High Energy Strong Interactions:
CCNU School for Young Asian Scientists

Non-Perturbative 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 for hot & dense matter

2. HQ probe: a strongly coupled framework

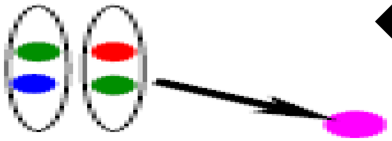
- Transport coefficient
- HQ diffusion in QGP: Langevin + hydro simulation
- Hadronization: coalescence vs fragmentation
- D-meson diffusion in hadronic phase

3. Heavy ion phenomenology

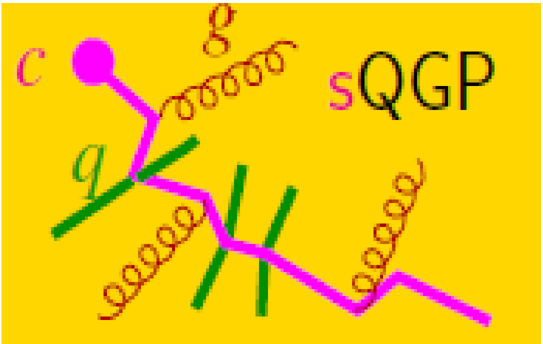
- RHIC: Non-photonic electrons, Ds vs D mesons
- LHC: D,B mesons, non-photonic electrons

4. Summary

HQ evolution in HIC



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



- **HQ diffusion in QGP: elastic scatterings with medium**

Brownian motion

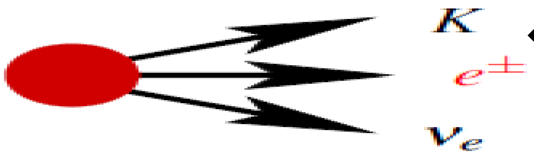
$$\frac{\partial f}{\partial t} = \gamma \frac{\partial (pf)}{\partial p} + D \frac{\partial^2 f}{\partial p^2}$$

thermalization rate **diffusion coefficient**

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

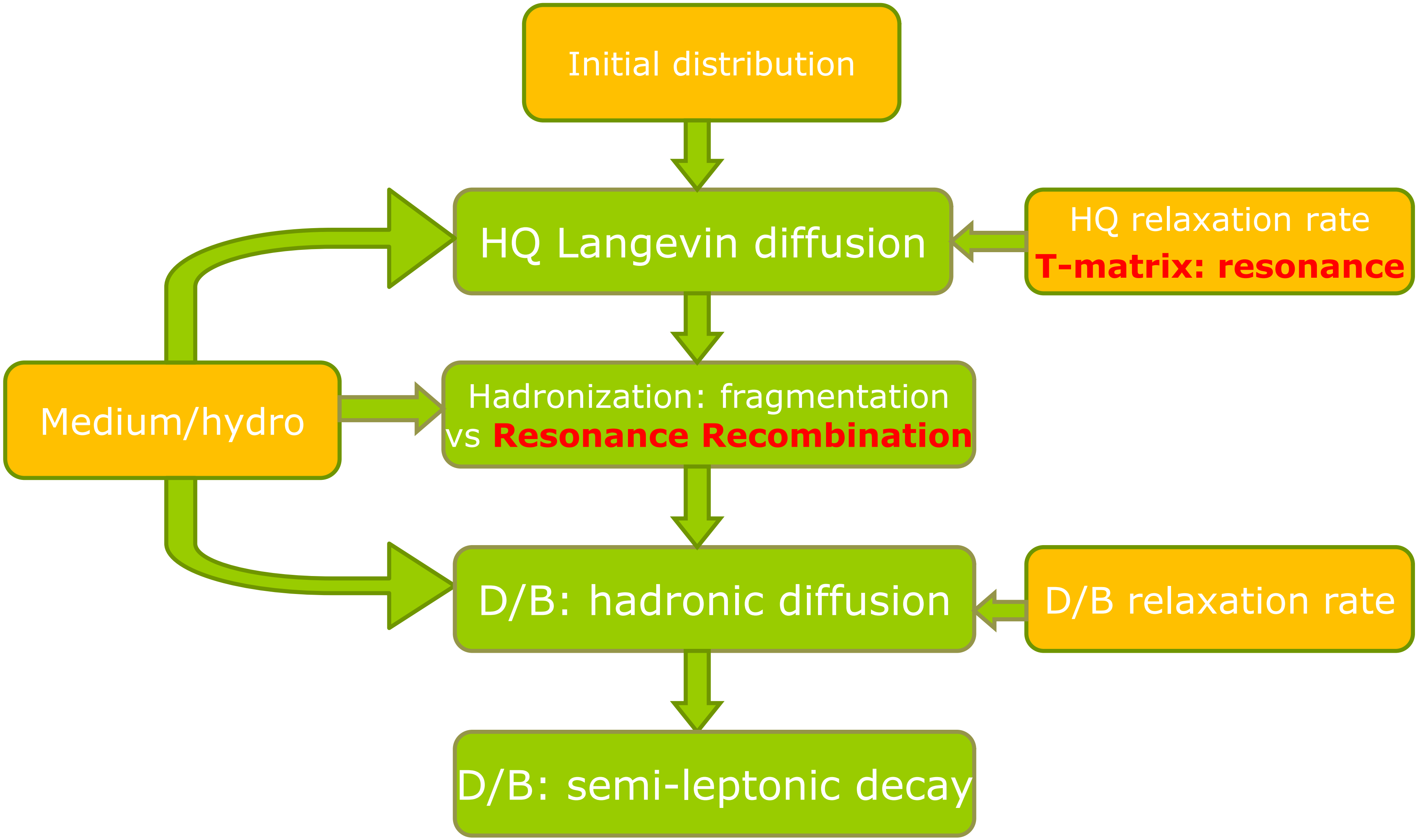
$$D = \gamma m_Q T$$

- **hadronization into D,B mesons via**
  recombination + fragmentation

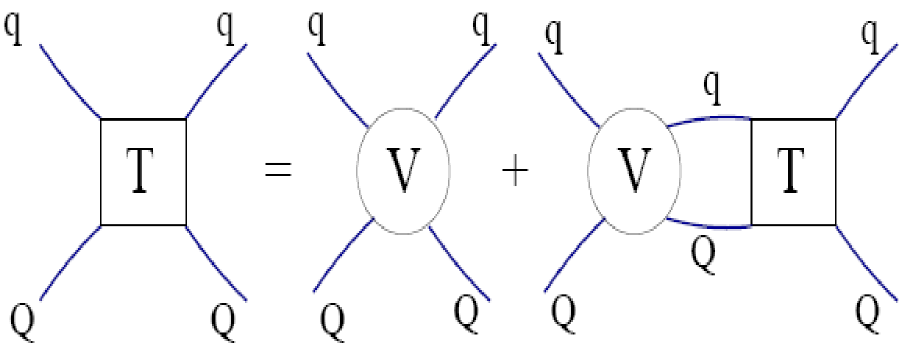


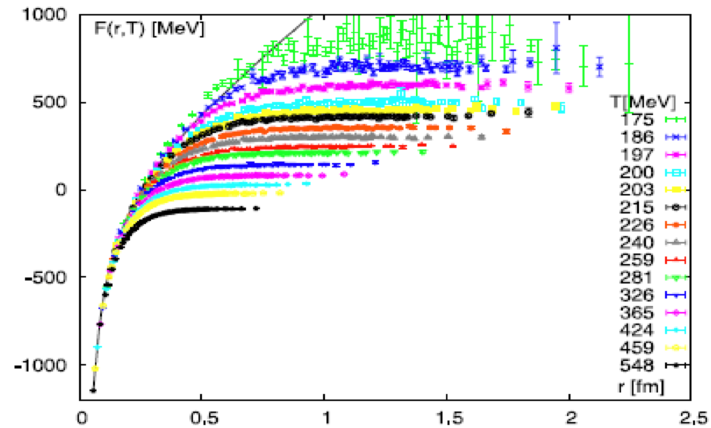
- **semi-leptonic decays: non-photonic electrons**

Non-Perturbative HQ Transport: flow chart



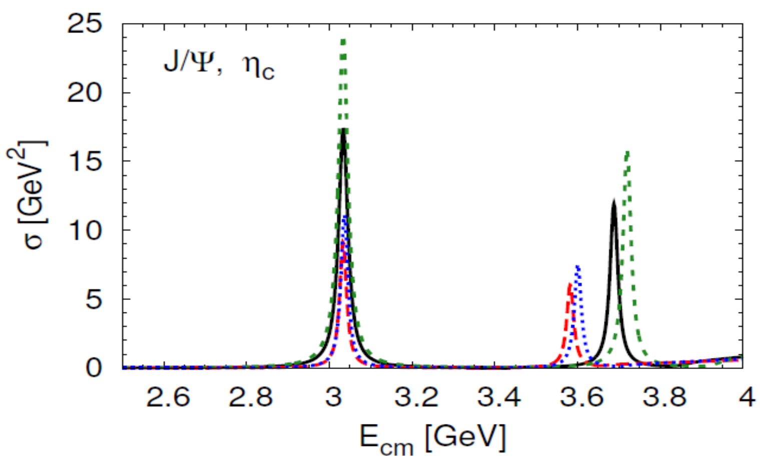
HQ thermal relaxation rate: T-matrix

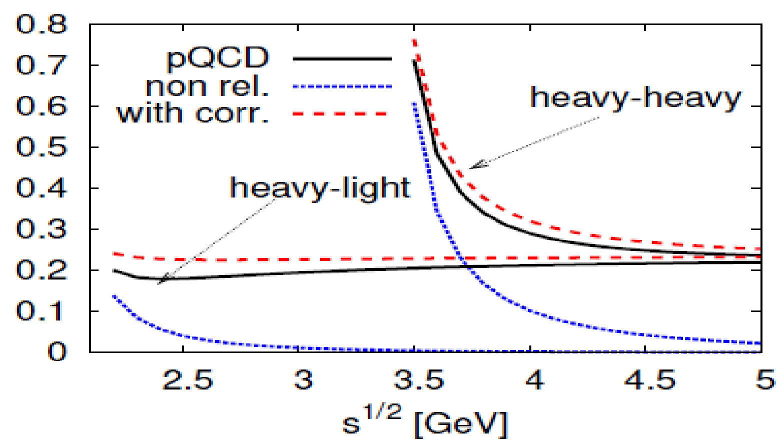




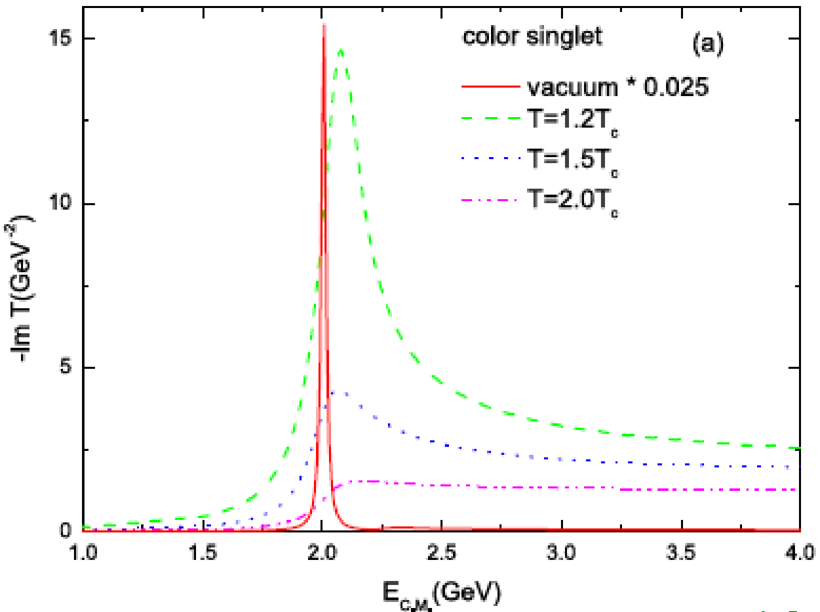
◆**lattice potential: Kaczmarek,2008** $U = F - T\frac{\partial F}{\partial T}$ ➔ **Resummation & Unitarization**

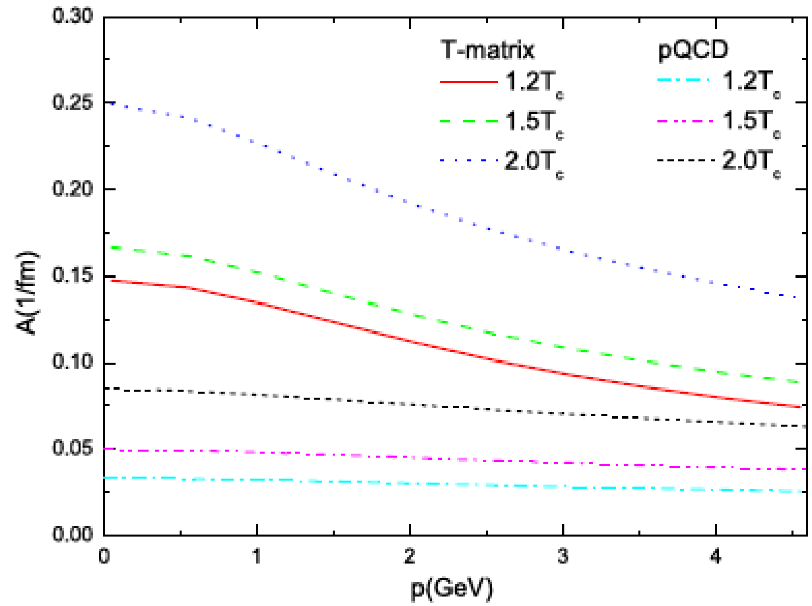
◆**Open/hidden HF: vacuum spectroscopy reproduced; high energy pQCD recovered**





Charm quark relaxation rate: QGP





Riek, Rapp

◆ **T-matrix resummation ➔ color singlet and anti-triplet broad Feshbach resonances up to ~1.5 T_C**

◆ **this resonance correlation ➔ resonance recombination**

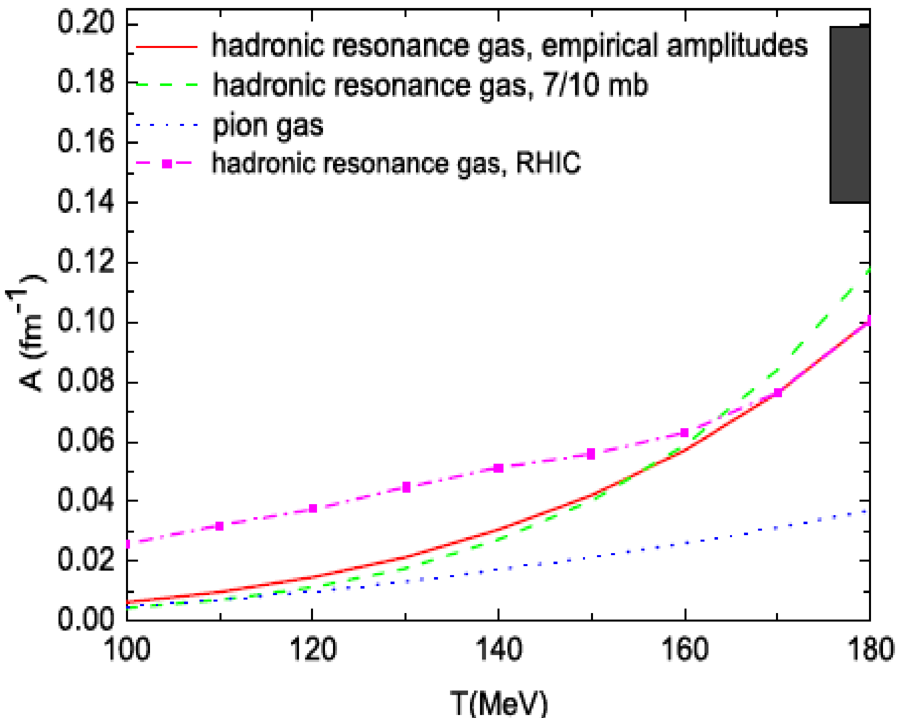
◆ **T-matrix relaxation rate: a factor ~4-5 larger than LO pQCD at T=1.2 T_c**

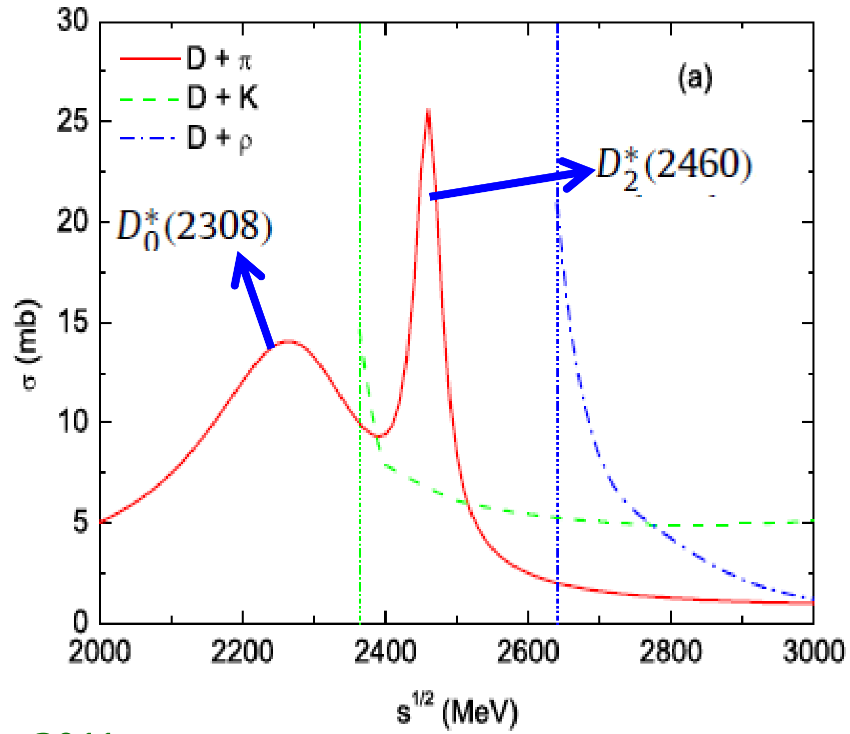
◆ **T-dependence: screening potential; p-dependence: less contribution from Feshbach resonance as p increases**

◆ **T-matrix calculation of HQ-gluon scattering [Huggins,Rapp]➔ ~25% enhancement of the full relaxation rate at low momentum**

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

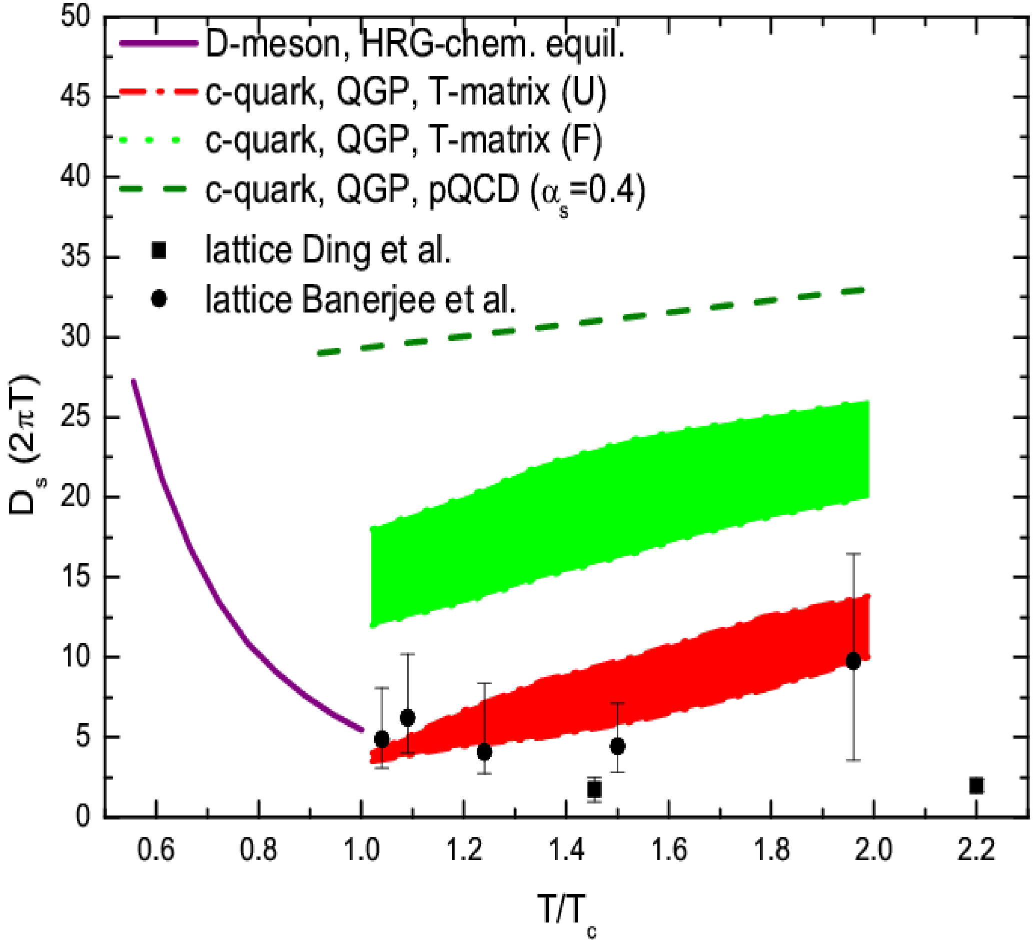




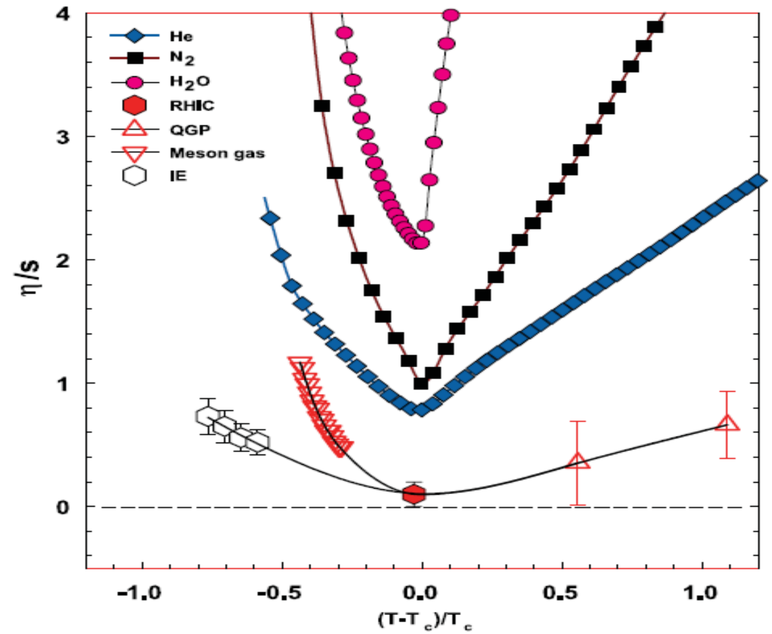
He,Fries,Rapp 2011

- **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.



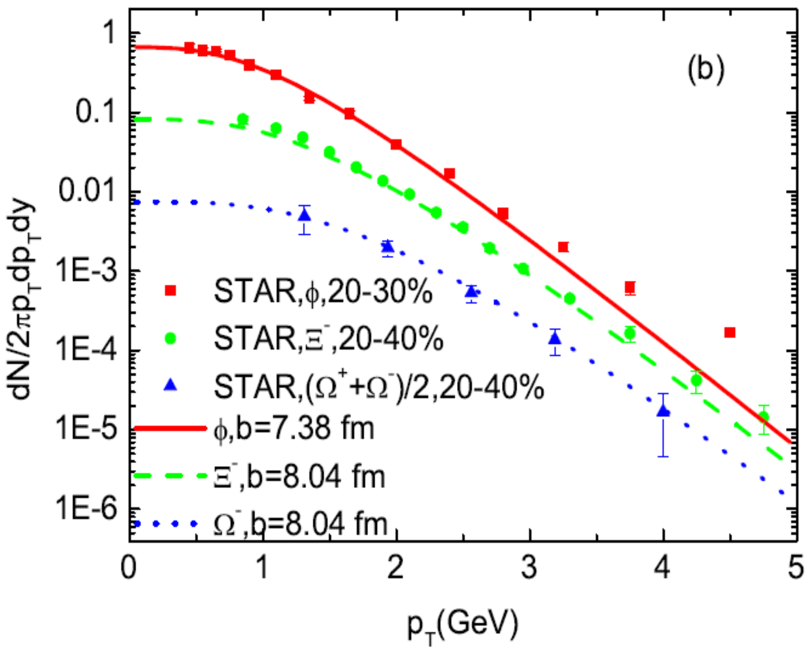
- **viscosity.**: **eta/s = (1/5 ~ 1/2)$D_s T$;** Danielewicz&Gyulassy, 1985
- **D_s translates into eta/s = (2-5)/4pi at T=180 MeV**

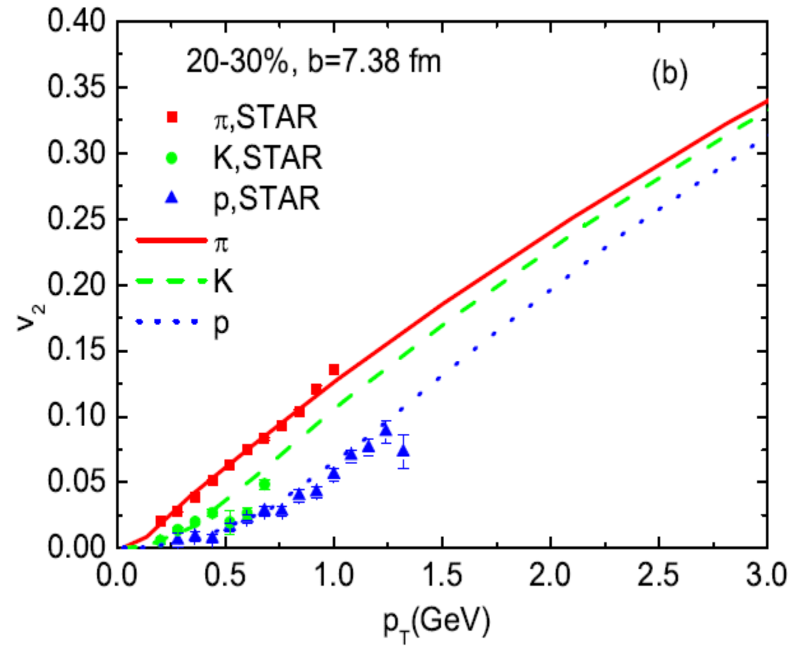


- **Ds=T/(mA): T-matrix vs lattice; Minimum around Tc + Quark-hadron duality?!**
- **The charm diffusion: another perspective of looking into the transport properties of sQGP/dense matter**

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 v2 around Tc





- multistrange hadrons ϕ, Ξ, Ω probably freeze out earlier STAR, PRC79,2009
- multi-strange particles' spectra and v2 fitted at Tch =160 MeV

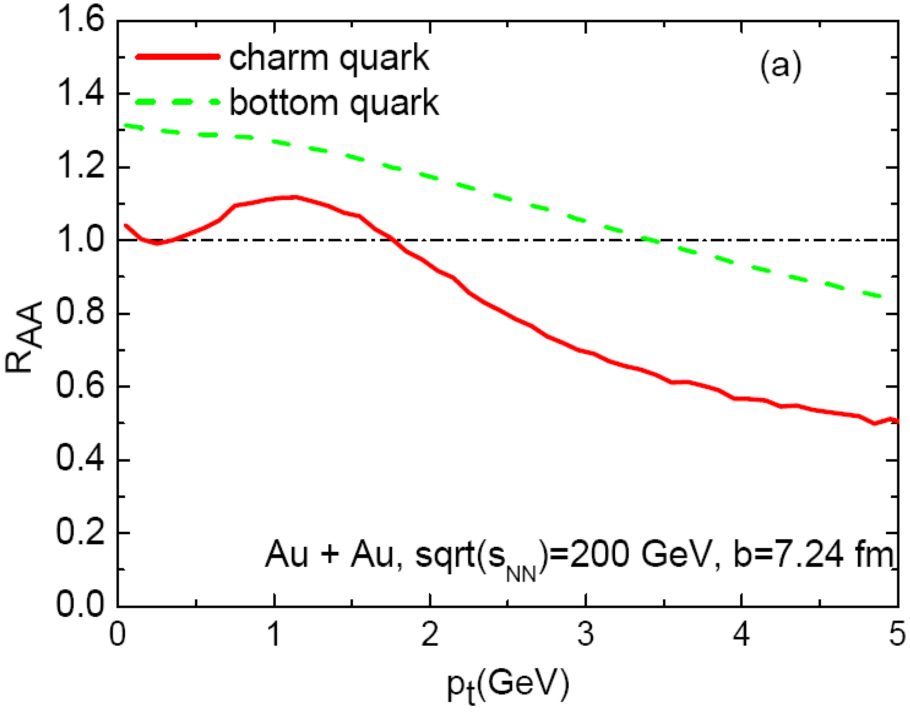
  bulk particles' spectra and v2 fitted at Tkin=110 MeV He, Fries,Rapp,2012

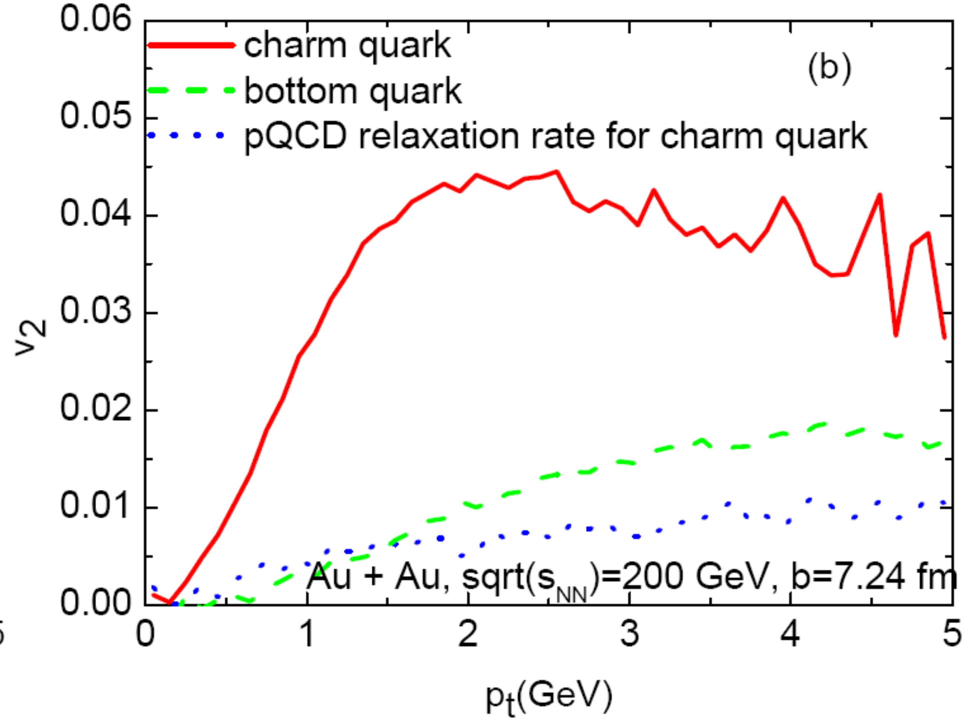
HQ diffusion: Langevin simulation

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

$$d\mathbf{x} = \frac{\mathbf{p}}{E}dt,$$

$$d\mathbf{p} = -\Gamma(p)\mathbf{p}dt + \sqrt{2D(\mathbf{p}+d\mathbf{p})\,dt}\rho$$





- **initial HQ distribution: PYTHIA pp + Glauber nBC**
- **quenching: early stage when medium particles' density is high**
- **v2 : develops at later stage when the medium particles' v2 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**

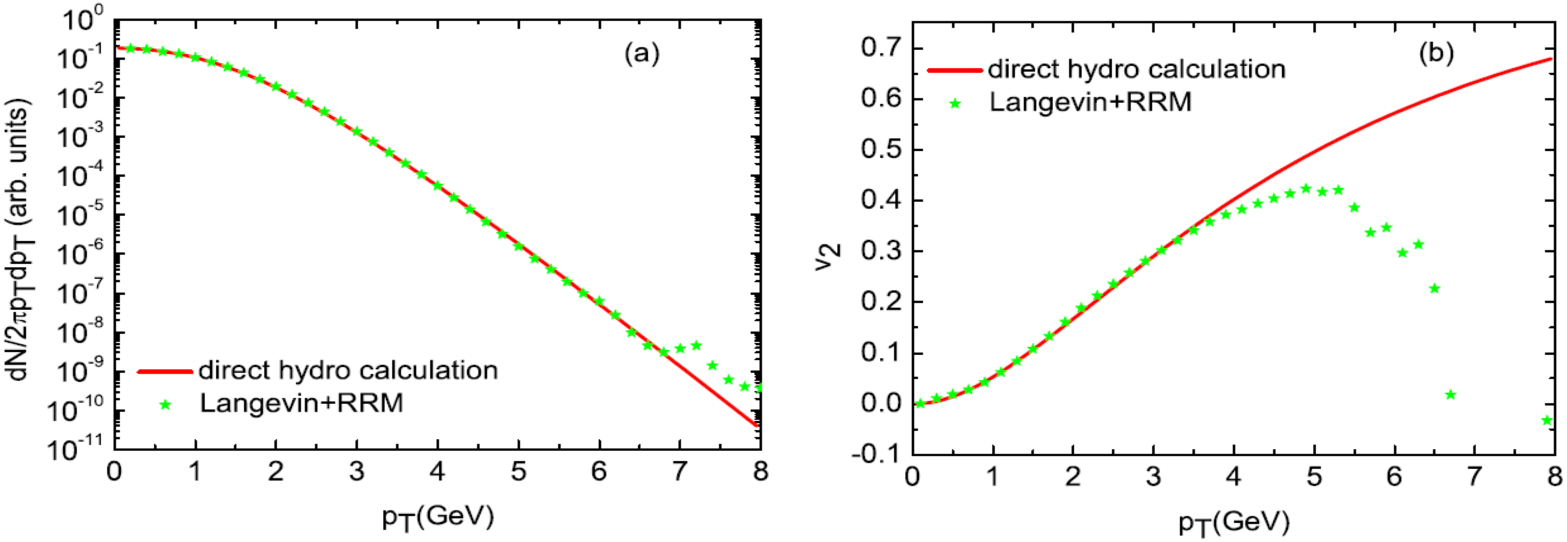
equilibrium mapping between quark & meson distributions

Hadronization: coal. vs frag.

- **RRM coalescence:**

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

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



- **Diffusion vs coalescence: conceptually consistent**

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

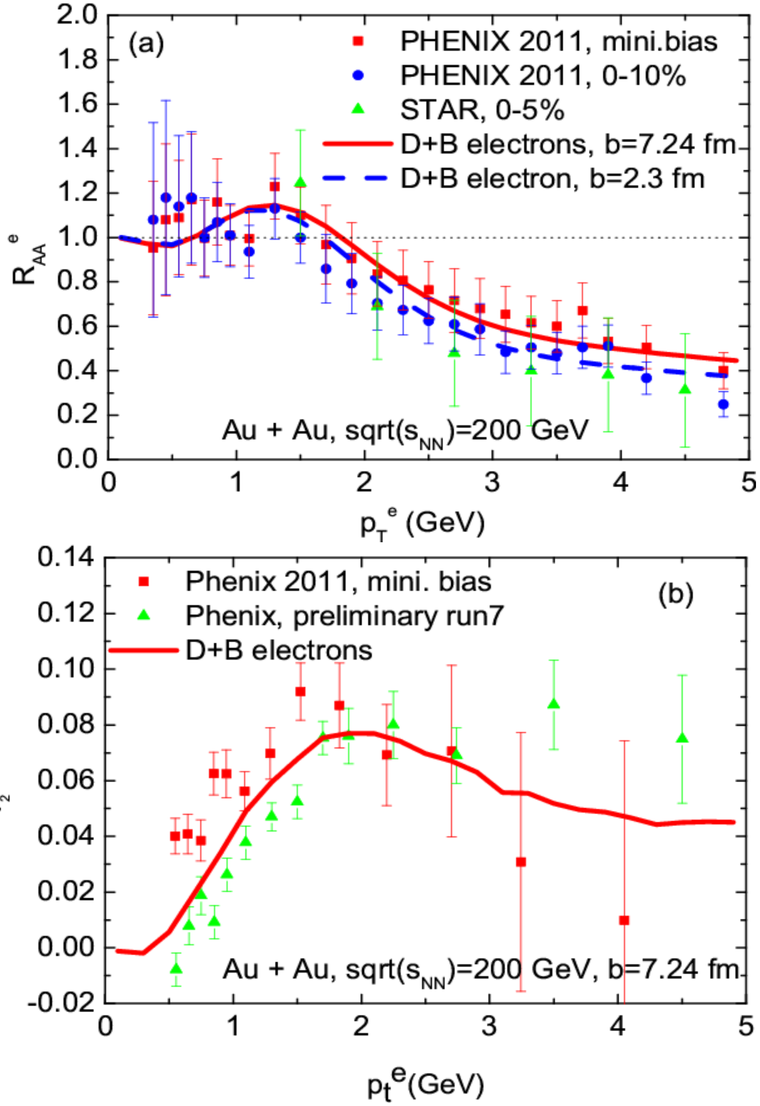
- **Fragmentation: incompatible with thermalization**

--- recombination (P_coal(pt)) dominates at low p_T but yields to frag. at higher p_T

Phenomenology at top RHIC energy

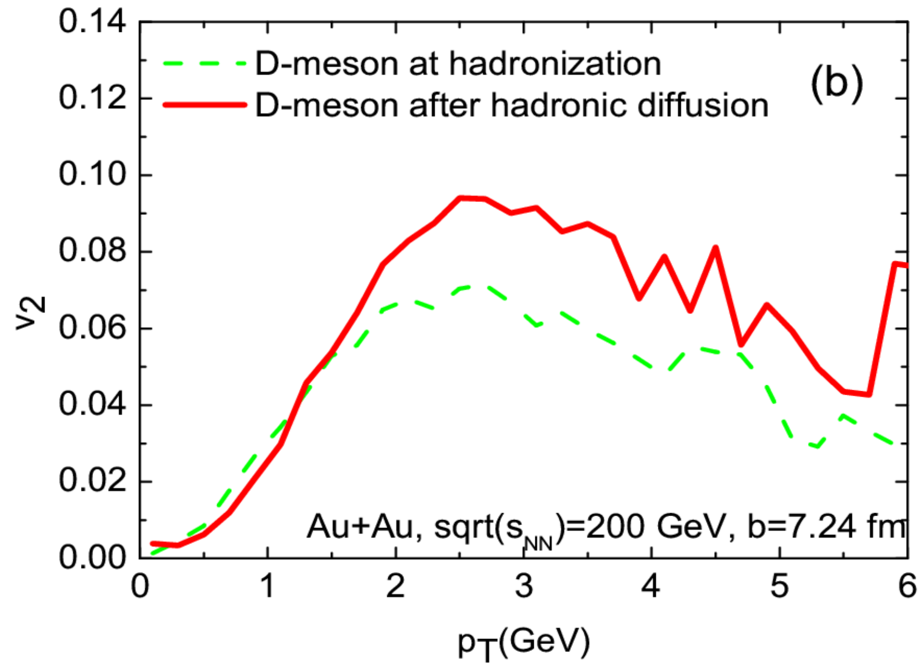
He, Fries, Rapp, Phys.Rev. C86,014903 (2012)
He, Fries, Rapp, Phys. Rev. Lett. 110, 112301 (2013)

e± Spectra @ RHIC

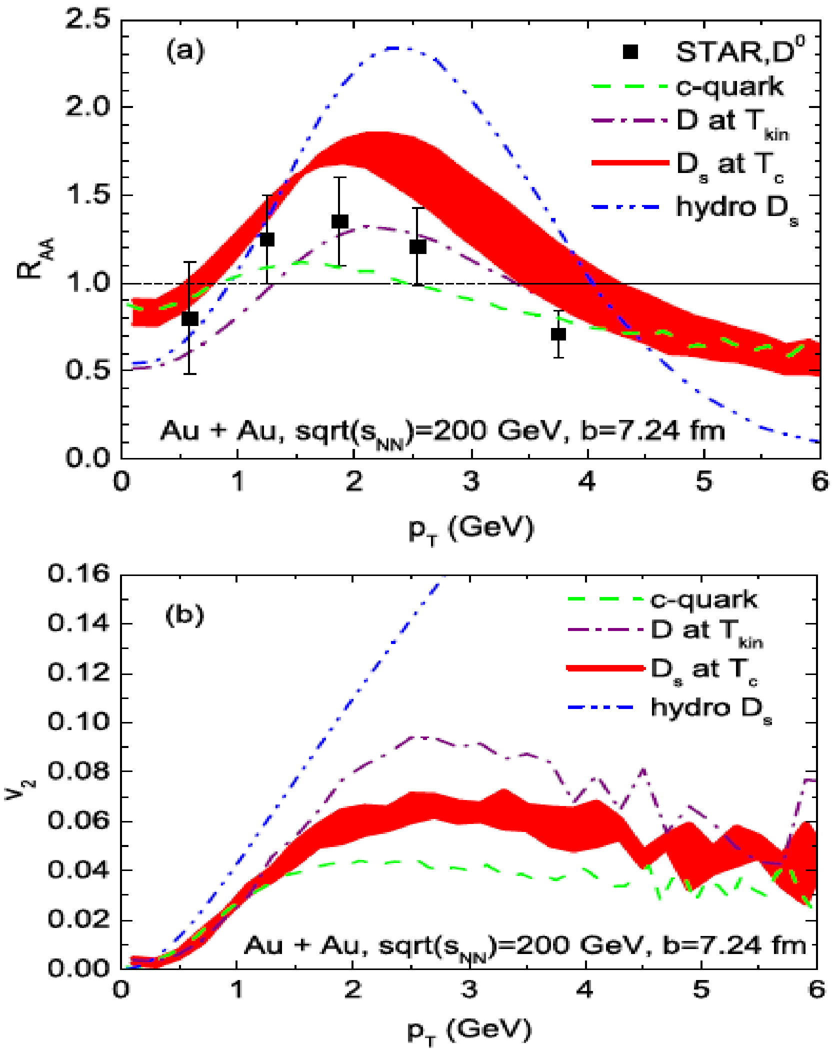


- medium modified D and B mesons: c/b diffusion + coal./frag. + hadronic diffusion
- semi-leptonic decays c(b) → s(c) + e + nu

D-meson Hadronic Diffusion



D vs Ds mesons RHIC



- **pronounced D/Ds flow-bump?!**
  RRM = an extra interaction, driving D-meson closer to equilibrium
- **Ds RAA ~ 1.5-1.8 at pT~2 GeV**
  strong coupling c-QGP + coalescence + strangeness enhancement (unique valence quark content csbar)
- **Ds freezeout at Tc, D at Tkin**
  D vs Ds v2: quantitative measure of charm interaction in hadronic phase

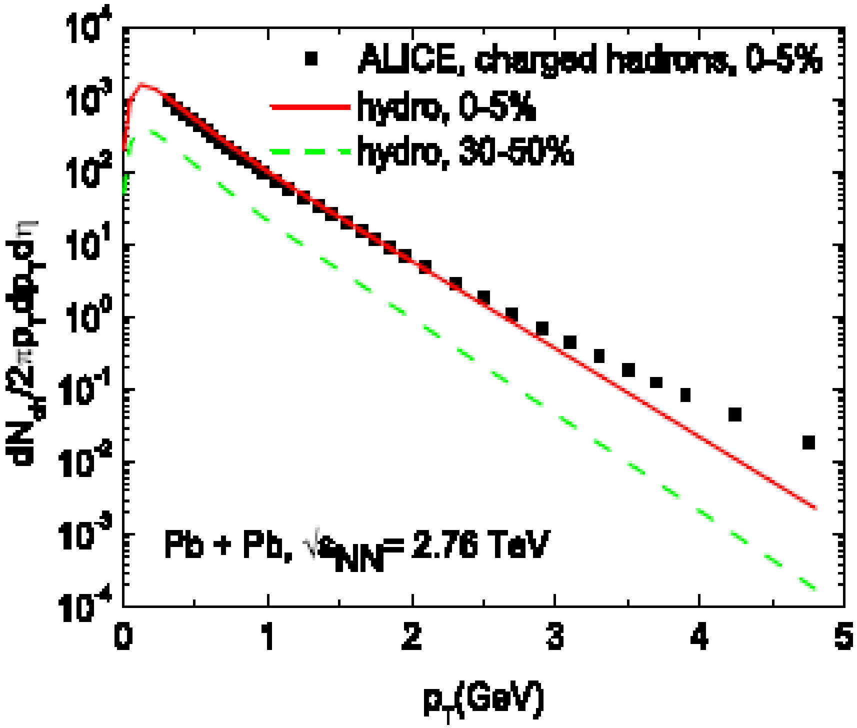
➔a unique pattern of RAA and v2 of Ds vs D mesons emerges

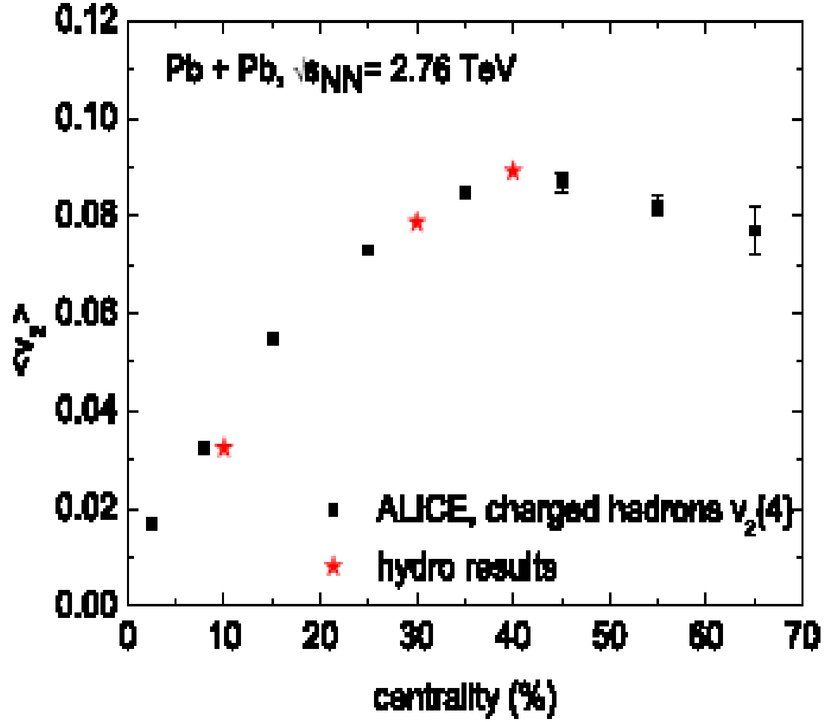
Phenomenology at the LHC
Pb-Pb 2.76 TeV

He, Fries, Rapp, Phys.Lett.B735,445 (2014)

Tuned ideal hydro + FONLL pp baseline + FONLL fragmentations

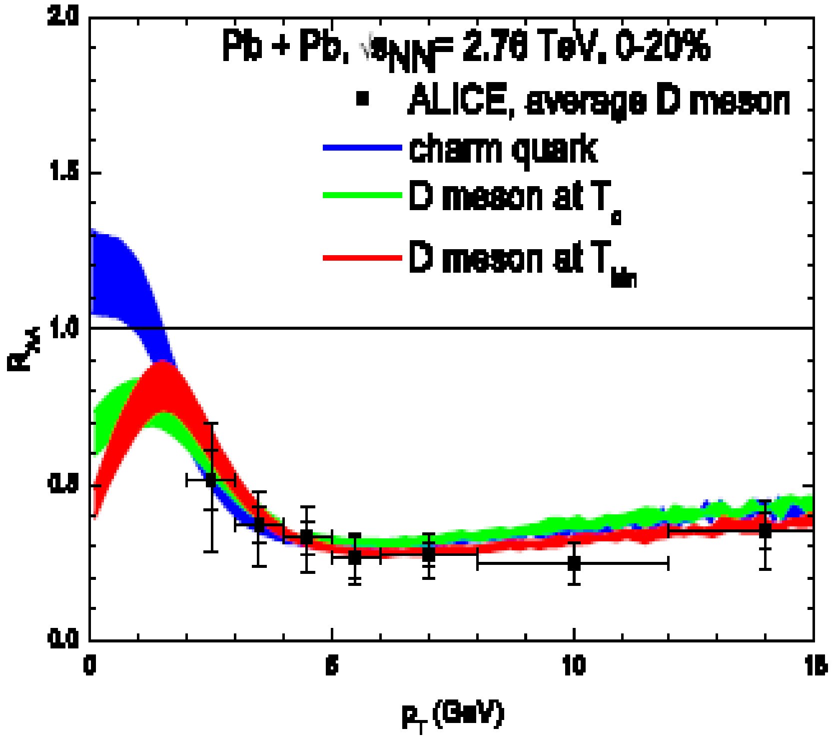
Hydro tune for the LHC

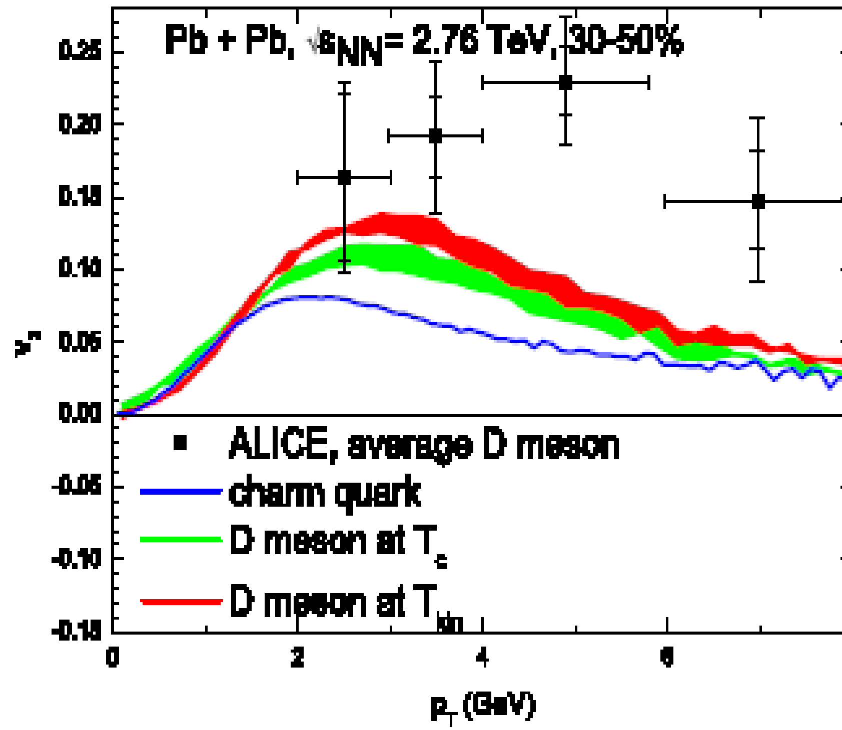




- p_T-spectra of charged hadrons fine
- v_2: integrated elliptic flow a good measure of the bulk momentum anisotropy
- background medium evolution well constrained

LHC D mesons

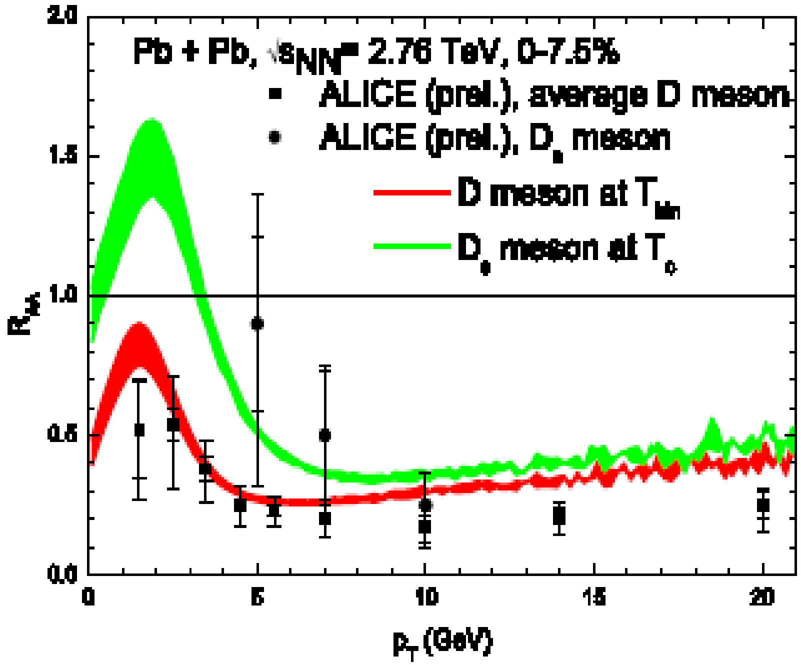


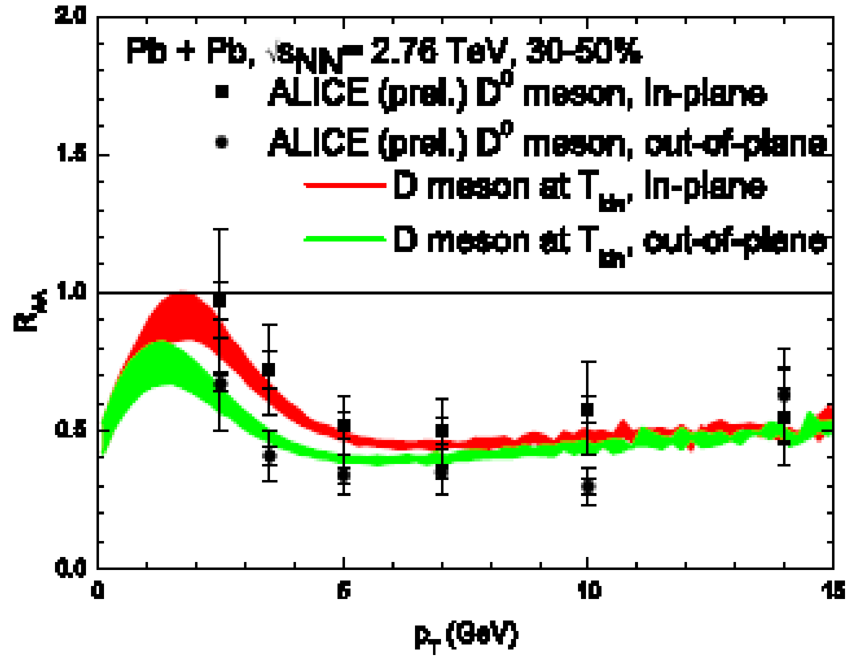


- R_{AA}: flow bump at low p_T, amplified by coalescence
  p_T-dependence shape OK; possible missing radiative energy loss at high pT

- v2: c-diffusion only accounts for ~50%
  recombination and hadronic phase diffusion essential

LHC D vs Ds mesons

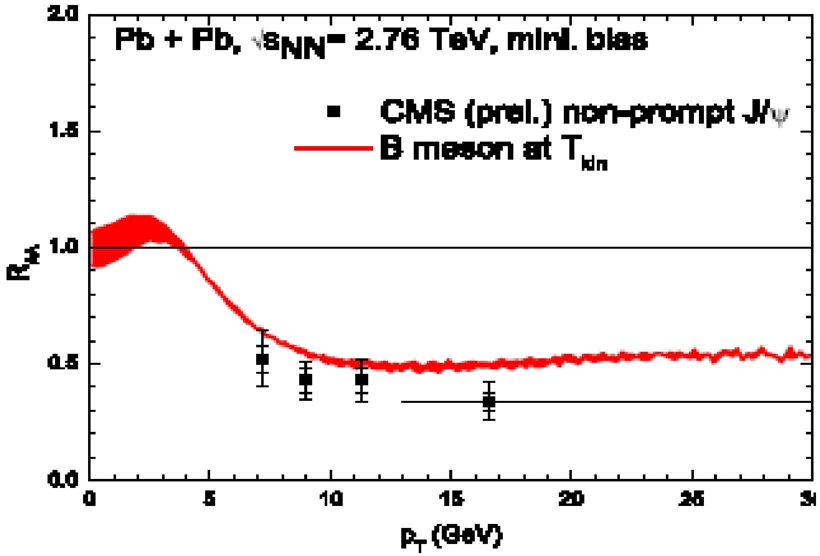


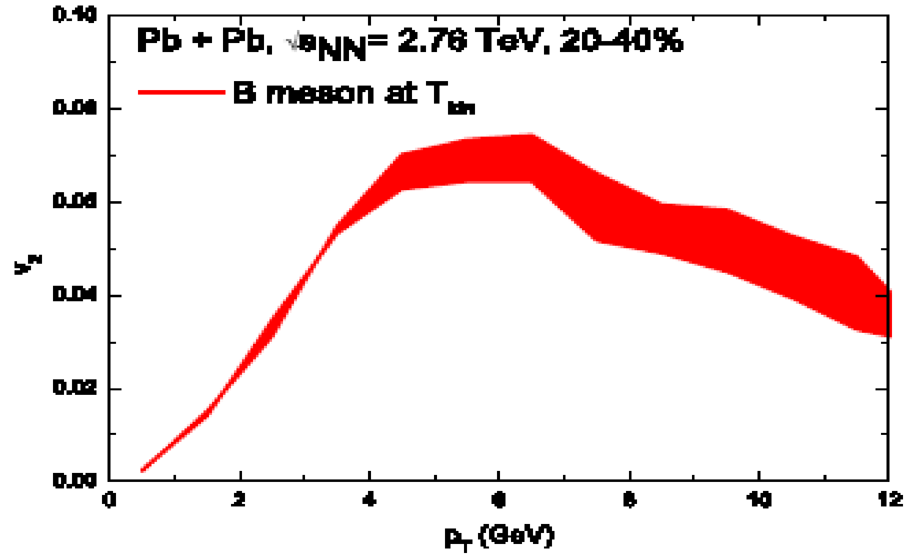


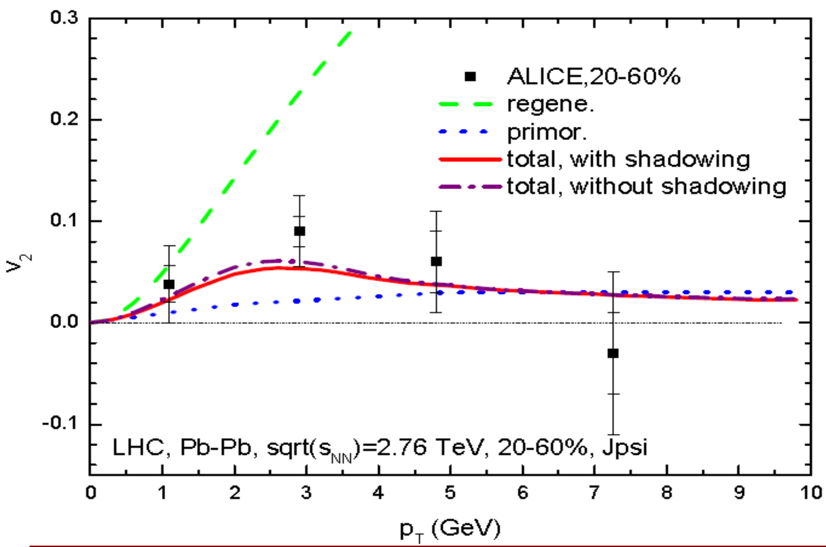
- **D vs D_s R_{AA} : low p_T, coalescence enhances D_s production in a strangeness-equilibrated, strongly-coupled QGP medium; high p_T, D & D_s tend to the same universal fragmentation**

- **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**

LHC B mesons & non-prompt Jpsi



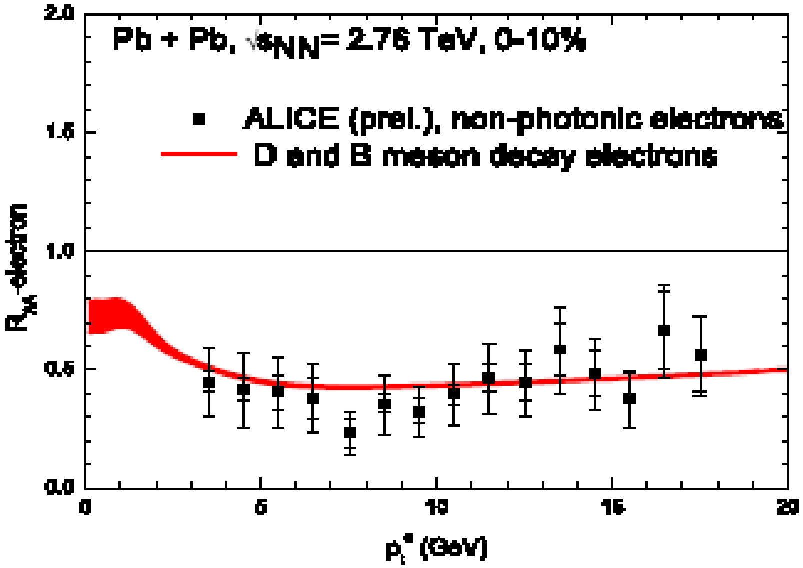


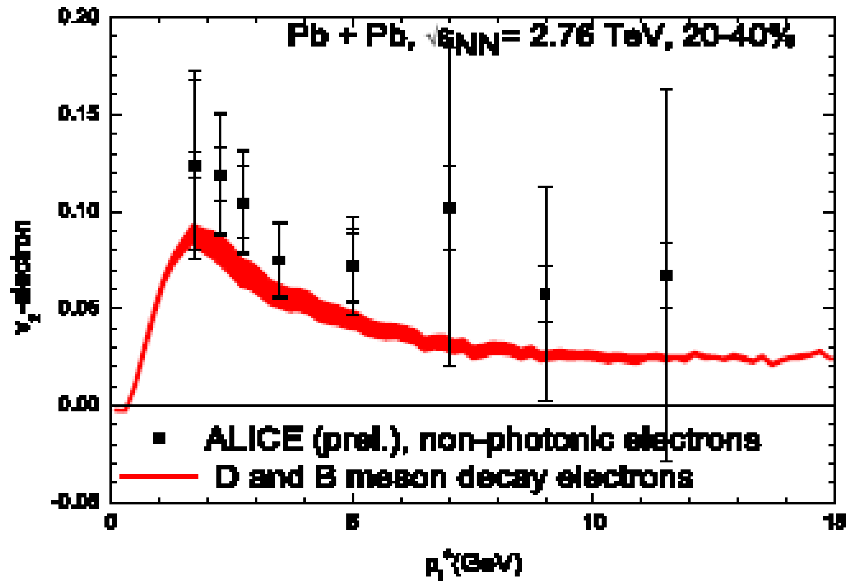


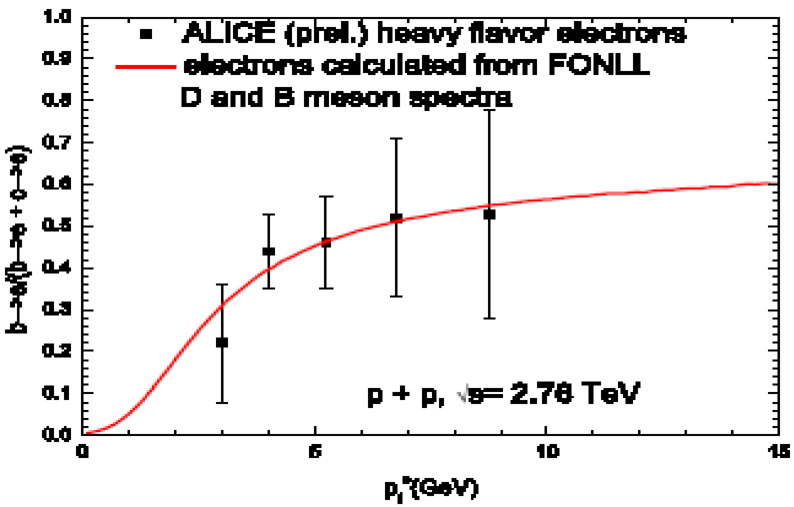
◆ **R_{AA} : substantial suppression (~0.5-0.6) at p_T>10 GeV; consistent with CMS non-prompt J/psi data point**

◆ **v2: up to ~7%, significant yet less collectivity than D mesons ➔ implications for J/psi v2 (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)

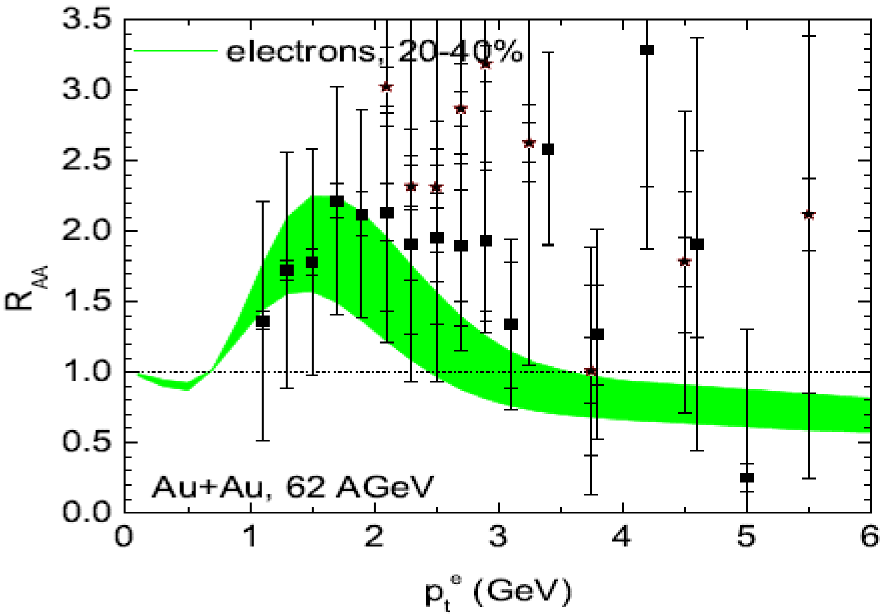
◆ v_2 : marginally hit data, radiative e-loss?

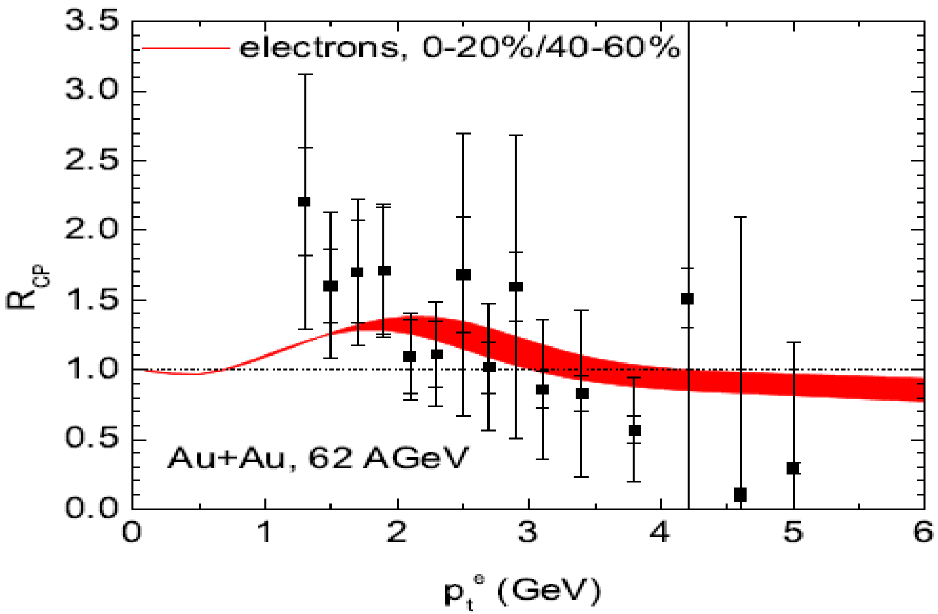
Phenomenology at RHIC
Au-Au 62.4 GeV

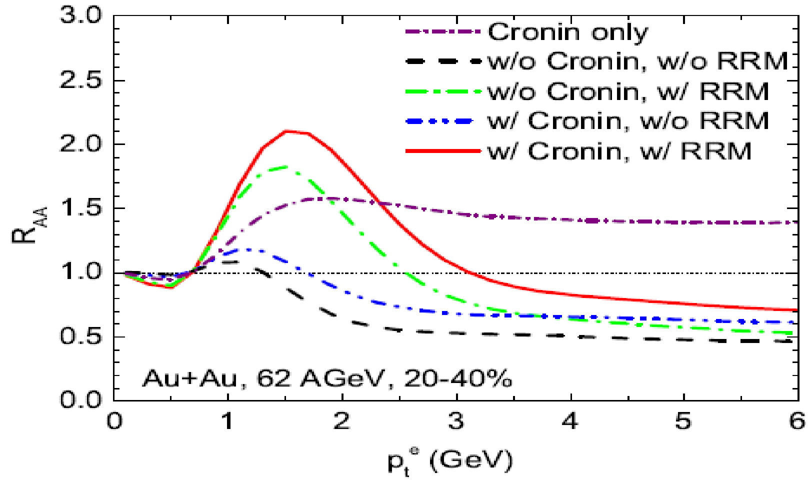
He, Fries, Rapp, arXiv:1409.4539 [nucl-th]

Tuned ideal hydro + FONLL pp baseline + FONLL fragmentations

HF electrons R_{AA} & R_{CP}

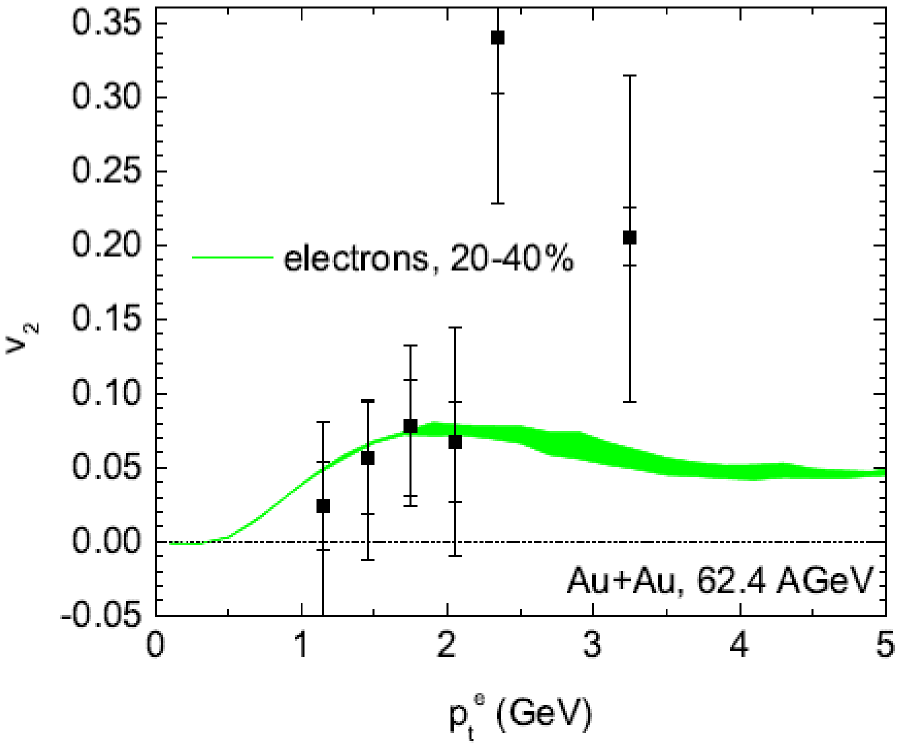


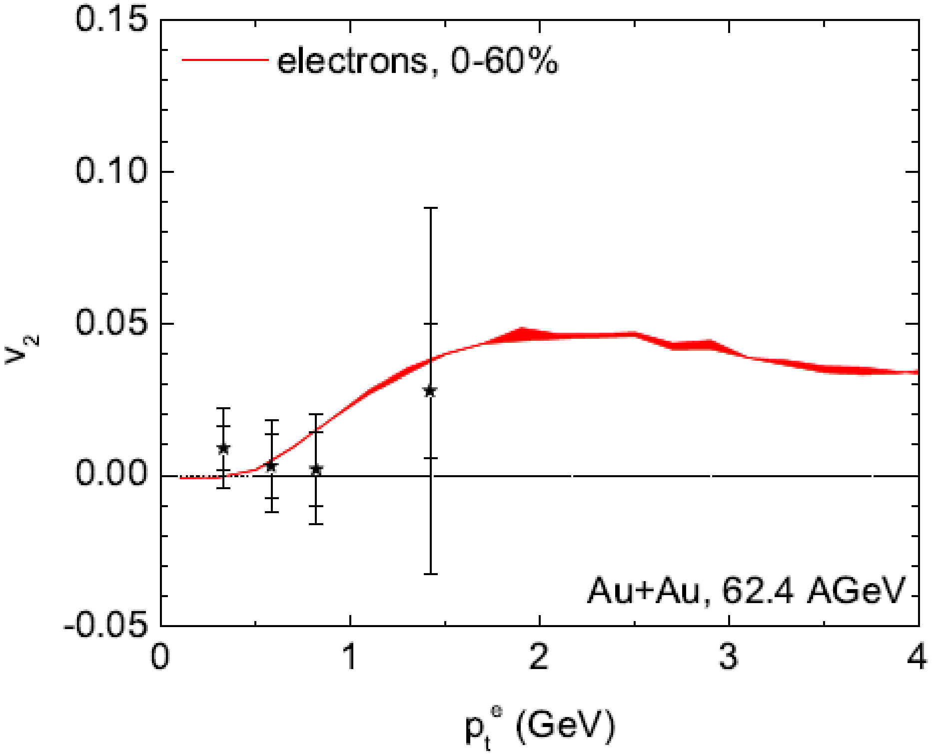




- ◆ **Significant CNM effect: Cronin enhancement even at high p_T bottom dominant region**
- ◆ **Rcp enhancement at p_T=1-3 GeV nicely reproduced, due to recombination flow bump through RRM**

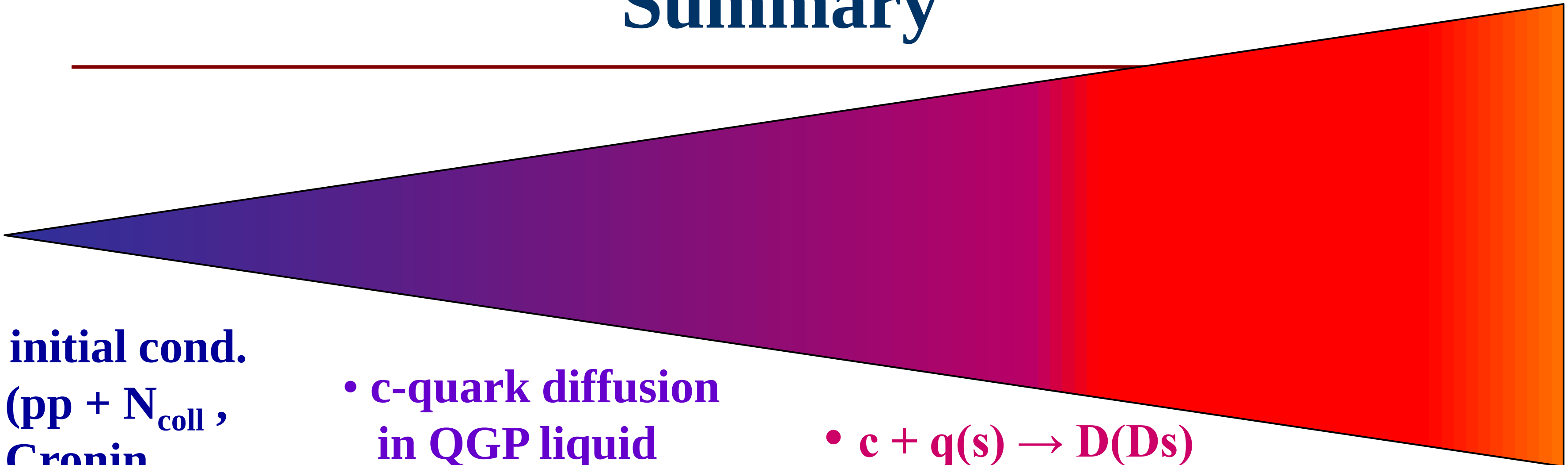
HF electrons v2





- **No discrepancies can be made out, albeit within rather large error bars in data**
- **0-60% centrality v2: from a Ncoll-weighted average of v2's of the 0-20%, 20-40% and 40-60% centrality bins**

Summary



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

● Conceptual Consistency

- diffusion ↔ hadronization:

  based on the same resonant interaction from T-matrix

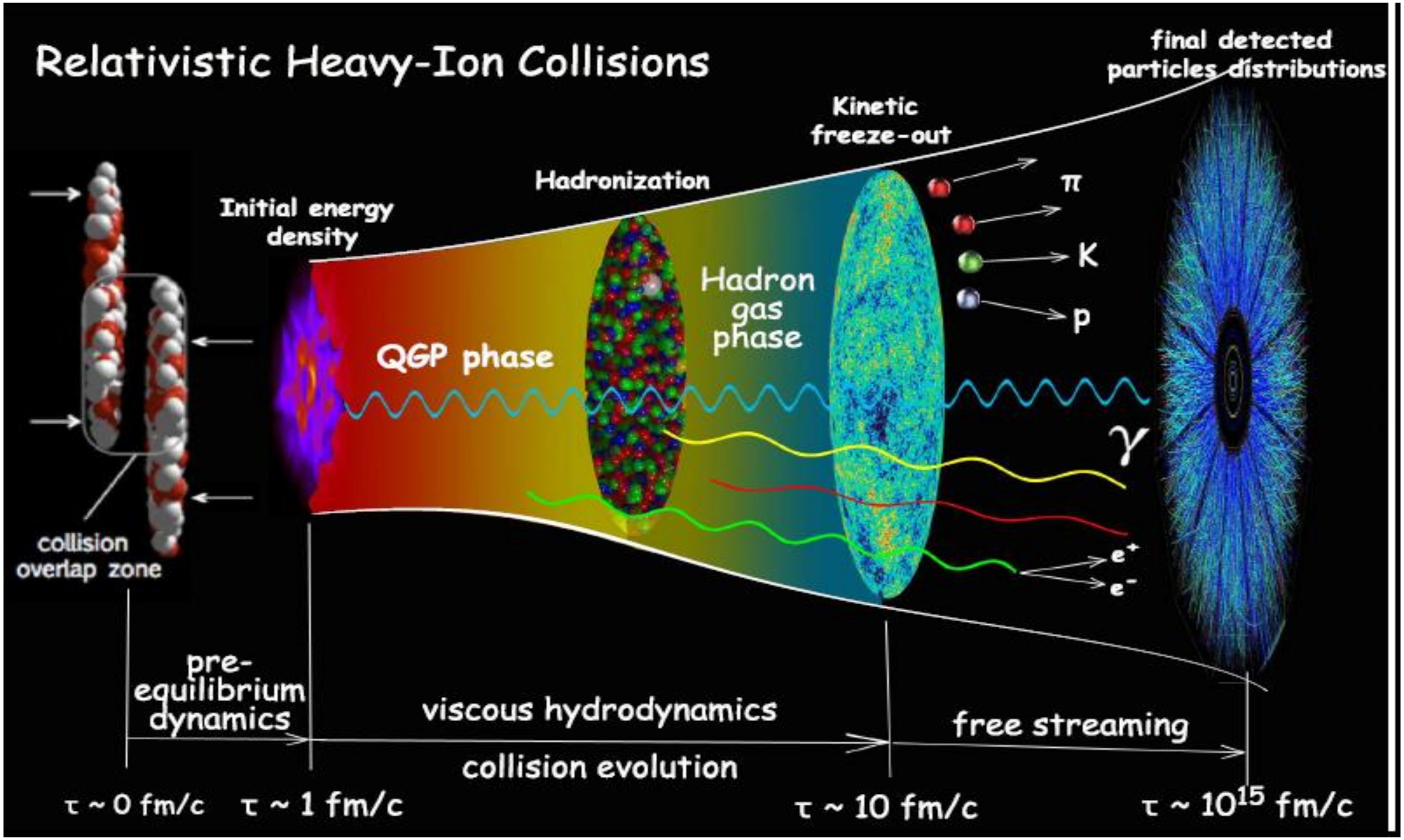
- diffusion ↔ bulk medium:

  both based on strongly coupled QGP, non-perturbative

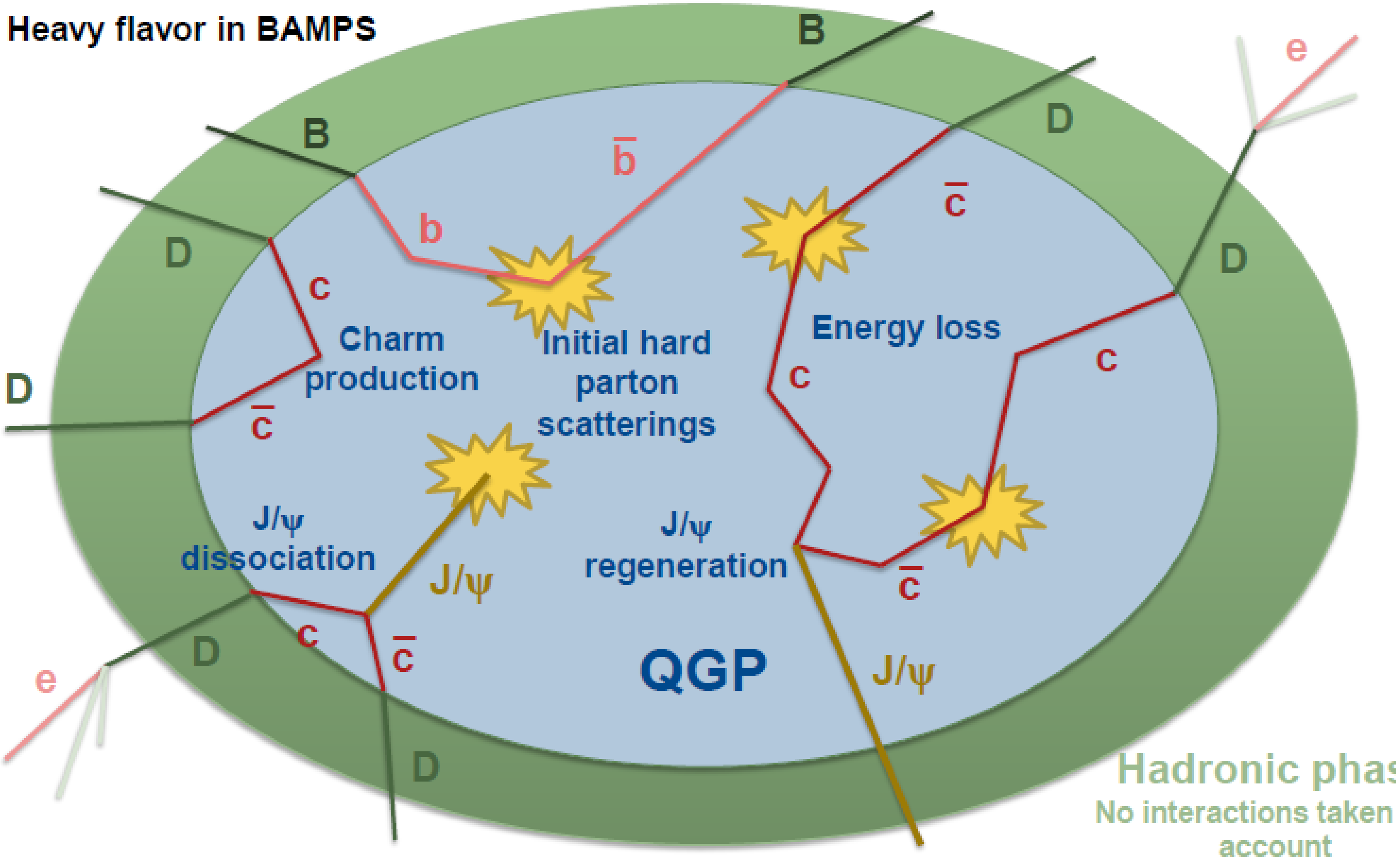
● Application: RHIC & LHC

dynamical charm flow features emerge

Backup: space-time evolution of HIC



Backup: Heavy quarks

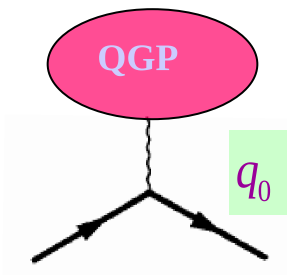


Backup: HQ probes

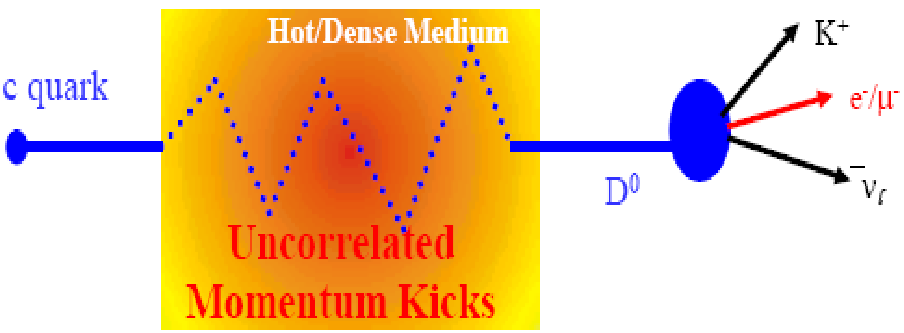
- primordial hard production + number conserved
- thermalization delayed $\tau_Q \approx \frac{m_Q}{T}\tau_q \approx 6 * \tau_q \geq \tau_{QGP}$

➔Heavy quarks make a direct probe of the medium

- HQ diffusion in QGP: elastic scatterings with medium



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



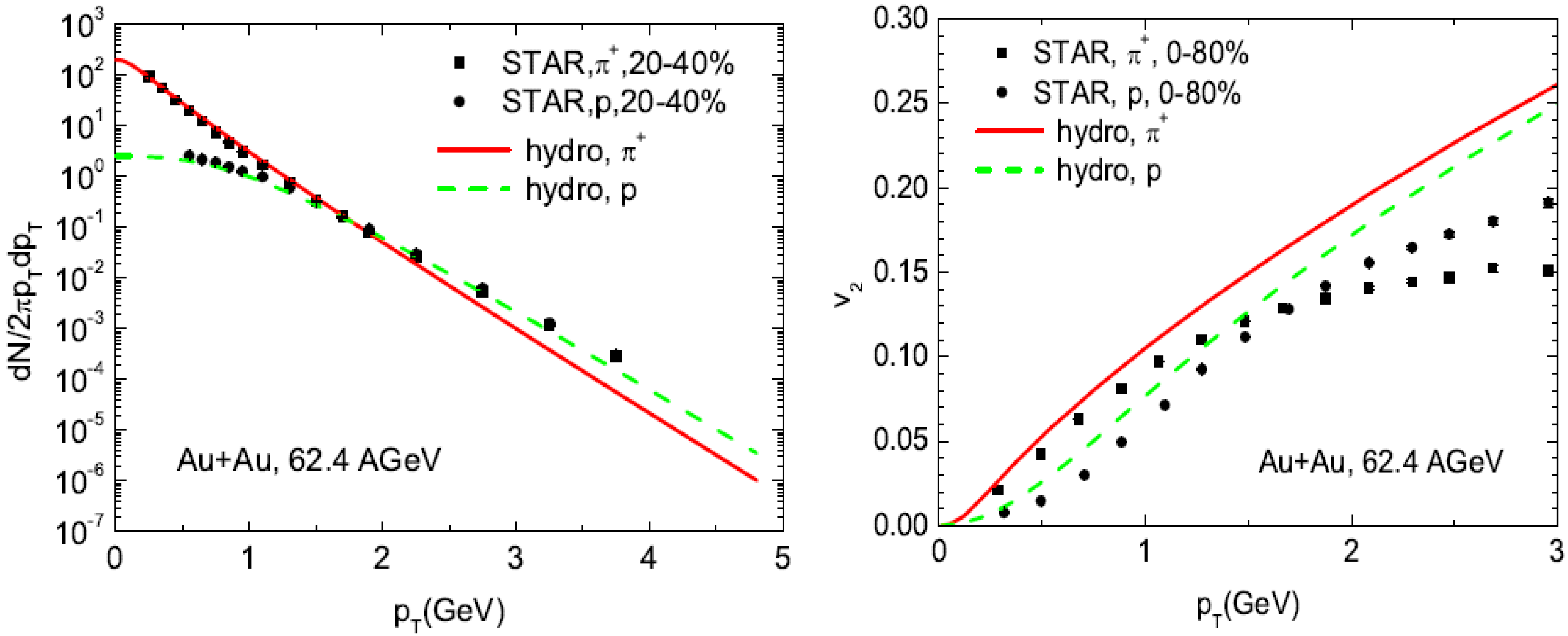
Brownian motion:
Fokker-Planck Equation

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

thermalization rate — diffusion coefficient

$\gamma : \int |T_{Qq}|^2 (1-\cos\theta) f^q$ $\quad D = \gamma m_Q T$

Hydro tune for the Au-Au 62.4 GeV



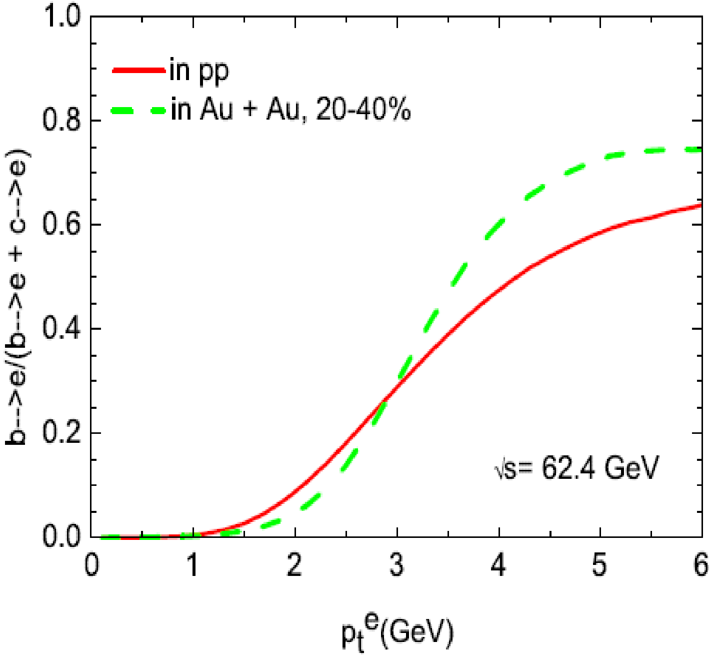
◆ p_T-spectra of pi, p well described, Tkin=130 MeV, initial radial flow tanh(0.035r)

◆ v_2: differential flow over-predicted a bit. No viscosity. And tau_0=0.9 fm/c.

◆ background medium evolution well constrained

b/c Au-Au 62.4 GeV; Compare R_{CP} by Duke

b/c=1.9E-3 from FONLL 62.4 GeV,
VS b/c=9E-3 from FONLL 200 GeV
VS b/c=5E-2 from FONLL 2.76 TeV



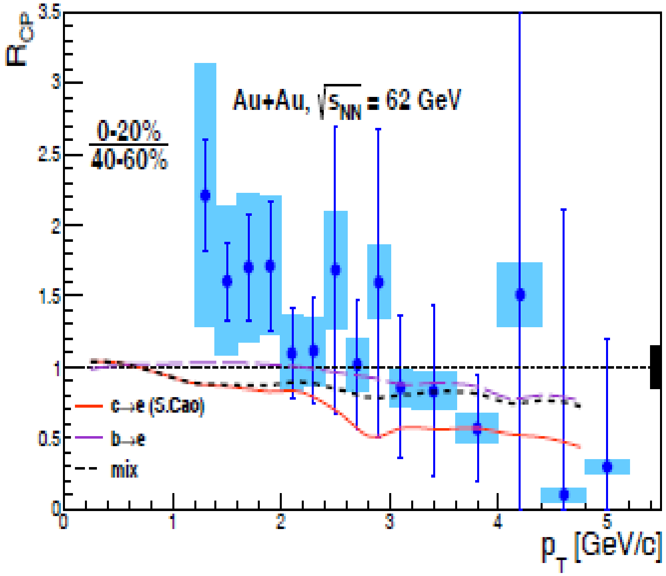
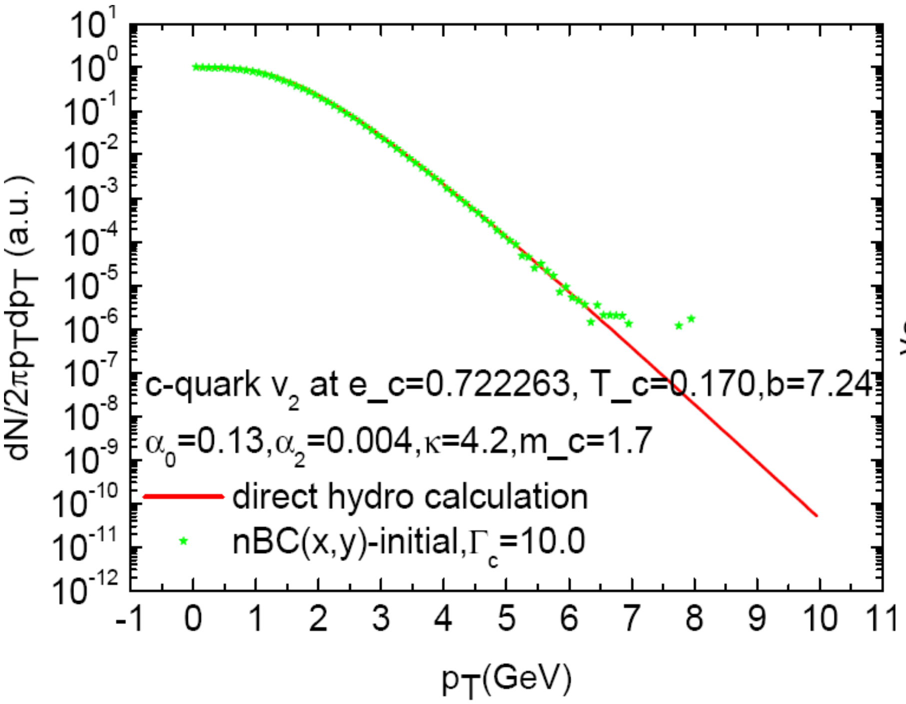
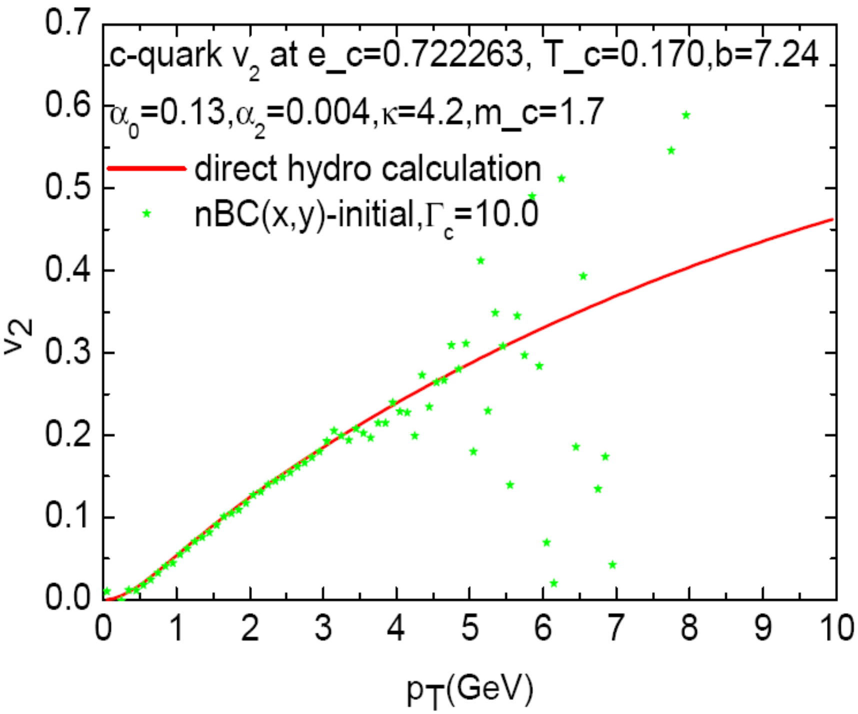


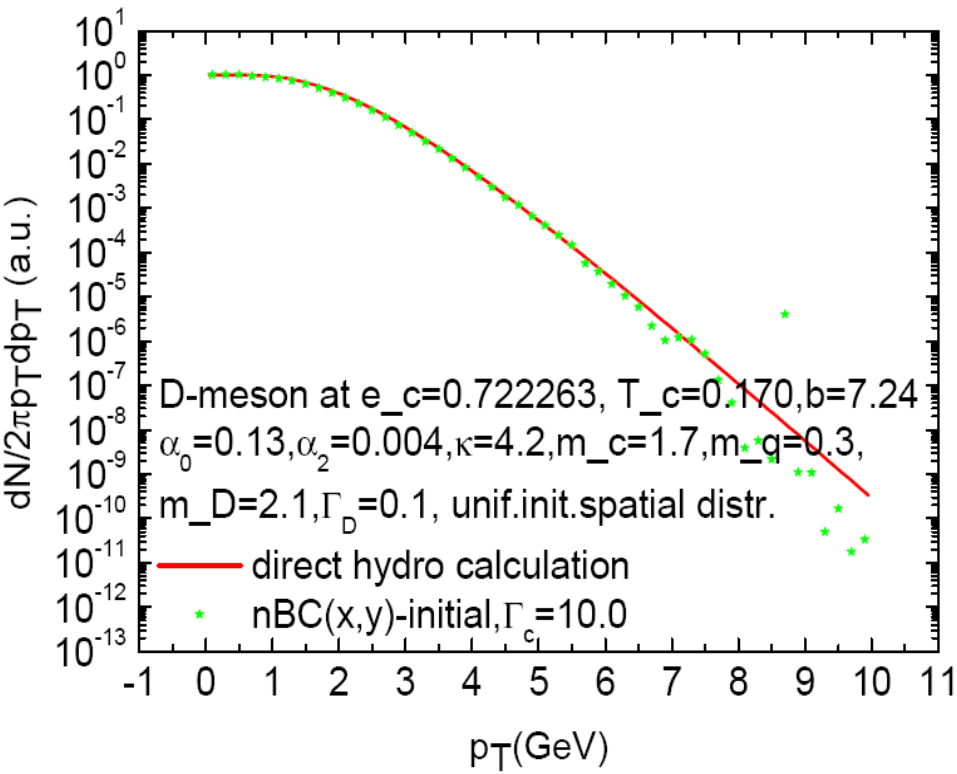
FIG. 19: (color online) Heavy flavor electron R_{CP} between centrality 0%–20% and 40%–60% in Au+Au collisions at $\sqrt{s_{NN}}$ = 62.4 GeV. The curves are calculated using a model based on energy loss [48].

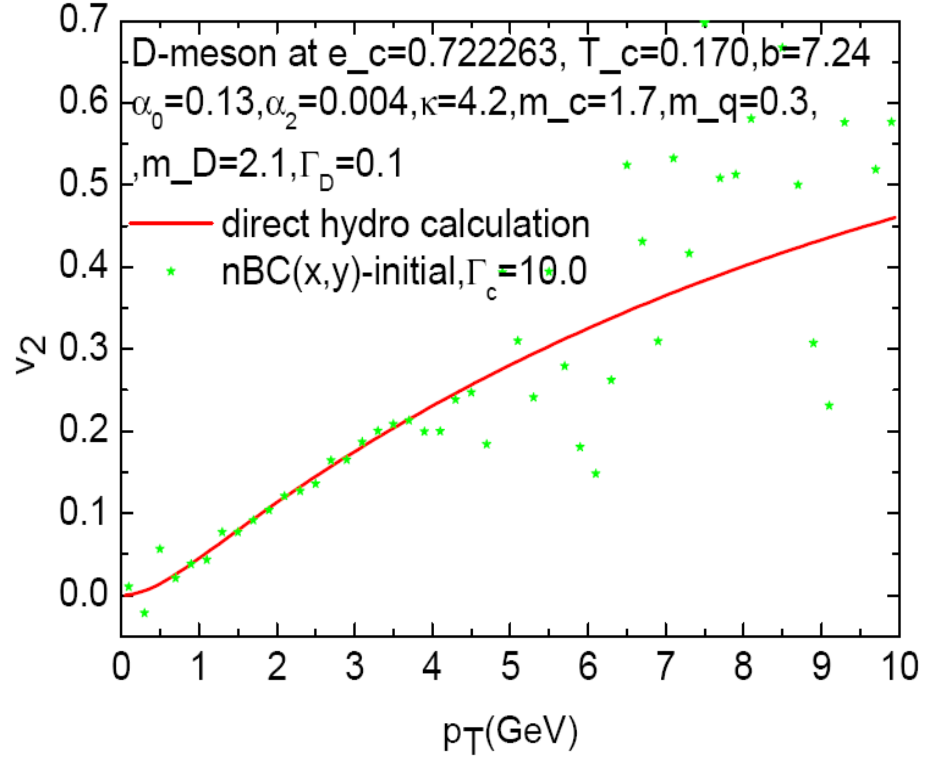
Backup 1: charm quark Langevin diffusion equilibrium





Backup 2: D-meson RRM equilibrium





Backup 3: D-meson hadronic phase Langevin diffuison equilibrium