Nonperturbative Approach to Open Heavy Flavor Transport in Heavey Ion Collisions

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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

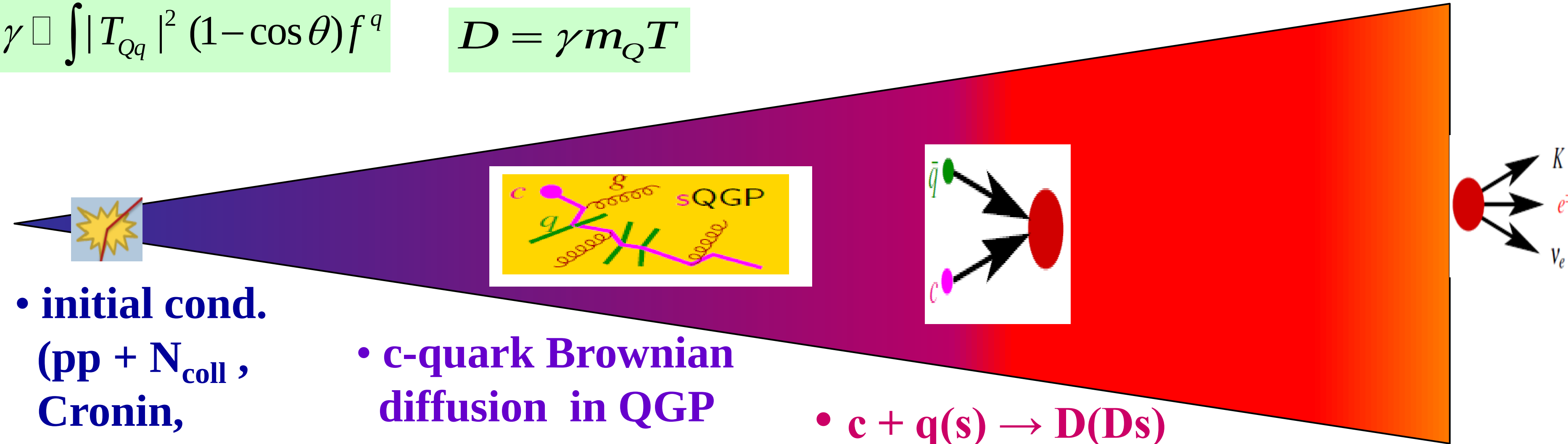
HQ evolution in HIC

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

thermalization rate   diffusion coefficient

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

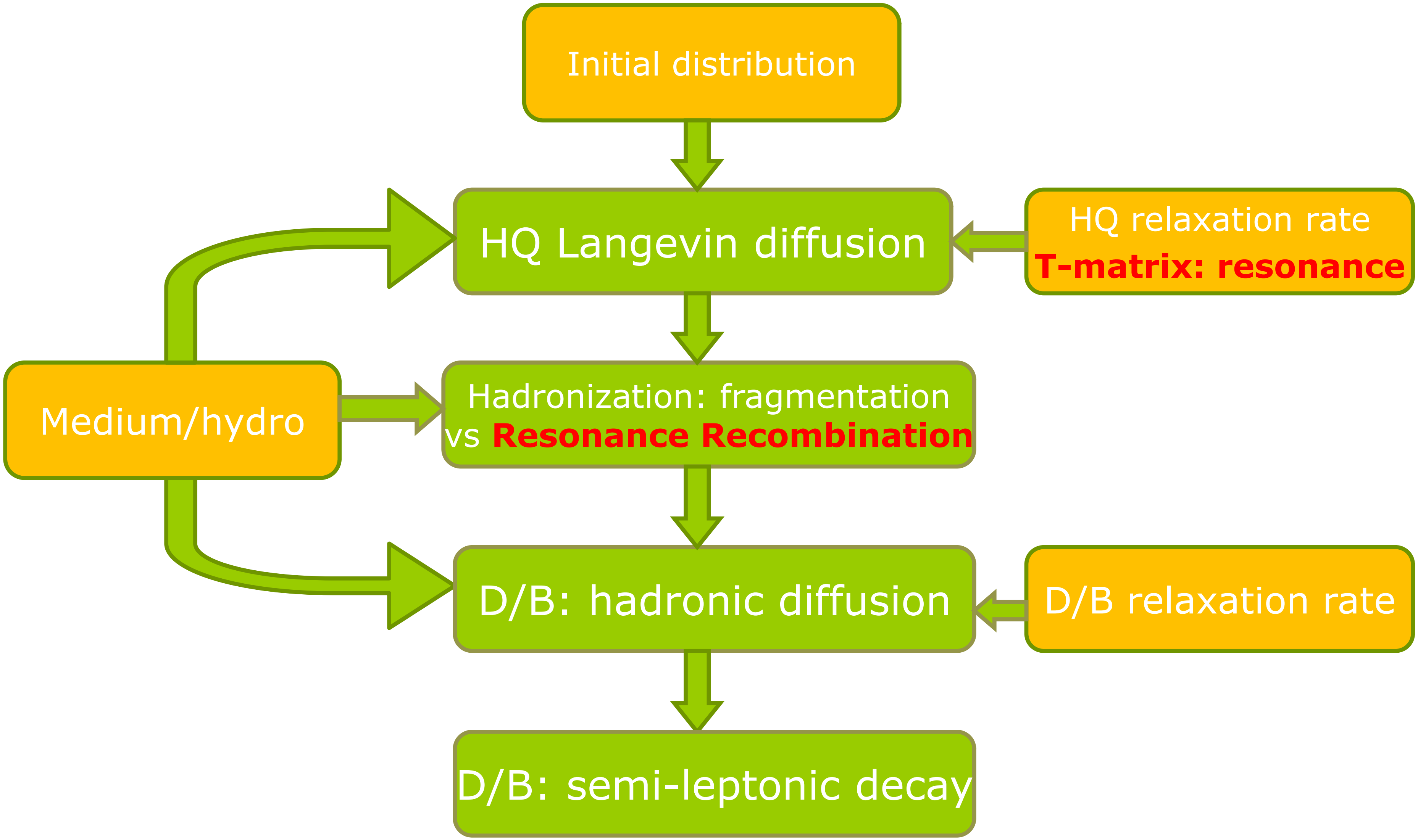
$$D = \gamma m_Q T$$



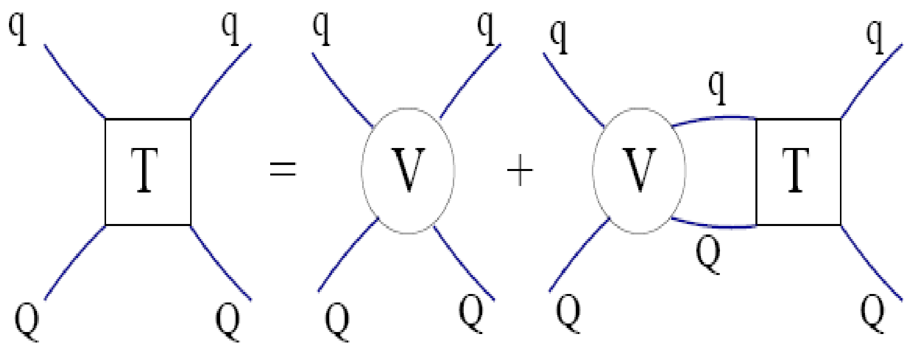
- initial cond. (pp + N_{coll}, Cronin, shadowing)
- c-quark Brownian diffusion in QGP liquid (T-matrix resonant correlation, *No K-factor*)
- c + q(s) → D(Ds) resonance recombination; Ds freezeout
- D-meson diffusion in hadron liquid

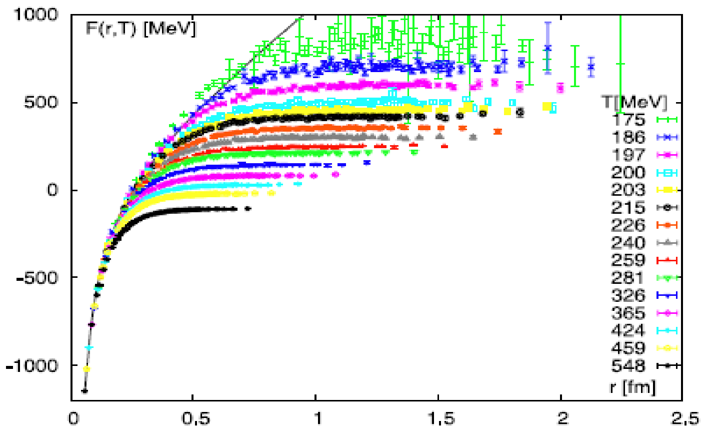
--- primordial hard production, pQCD (FONLL/PYTHIA)
m_Q >> T, Lambda_QCD ➔number conserved

Non-Perturbative HQ Transport: flow chart



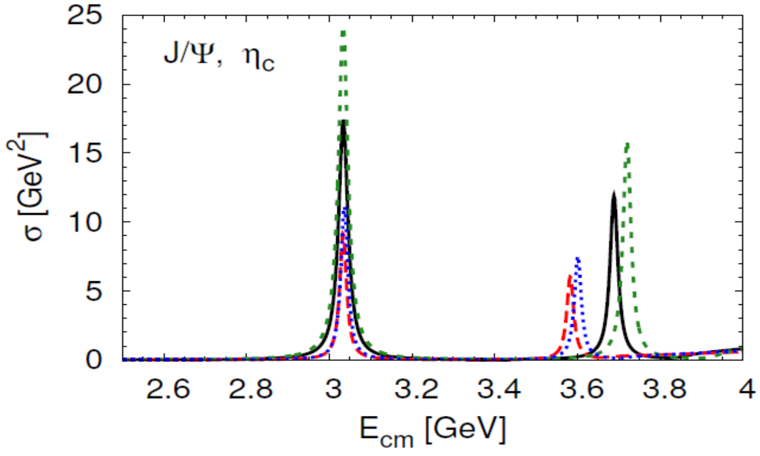
HQ thermal relaxation rate: T-matrix

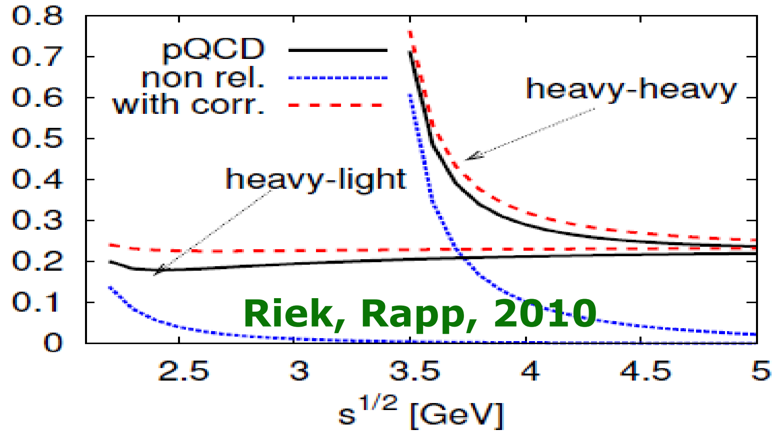




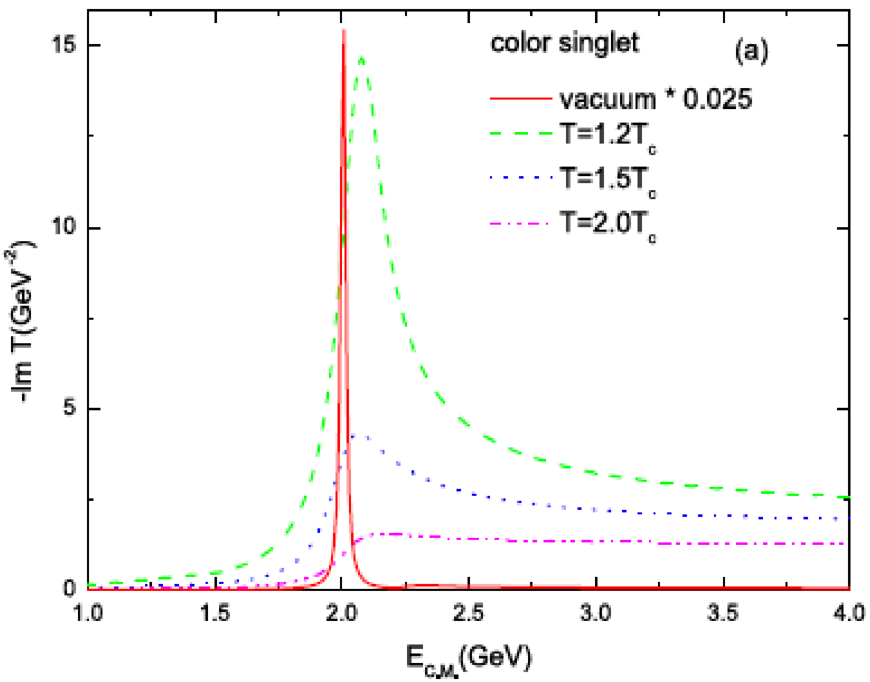
◆**lattice potential: Kaczmarek,2008** $U = F - T\frac{\partial F}{\partial T}$ ➔ **Resummation & Unitarization**

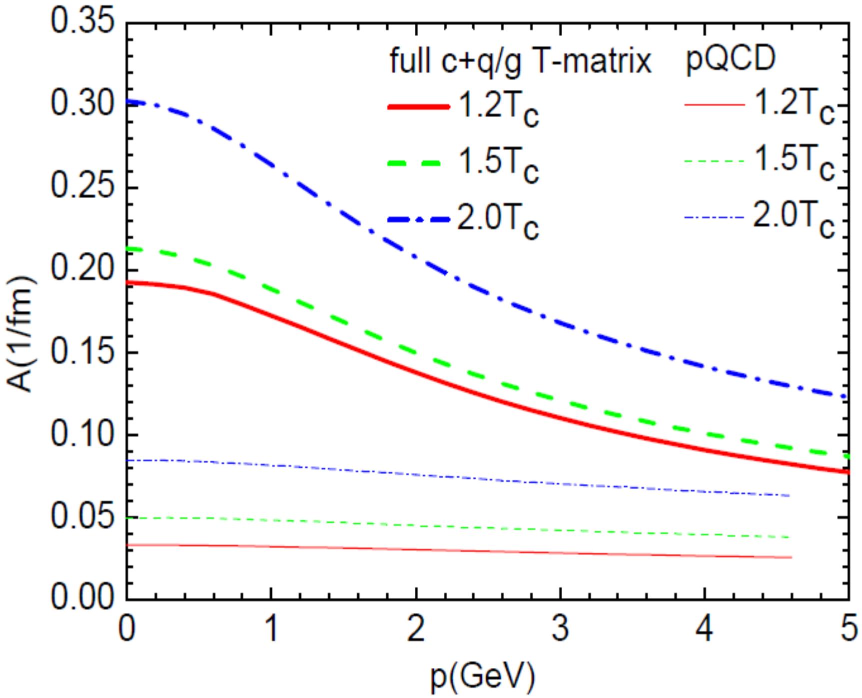
◆**Open/hidden HF: vacuum spectroscopy reproduced; high energy pQCD recovered**





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

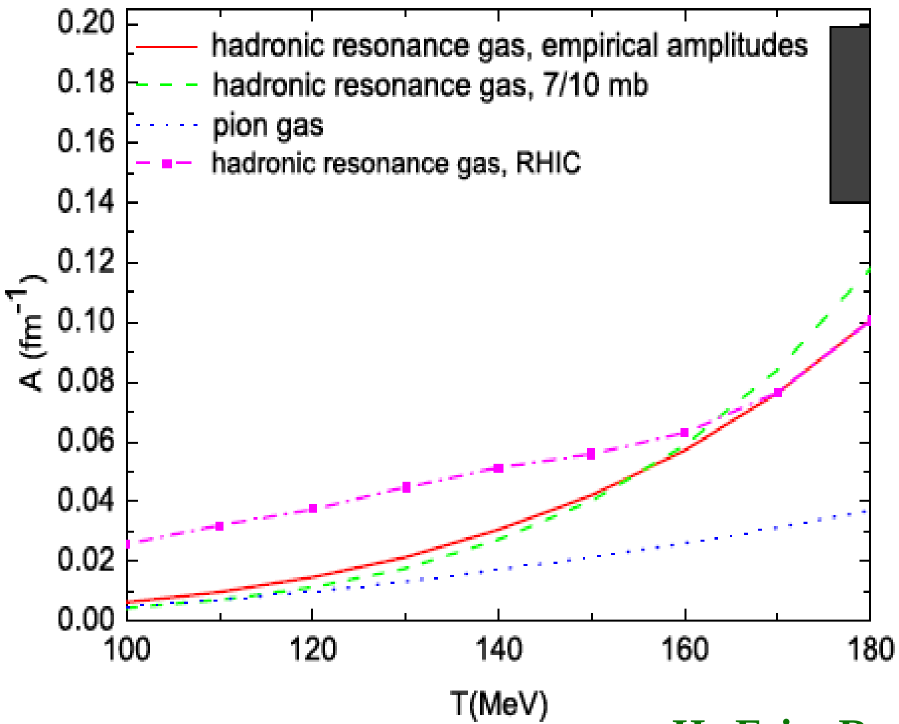
◆ this **resonance correlation** ➔ **resonance recombination**

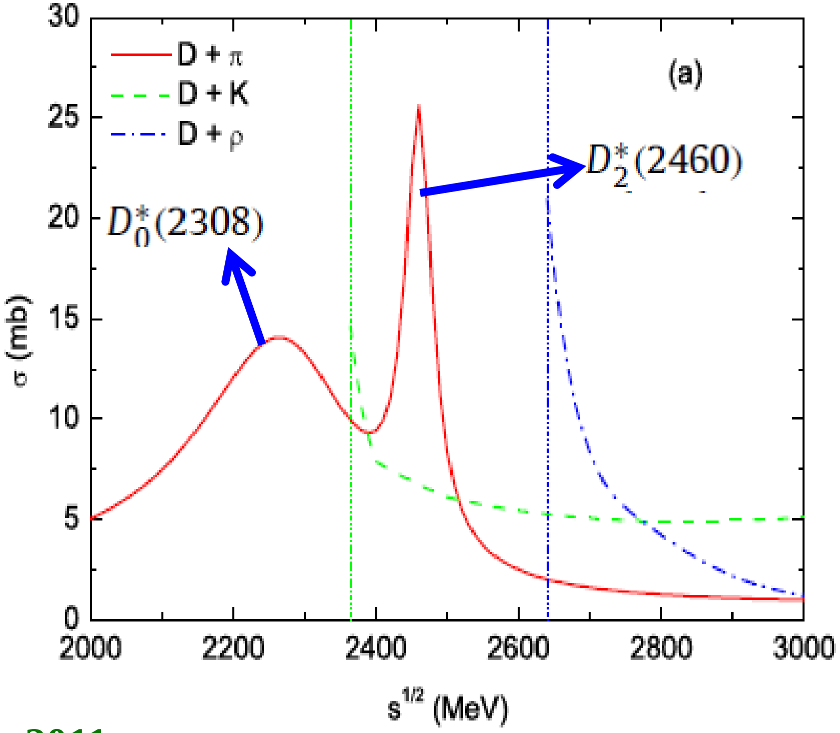
◆ T-matrix relaxation rate: a factor ~4-5 larger than LO pQCD at T=1.2 T_c

◆ 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

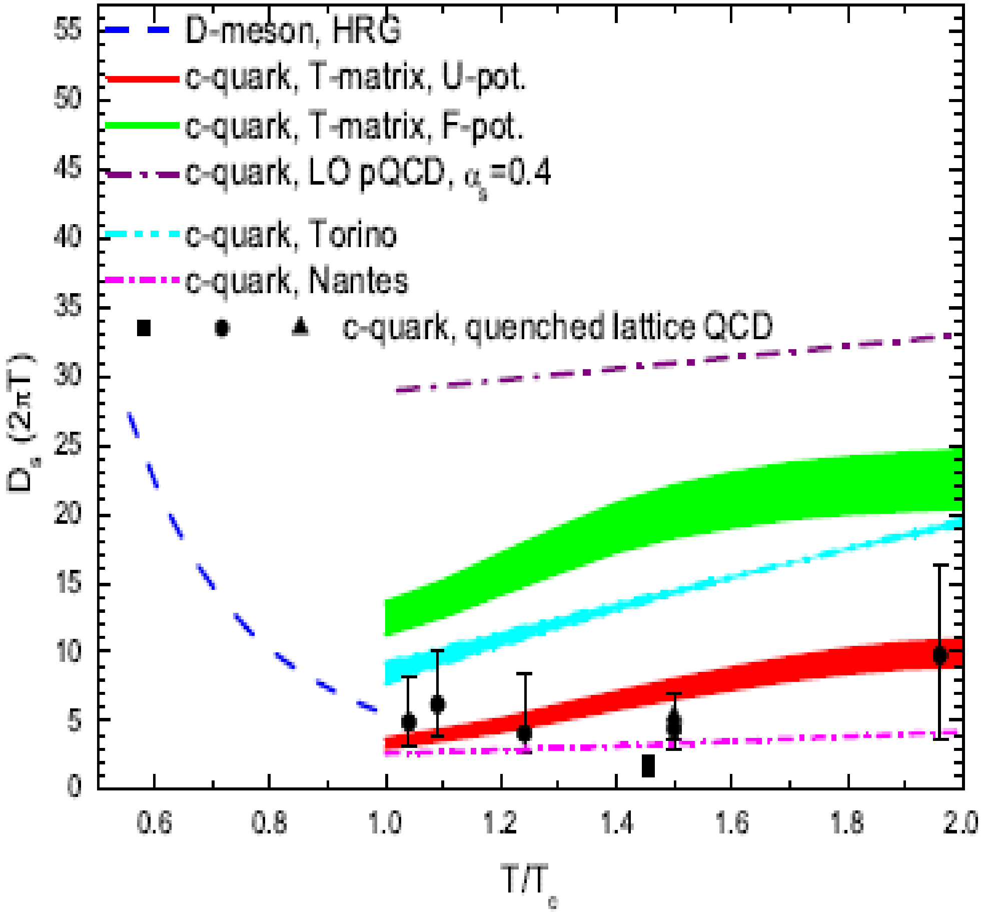




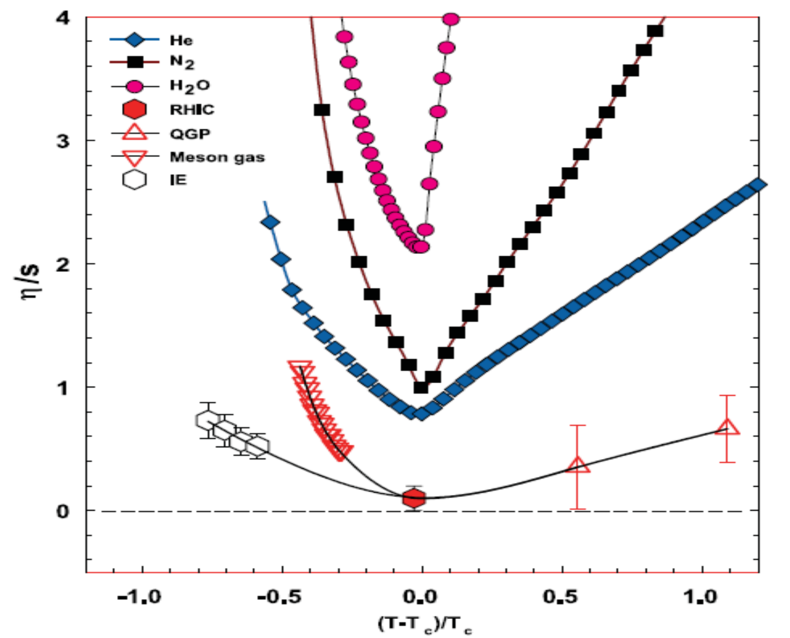
He,Fries,Rapp 2011

◆ **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.

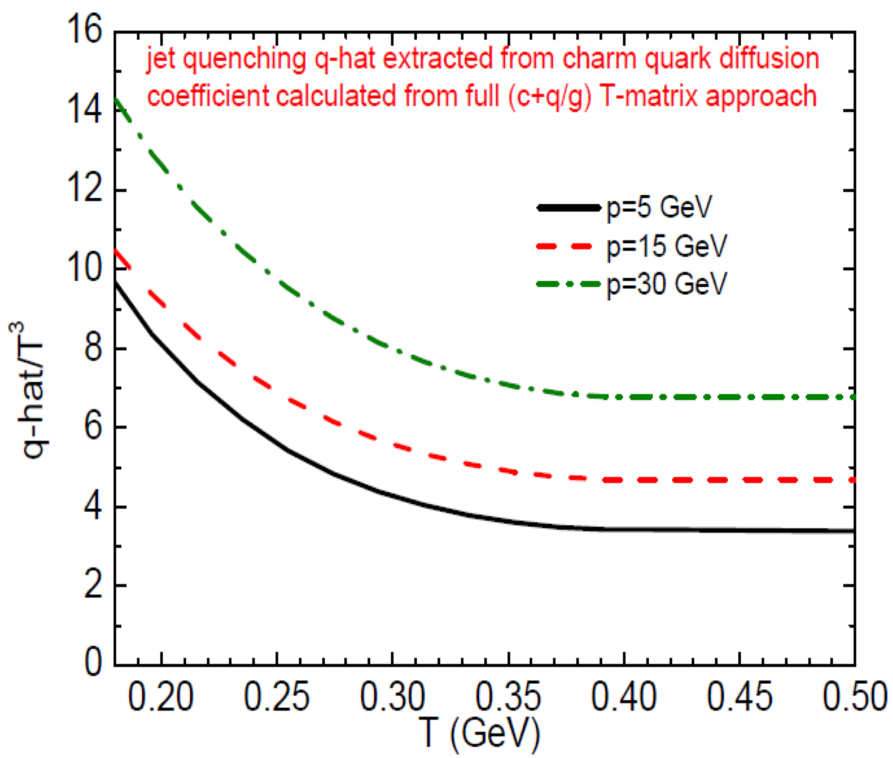


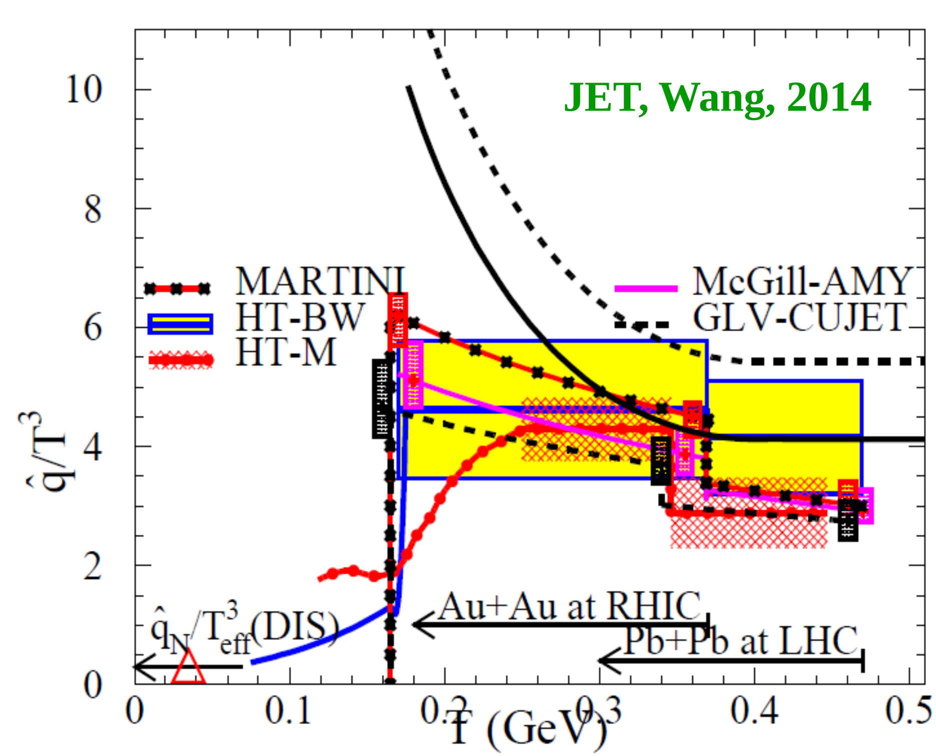
- viscosity.: eta/s = (1/5 ~ 1/2)D_sT, Danielewicz&Gyulassy, 1985
- D_s translates into eta/s = (2-5)/4pi at T=180 MeV



- 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



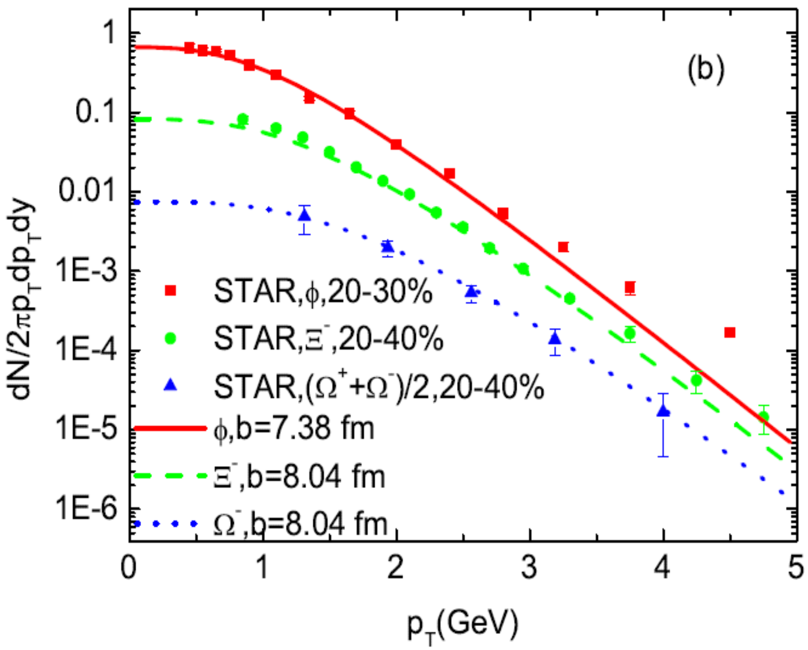


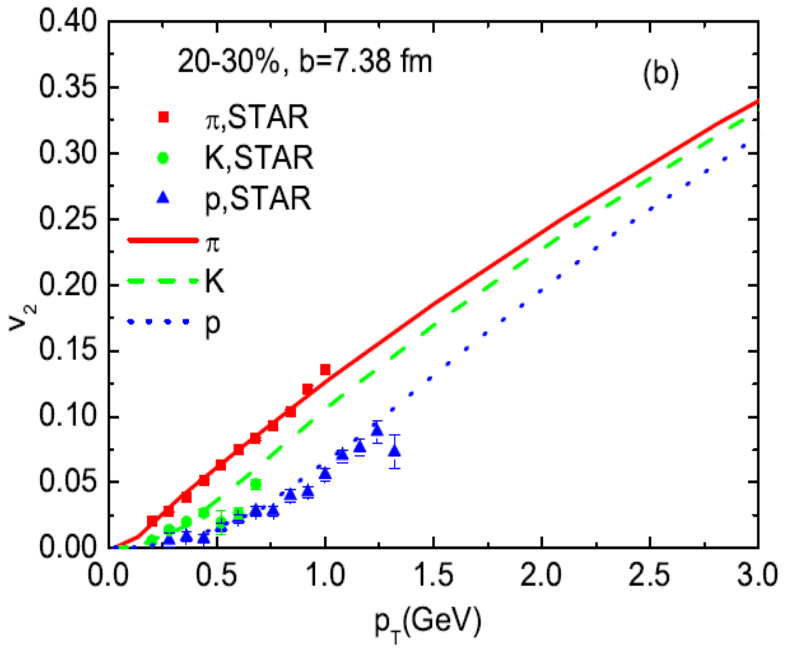
- **At high T, consistent with emperical values used in Jet models**
- **At T~T_c, enhanced due to non-perturbative charm diffusion, similar to CUTJET3.0 accounting for non-perturbative chromo-EM quasiparticles**

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





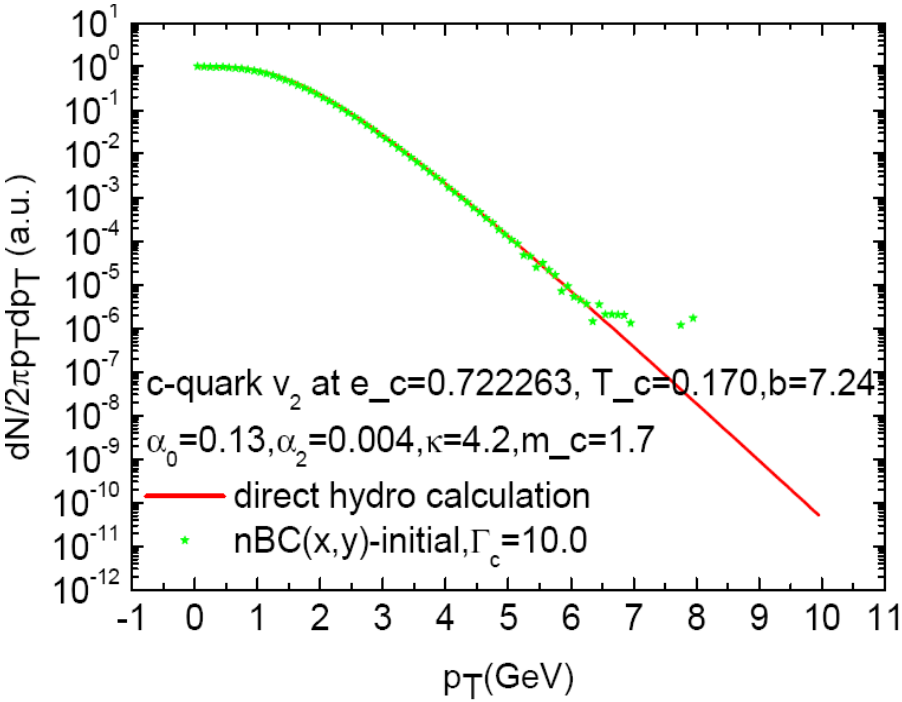
- multistrange hadrons ϕ, Ξ, Ω probably freeze out earlier STAR, PRC79,2009
- multi-strange particles' spectra and v_2 fitted at T_{ch} =160 MeV
  bulk particles' spectra and v_2 fitted at T_{kin}=110 MeV He, Fries,Rapp,2012

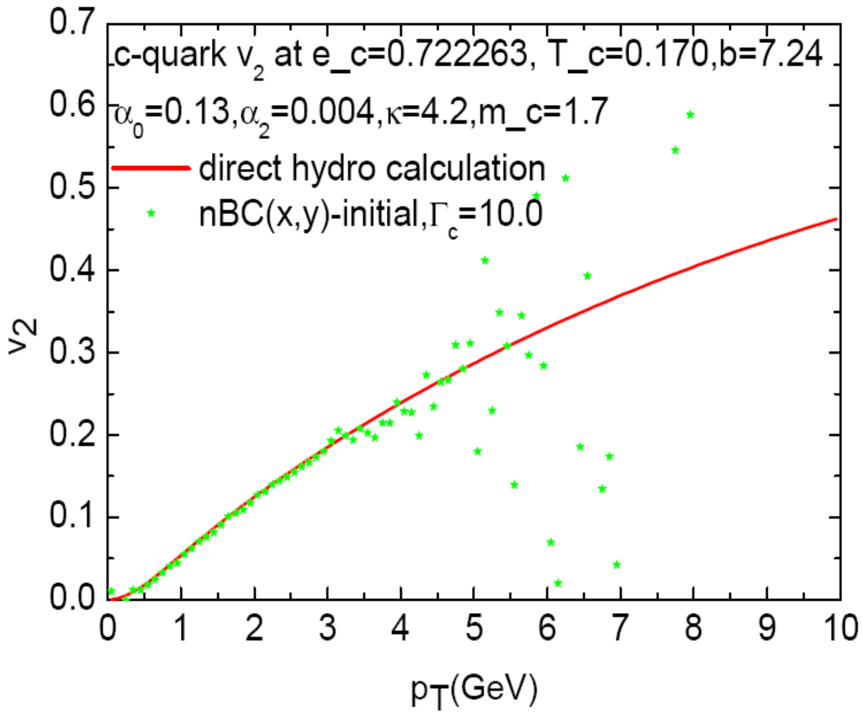
HQ diffusion: Langevin equilibrium limit check

- **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**

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

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

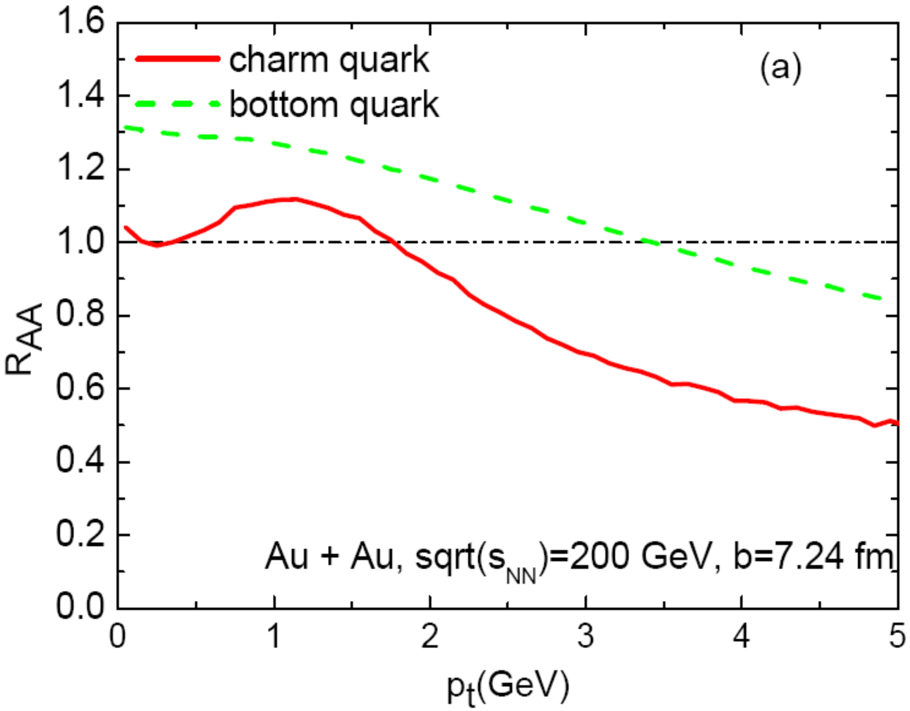
$$\Gamma(p) = A(p) + \frac{1}{E(p)} \frac{\partial D[E(p)]}{\partial E}.$$

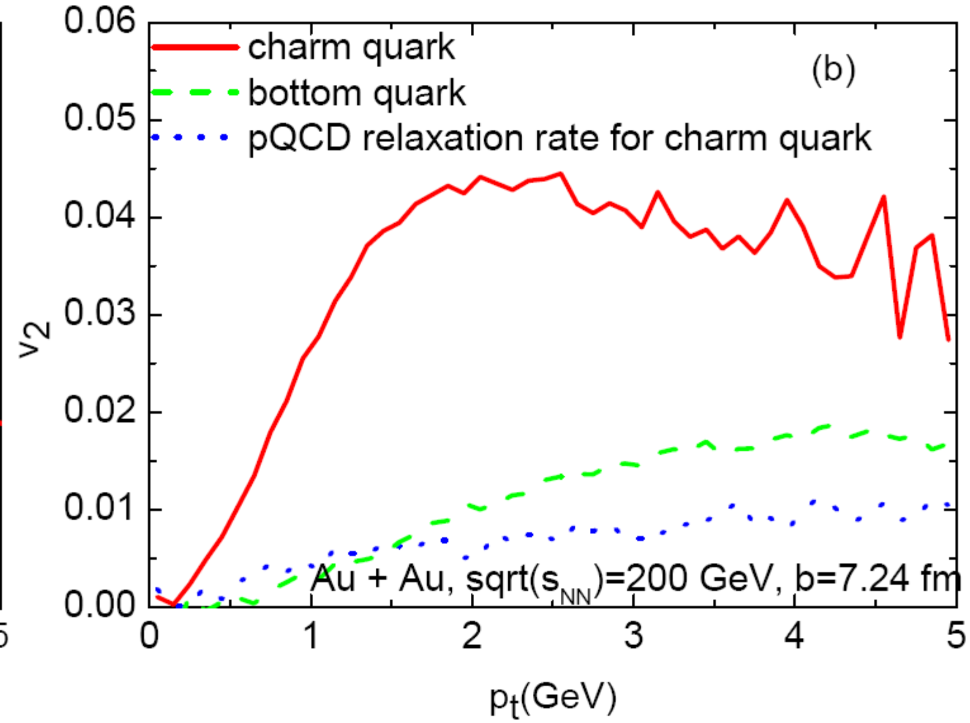
HQ diffusion: Langevin simulation

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**

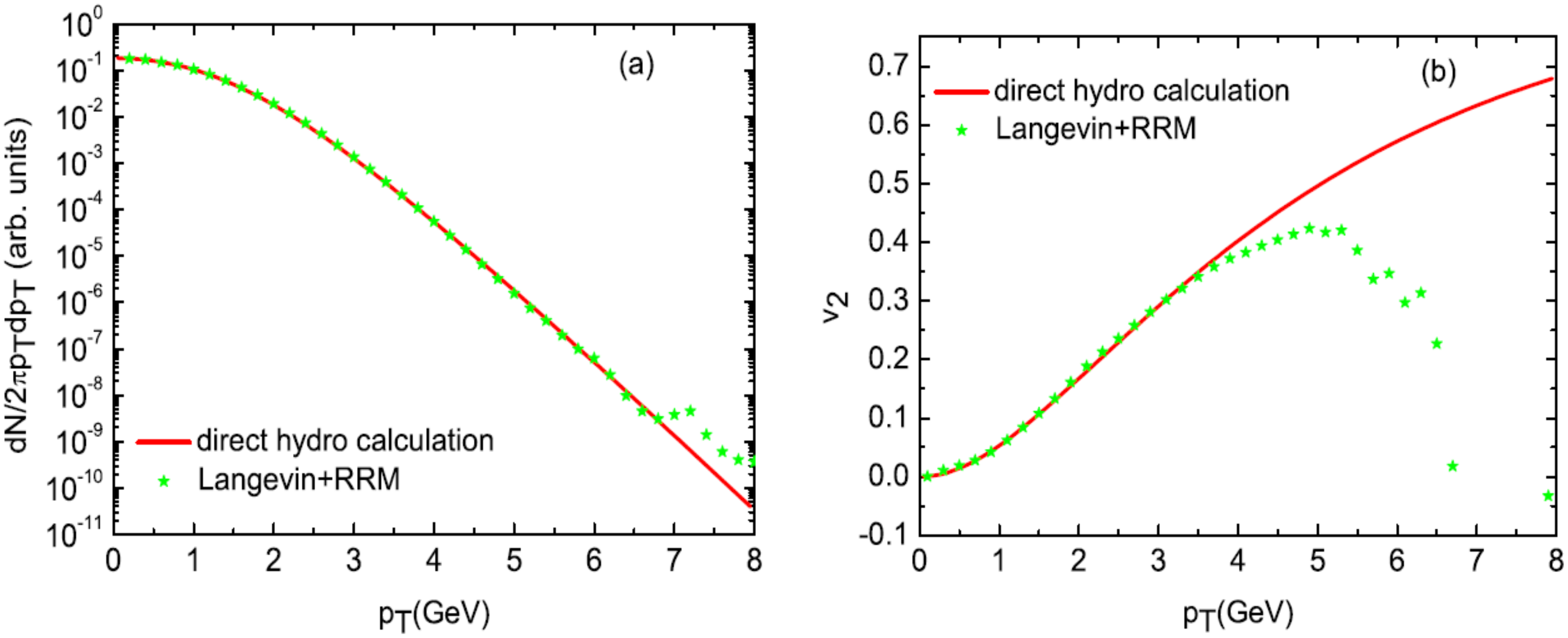
Hadronization: Coalescence(RRM)

- **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

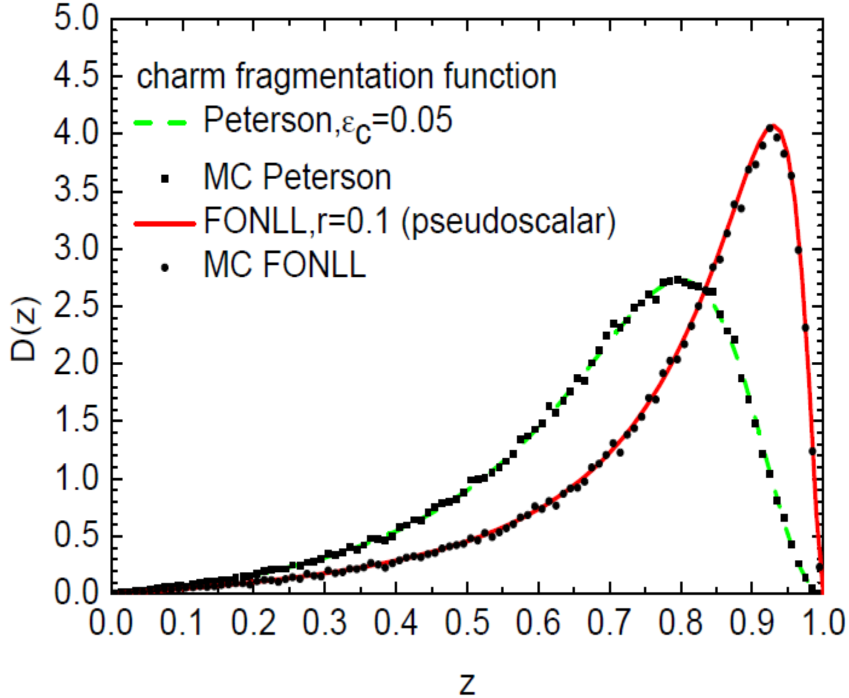


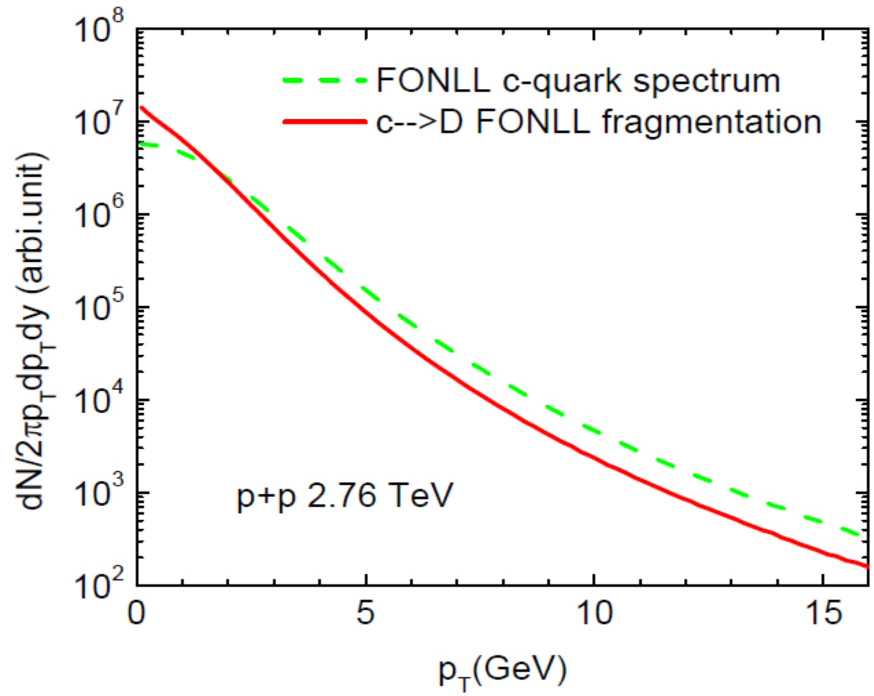
- **Diffusion vs coalescence: conceptually consistent**

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

Hadronization: Fragmentation (FONLL)

- **Fragmentation: incompatible with thermalization**





- **Coalescence vs fragmentation:**

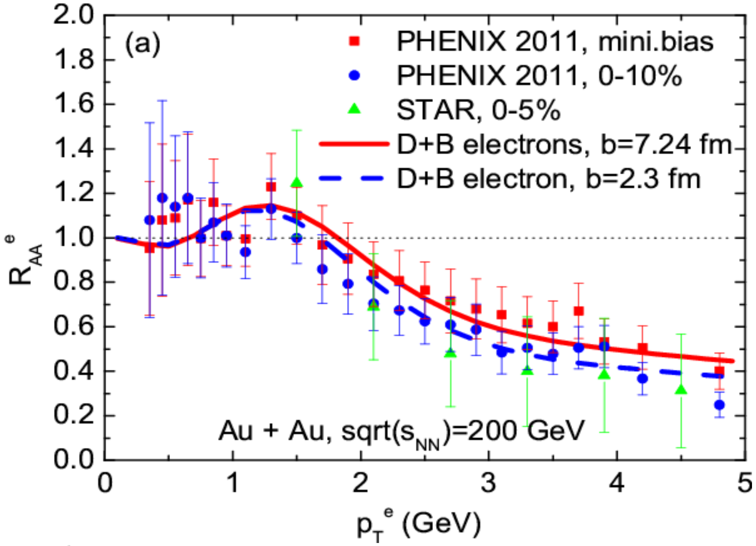
Recombination dominates at low p_T but yields to fragmentation at higher p_T

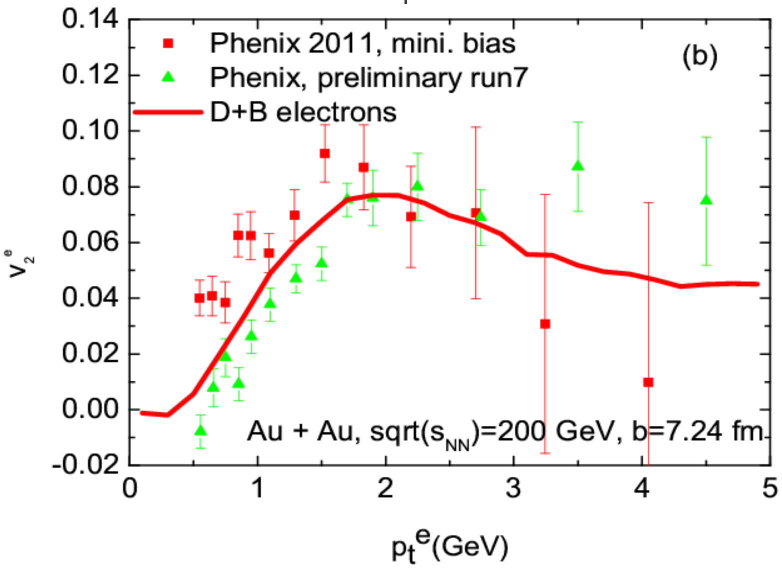
i.e. coal.prob. function $P_{coal}(pt)$: a dropping function of pt

Phenomenology at top RHIC energy

Tuned ideal hydro, FONLL baseline + fragmentation

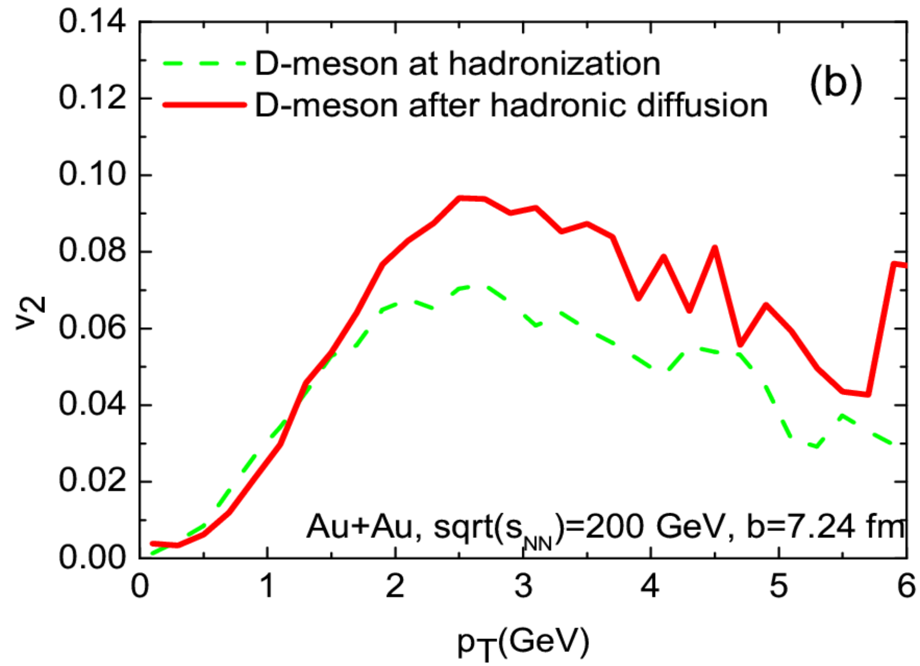
e± Spectra @ RHIC



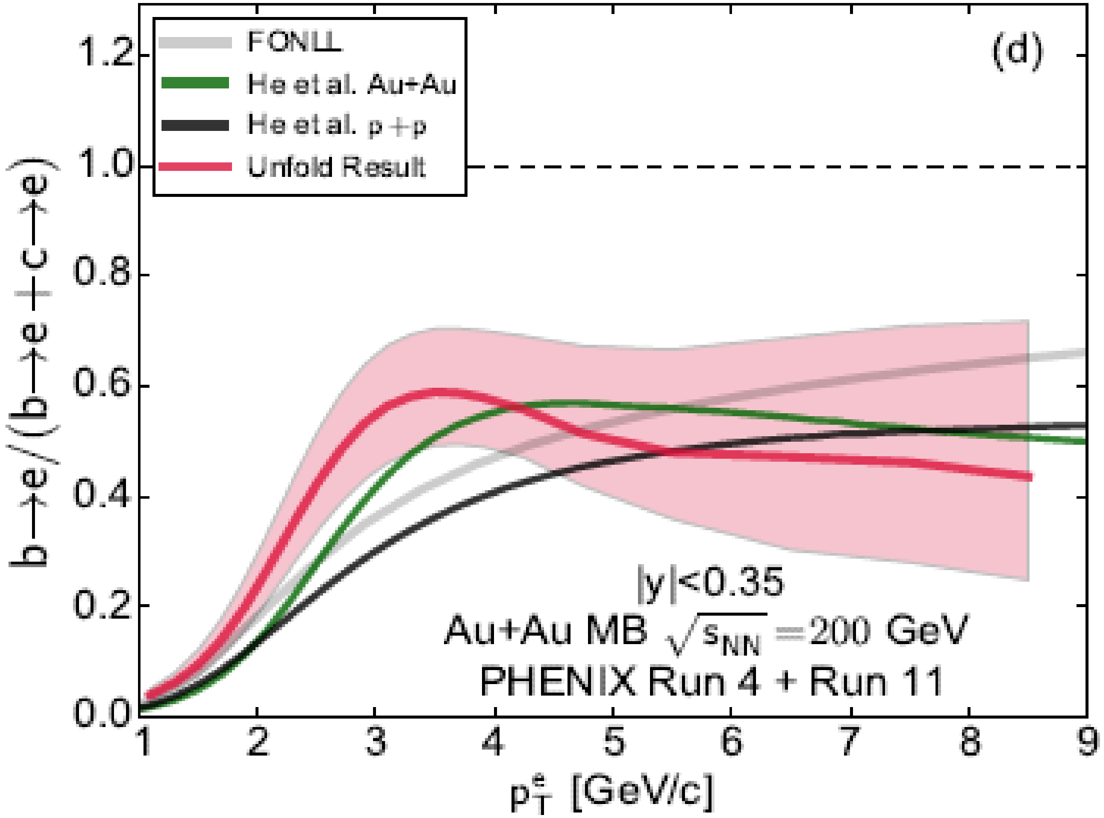


- **medium modified D and B mesons: c/b diffusion + coal./frag. + hadronic diffusion**
- **semi-leptonic decays c(b) → s(c) + e + nu**

D-meson Hadronic Diffusion



b→e / (b→e + c→e)



PHENIX, arXiv: 1509.04662

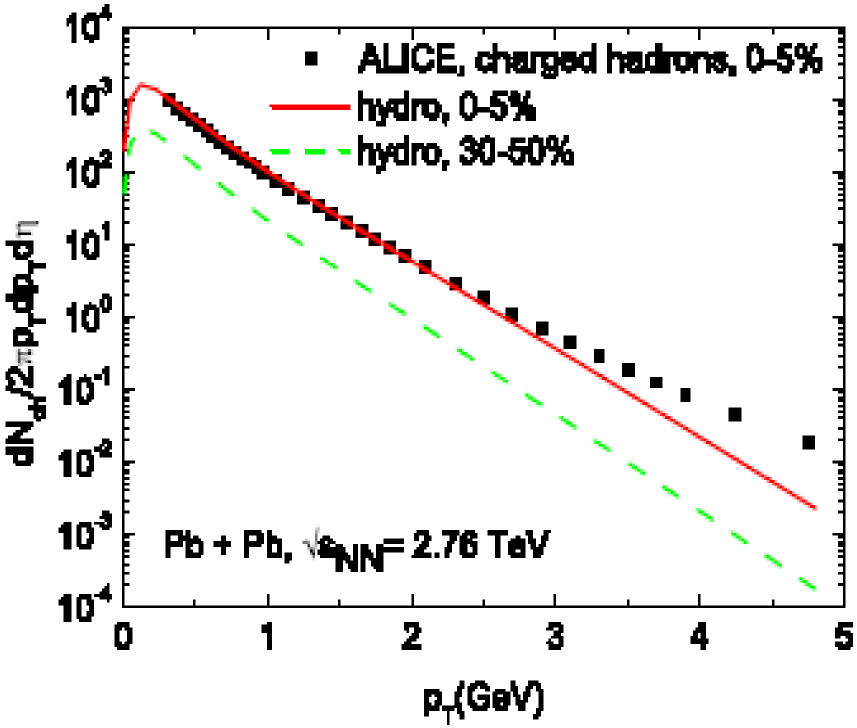
A slight decrease at high p_T nicely reproduced!

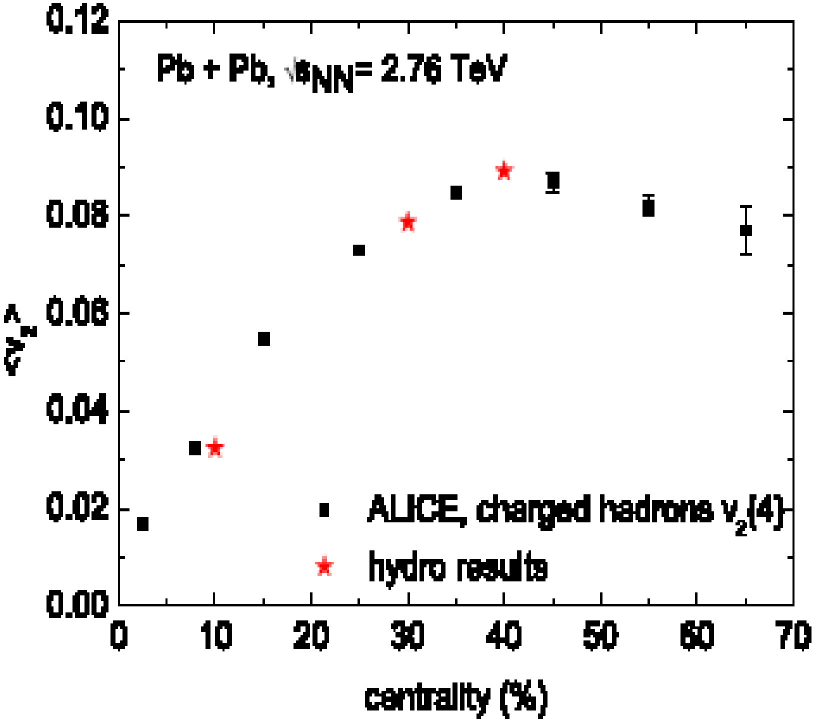
- Low p_t, c→e dominates, and charm more suppressed than bottom
  ➔ above the pp curve
- Higher p_t, b→e takes over, and bottom significantly suppressed
  ➔ below the pp curve

Phenomenology at the LHC
Pb-Pb 2.76 TeV

Tuned ideal hydro + FONLL pp baseline + FONLL fragmentations

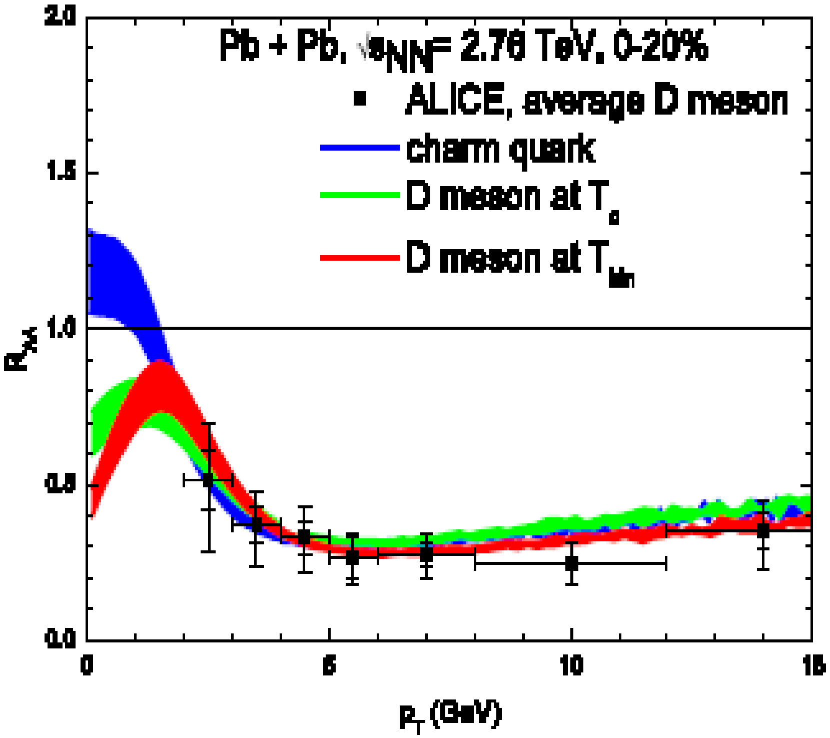
Hydro tune for the LHC

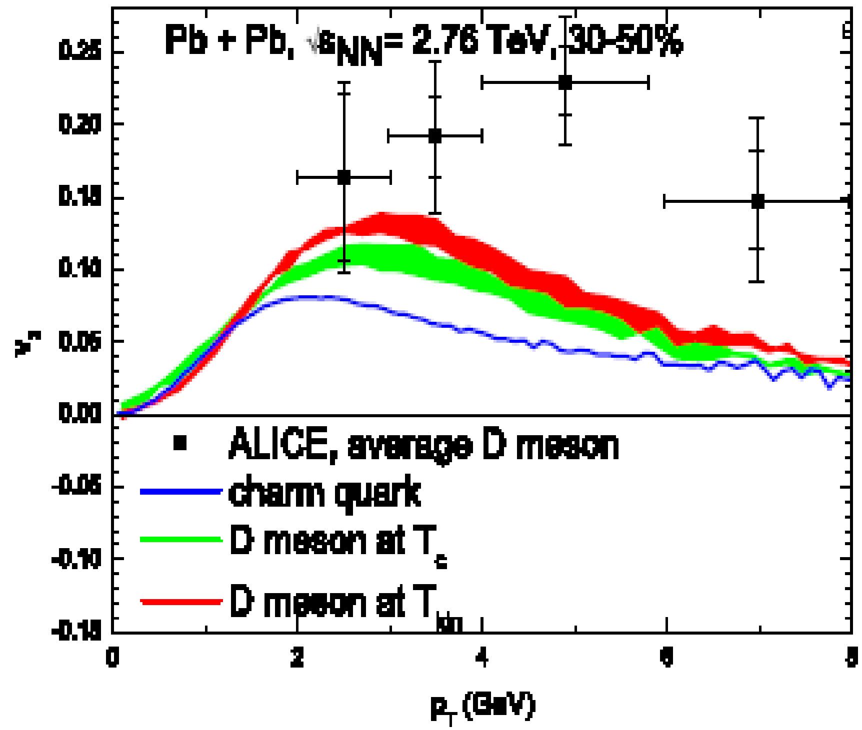




- p_T-spectra of charged hadrons fine
- v_2: integrated elliptic flow a good measure of the bulk momentum anisotropy
- background medium evolution well constrained

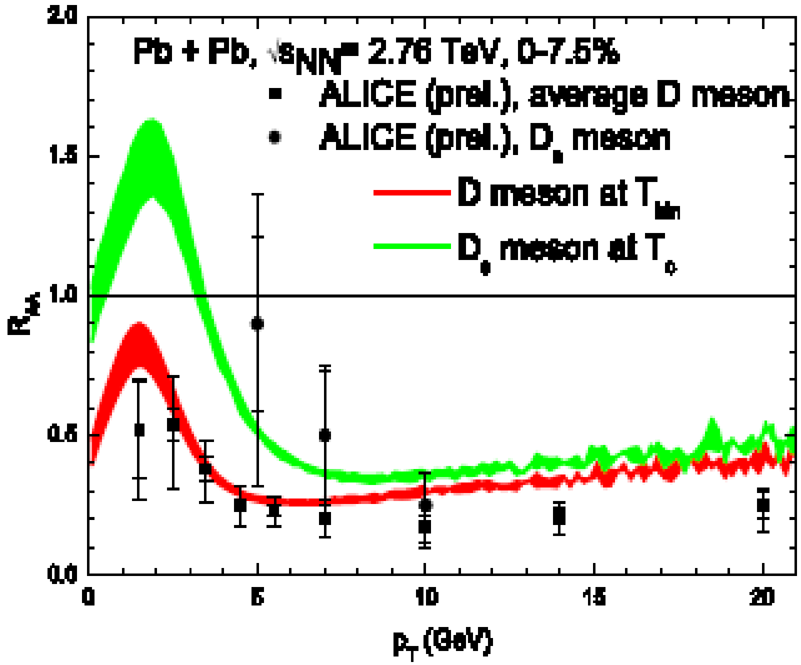
LHC D mesons

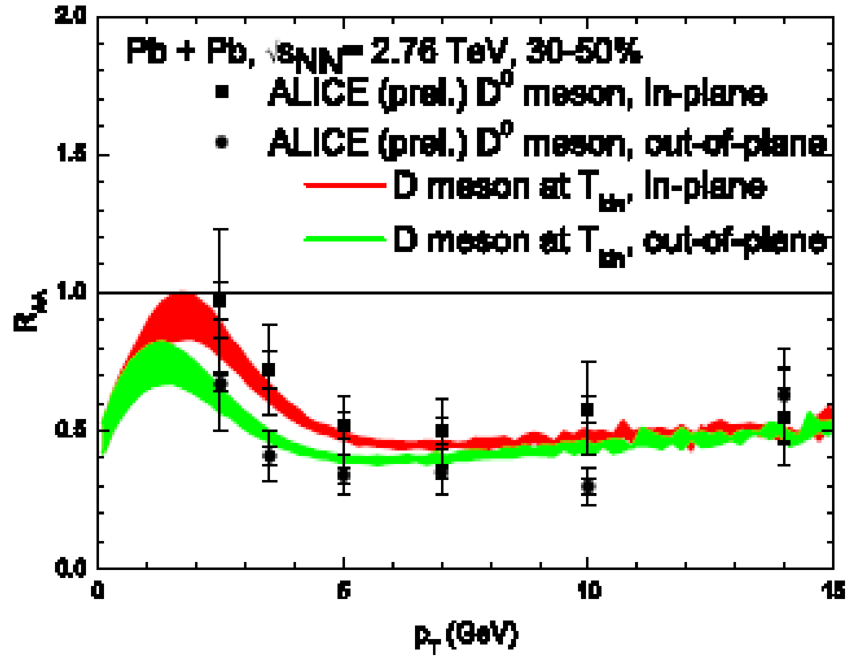




- R_{AA}: flow bump at low p_T, amplified by coalescence
  p_T-dependence shape OK; possible missing radiative energy loss at high p_T
- v_2: c-diffusion only accounts for ~50%
  recombination and hadronic phase diffusion essential

LHC D vs Ds mesons

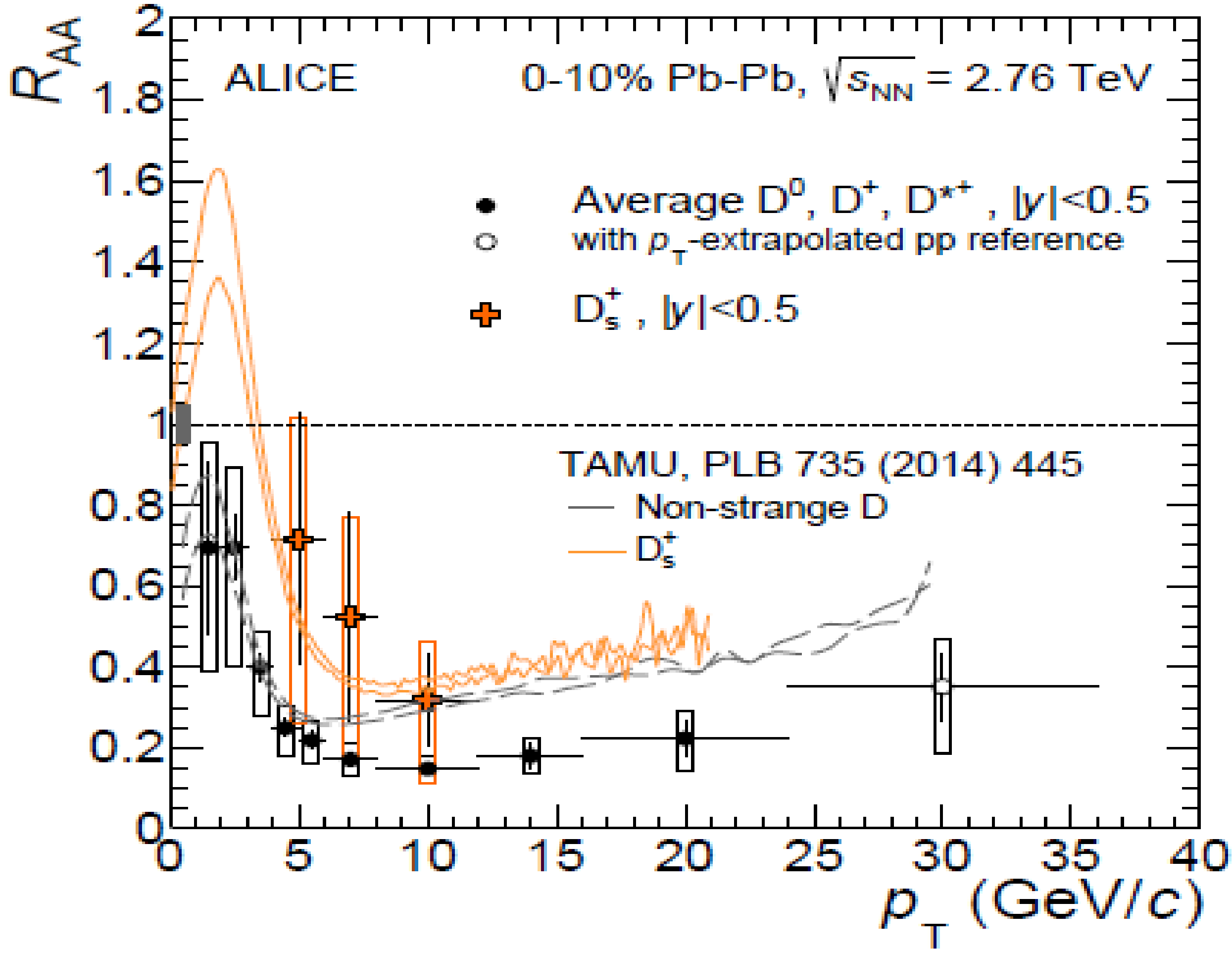




◆ **D vs D_s R_{AA} : low p_T, coalescence enhances D_s production in a strangeness-equilibrated, strongly-coupled QGP medium, relative to pp; high p_T, D & D_s tend to the same universal fragmentation**

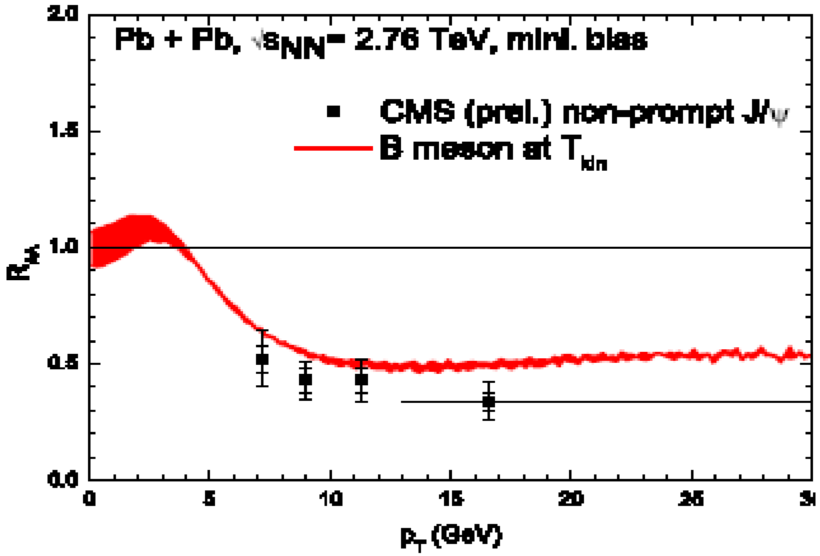
◆ **D R_{AA} in-plane vs out-of-plane: splitting at low p_T reflects finite v_2 high p_T splitting underestimated, indicative of missing radiative energy loss**

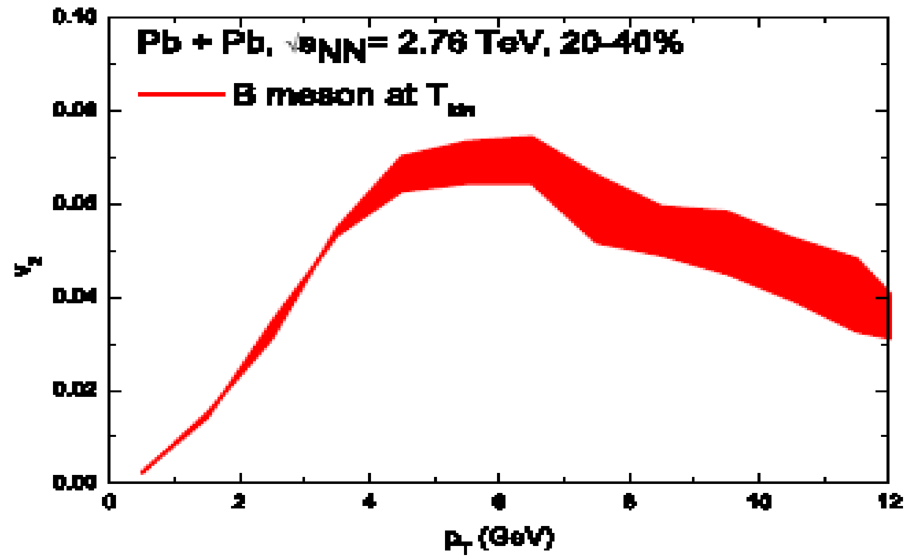
ALICE: D vs Ds JHEP03(2016)082

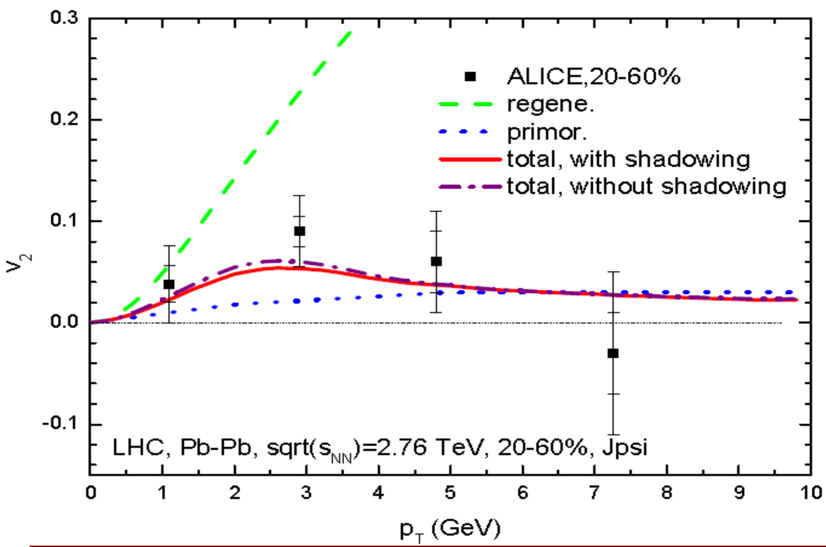


Enhanced Ds-meson R_{AA} tests out interactions at hadronization!

LHC B mesons & non-prompt Jpsi



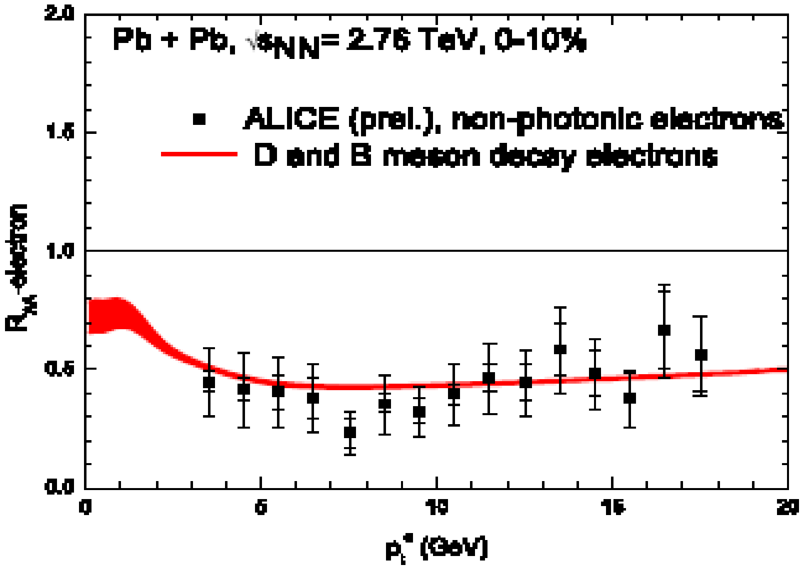


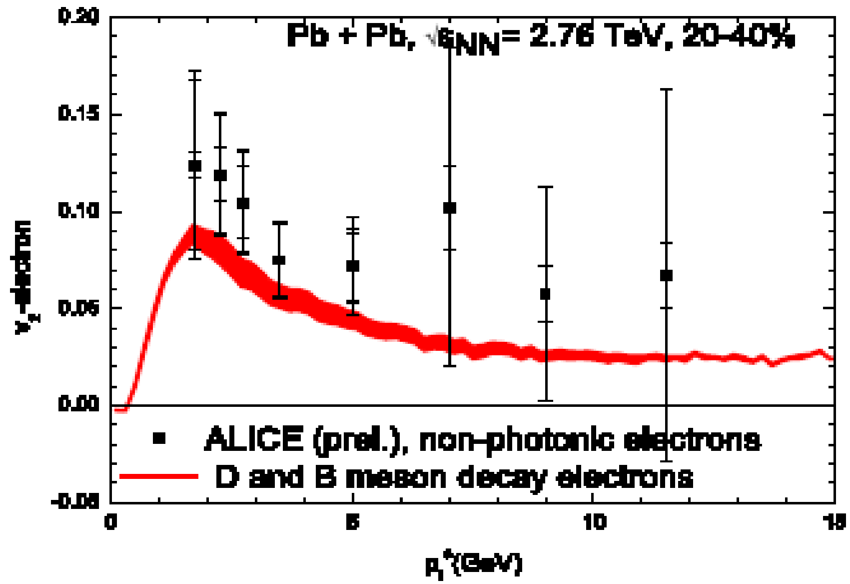


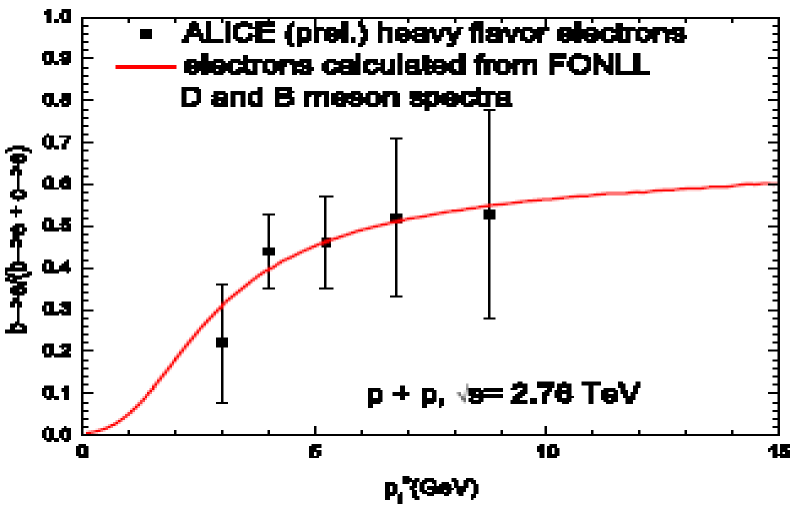
◆ **R_{AA} : substantial suppression (~0.5-0.6) at p_T>10 GeV; consistent with CMS non-prompt J/psi data point**

◆ **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

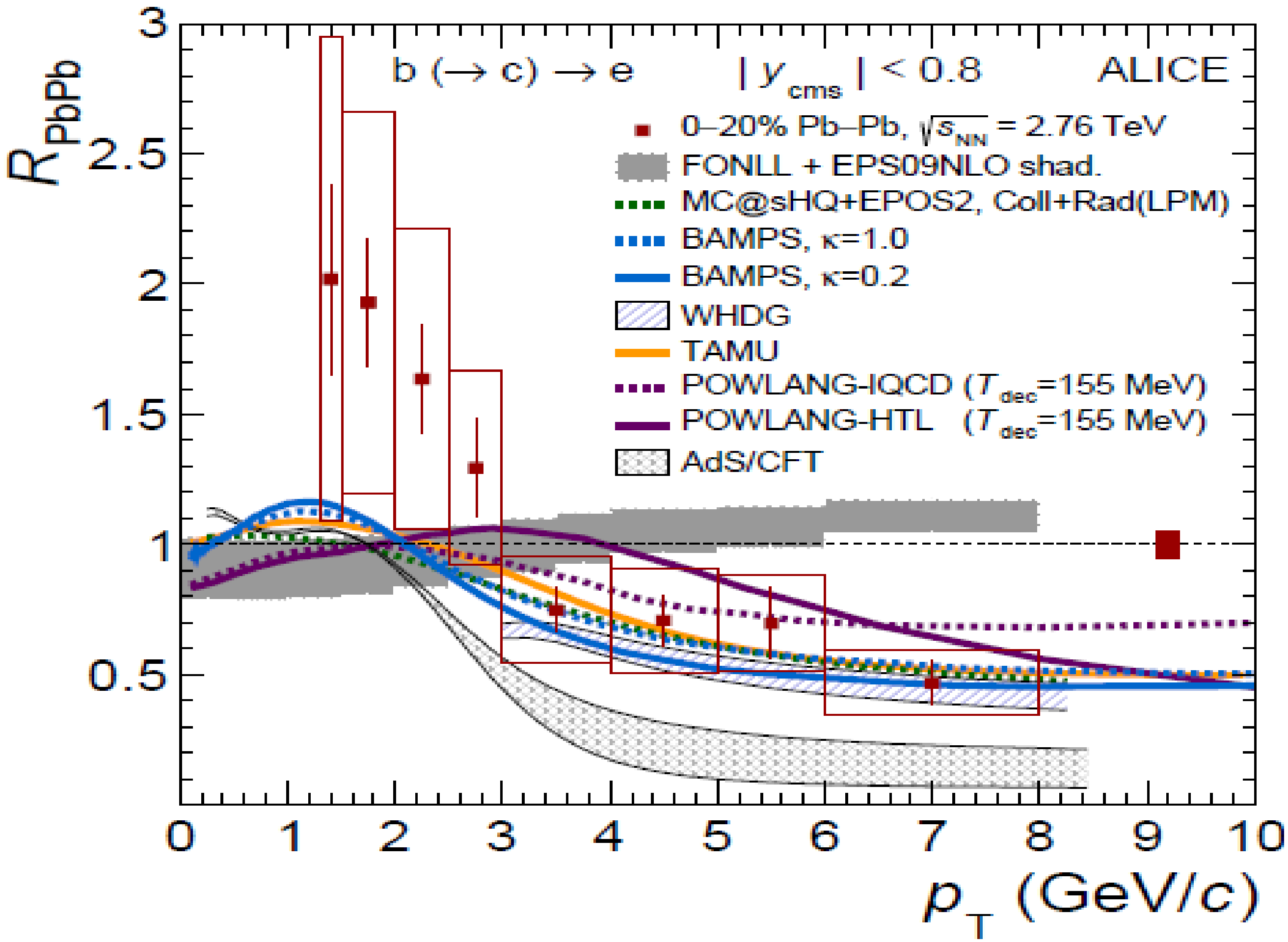






- ◆ R_{AA} : overpredicted in the D dominant region; fairly good in the B dominant region (elastic e-loss only)
- ◆ v_2 : marginally hit data, radiative e-loss?

LHC bottom electrons: first data



ALICE: 1609.03898

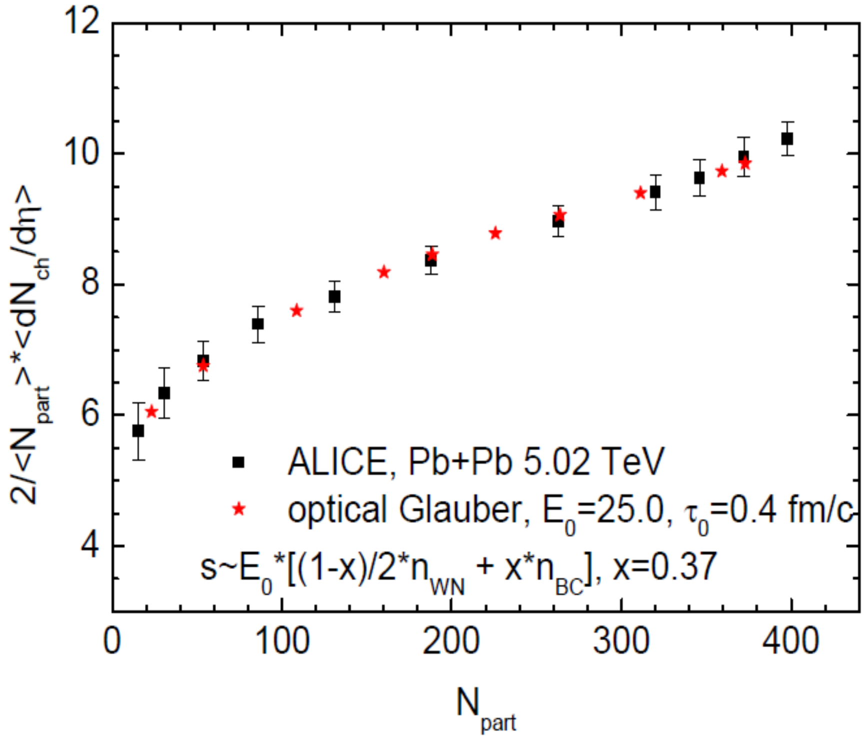
bottom: a better & cleaner lab for Langevin & elastic e-loss only

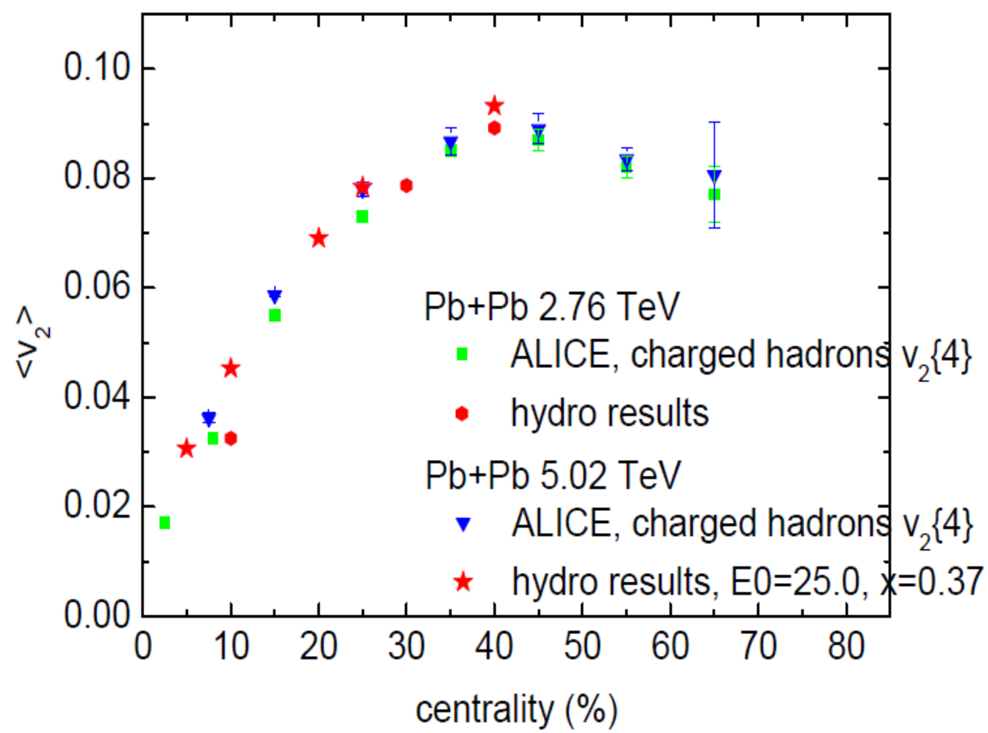
No shadowing, flow bump at low pt; high pt suppression

Phenomenology at the LHC
Pb-Pb 5.02 TeV

Tuned ideal hydro + FONLL pp baseline + FONLL fragmentations

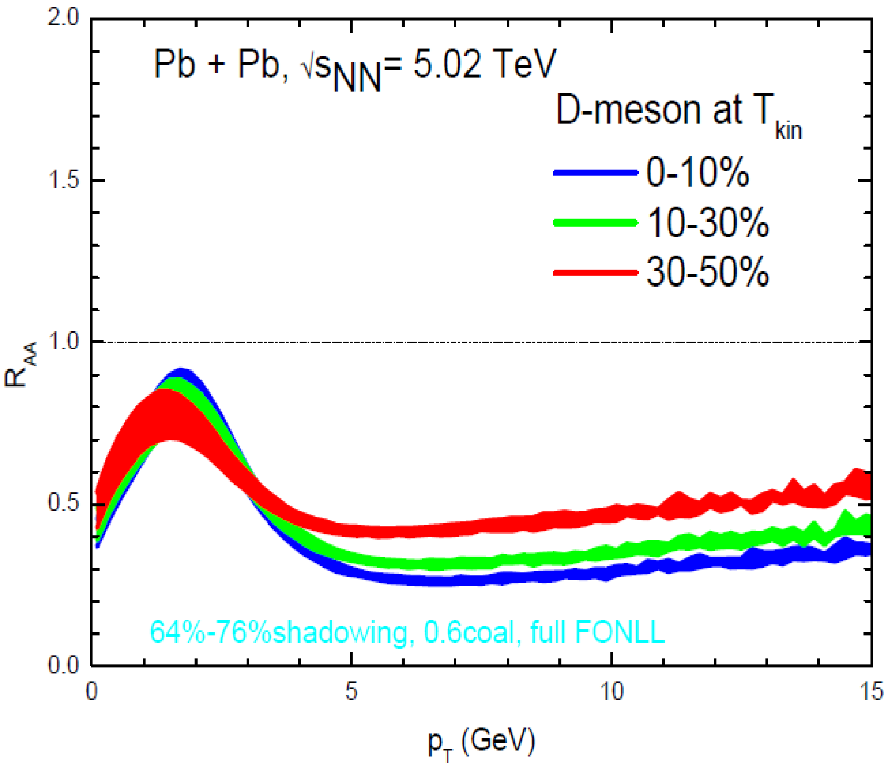
Hydro tune Pb+Pb 5.02 TeV

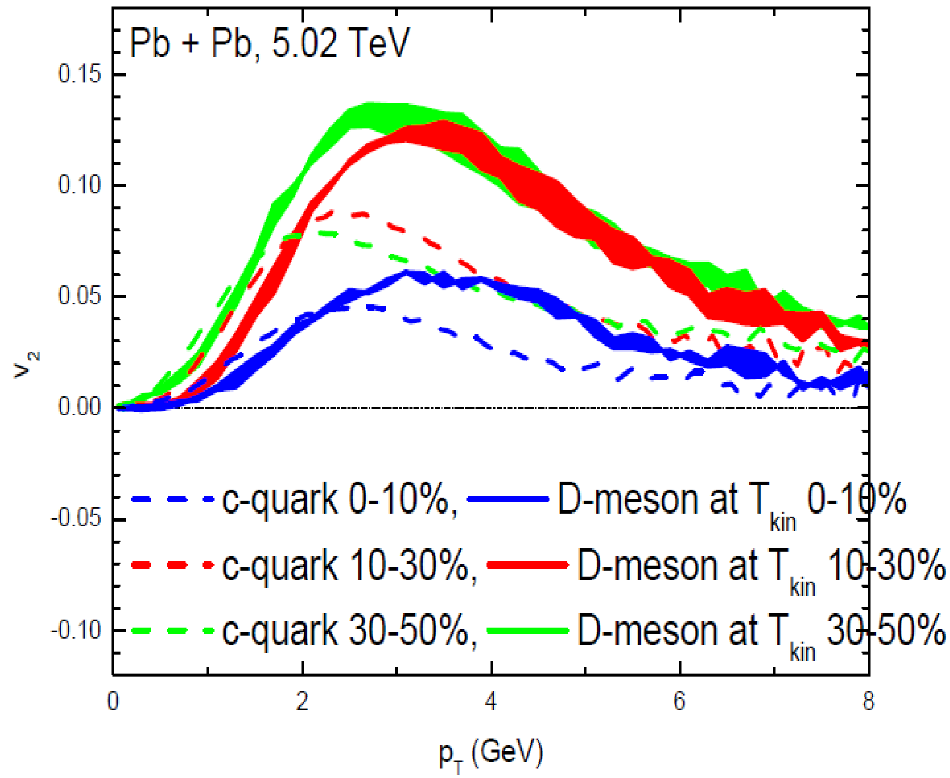




- **centrality cut: dN_{ch}/deta vs N_{part} nicely reproduced by Glauber**
- **v_2: integrated elliptic flow a good measure of the bulk momentum anisotropy**
- **background medium evolution well constrained**

D mesons

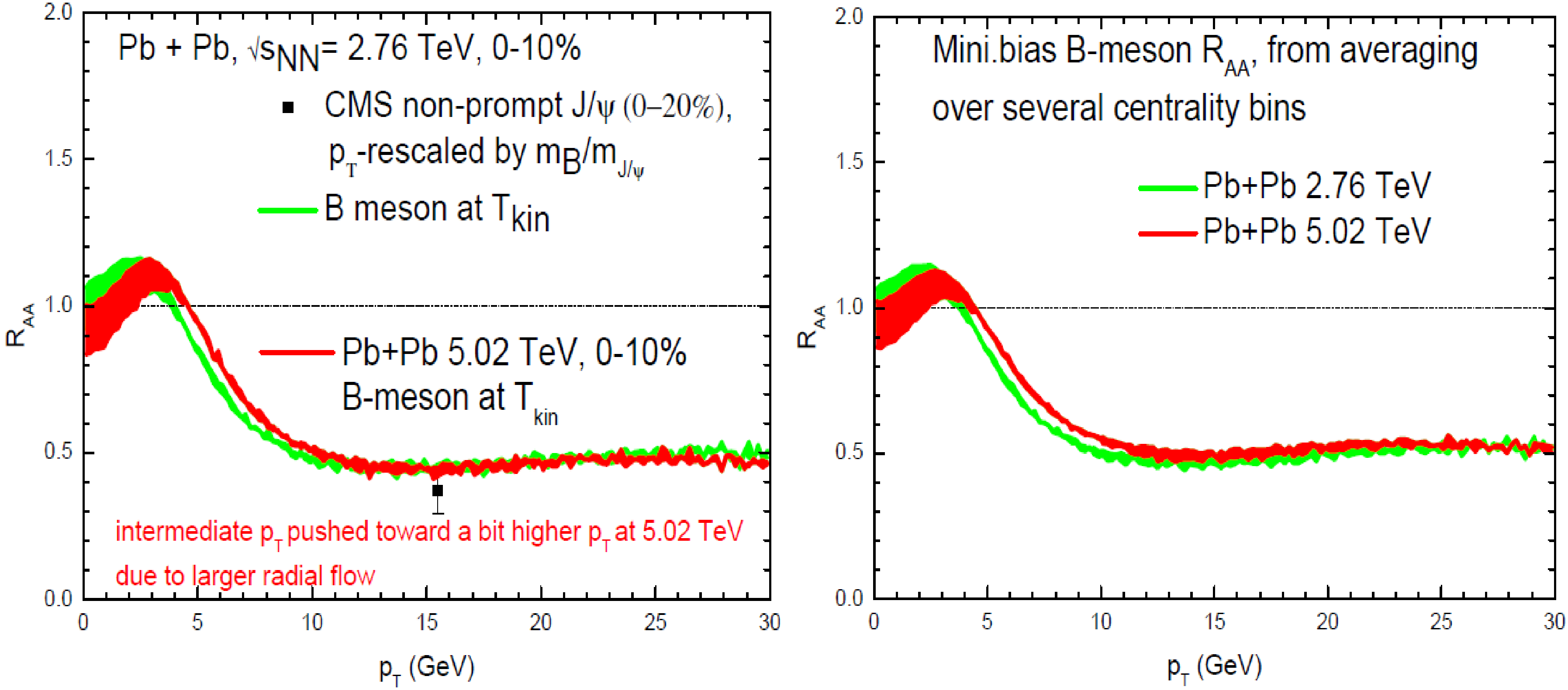




- R_{AA}: **charm shadowing & flow bump at low p_T; suppression at high p_T, a hierachy patten vs centralities**

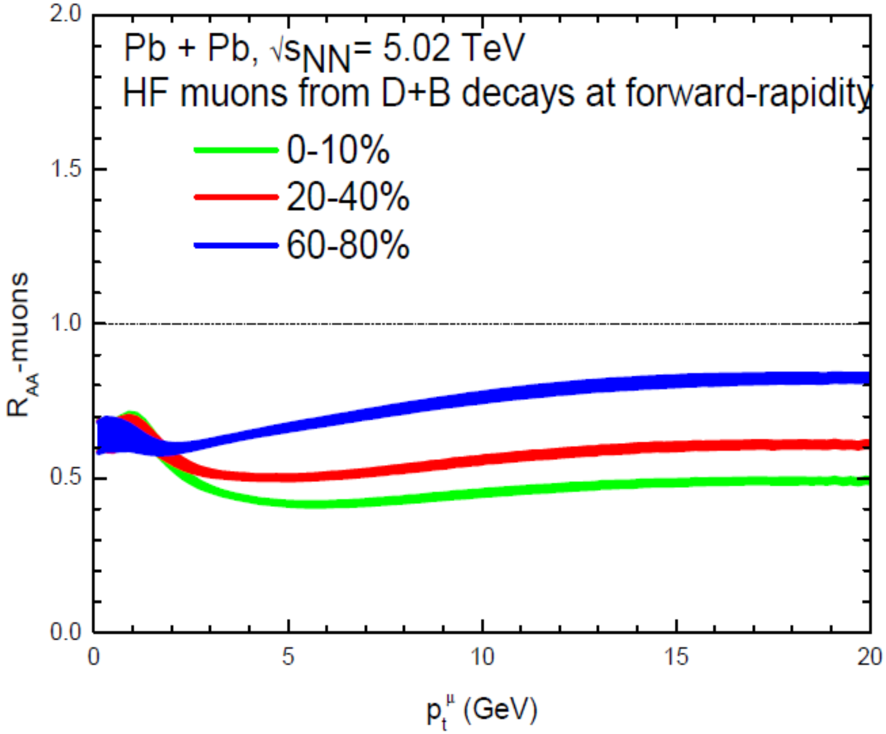
- v_2: **different peak locations due to different radial flows in different centrality different coalescence contribution added on top of charm quark v_2**

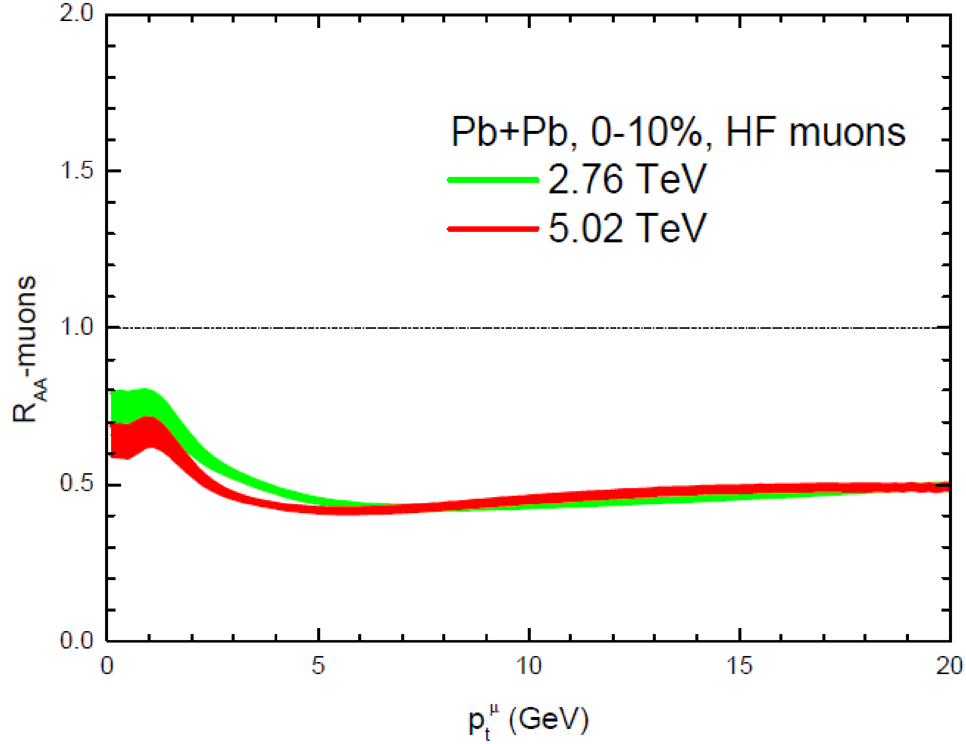
B mesons



◆ **R_{AA}: high p_T --- Similar suppression at as in 2.76 TeV**
low p_T --- shift toward a bit higher pT due to stronger radial flow

HF muons at forward-y





- R_{AA}: charm shadowing & flow bump at low p_T; suppression at high p_T, a hierachy patten vs centralities
- 5.02 vs 2.76 TeV: a bit more charm shadowing manifest in R_{AA} at low p_T

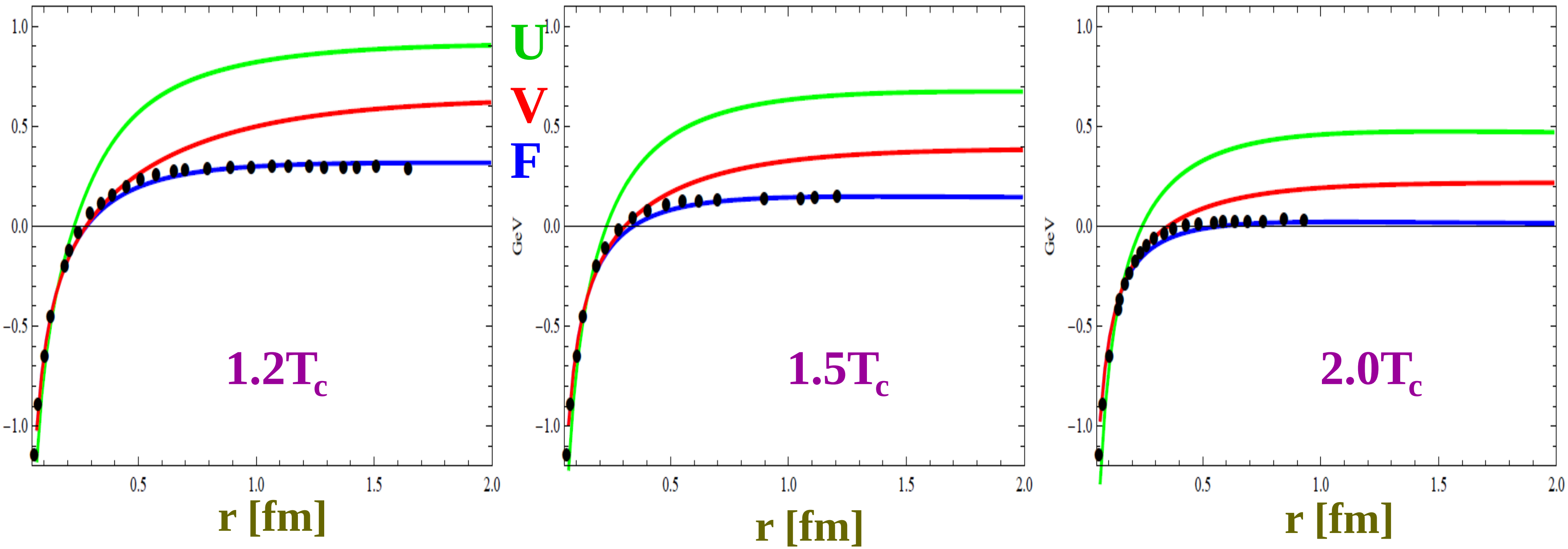
Step Forward …

A New HQ potential + phenomenological consequence

Liu, He, Rapp et.al, in preparation

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

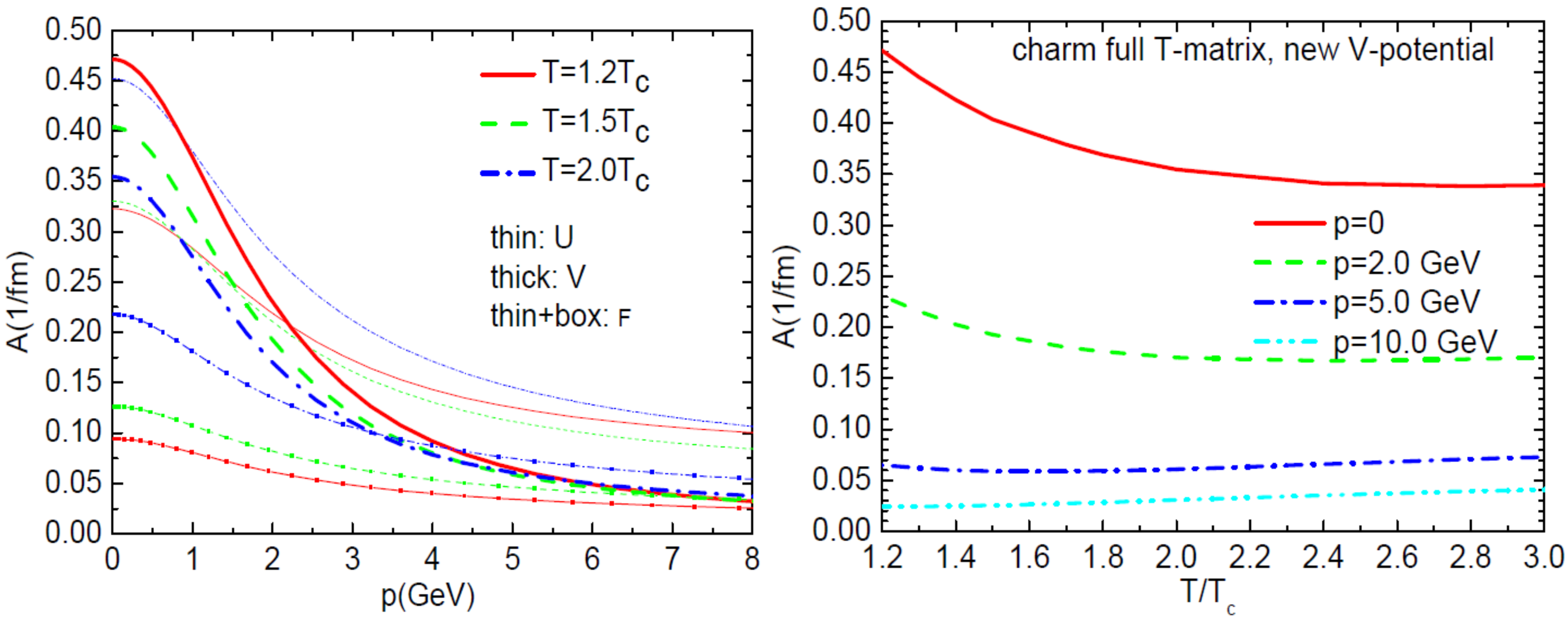
A new HQ potential from T-matrix



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



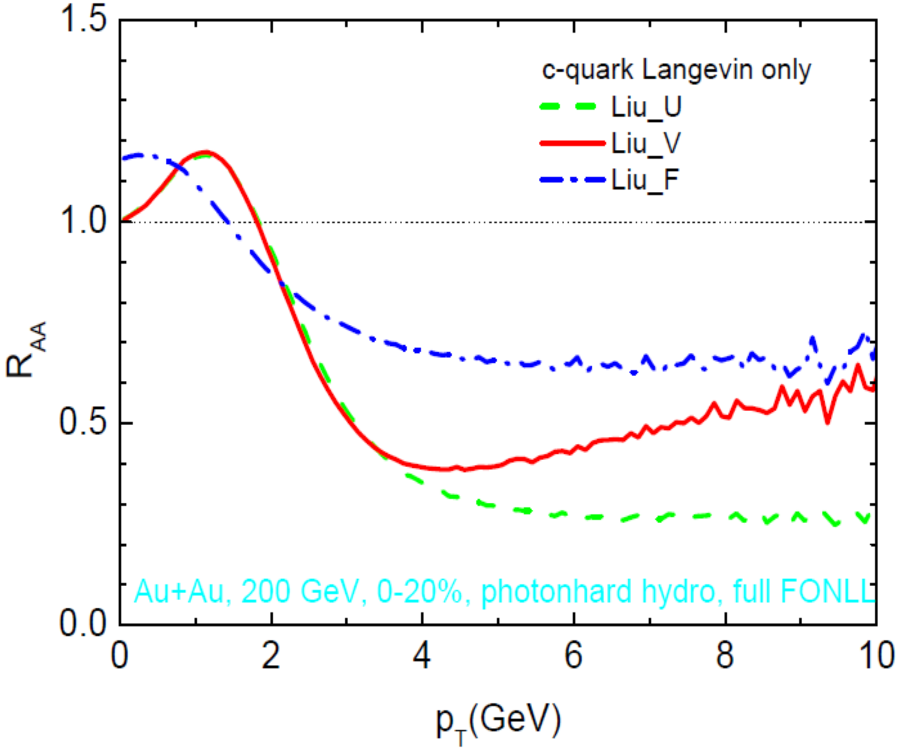
◆p<2.5 GeV & low T<1.5Tc, V results overtake U results due to longer range remnant confining force; high p: tends to pQCD results

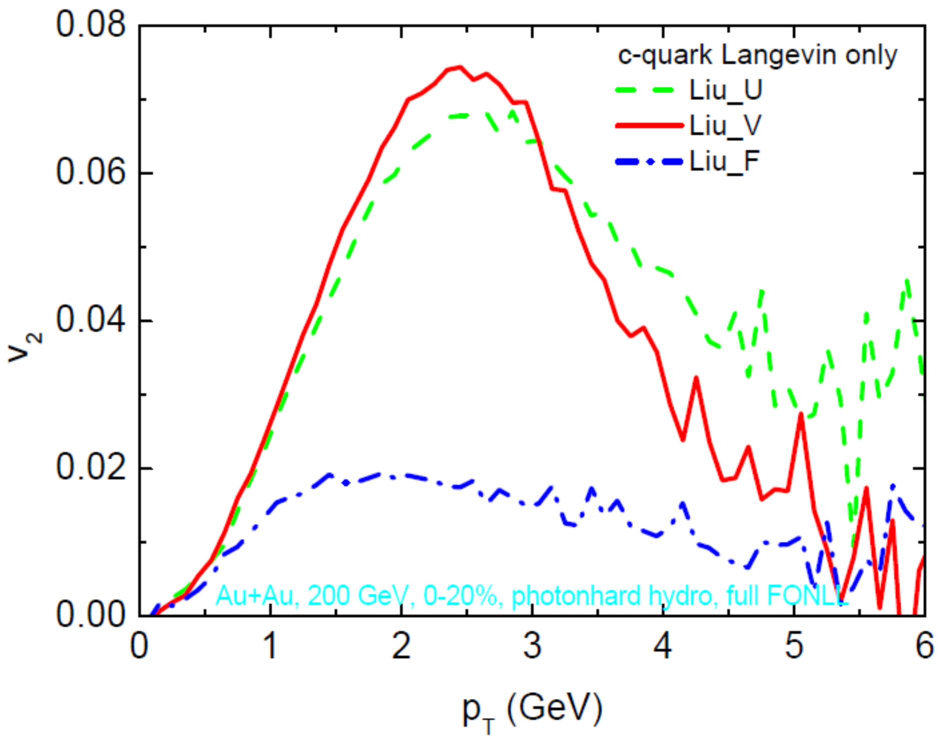
◆unique T-dependence: reversed relative to U/F

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) ➔ $v_2^c(p_T \approx 2\text{GeV})$ 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

- New HQ potential

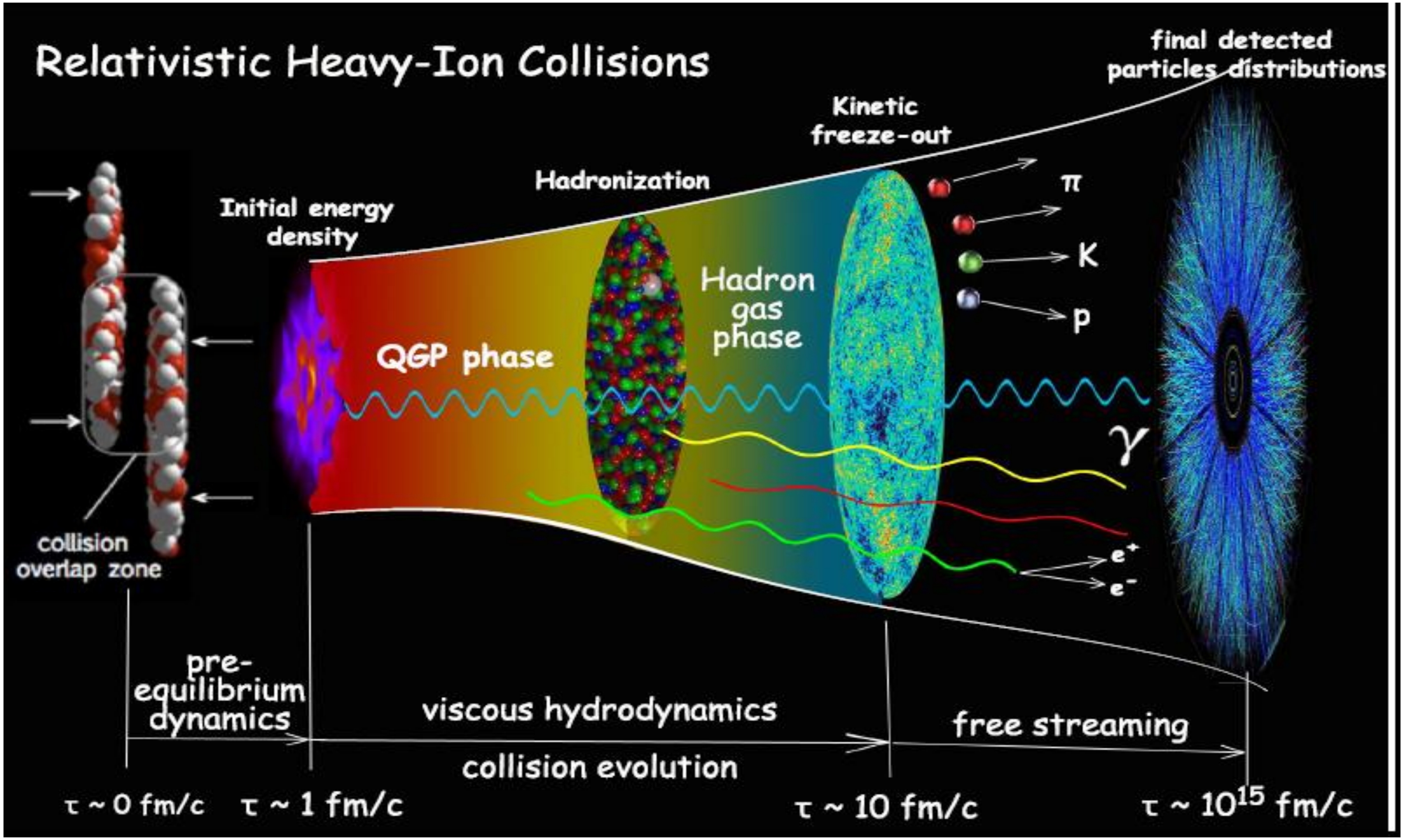
  --- role of the remnant confining force enphasied

  --- phenomenologically larger charm v_2 at p_T~2 GeV

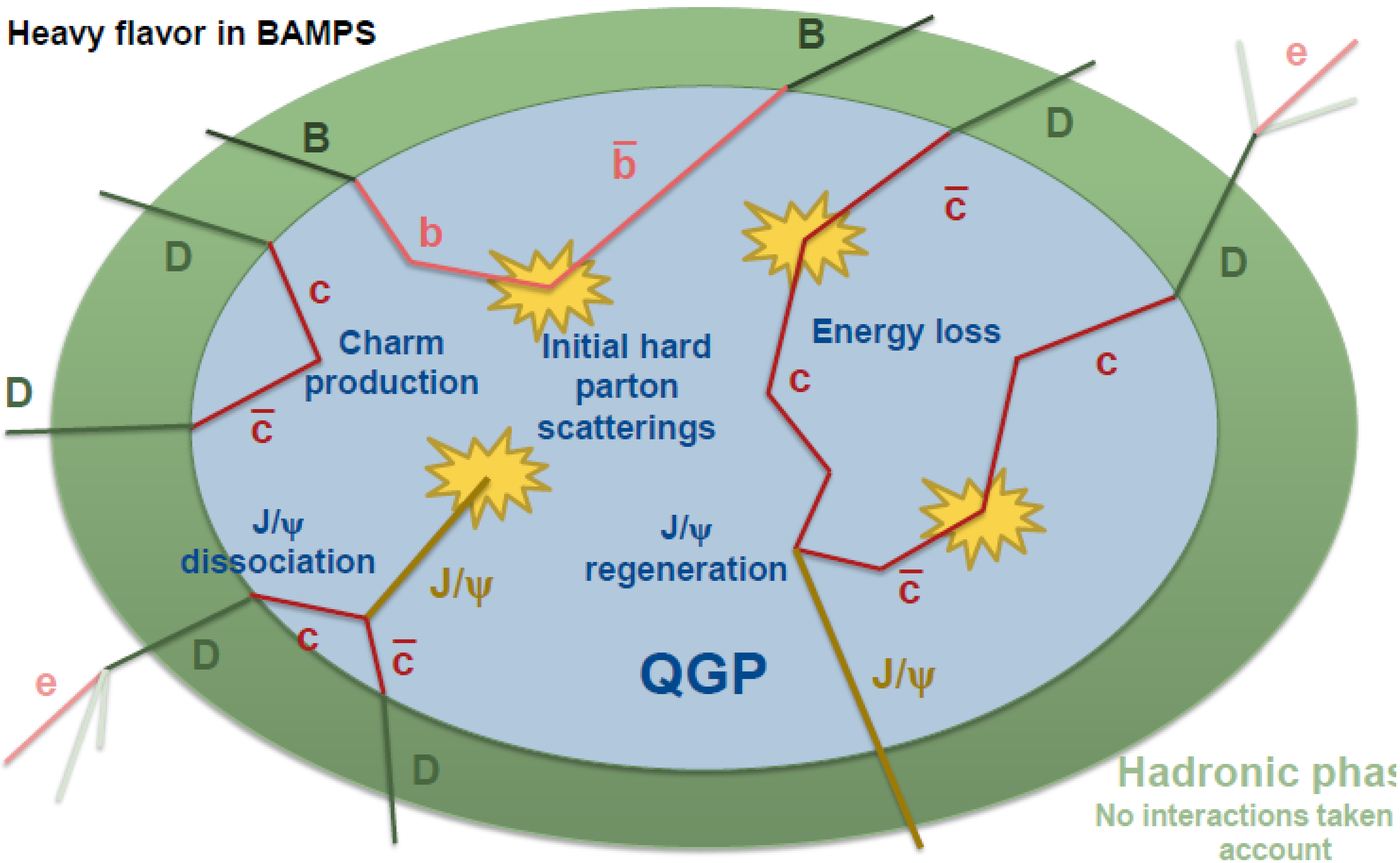
- Elastic vs radiative energy loss

  --- 2→3 radiative T-matrix calculation is going on

Backup: space-time evolution of HIC



Backup: Heavy quarks



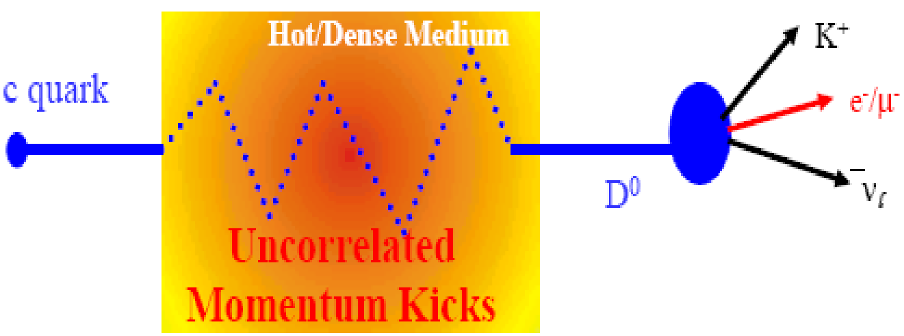
Backup: HQ probes

- 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

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

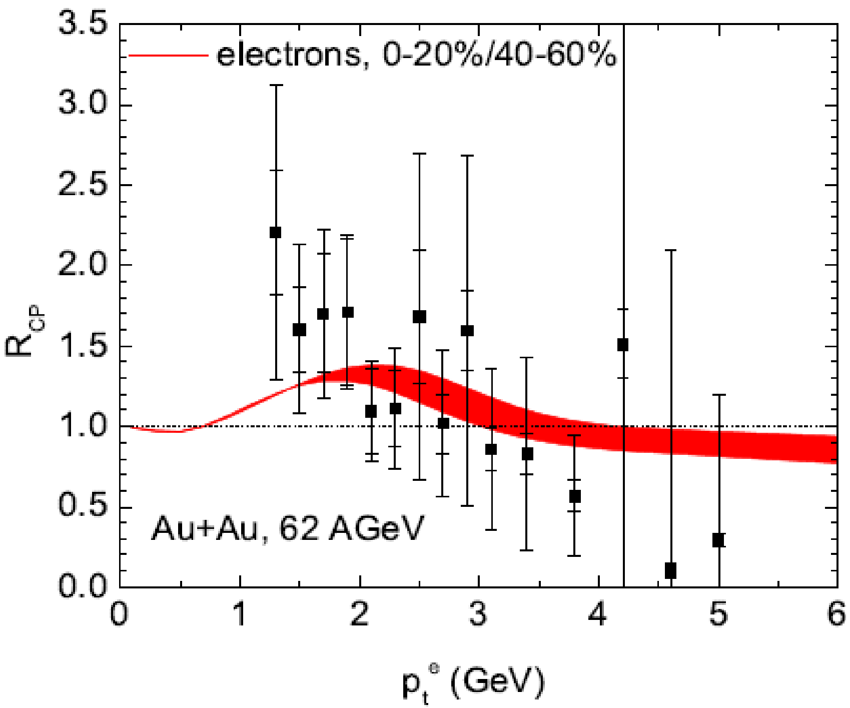
thermalization rate

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

diffusion coefficient

$$D = \gamma m_Q T$$

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



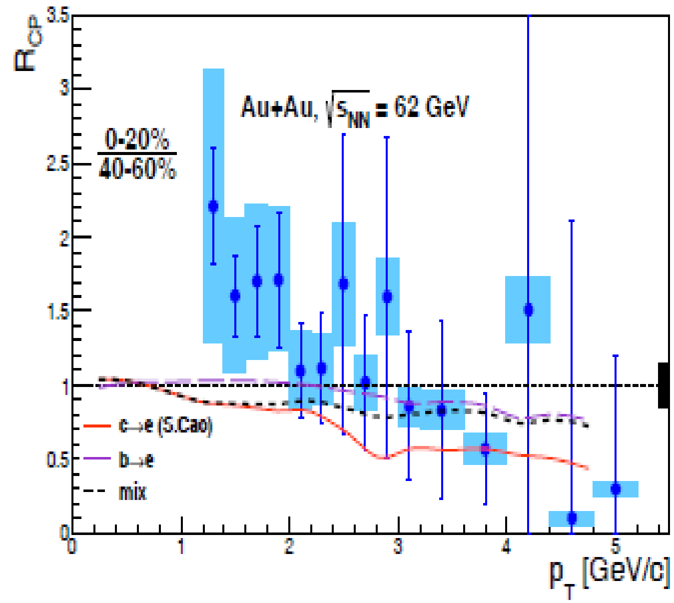
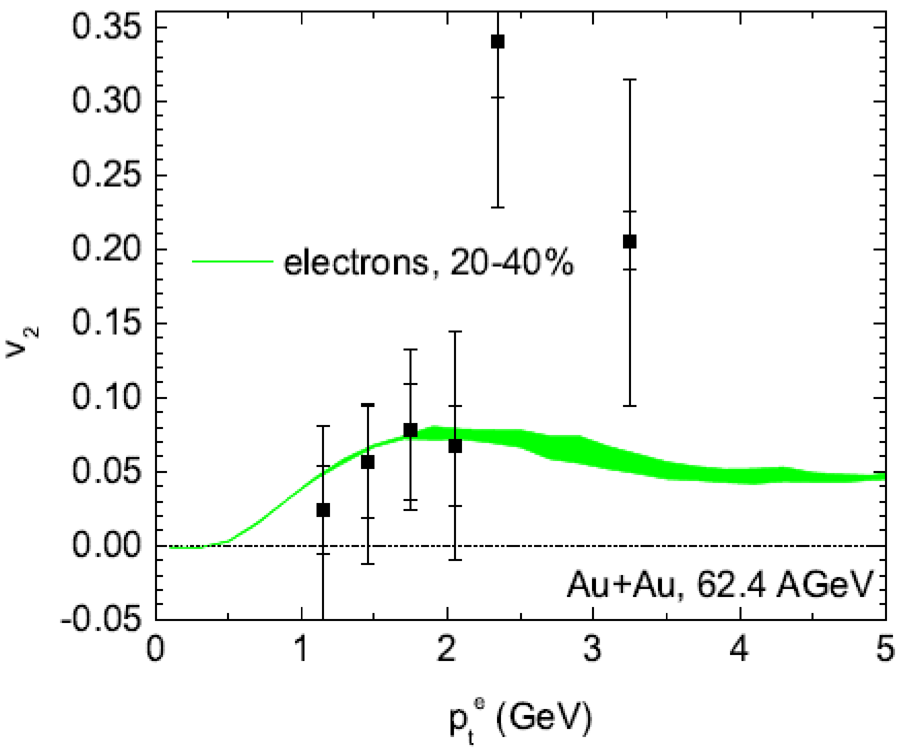
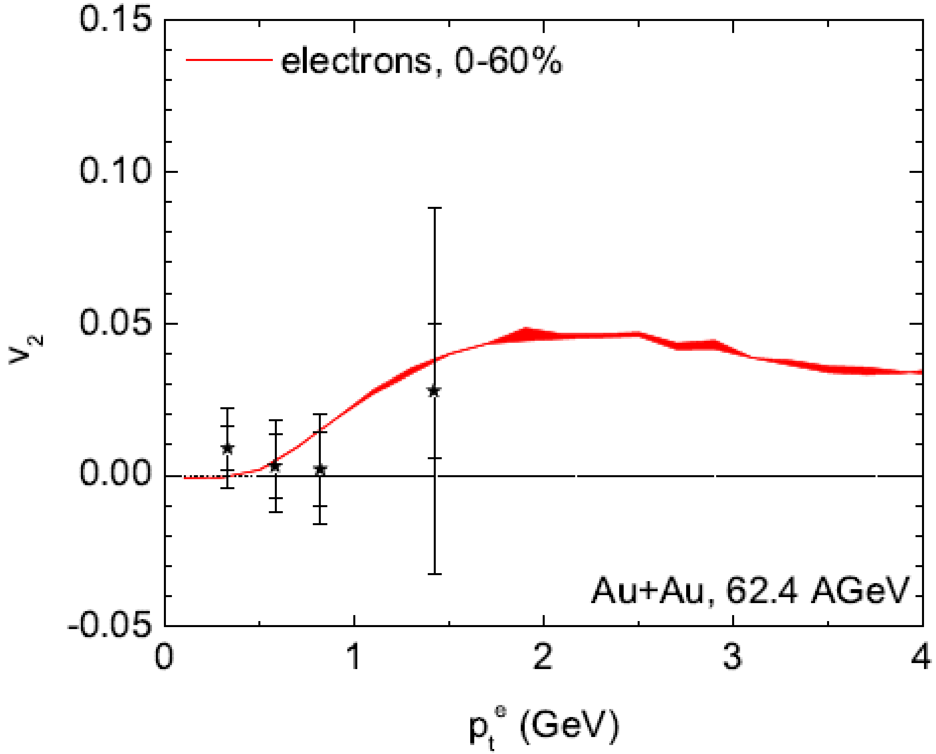


FIG. 19: (color online) Heavy flavor electron R_{CP} between centrality 0%–20% and 40%–60% in Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV. The curves are calculated using a model based on energy loss [48].

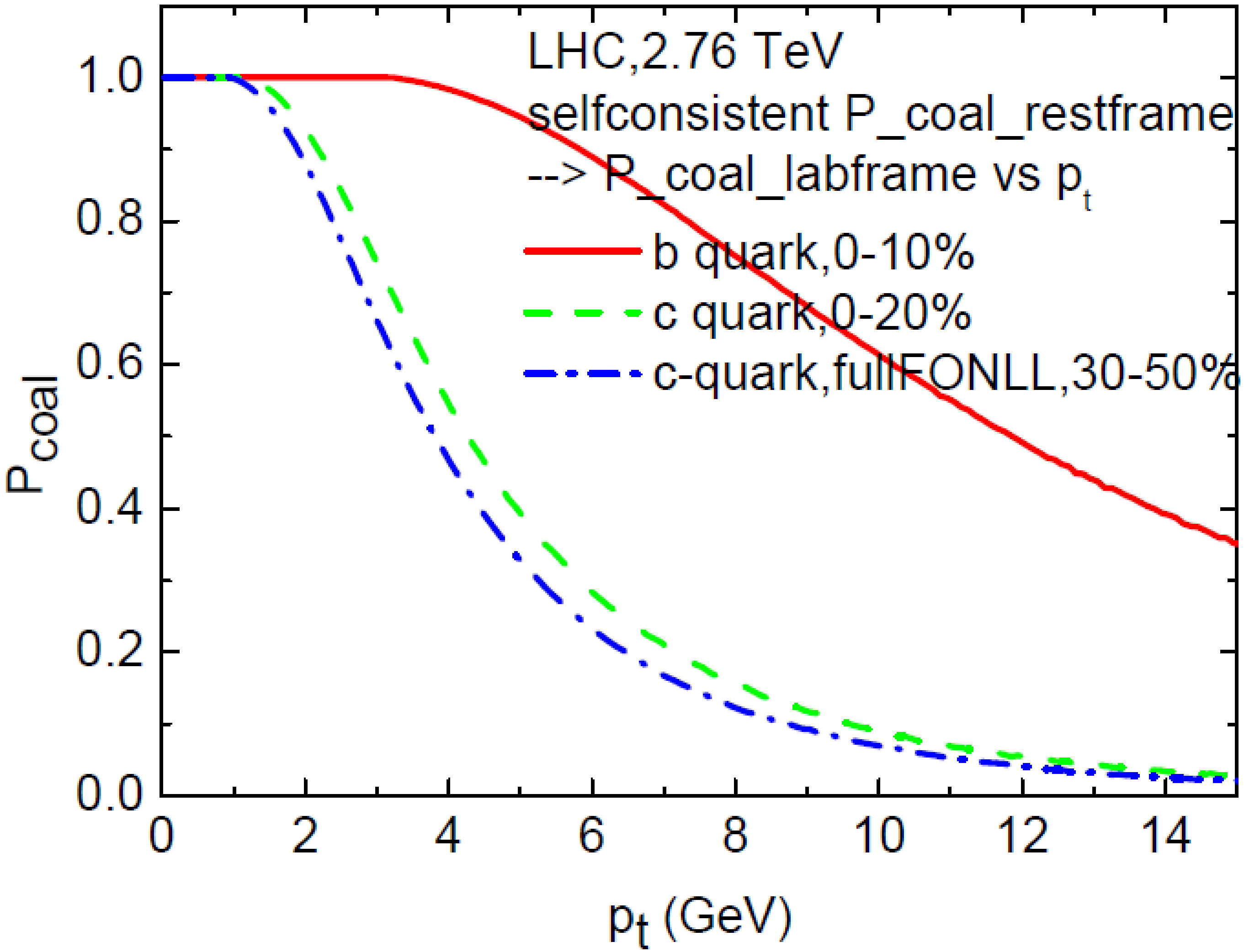
Au-Au 62.4 GeV HF electrons v2



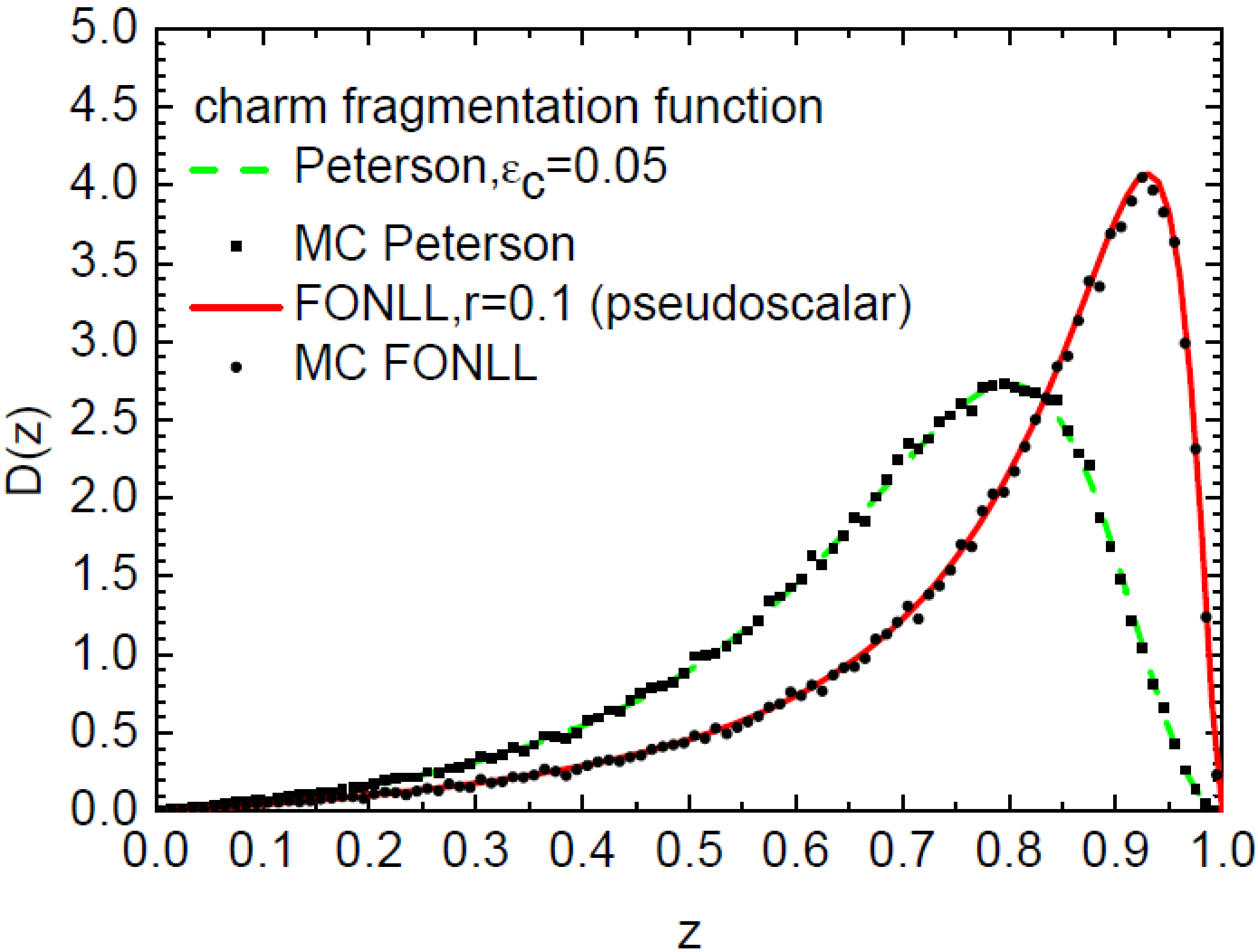


- **No discrepancies can be made out, albeit within rather large error bars in data**
- **0-60% centrality v_2: from a N_{coll}-weighted average of v_2's of the 0-20%, 20-40% and 40-60% centrality bins**

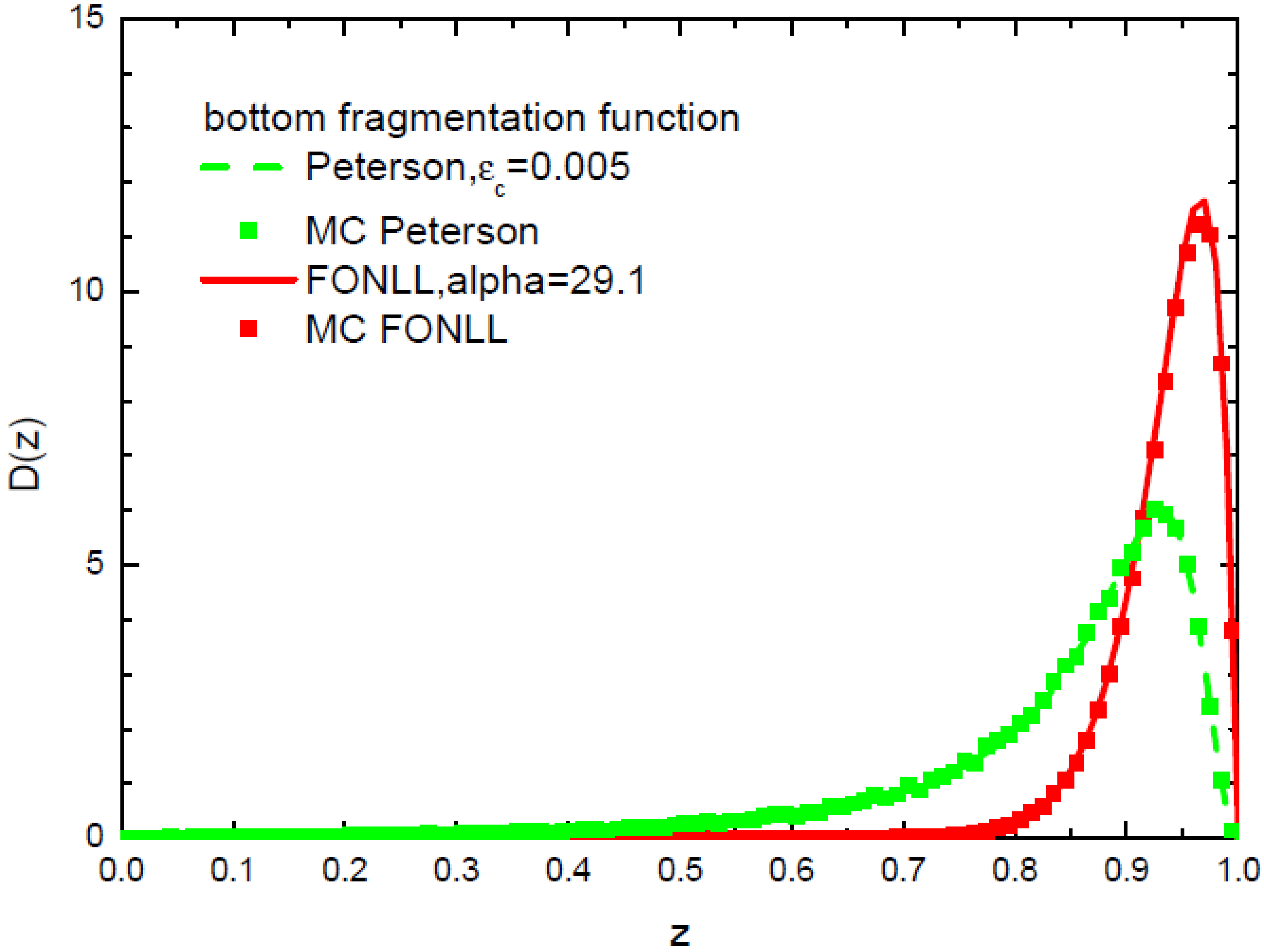
Charm/bottom quark coal.prob.



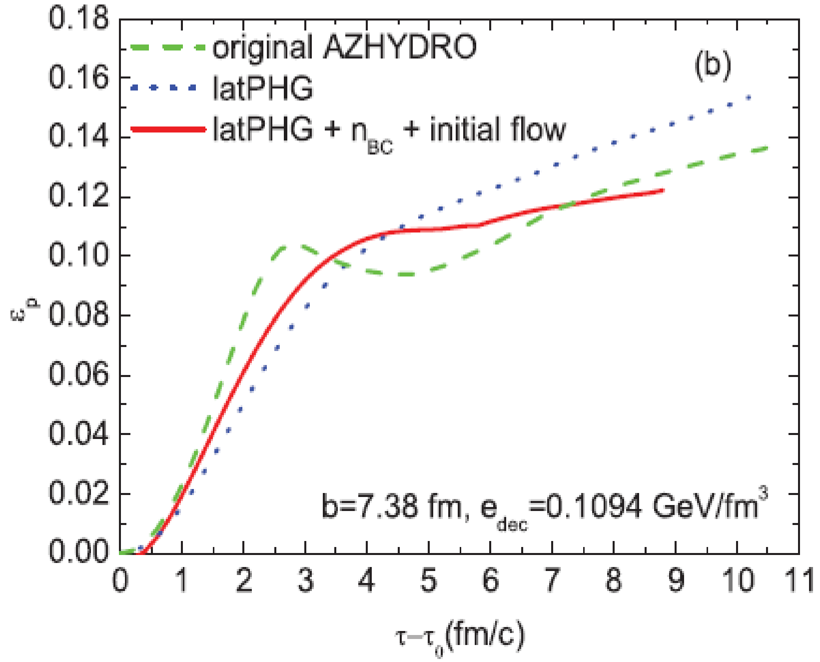
Charm quark FONLL vs Peterson frag.

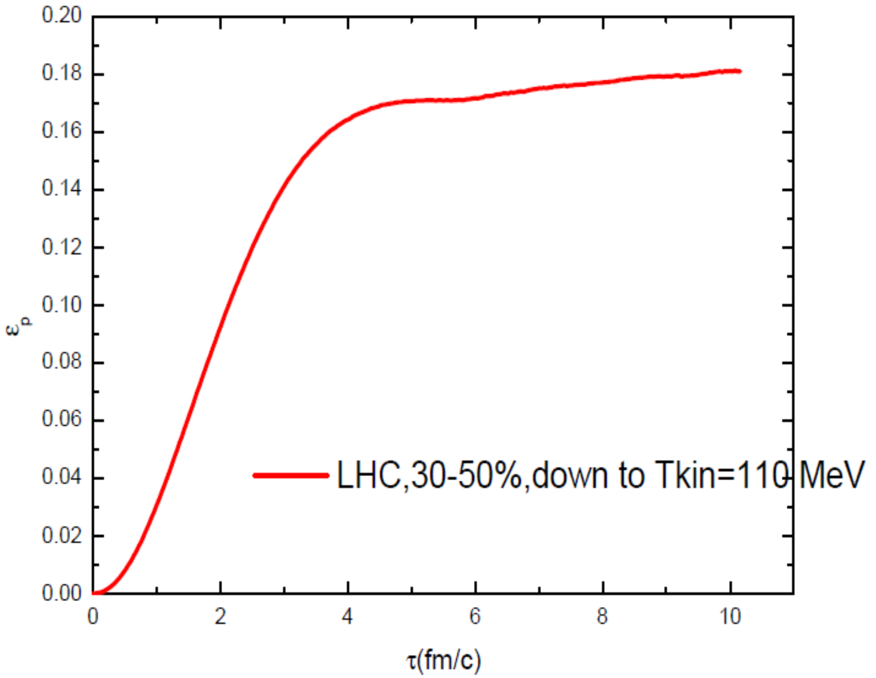


Bottom quark FONLL vs Peterson frag.

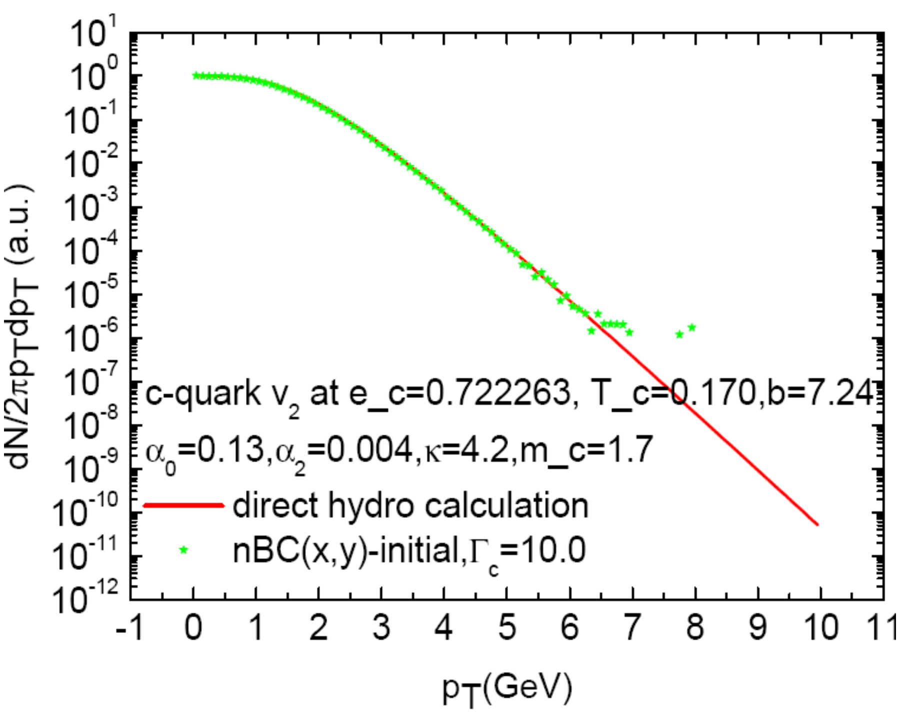


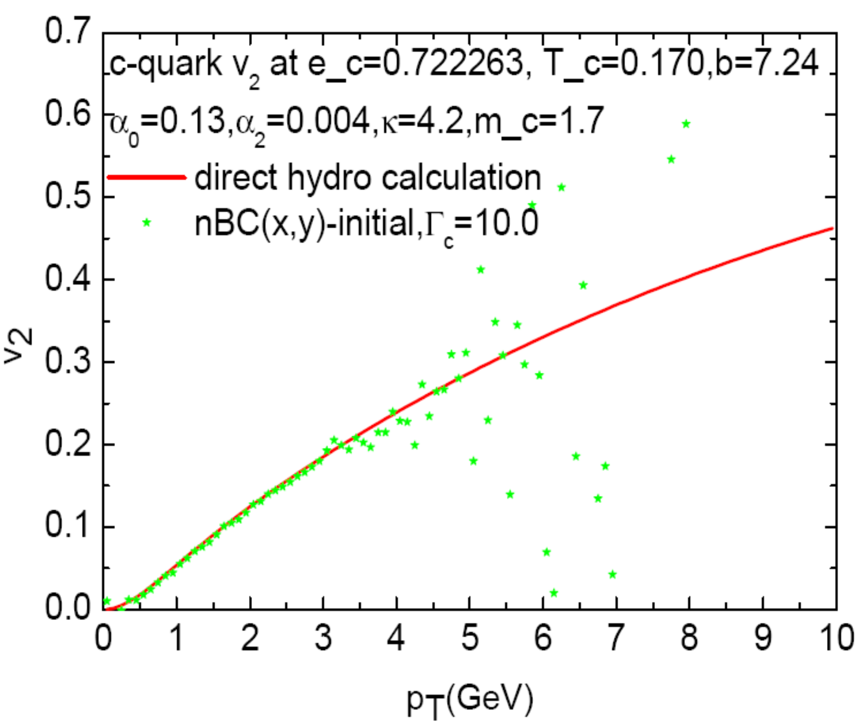
Energy-momentum tensor anisotropy



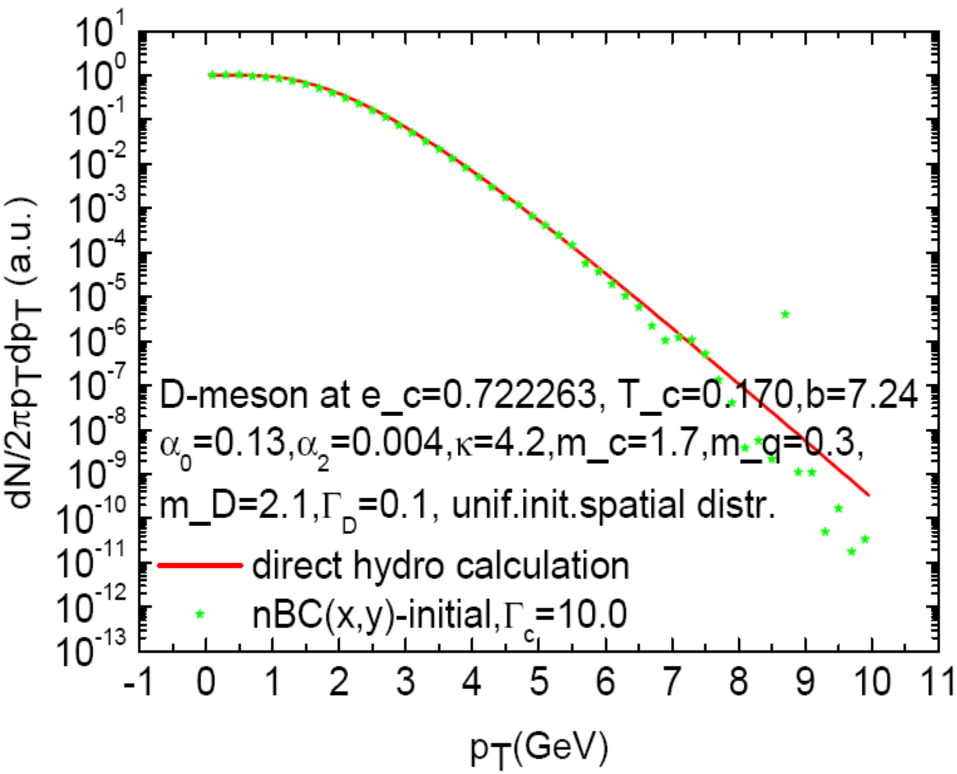


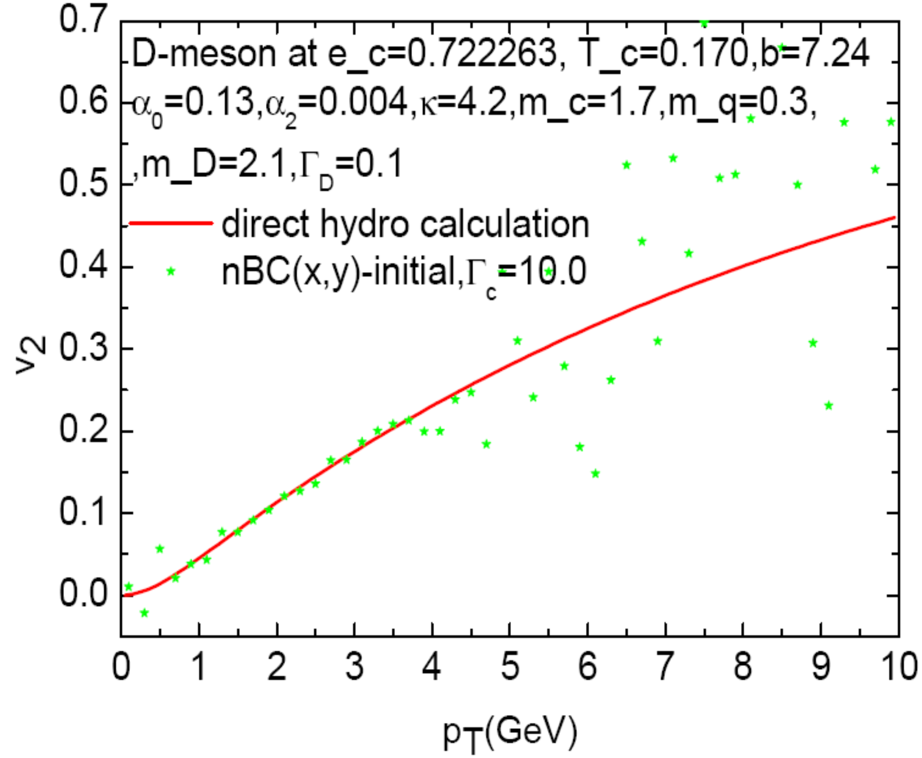
Backup 1: charm quark Langevin diffusion equilibrium



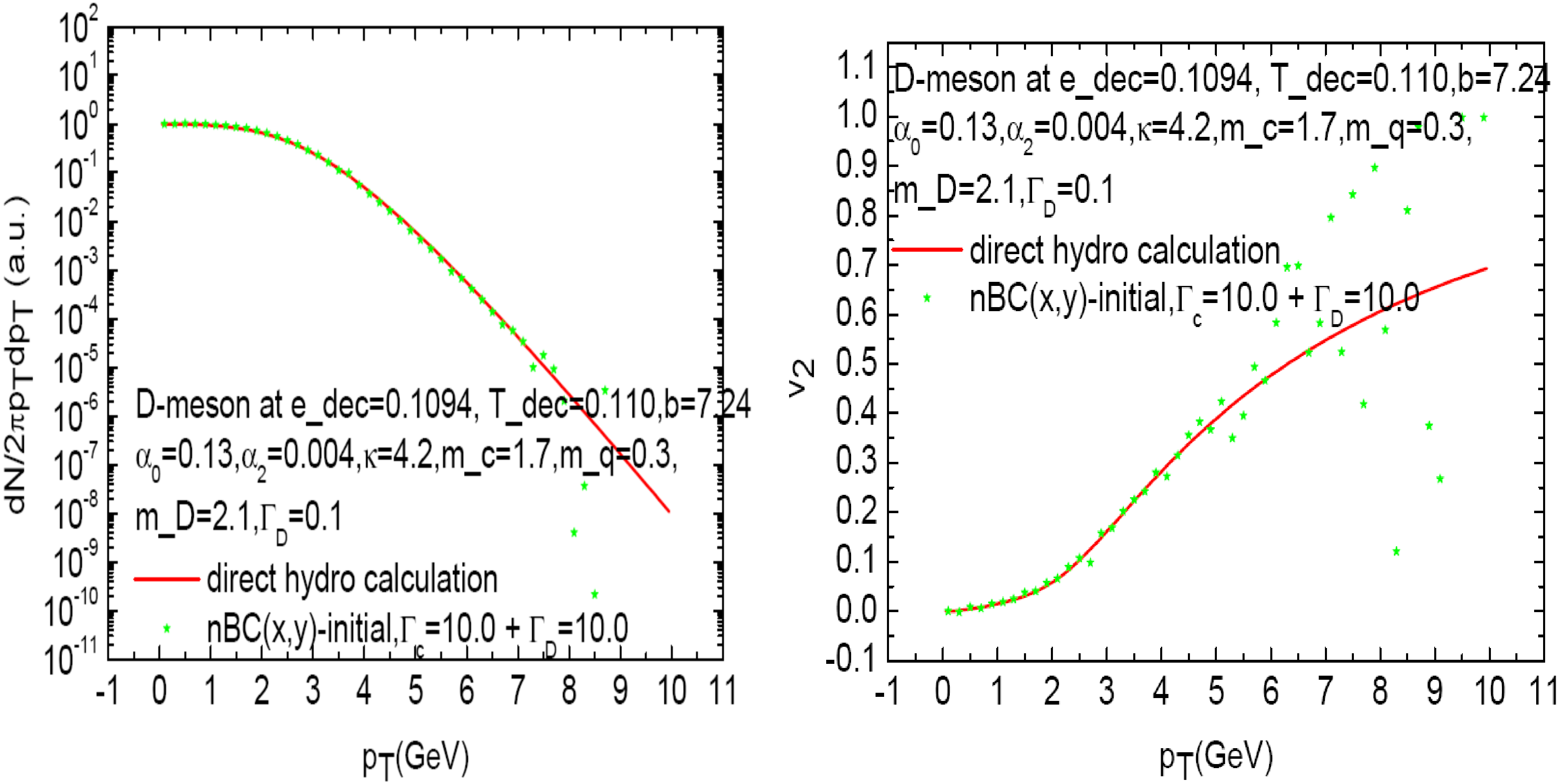


Backup 2: D-meson RRM equilibrium

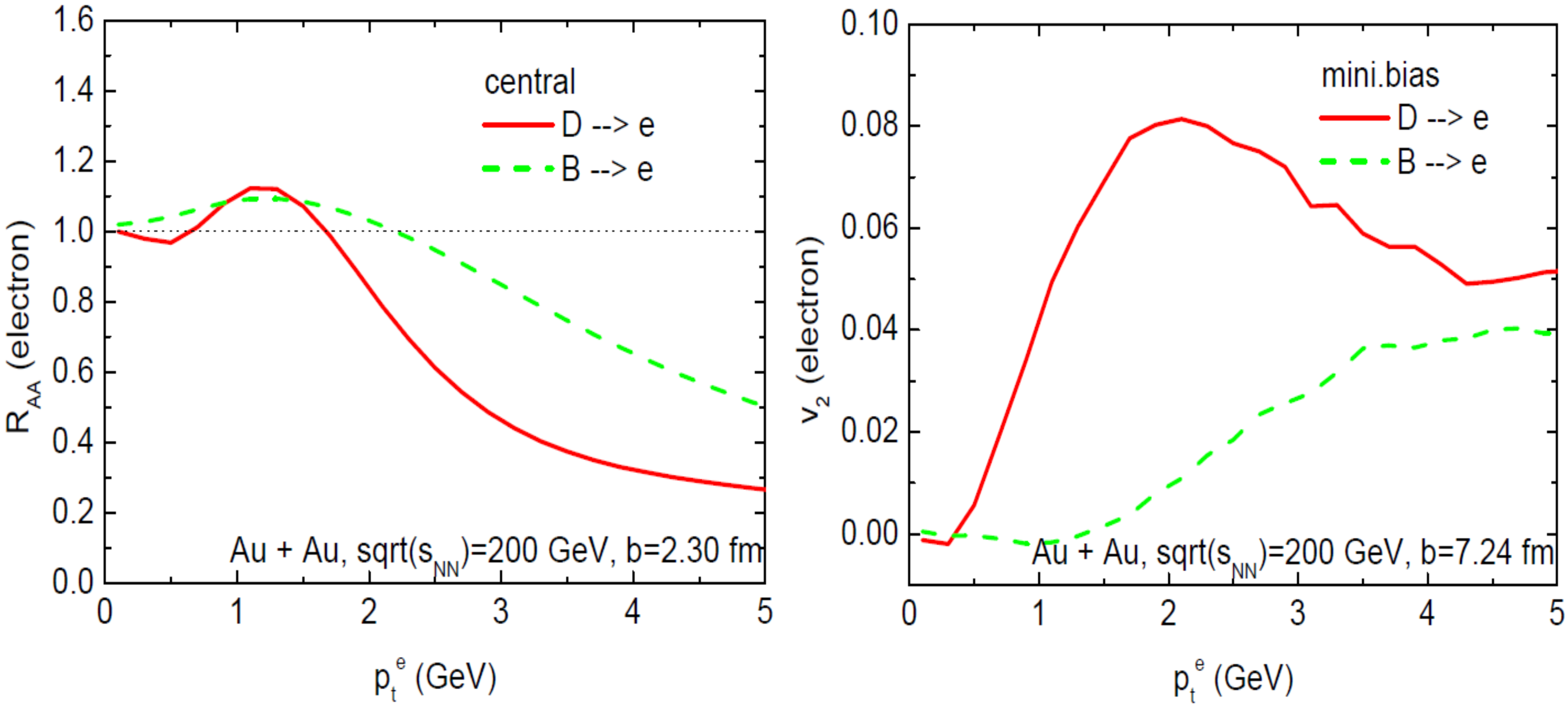




Backup 3: D-meson hadronic phase Langevin diffuison equilibrium

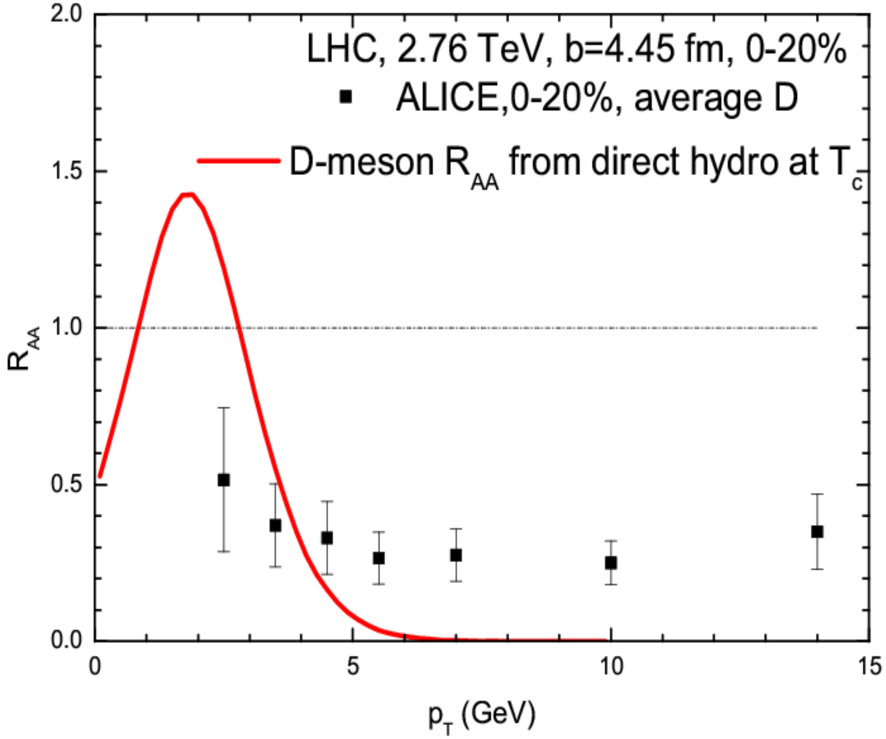


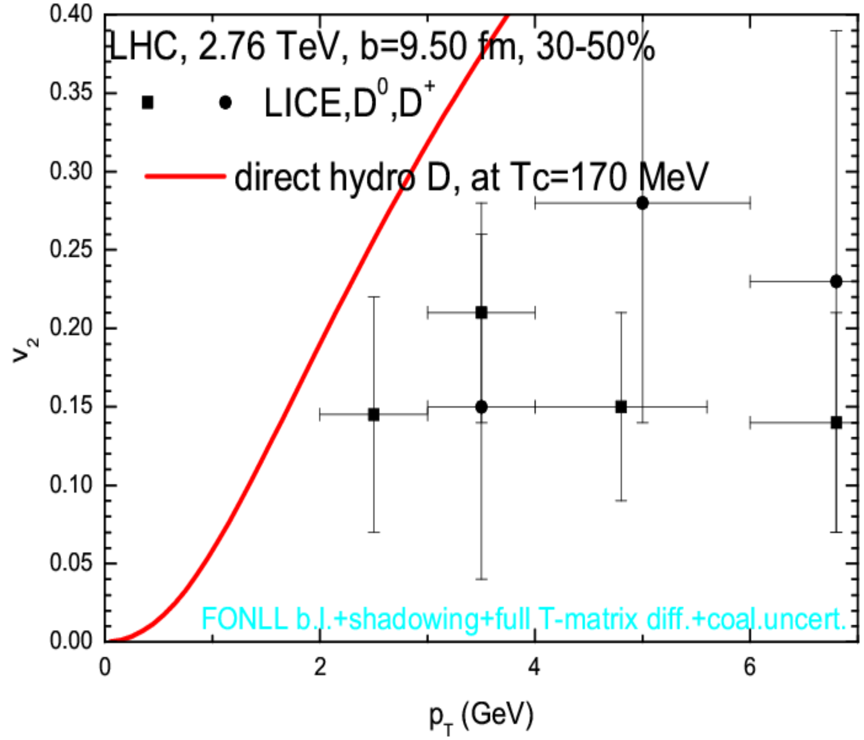
RHIC b/B →e vs c/D →e



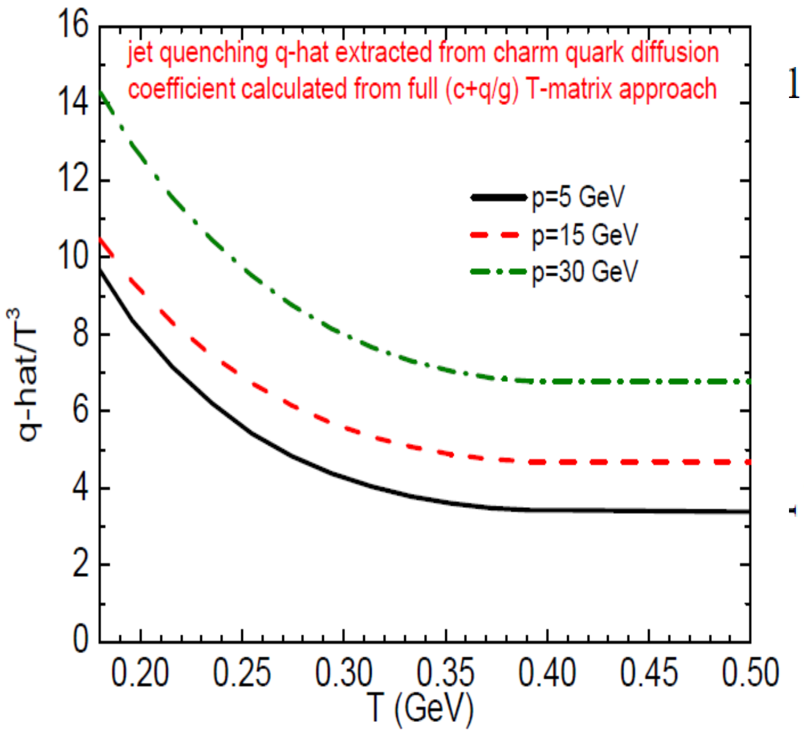
- **Bottom less suppression, less collectivity than charm: mass effect**
- **Now HFT@STAR able to disentangle charm vs bottom lectrons, time to compare the prediction with data**

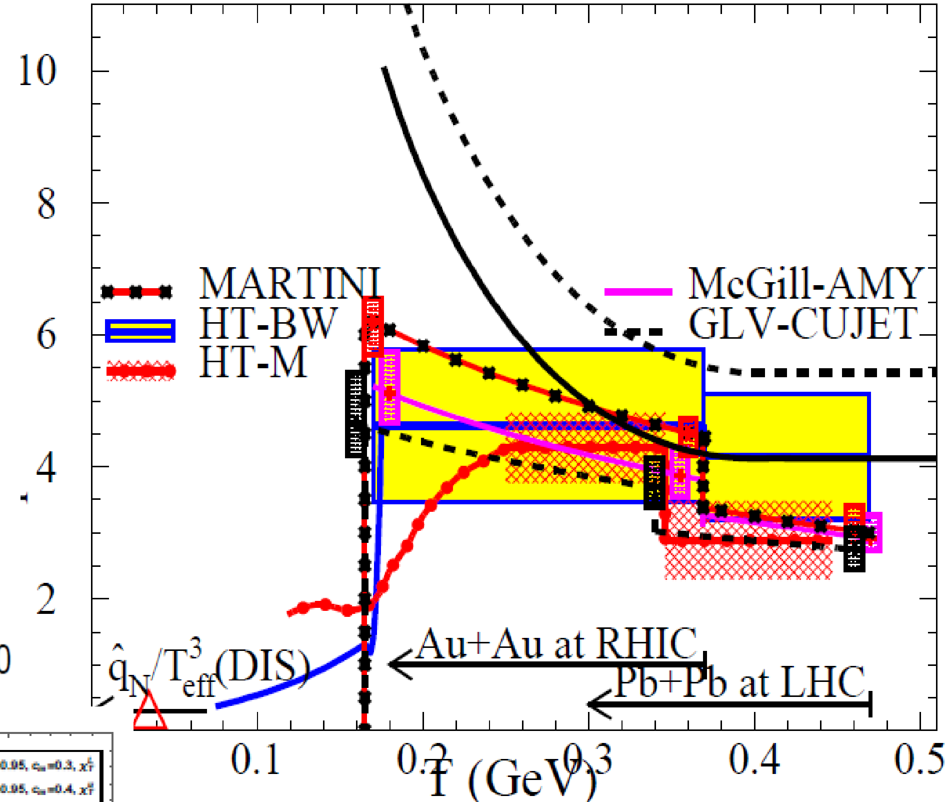
Backup 4: fully thermalized D mesons@LHC

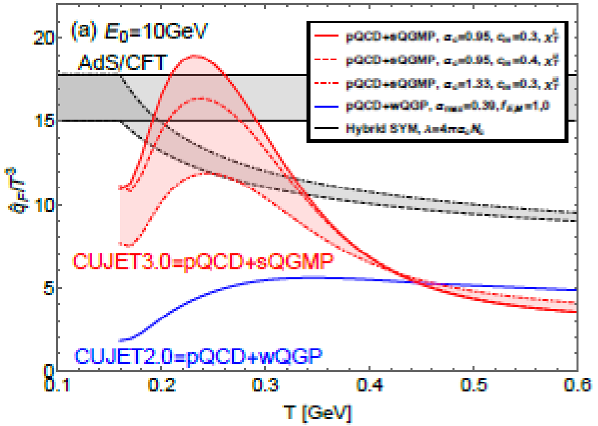




Jet quenching q-hat from charm diffusion







Xu, Liao, Gyulassy, 2015