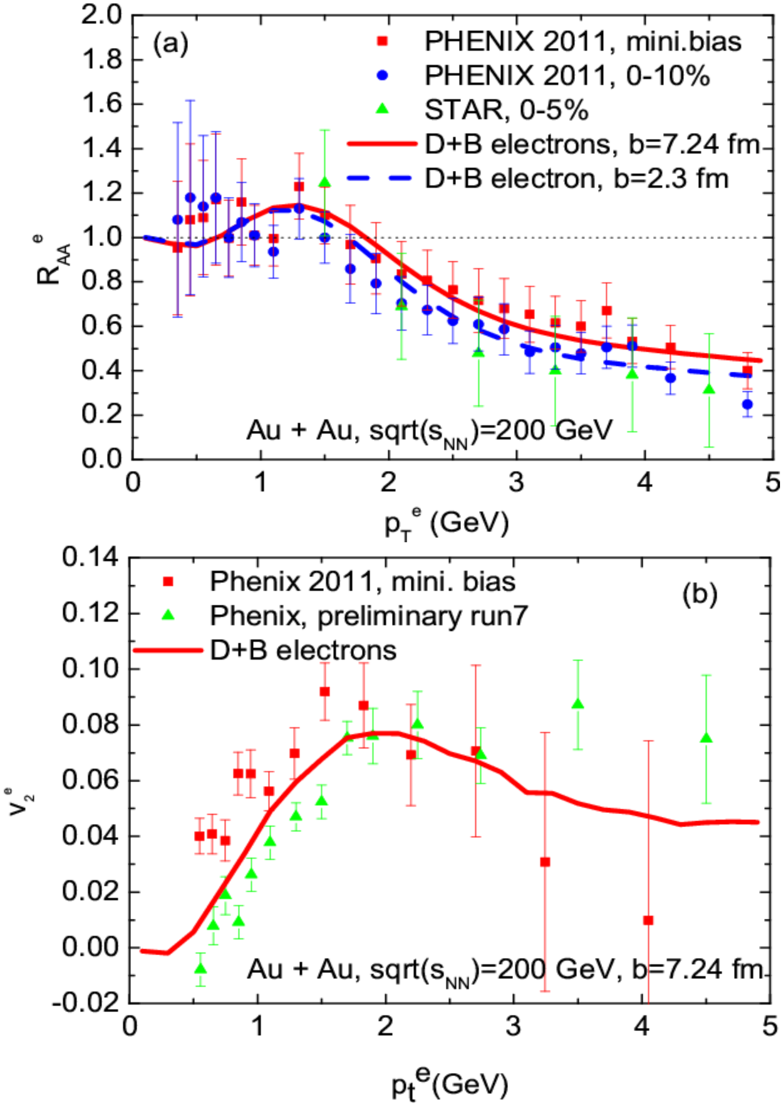
Recombination dominates at low p_T but yields to fragmentation at higher p_T

i.e. coal.prob. function P_{coal}(pt): a dropping function of pt

Phenomenology at top RHIC energy

Tuned ideal hydro, FONLL baseline + fragmentation

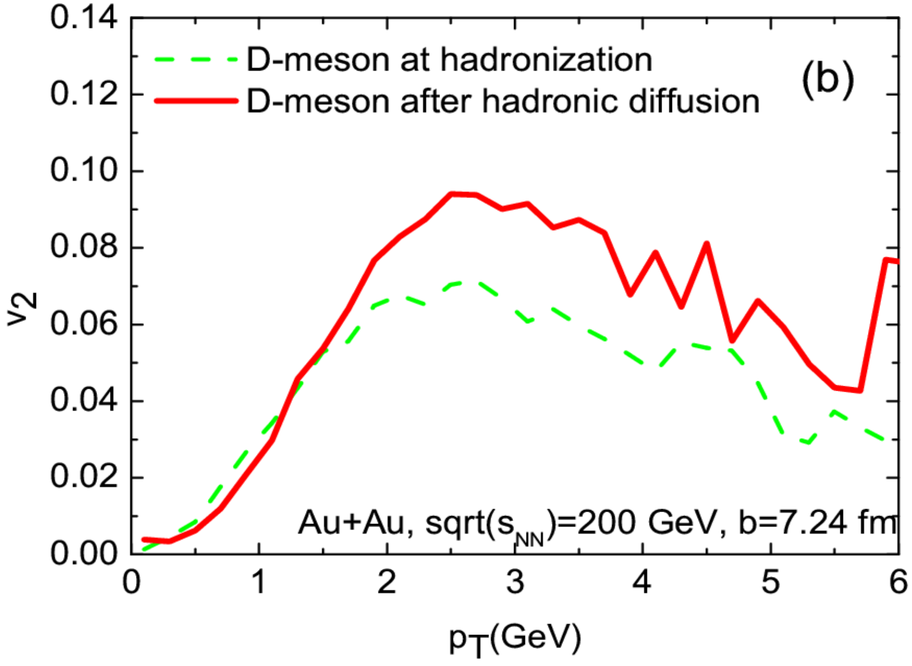
e± Spectra @ RHIC



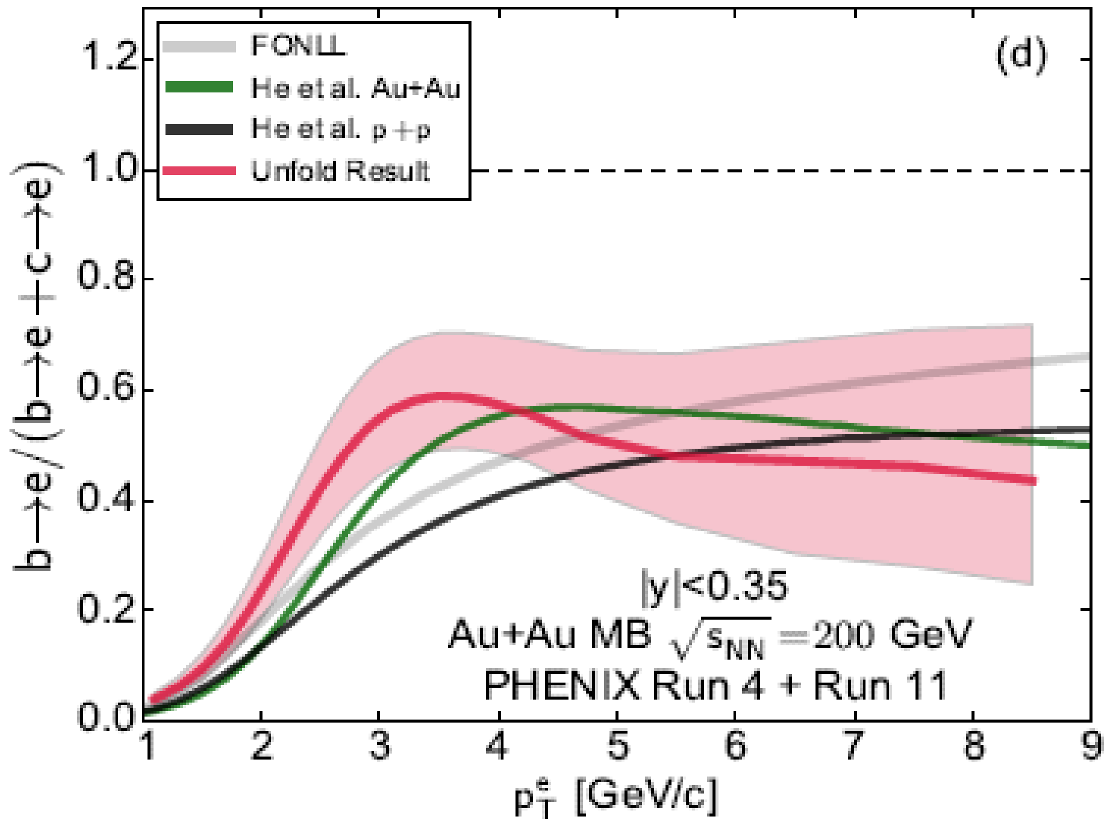
● medium modified D and B mesons: c/b diffusion + coal./frag. + hadronic diffusion

● semi-leptonic decays c(b) → s(c) + e + nu

D-meson Hadronic Diffusion



b→e / (b→e + c→e)

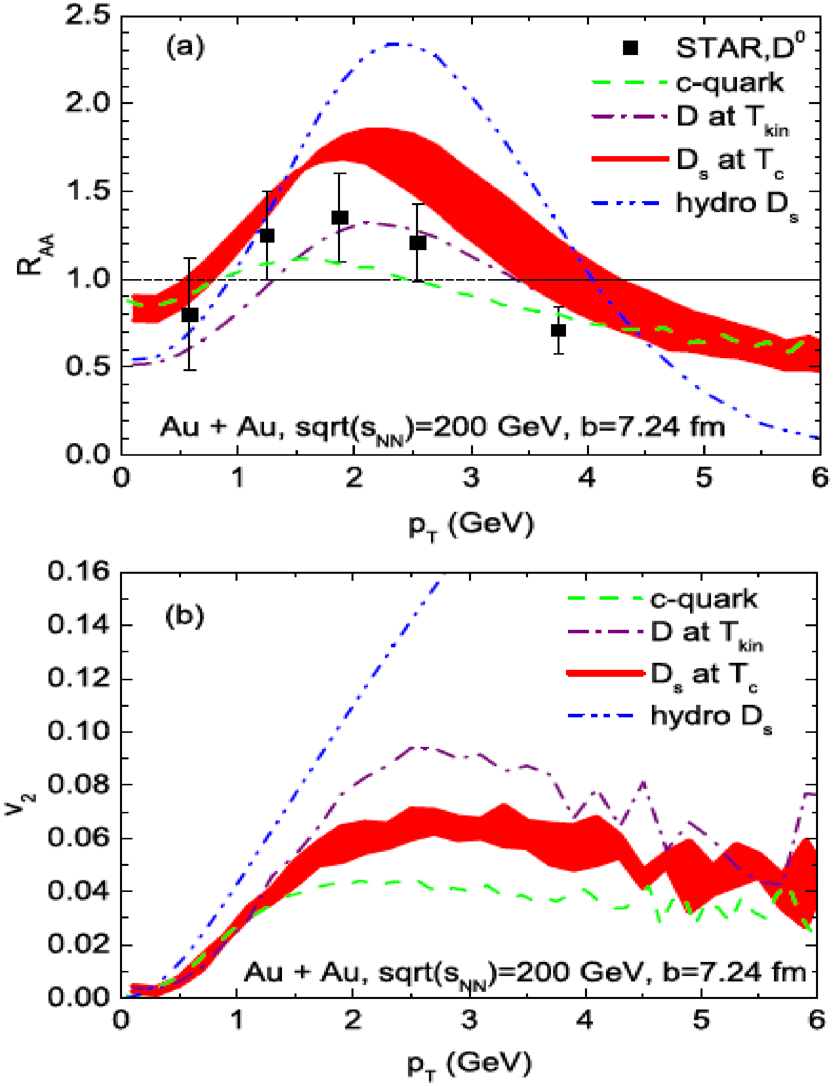


PHENIX, arXiv: 1509.04662

A slight decrease at high p_T!

- Low pt, c→e dominates, and charm more suppressed than bottom
  → above the pp curve
- Higher pt, b→e takes over, and bottom significantly suppressed
  → below the pp curve

D vs Ds mesons RHIC



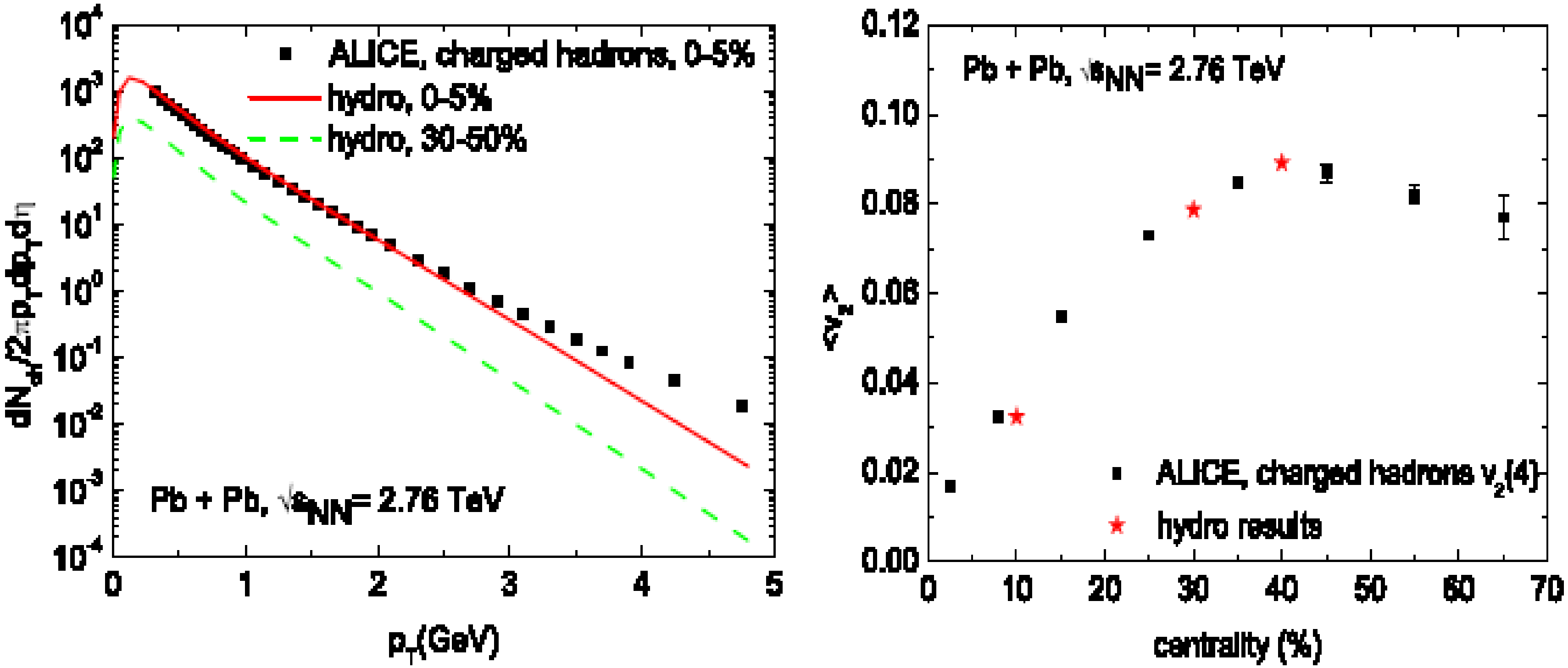
- **pronounced D/D_s flow-bump?!**
  RRM = an extra interaction, driving D-meson closer to equilibrium
- **D_s RAA ~ 1.5-1.8 at p_T~2 GeV**
  strong coupling c-QGP + coalescence + strangeness enhancement (unique valence quark content csbar)
- **D_s freezeout at T_c, D at T_{kin}**
  D vs D_s v_2: quantitative measure of charm interaction in hadronic phase

→a unique pattern of RAA and v_2 of D_s vs D mesons emerges

Phenomenology at the LHC
Pb-Pb 2.76 TeV

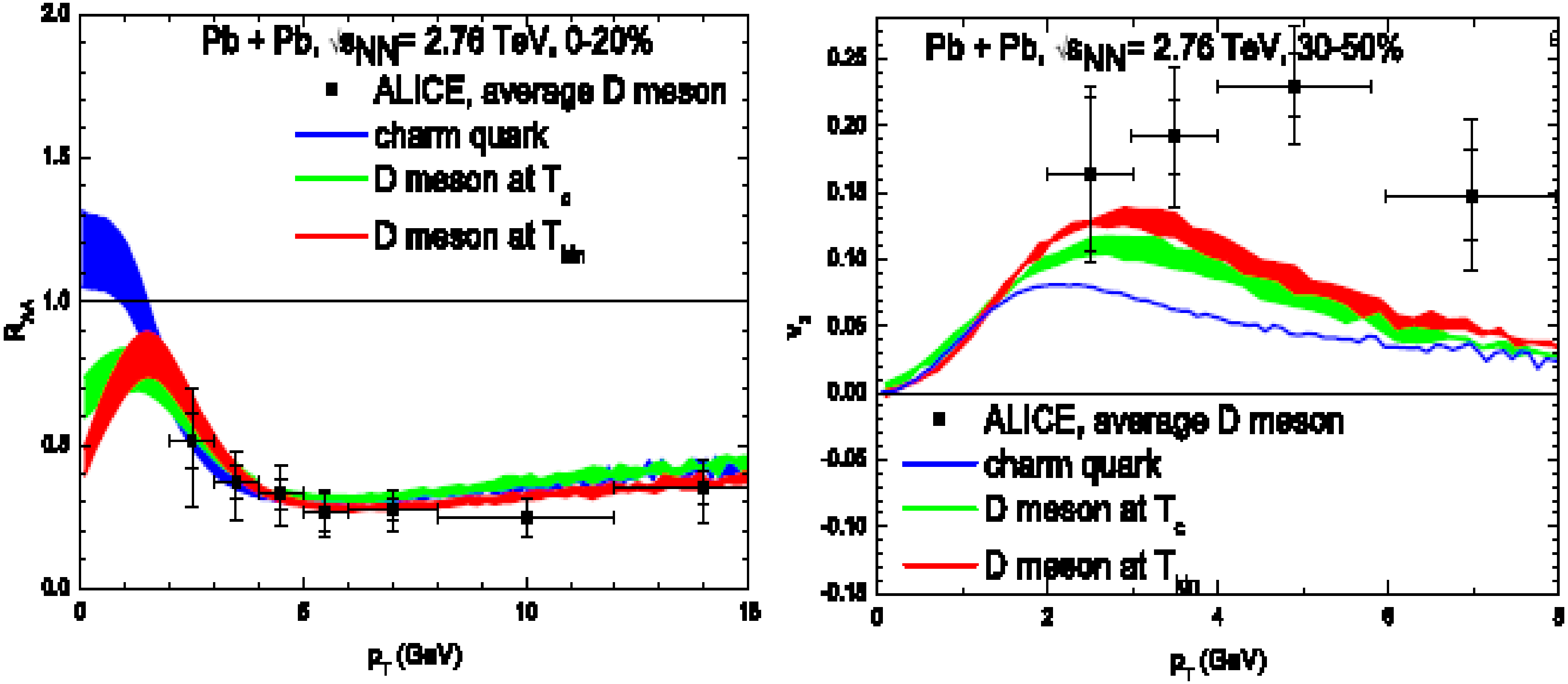
Tuned ideal hydro + FONLL pp baseline + FONLL fragmentations

Hydro tune for the LHC



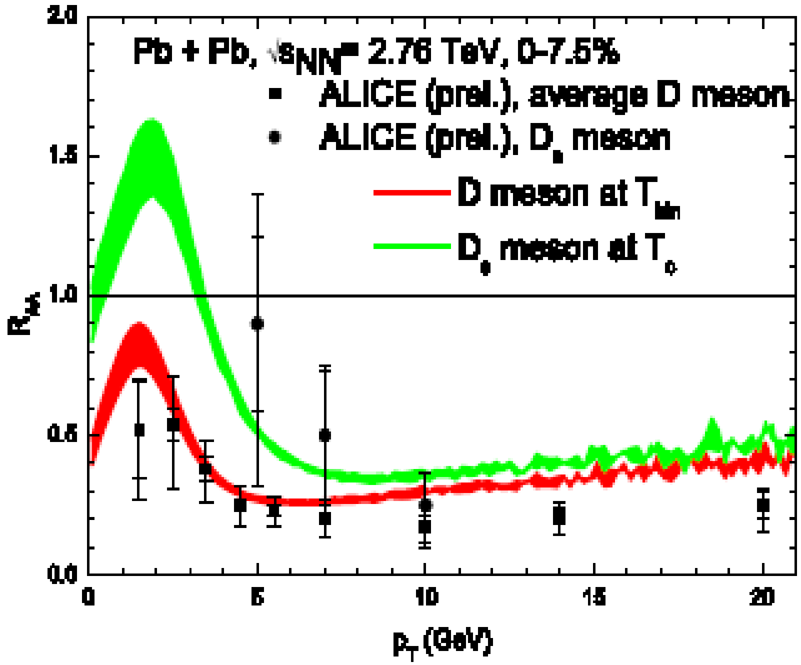
- p_T-spectra of charged hadrons fine
- v_2: integrated elliptic flow a good measure of the bulk momentum anisotropy
- background medium evolution well constrained

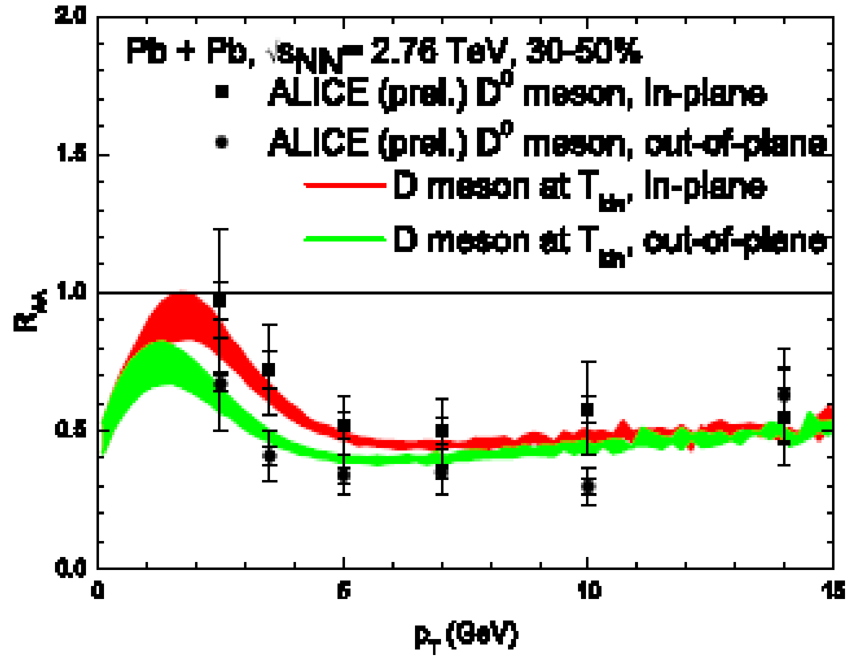
LHC D mesons



- R_{AA}: flow bump at low p_T, amplified by coalescence
  p_T-dependence shape OK; possible missing radiative energy loss at high pT
- v_2: c-diffusion only accounts for ~50%
  recombination and hadronic phase diffusion essential

LHC D vs Ds mesons

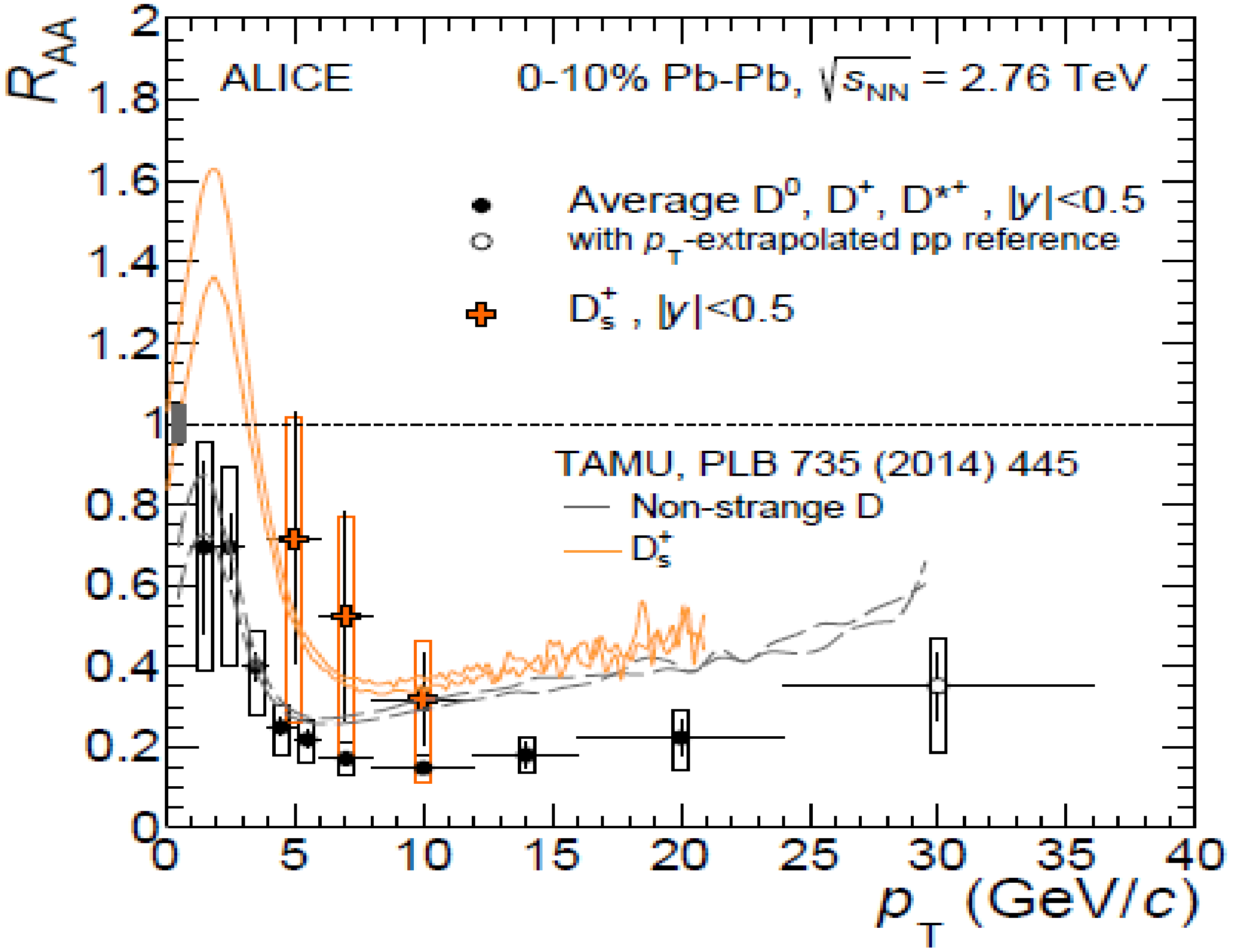




- **D vs D_s R_{AA} : low p_T, coalescence enhances D_s production in a strangeness-equilibrated, strongly-coupled QGP medium, relative to pp; high p_T, D & D_s tend to the same universal fragmentation**

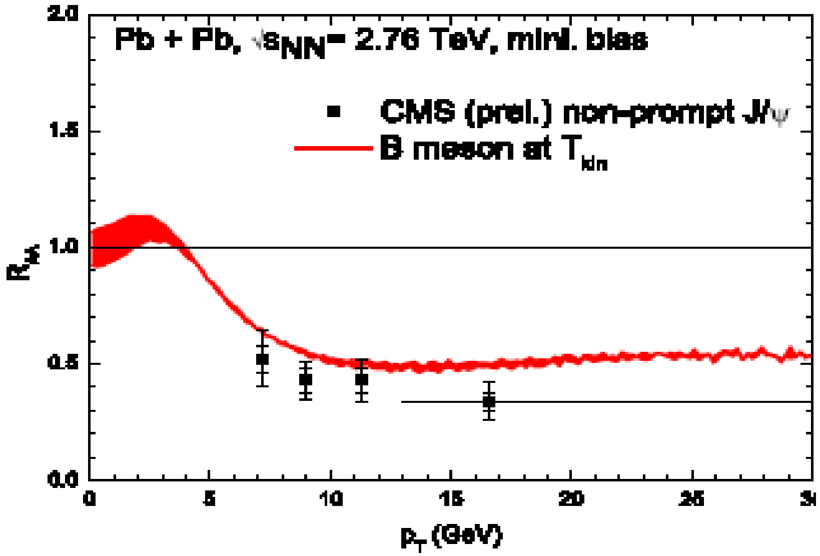
- **D R_{AA} in-plane vs out-of-plane: splitting at low p_T reflects finite v_2 high p_T splitting underestimated, indicative of missing radiative energy loss**

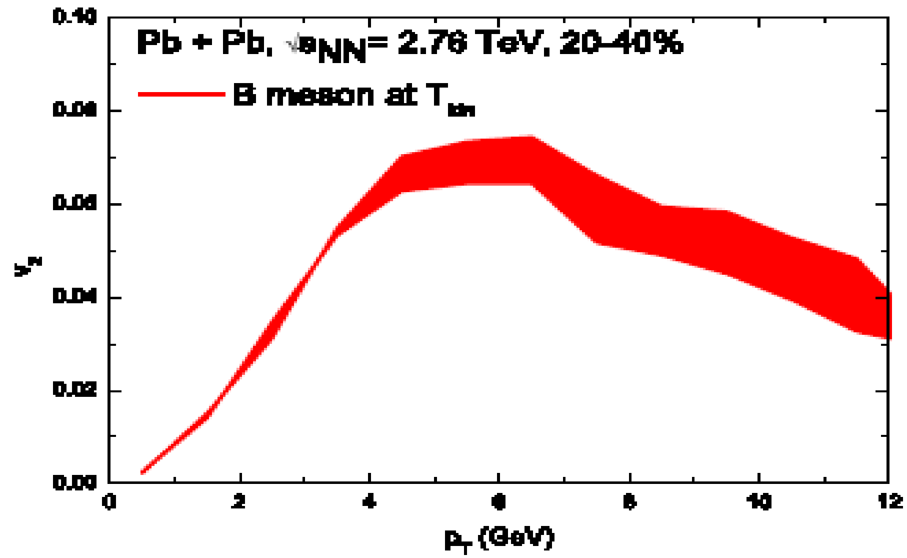
ALICE: D vs Ds JHEP03(2016)082

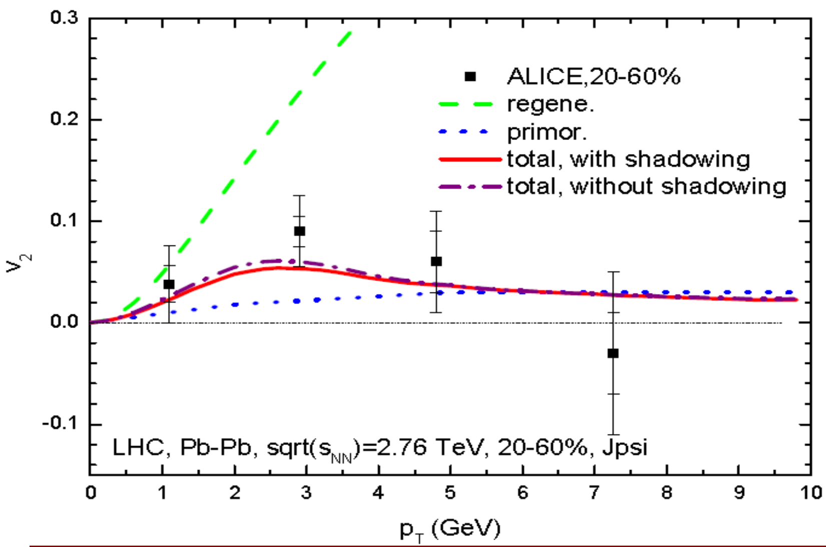


Enhanced Ds-meson R_{AA} tests out interactions at hadronization!

LHC B mesons & non-prompt Jpsi



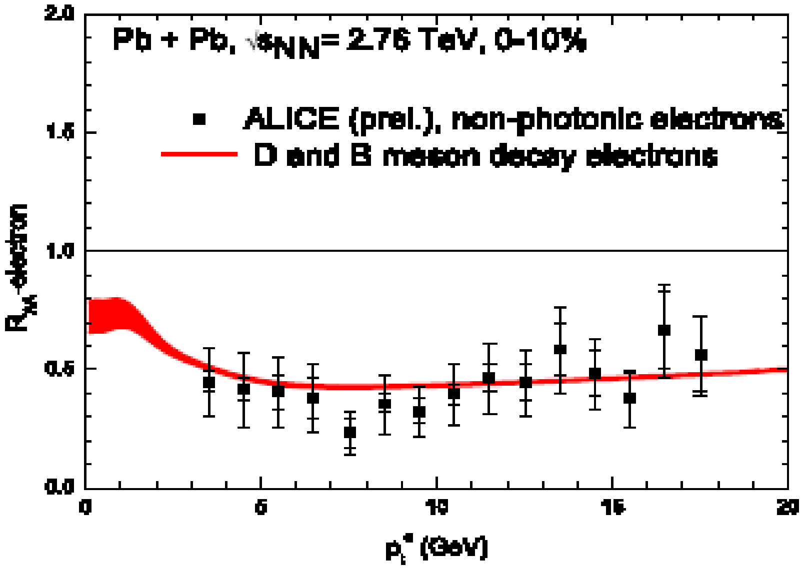


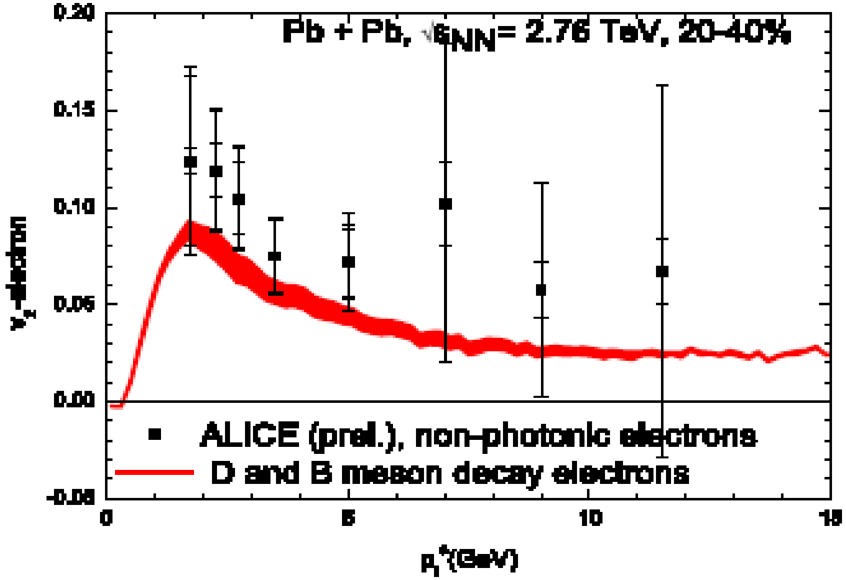


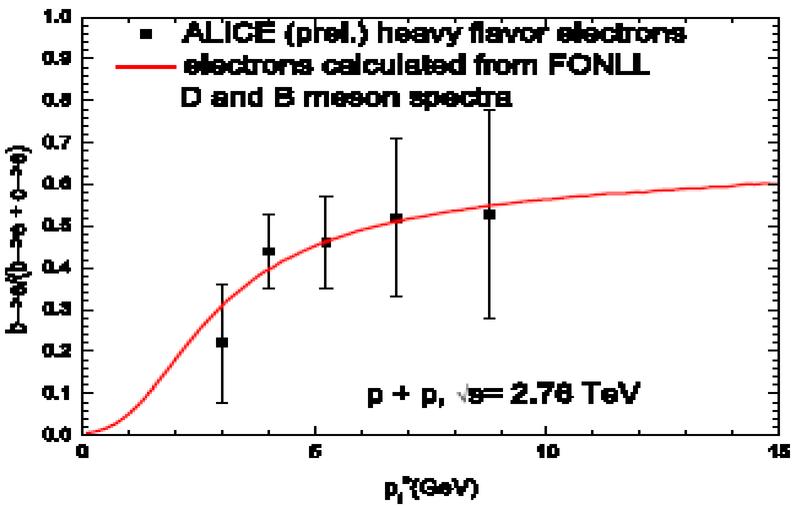
◆ R_{AA} : substantial suppression (~0.5-0.6) at p_T>10 GeV; consistent with CMS non-prompt J/psi data point

◆ v_2: up to ~7%, significant yet less collectivity than D mesons ➔ implications for J/psi v_2 (B➔J/psi+X)

LHC HF electrons







◆ R_{AA} : overpredicted in the D dominant region; fairly good in the B dominant region (elastic e-loss only)

◆ v_2 : marginally hit data, radiative e-loss?

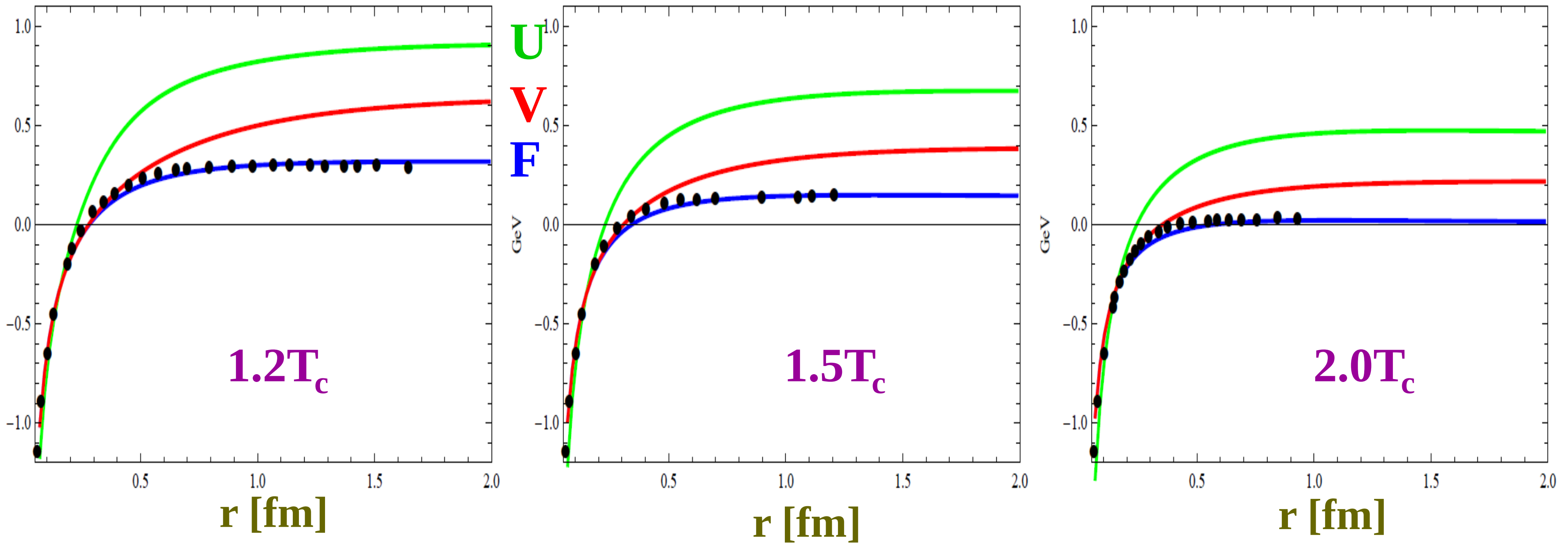
Step Forward …

A New HQ potential +
phenomenological consequence

Liu, He, Rapp et.al, in preparation

Tuned ideal (hardphoton) hydro + FONLL pp baseline + FONLL fragmentations

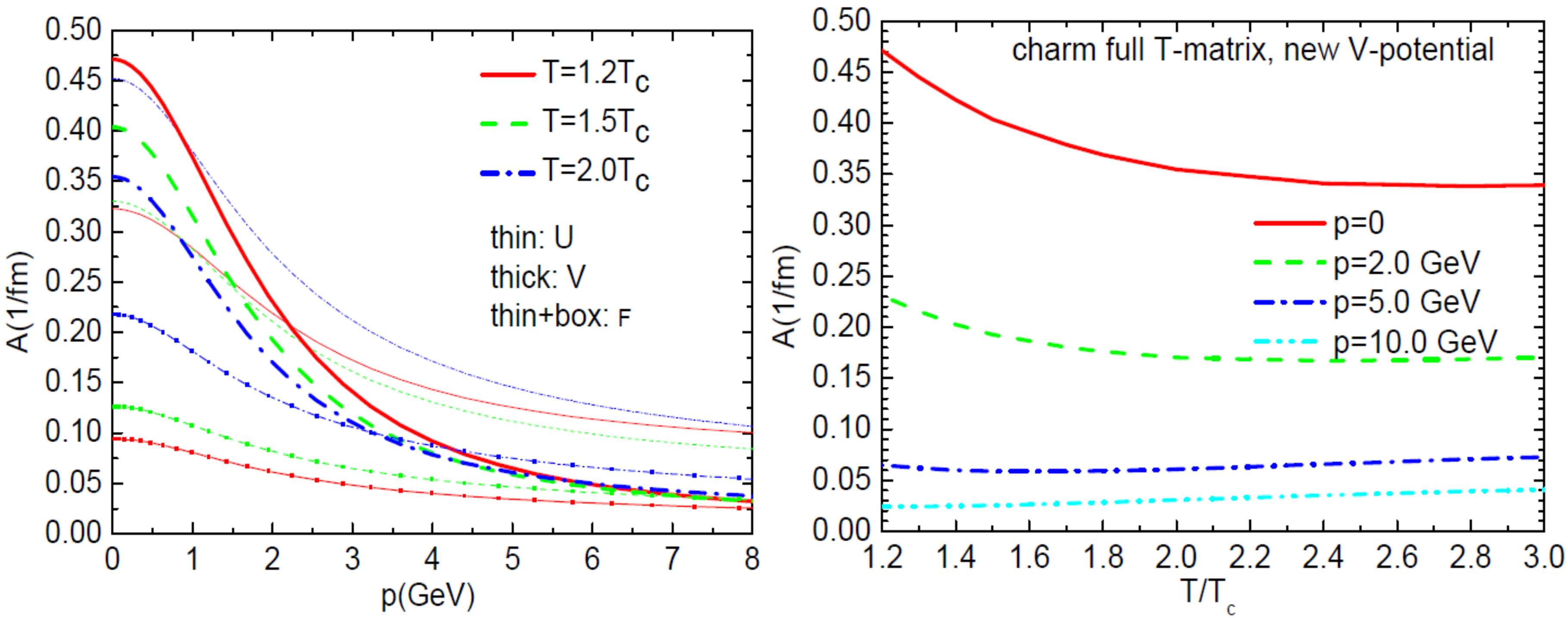
A new HQ potential from T-matrix



Liu, Rapp 2015

- new potential V(r): larger slope than U at medium r & T~1.2T_c
  ➔ larger remnant confining force in medium range r ~ 1fm
- phenomenological ly: charm quarks couple to more medium particles, relative to short-range force from U/F

Charm thermal relaxation rate



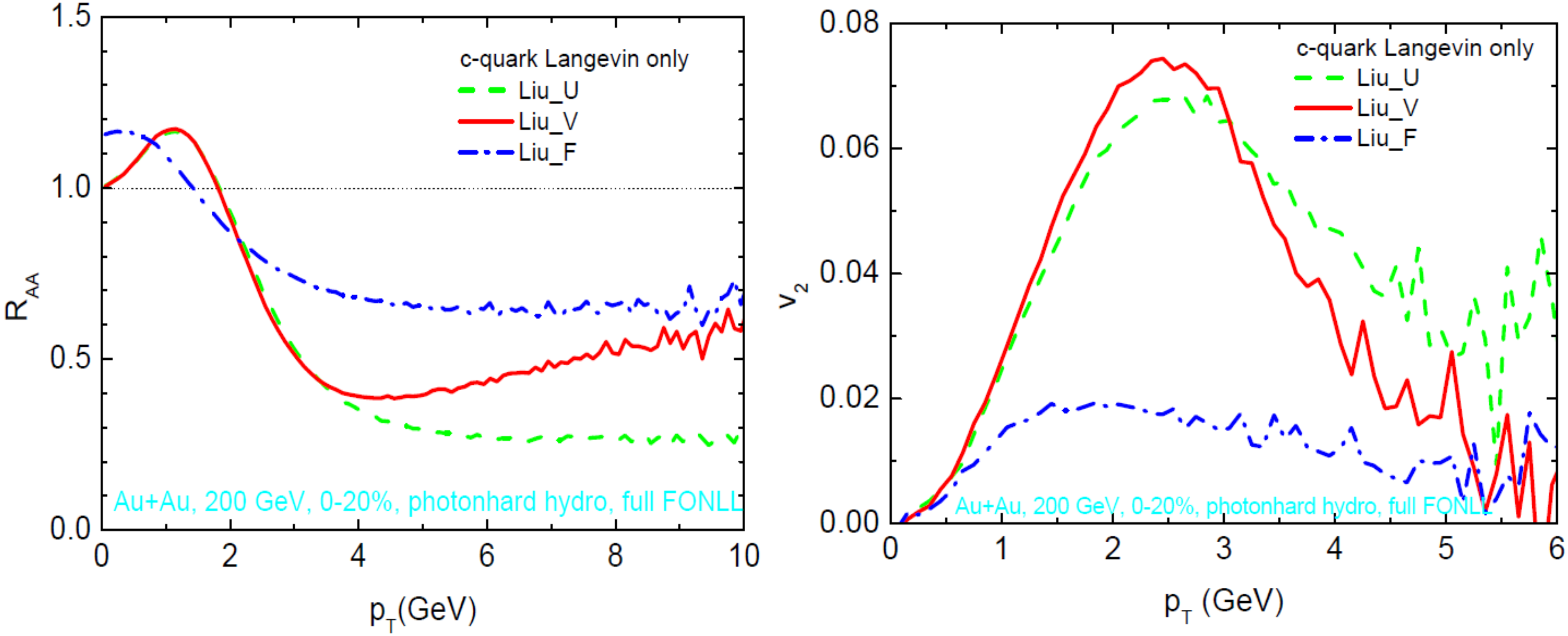
◆**p<2.5 GeV & low T<1.5Tc, V results overtake U results due to longer range remnant confining force; high p: tends to pQCD results**

◆**unique T-dependence: reversed relative to U/F**

low p: increasing as T →T_c , help develop large v_2 ,

high p: increasing with T, pQCD

Phenomenology: Charm quark v_2 and R_{AA}



Liu, He, Rapp in preparation

◆ **new potential V(r): larger v_2 (which is most efficiently built up near T_c when the background medium v_2 large) ➔ $v_2^c(p_T \approx 2GeV)$ probes transport coeffi. via intermediate-range confining force**

◆ **At high p_T : less suppression, calling for radiative energy loss ?!**

Summary & Outlook

------ Summary: nonperturbative open HF interaction & transport

- **Conceptual Consistency**

  --- diffusion ↔ hadronization:

  based on the same resonant interaction from T-matrix

  --- diffusion ↔ bulk medium:

  both based on strongly coupled QGP, non-perturbative

- **Application: RHIC & LHC**

  --- dynamical charm flow emerges; successful for low & intermediate p_T

------ Outlook

- **elastic vs radiative energy loss**

  --- to be nonperturbatively & selfconsistently incorporated simultaneously

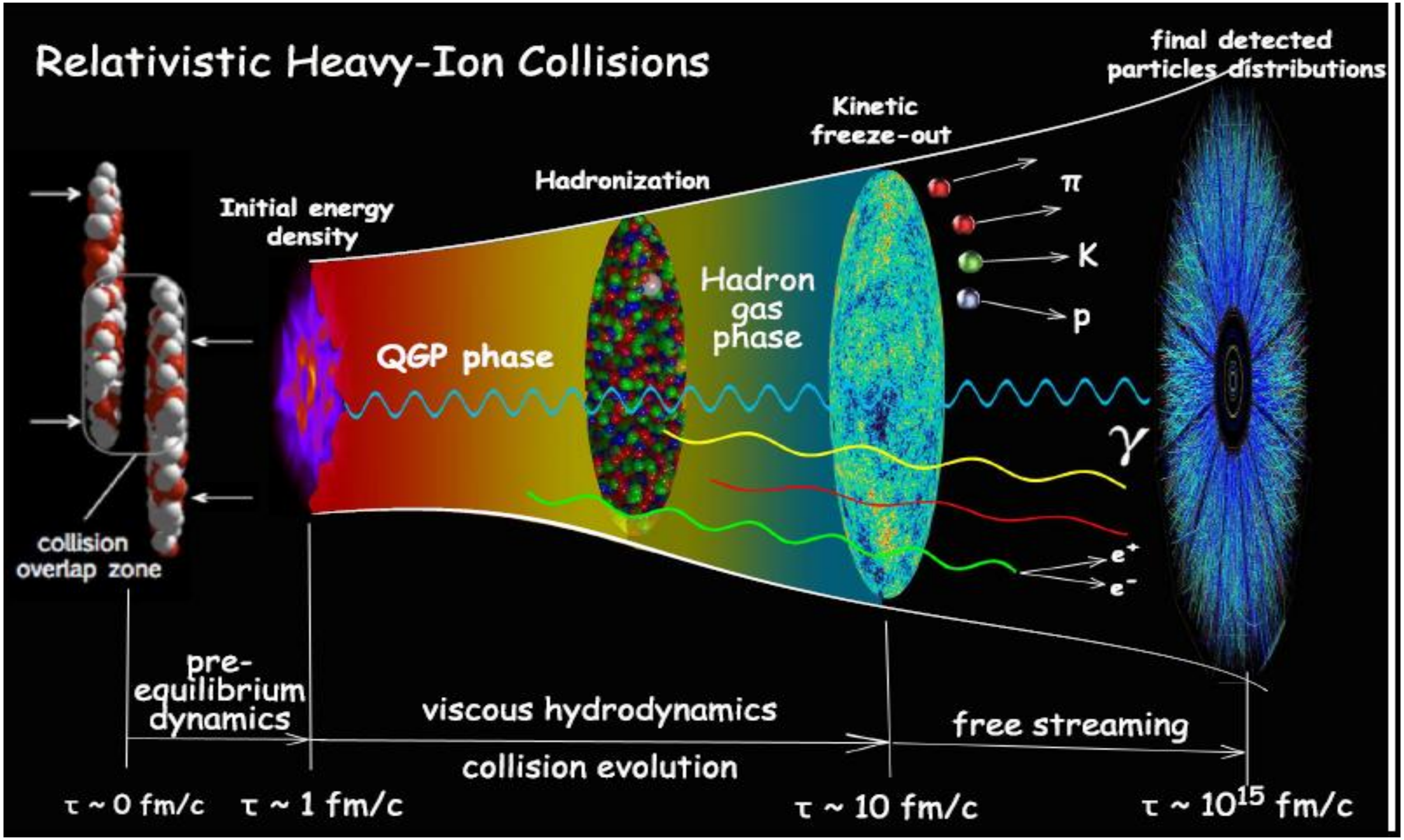
  --- coupled-channel T-matrix approach

- **open vs hidden HF**

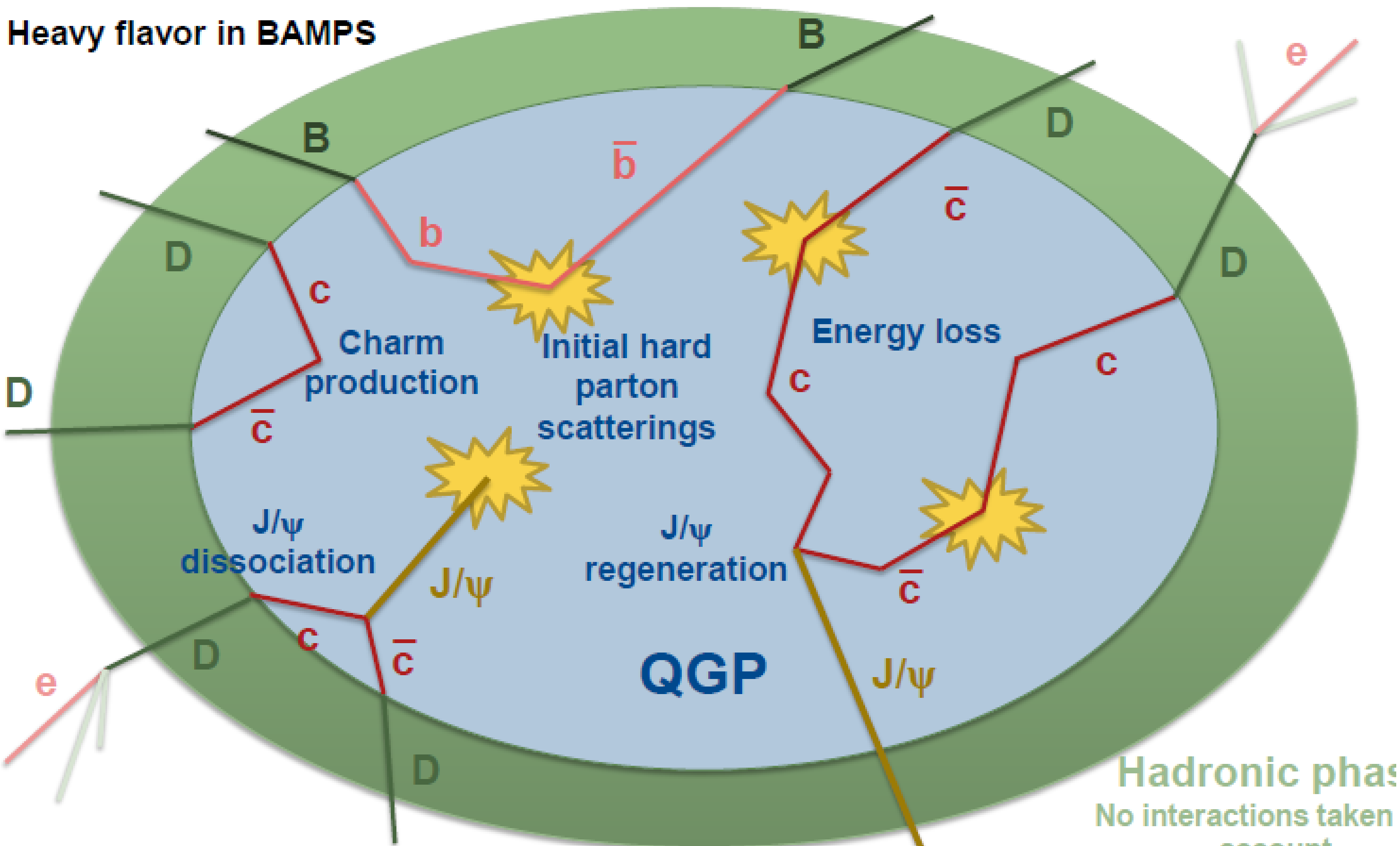
  --- implications of open HF transport on hidden HF production

  --- a unified Langevin dynamical approach to incorporate both

Backup: space-time evolution of HIC



Backup: Heavy quarks



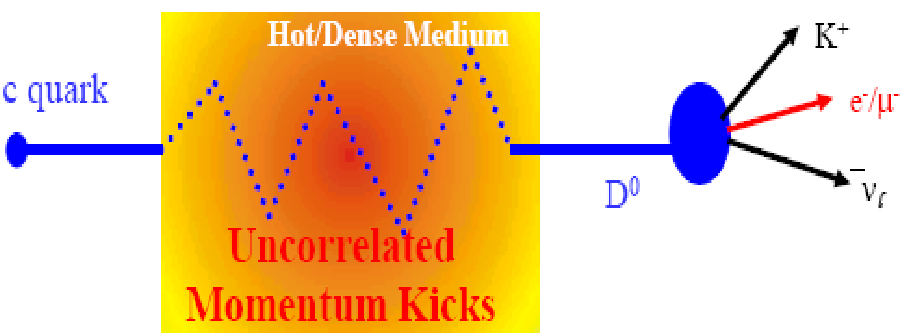
Backup: HQ probes

- primordial hard production + number conserved
- thermalization delayed $\tau_Q \approx \frac{m_Q}{T}\tau_q \approx 6 * \tau_q \geq \tau_{QGP}$

➔Heavy quarks make a direct probe of the medium

- HQ diffusion in QGP: elastic scatterings with medium

$$q_0 \sim \vec{q}^{\,2}/2m_Q << |\vec{q}|$$



Brownian motion:
Fokker-Planck Equation

$$\frac{\partial f}{\partial t} = \gamma \frac{\partial (pf)}{\partial p} + D\frac{\partial^2 f}{\partial p^2}$$

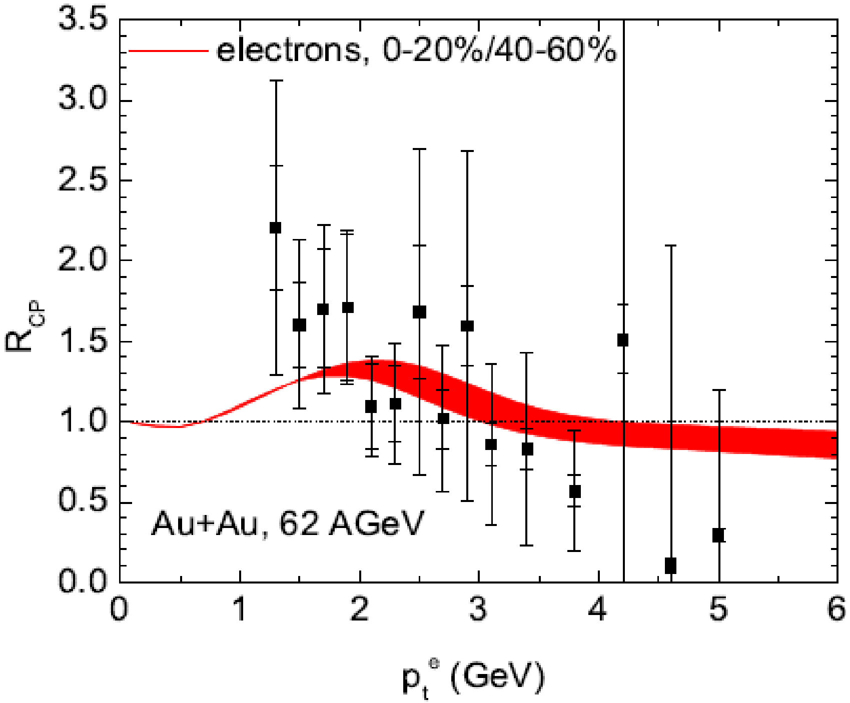
thermalization rate

$$\gamma \propto \int |T_{Qq}|^2 (1-\cos\theta) f^q$$

diffusion coefficient

$$D = \gamma m_Q T$$

Au-Au 62.4 GeV Compare R_{CP} by Duke



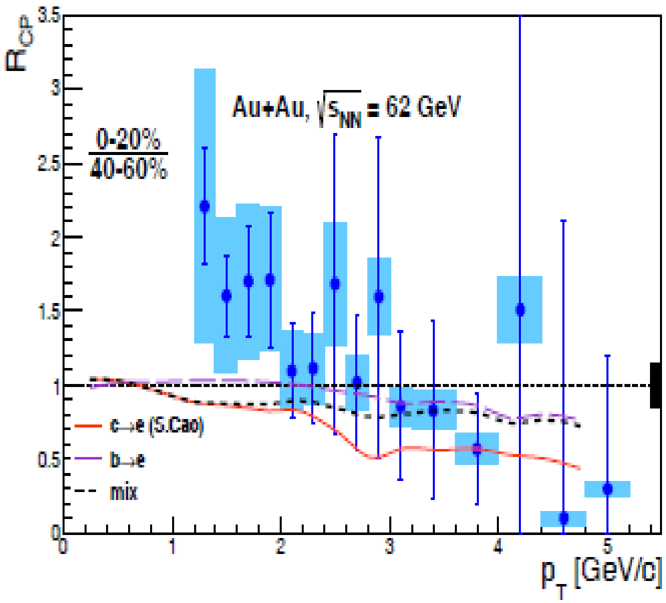
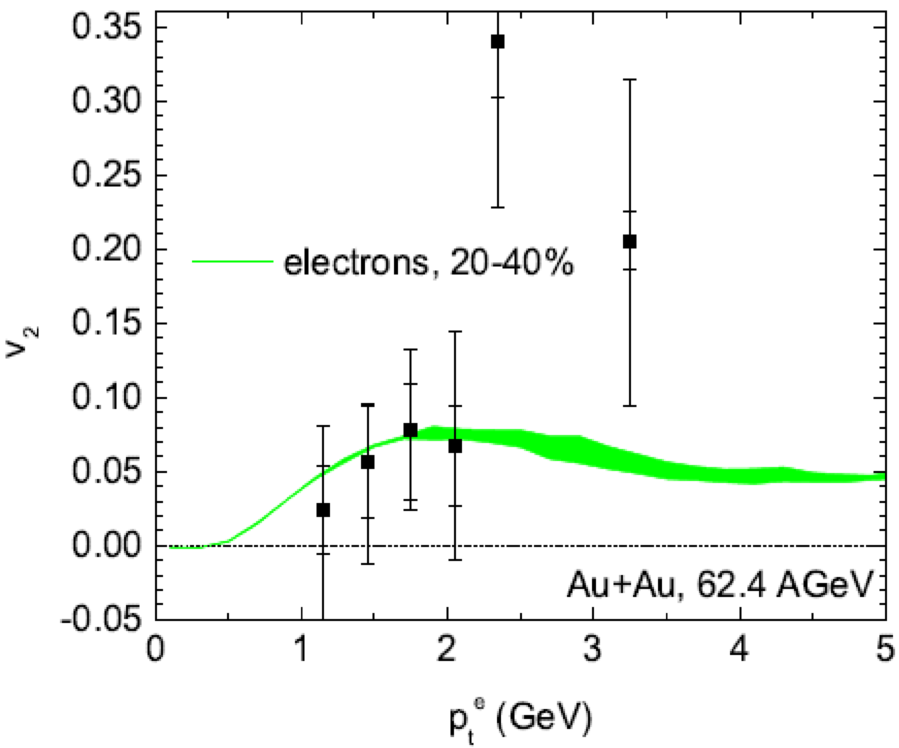
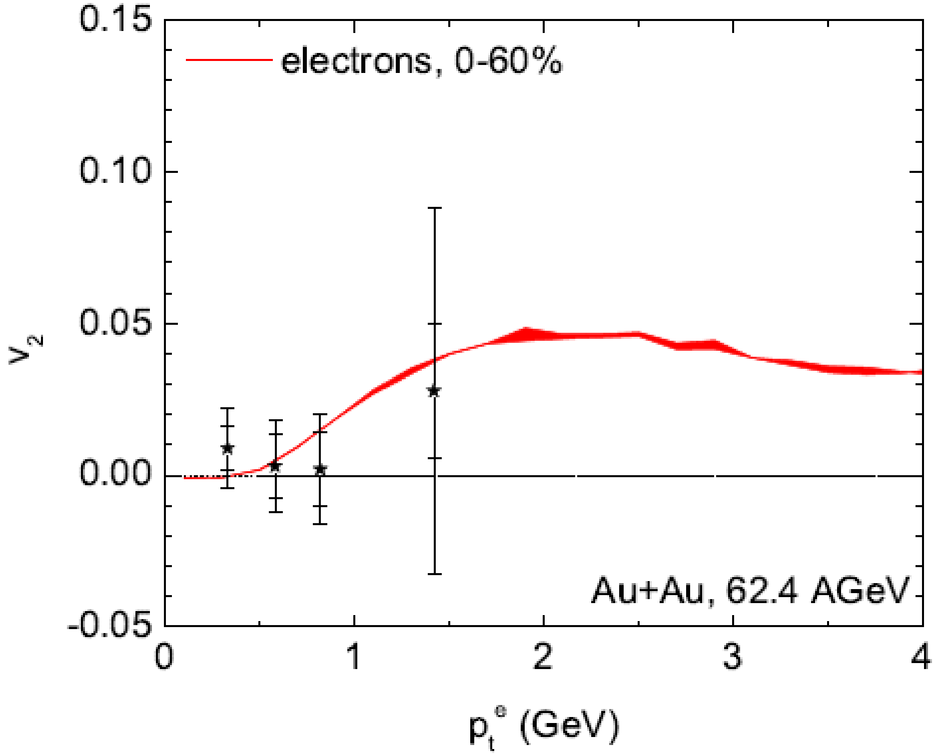


FIG. 19: (color online) Heavy flavor electron R_{CP} between centrality 0%–20% and 40%–60% in Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV. The curves are calculated using a model based on energy loss [48].

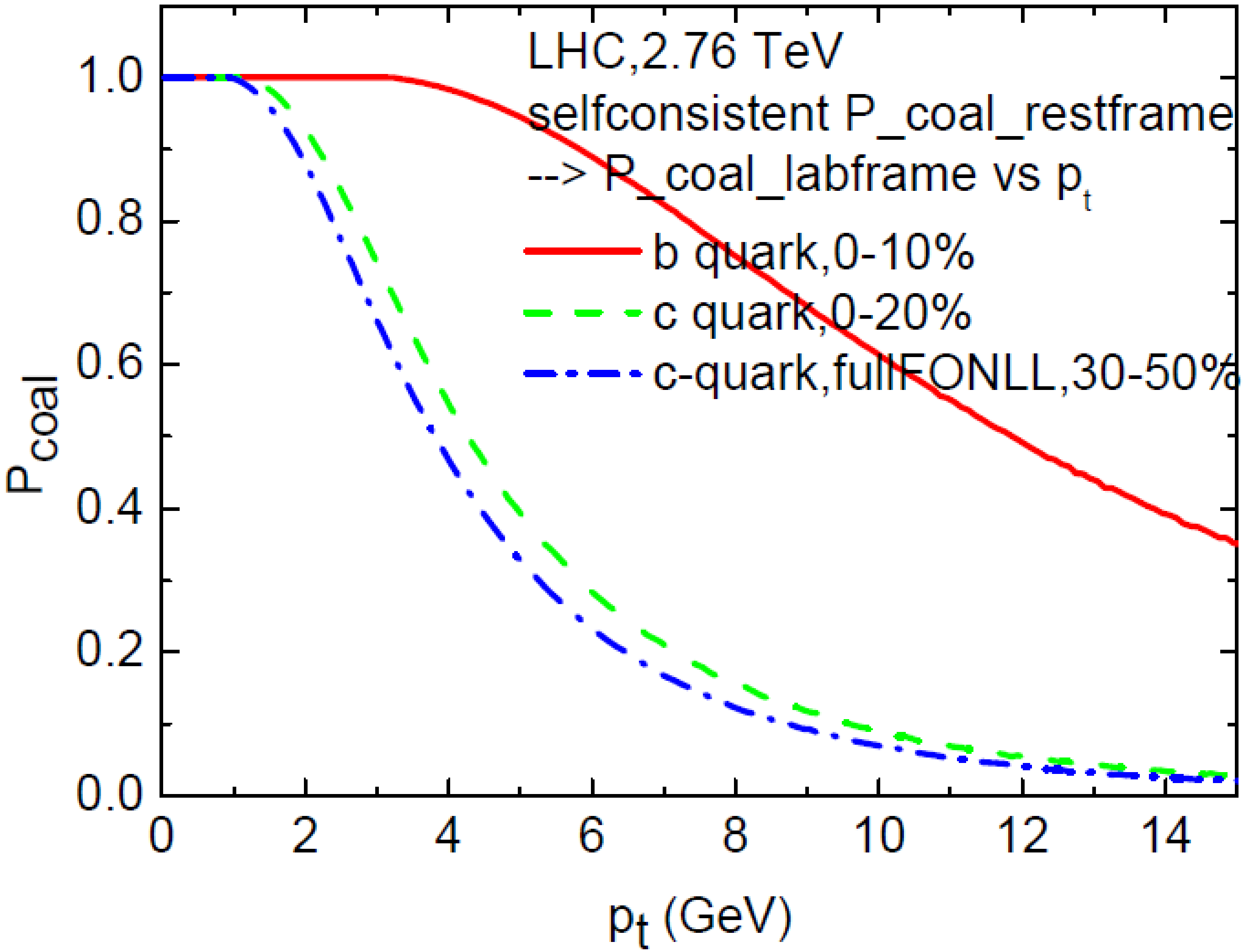
Au-Au 62.4 GeV HF electrons v2



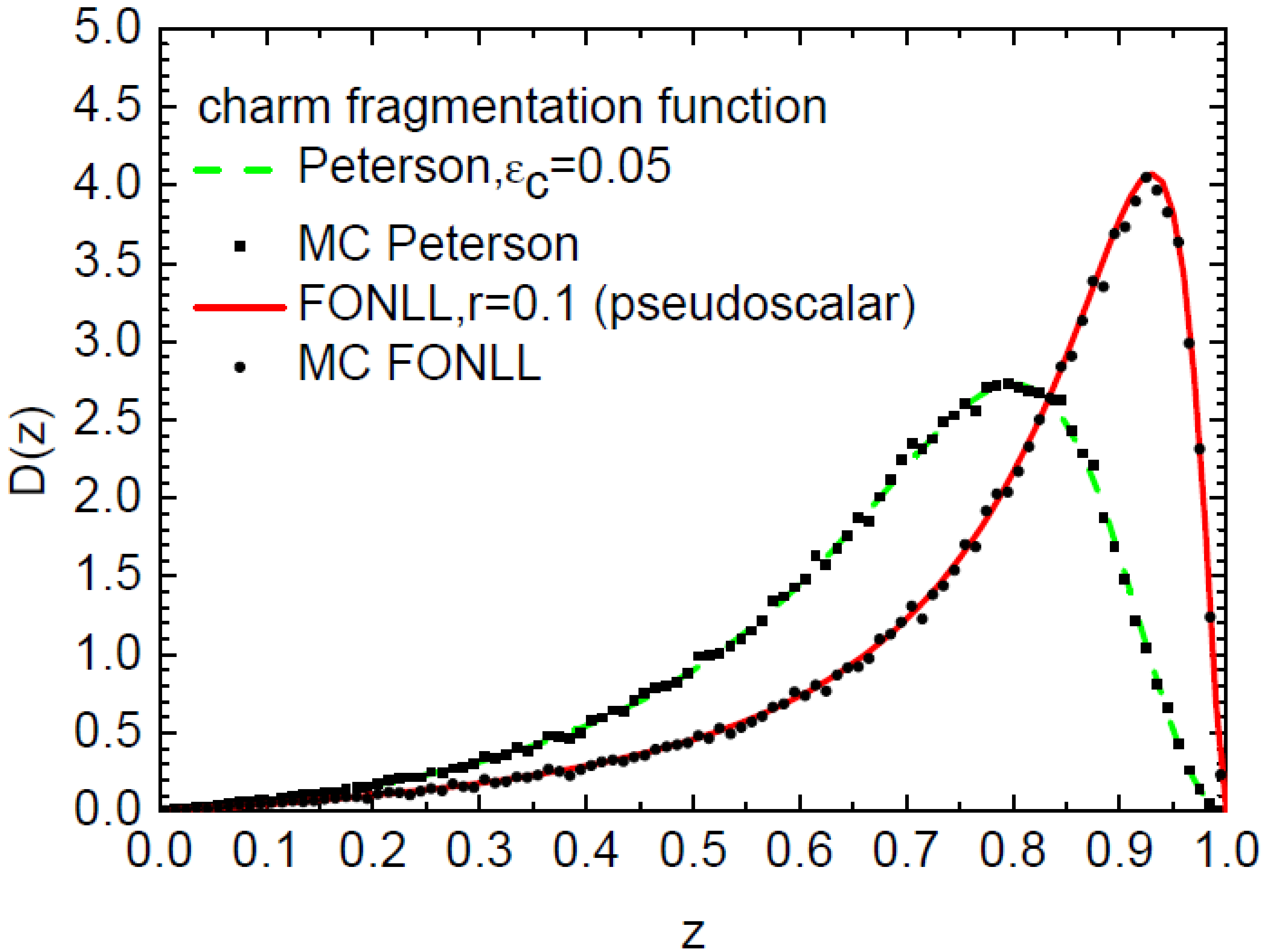


- ◆ No discrepancies can be made out, albeit within rather large error bars in data
- ◆ 0-60% centrality v_2: from a N_{coll}-weighted average of v_2's of the 0-20%, 20-40% and 40-60% centrality bins

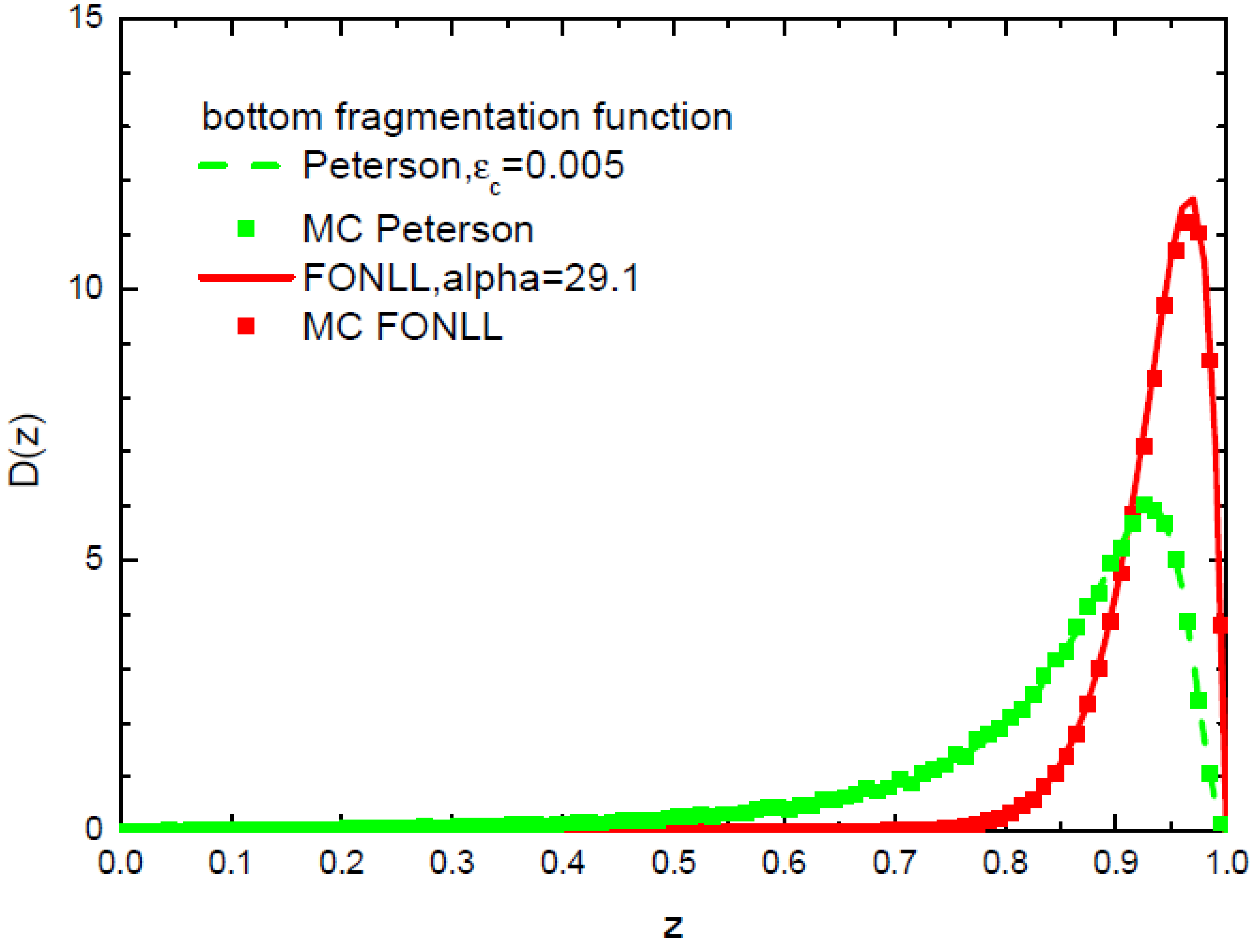
Charm/bottom quark coal.prob.



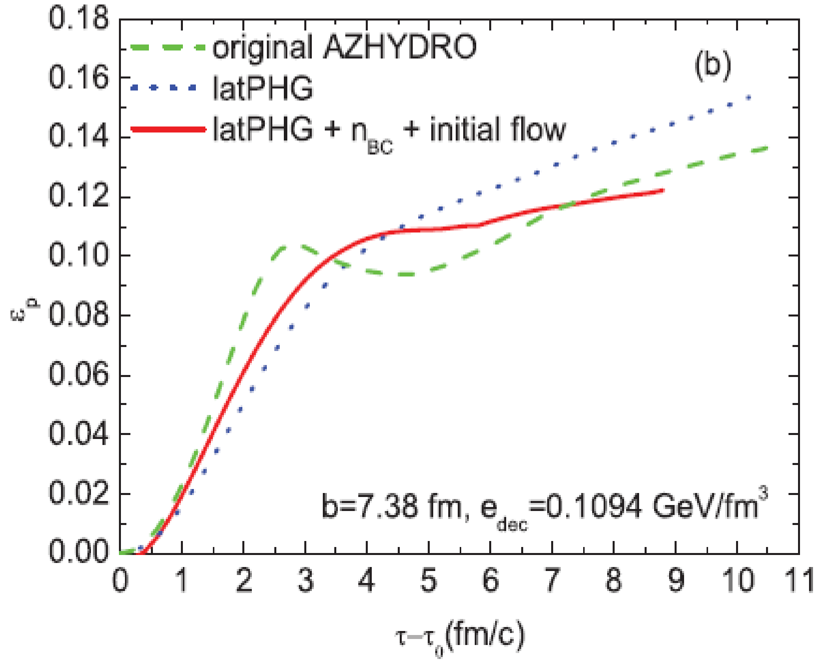
Charm quark FONLL vs Peterson frag.

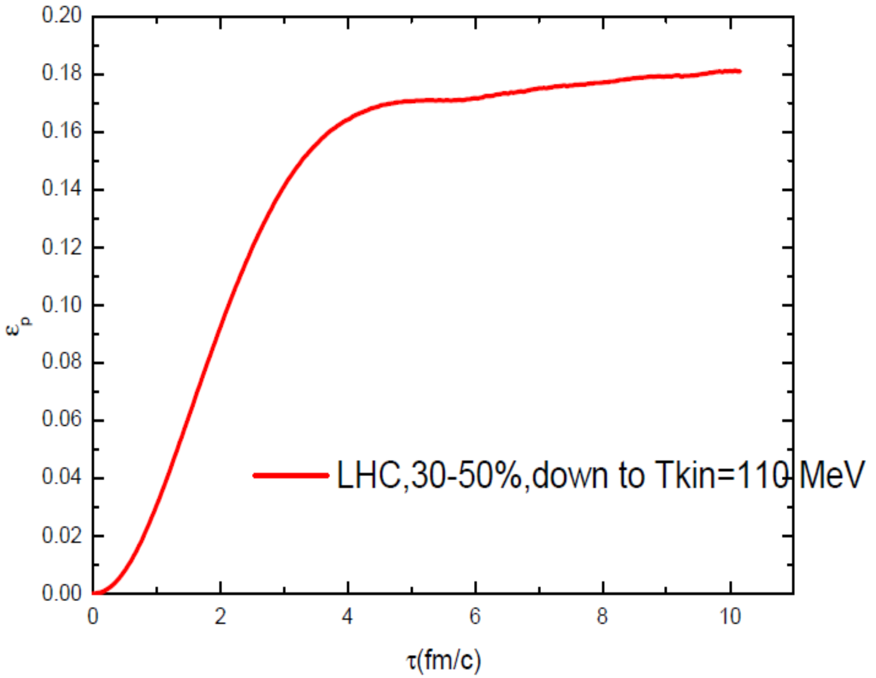


Bottom quark FONLL vs Peterson frag.

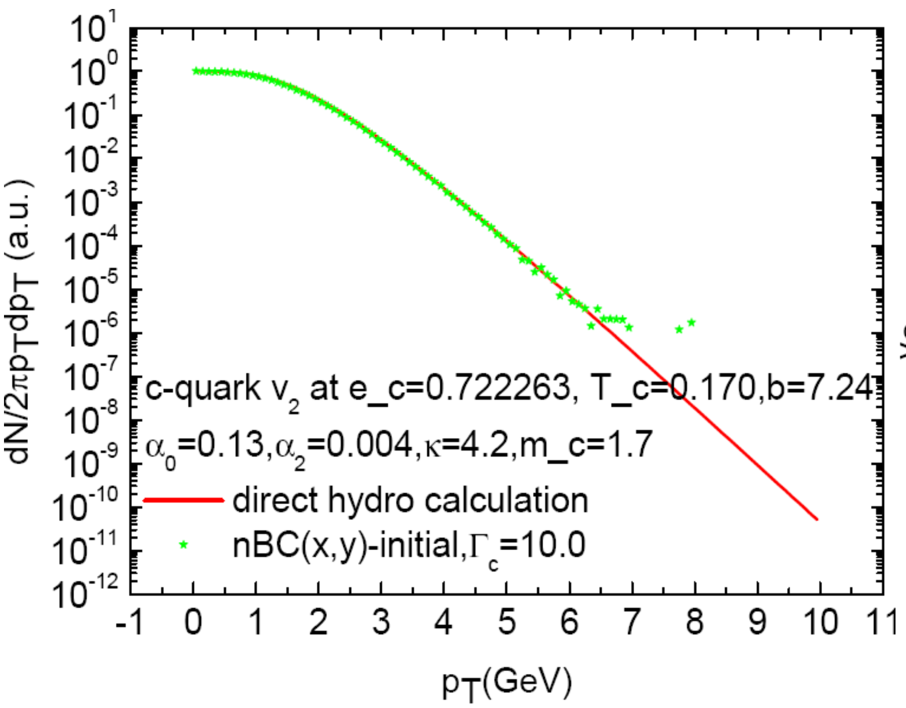


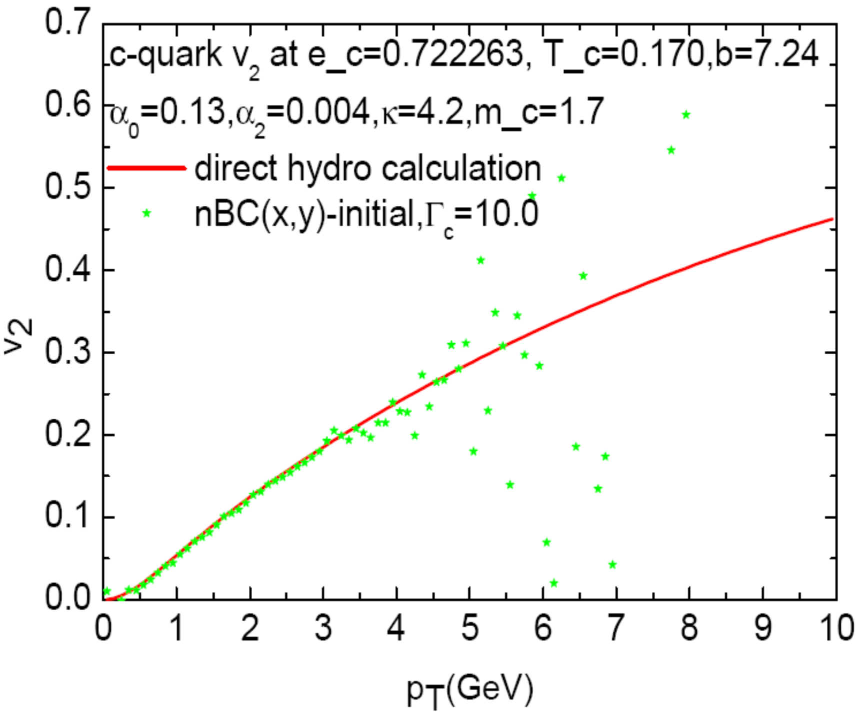
Energy-momentum tensor anisotropy



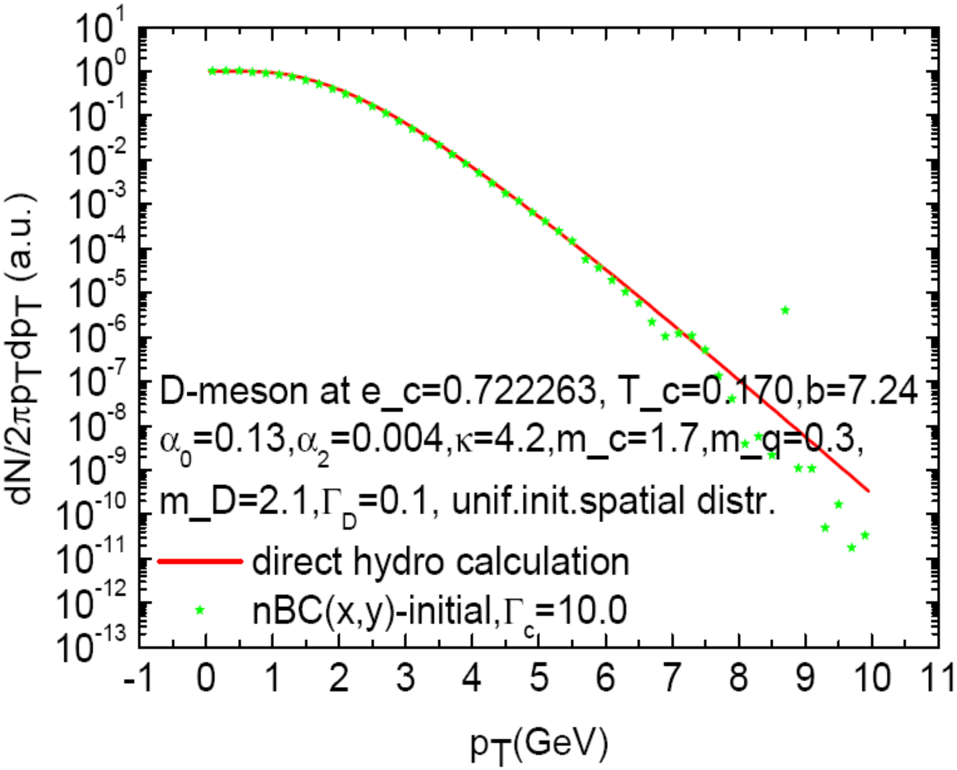


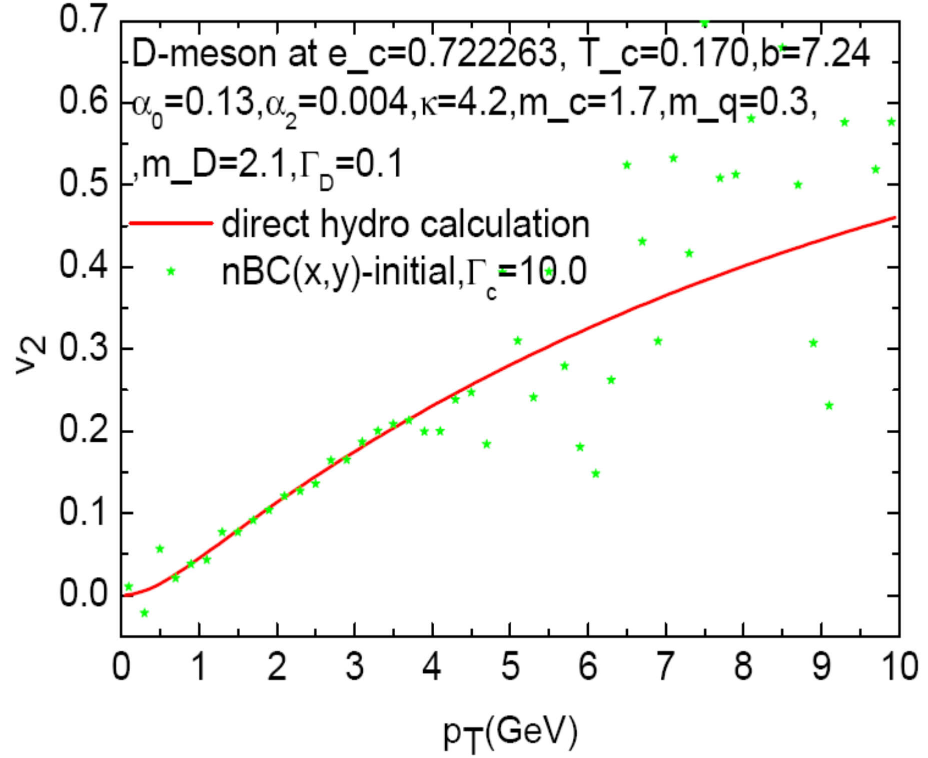
Backup 1: charm quark Langevin diffusion equilibrium



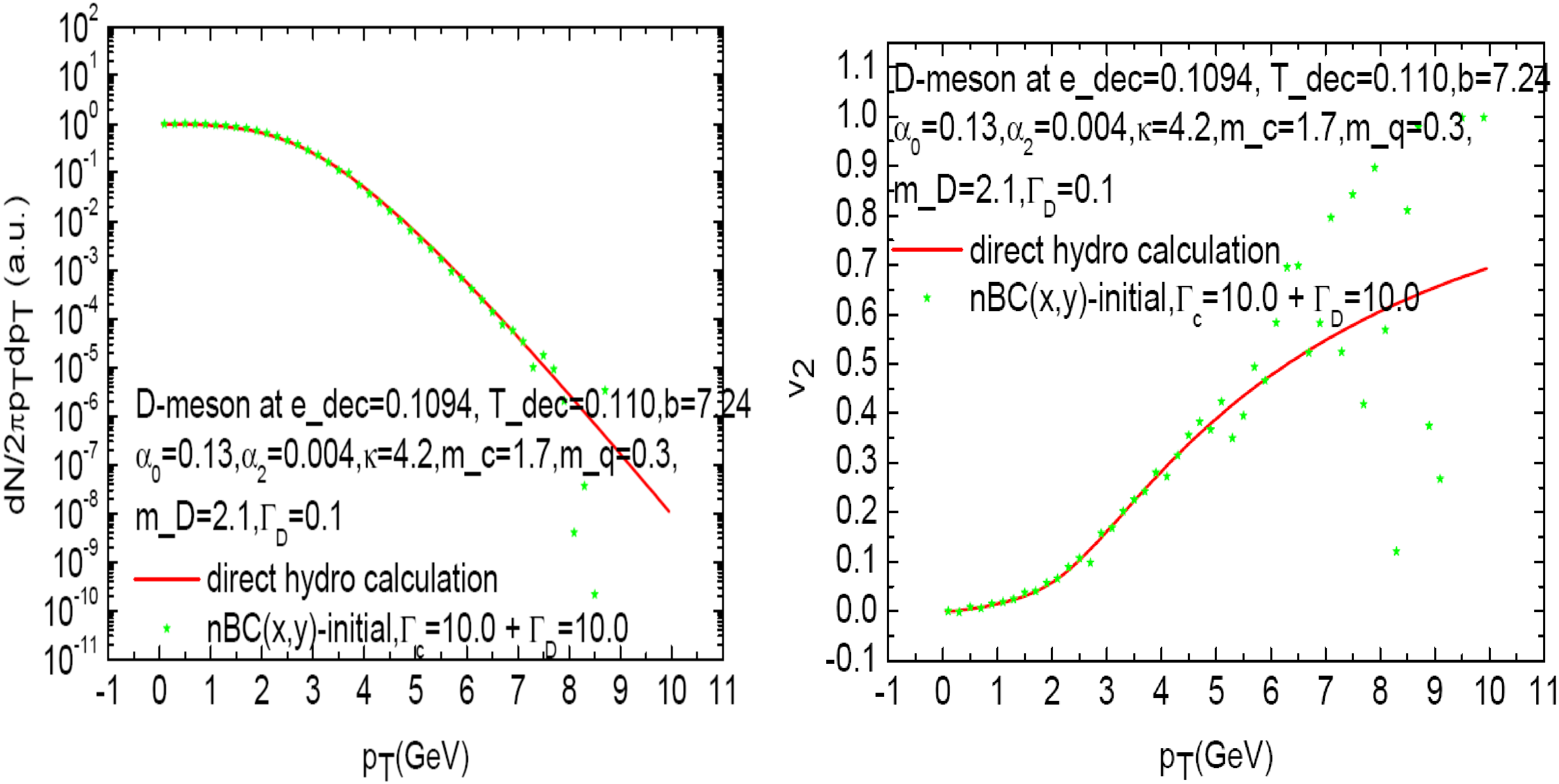


Backup 2: D-meson RRM equilibrium

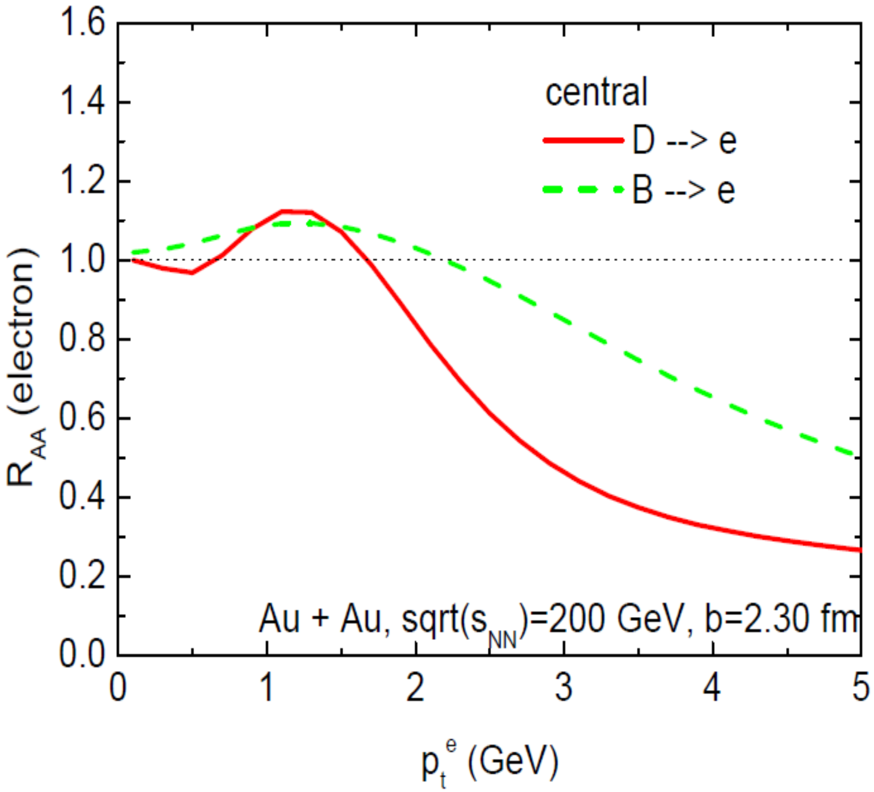


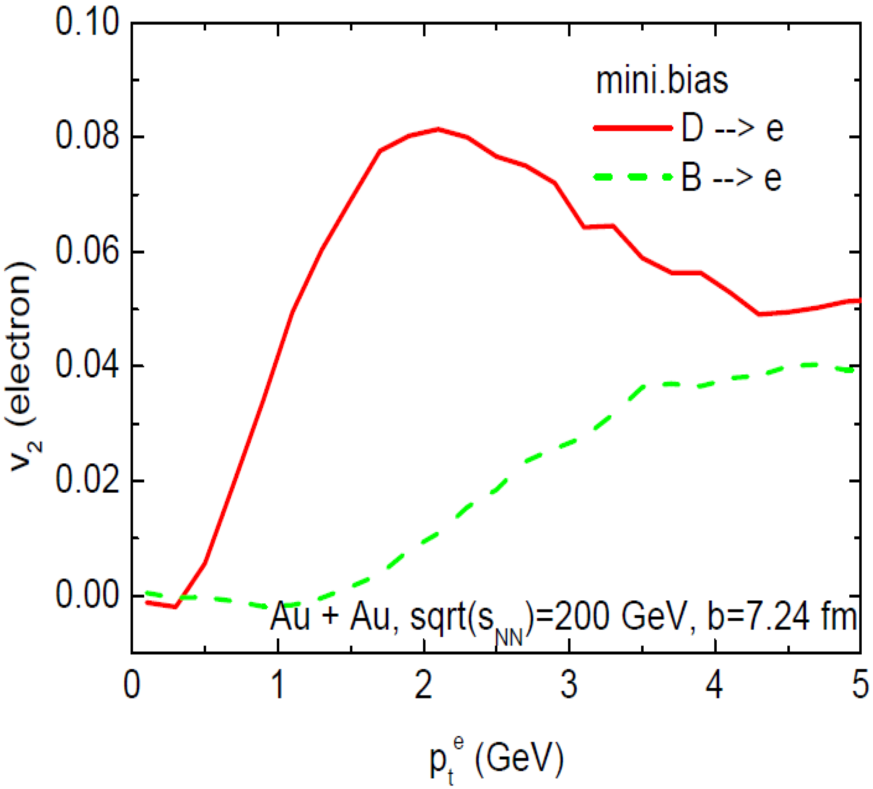


Backup 3: D-meson hadronic phase Langevin diffuison equilibrium



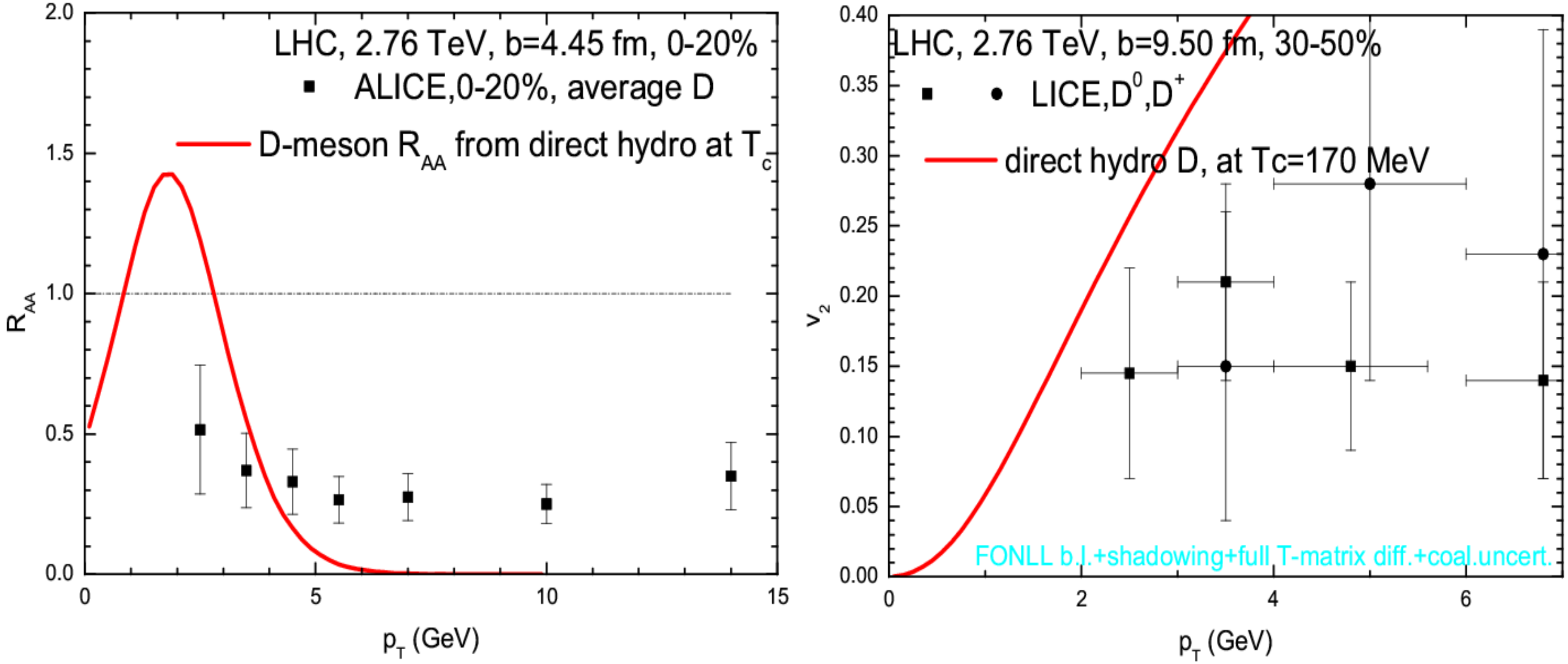
RHIC b/B →e vs c/D →e



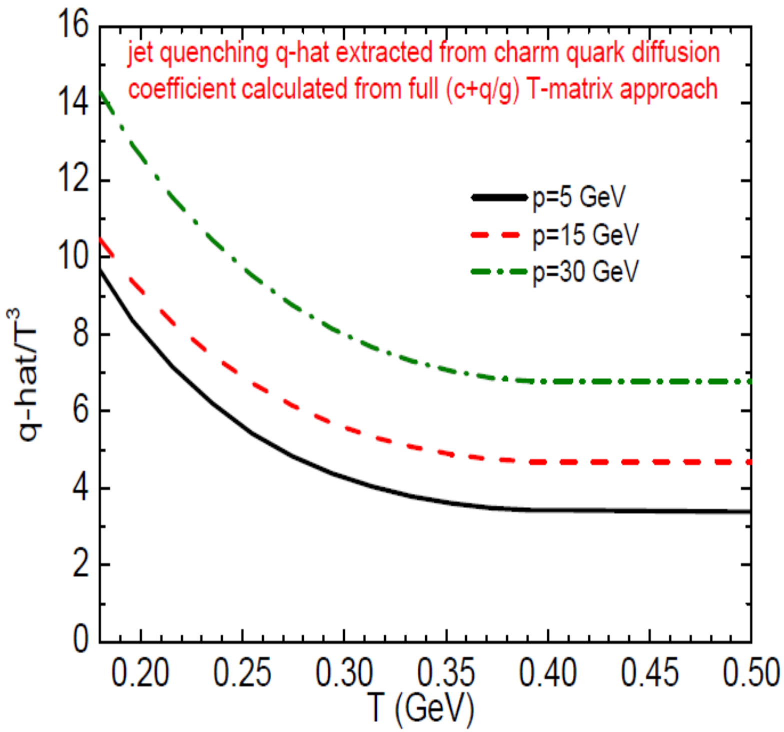


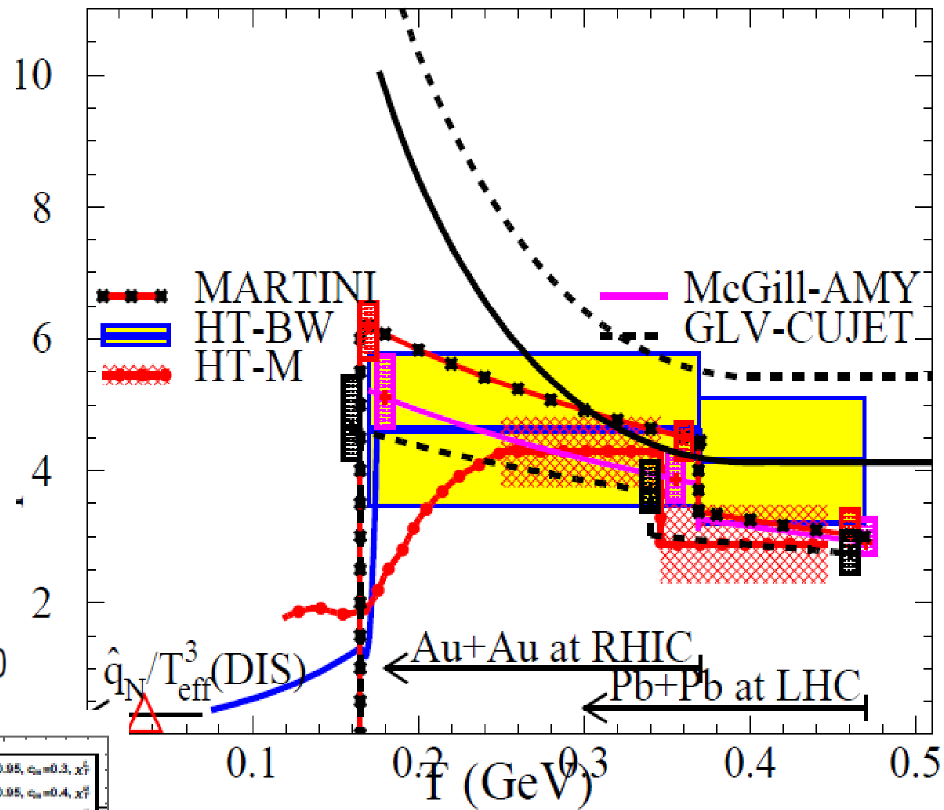
- **Bottom less suppression, less collectivity than charm: mass effect**
- **Now HFT@STAR able to disentangle charm vs bottom lectrons, time to compare the prediction with data**

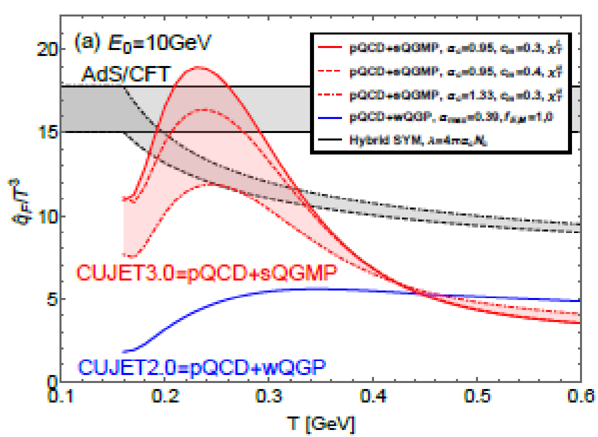
Backup 4: fully thermalized D mesons@LHC



Jet quenching q-hat from charm diffusion







Xu,Liao,
Gyulassy, 2015